Journal of Hydrology 511 (2014) 665–674

Contents lists available at ScienceDirect

Journal of Hydrology

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

Flow dynamics and salt transport in a coastal aquifer driven by a stratified saltwater body: Lab experiment and numerical modeling

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ARTICLE INFO

Article history:
Received 25 July 2013
Received in revised form 3 February 2014
Accepted 4 February 2014
Available online 15 February 2014
This manuscript was handled by Peter K. Kitanidis, Editor-in-Chief, with the assistance of Xunhong Chen, Associate Editor

Keywords:
Interface
Laboratory experiment
Numerical model
Salinity
Stratification
Intrusion

SUMMARY

This paper examines the transient development and the steady-state configuration of groundwater within a coastal aquifer adjacent to a stratified saltwater body. Such systems consist of three different water types: the regional fresh groundwater, and low and high salinity brines forming the upper and lower water layers of the stratified water body, respectively. The dynamics, location and the geometry of the interfaces and the density-driven circulation flows that develop in the aquifer are examined using laboratory experiments and numerical modeling at the same scale. The results show that the transient intrusion of the different water bodies into the aquifer takes place at different rates, and that the locations of the interfaces between them change with time, before reaching steady-state. Under steady-state conditions both the model and the experiments show the existence of three interfaces between the three water types. The numerical model, which is calibrated against the salinity distribution and groundwater discharge rate in the laboratory experiments, allows the quantification of the flow rates and flow patterns within the aquifer. These flow patterns, which cannot be derived from laboratory experiments, show the transient development of three circulation cells which are confined between the three interfaces. These results confirm the hypothesis that has been previously suggested based solely on a steady-state numerical modeling defined by a conceptual understanding. Parametric analysis shows that the creation of three circulation cells and three interfaces is limited to certain conditions and defines the ranges for the creation of this unique system.

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1. Introduction

A freshwater–saltwater interface (FSI) is a well-known phenomenon found within coastal aquifers (Bear, 1979; Cooper, 1959; Henry, 1964; Todd, 1980). Understanding the configuration of the FSI and the general flow patterns in such aquifers is highly important with regard to water resource management and planning in coastal areas (Van Dam, 1999).

Numerical models are commonly used to predict the location and movement of the FSI (e.g. Abarca et al., 2007; Abd-Elhamid and Javadi, 2011; Simpson and Clement, 2003, 2004 and references and therein), to support and validate field observations (e.g. Michael et al., 2005; Narayan et al., 2007; Shalev et al., 2009; Voss and Souza, 1987), and to model the FSI under the effect of sea or lake level changes (e.g. Chang et al., 2011; Kiro et al., 2008; Robinson et al., 2007; Yechieli et al., 2010). Laboratory experiments are often quantified by numerical models (e.g. Abarca and Clement, 2009; Chang and Clement, 2012; Goswami and Clement, 2007; Kuan et al., 2012; Morgan et al., 2013; Stoeckl and Houben, 2012; Thorenz et al., 2002). All the above studies consider only seas and lakes with a non-stratified water column.

Lately, Oz et al. (2011) used a numerical model to show the steady-state configuration of the FSI and general flow patterns within a homogeneous coastal aquifer adjacent to a long-term stratified lake. They showed that the system is more complicated, as three interfaces between the three different water types (the fresh groundwater and the two layers of the saltwater body) develop within the aquifer along with three circulation cells. However, no field data and/or laboratory work were used to support this hypothesis. In addition, the transient development of such system was not studied.

The objectives of the present study are to (1) use a laboratory-scale experiment, combined with numerical simulation at the same scale in order to confirm the concept suggested by Oz et al. (2011); and (2) study the transient development of the system.

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http://dx.doi.org/10.1016/j.jhydrol.2014.02.020
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2. Materials and methods

2.1. Laboratory experiment

The laboratory experiment was conducted in a two-dimensional rectangular flow tank made of 3 cm thick Plexiglas, simulating a homogenous and phreatic coastal aquifer (Fig. 1). The flow tank is 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 during the experiment. The left chamber represents the saltwater boundary (the open water system) and contains a stratified water column (see below). The right chamber represents the inland boundary of the regional fresh groundwater. The two side chambers are each separated from the porous medium chamber by plastic screens with a fine net in order to prevent the passage of granular material from the main chamber to the side ones.

The experimental results were derived by two independent methods: (1) visual observation of the dye tracers in the different water types within the cross section; and (2) sampling and analysis of water from specific points of interest within the central chamber. The three water types used in the laboratory experiments are: (1) fresh groundwater (FG); (2) low salinity brine (LSB); and (3) high salinity brine (HSB) (Table 1). Both brines were prepared prior to the experiment by dissolving NaCl in distilled water. 10 g of dye tracers are then added to 20 l of the solutions – commercial red food color (AmeriColor, Ltd.) to the LSB and Pyranine (Green color, 8-Hydroxypyrene-1,3,6-trisulfonic acid, trisodium salt; 75%) to the HSB. The adsorption of the food color and the Pyranine to the quartz grains in these concentrations is negligible (our own batch experiments, (Magal et al., 2008). The densities were measured by a digital density meter (Kyoto Electronics, DA130N) normalized to a temperature of 25 °C. The salinities were determined by chemical analysis. The influence of temperature on the density of the waters was neglected as the initial temperature of the waters (20.8 °C) did not vary by more than 1 °C throughout the experiment. The sampling points were used in order to obtain the in situ salinity distribution within the porous medium. This method was used only under steady-state conditions, since the changes in the water type configurations during the transient development are faster than the sampling of a full set of points. 40 Septum caps were placed within drilled holes at the back of the central chamber, from which water was sampled by pumping a small volume with a syringe (0.5 ml) from selected points. This method ensures minimum distortion of the flow field. The salinity of the samples was determined by their electrical conductivity values after calibration against solutions with known salinity.

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. Stratification in the saltwater chamber was maintained by injecting HSB and LSB through pipes E and C, respectively, using a peristaltic pump (a1) with a constant flow rate. The LSB flows out of the saltwater chamber into the upper overflow collector through pipe B. The height of this outflow pipe (B) determines the water level within the saltwater chamber, which simulates the level of the stratified water body. The HSB flows out of the saltwater chamber into the lower overflow collector through pipe D. In order to control the height of the transition zone (7 cm) between the LSB and the HSB within the saltwater chamber (which represents the halocline of the saline lake), the lower overflow collector was located on an elevator (b1). This configuration enables us to control the hydraulic head of the HSB, and to ensure that only the HSB is drained through pipe D which its height is below it (5 cm). The FG flows into the chamber through pipe A. Its level was determined by an overflow bottle, located on an elevator (b2), and connected to pipe A. The FG flows out of the system on top of the LSB through pipe B.

Silica sand from Negev Industrial Minerals, Ltd. was used as porous medium. The sand was sieved to a diameter range of 180–250 μm, and washed with distilled water to remove dust and clay minerals. The oxide coatings of the quartz grains were removed by HCl acid to prevent the sorption of the Pyranine added to the HSB (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 slight horizontal stratification was formed. Prior to the experiment, the in situ horizontal hydraulic conductivity was calculated using a

Table 1
The characteristics of the water types used in the laboratory experiment.

	High salinity brine (ρ_2)	Low salinity brine (ρ_1)	Fresh groundwater (ρ_0)
Measured density (kg m^{-3}) (25 °C)	1197.8	1100.1	996.8
Salinity (g/g)	0.258	0.137	0
Color	Green	Red	No color

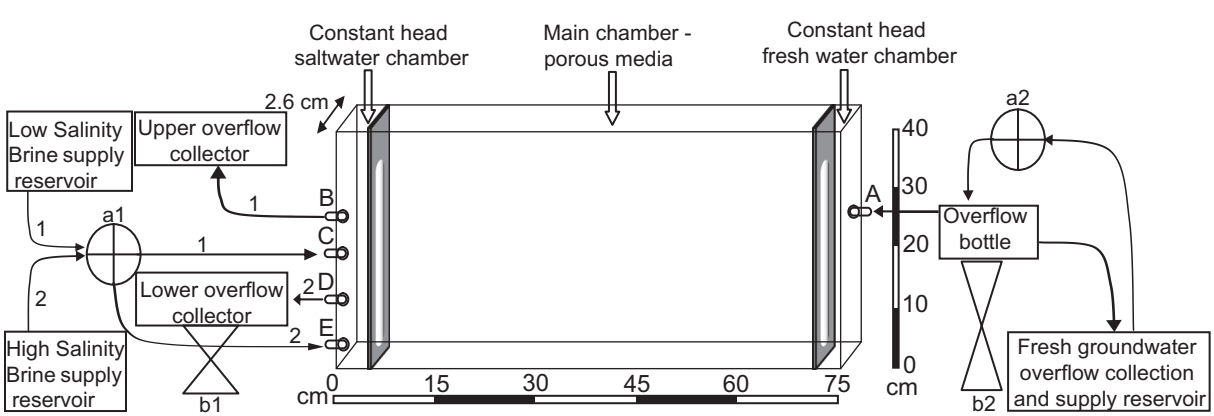

Fig. 1. A schematic diagram showing the laboratory set up with the experimental sand tank and its side chambers. Units a_1 and a_2 are peristaltic pumps (a_1 pumps both the LSB and the HSB), and b_1 and b_2 are laboratory elevators which control the overflow outlet heights.

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