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Laboratory scale simulation of hydraulic barriers to seawater intrusion in confined coastal aquifers considering the effects of stratification

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Abstract

Instability caused in fresh/salt water system in coastal aquifers due to overexploitation, produces the landward movement of the seawater wedge. Hydraulic barriers are created to reduce seawater invasion by injecting freshwater and raising aquifer's hydraulic head. Sensitivity of rate and location of water injection over the wedge length reduction were measured at two laboratory-scale sandboxes under hydraulic confinement. Homogeneous and stratified media were evaluated, being the latter case a prevalent condition in natural coastal aquifers [9]. Sandboxes disposed to simulate seawater wedge and afterwards, allow the injection through horizontal wells installed in a 10cm x 10cm mesh. The best hydraulic barrier performance was observed in the extreme point of wedge, 17.8% of reduction in homogeneous media and 78.9% in stratified media. Regarding rates of injection, the highest reduction of saltwater intrusion was achieved with the highest injection rate applied at one location. Stratification affects performance of hydraulic barrier, for stratified medium smaller injection rates were necessary to reduce saltwater intrusion. It could be also concluded that for stratified medium, injected freshwater caused almost a complete wash of the wedge at the layer of injection and layers of coarse grain size maintain traces of saltwater wedge at steady state attained after injection. On the other hand, contrast between layers of stratified media, caused important changes in thickness of mixing zone, increasing as dispersivities rise, K decays and layer thickness increment.

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Keywords: Seawater intrusion; coastal aquifer; hydraulic barrier; aquifer stratification; laboratory experiment.

1. Introduction

Coastal aquifers are principal sources of fresh water in various parts of the world due to its groundwater quantity and quality, suitable to cover water needs of cities, rural villages and agricultural and industrial activities. Approximately 70% of world population lives in coastal regions [12], causing over-exploitation of aquifers. As a result, aquifer hydrodynamic balance is modified, allowing seawater to penetrate into it causing groundwater pollution and the abandon of agricultural lands [4], a problem known as seawater intrusion. To control its effects, hydraulic barriers are

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created, they raise freshwater head and pull back salt water advancing front. Under normal conditions, the characteristic seawater wedge is formed underneath freshwater. Pumping wells reduce aquifer hydraulic head causing seawater advancing front moves inland by density driven flow. Governing equations of density driven flow are mass conservation and Darcy flux for flow and advection dispersion equation for transport, this two are coupled by density-concentration relation, which make this problem highly nonlinear [14].

This phenomenon has been widely studied; Tsanis & Song [13] modeled numerically remediation process to seawater intrusion in coastal aquifers; Younes & Fahs [14] and Huyakorn et. al. [7] apply algorithms to solve governing equations in a semi analytical way. Nevertheless, Bear [3] presents this phenomenon as a case where analytical and even numerically solution, is impossible to find and proposes sandbox models as a satisfactory way to model transition zone and its movement. Reason why Luyun et al. [10], Goswami & Clement [6] and Karasaki et al. [8] studied seawater intrusion by laboratory-scale porous media tanks.

In the present work experiments were completed in two sandboxes to study hydraulic barriers performance in the control of seawater intrusion under homogeneous and stratified conditions, as well as the effects of rate and location of injection with regard to initial wedge position. Stratified media was taken into account due to the fact that this kind of formations are predominant in coastal aquifers [9]. Abarca [1] and Lu et. al. [9] studied the role of stratification in density driven flow, finding important effects over denser plume flow patrons. Setups consisted in acrylic boxes of 70 cm x 45 cm x 4 cm, representing a quasi-two-dimensional confined aquifer. Two towers allowed to control lateral boundary conditions. An overflow pipe was adapted to the towers to maintain hydraulic gradient constant in order to have a constant input flow in the inland boundary and constant hydrostatic pressure in coastal boundary (Fig 1a). Tidal effect was not considered in the simulation. Density variation causes the intrusion of salt water into the sandbox. When induced saltwater wedge reached steady state, the hydraulic barrier was created by water injection in certain location and with a particular rate. A continue injection was carried out till seawater wedge did not present any reduction. Initial and final seawater wedge lengths were used to evaluate barrier performance. Different rates and locations were used to create different scenarios of hydraulic barriers in both homogeneous and stratified media. On the other hand, the effects of media stratification were evaluated in a qualitative way by identifying the differences between wedge shapes and mixing zone thickness between the two medias.

2. Laboratory approach

2.1. Experimental setup

Two sandboxes were used to simulate effects of hydraulic barriers to seawater intrusion. Each sandbox was made by 8 mm thickness pieces of transparent acrylic, allowing to see flow paths in porous media. Sandbox sizes were set to 70 cm x 45 cm x 4 cm. Horizontal wells were disposed in a 10 cm x 10 cm mesh. These 30 wells served as pumping or injection wells as necessary, each well penetrate back side wall and enter 2 cm into the media to guarantee contact directly with porous media. Geotextile was installed in all injection wells and in lateral walls to avoid plugging of pipes. The lateral boundary conditions were achieved with two towers with adjustable drainage pipes (Fig 1b). They have the possibility of measure drainage outflow, useful to estimate hydraulic conductivity and freshwater flux through the sandbox. Upper and inferior boundaries were impervious layers. To avoid preferential flux in the space between acrylic cover and sand, a bentonite layer was added, eliminating upper spaces.