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Research article

Experimental and numerical study for seawater intrusion remediation in heterogeneous coastal aquifer

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ABSTRACT

The contamination of fresh groundwater by saltwater intrusion (SWI) becomes a worldwide alarming problem, which threatens all countries depending on groundwater abstraction from coastal areas. Various control and treatment strategies have been suggested to prevent SWI. The construction of subsurface physical barriers is one of the most practical implementation methods to prevent SWI. In this work, the use of subsurface dam as a remediation and protection tool was investigated in a heterogeneous aquifer via lab scale experiments and numerical simulation. The experiments depended on a novel automated imaged analysis method for SWI measurements. Glass beads of different grain sizes were used in sandbox experiments. The simulation works adopted the SEAWAT code for validation of the experimental results and making numerical sensitivity analyses for affecting parameters. Results proved the significant impact of using sub water dams with heterogonous aquifers. The remediation impacts of the dam was captured clearly in preventing and backwashing of the existed SWI. The results revealed also that the heterogeneous aquifers with high permeability in the bottom boundary behave closer to the homogenous aquifers in SWI than those having low hydraulic conductivity in the bottom. Sensitivity analyses results showed that the closer dam to seawater boundary led to the quicker and more effective backwashing process. Results exhibited also that the dam height with 50% of the aquifer dam has the ability to hold the seawater so long as the hydraulic gradient is high and dams with 67% of aquifer height prevent the saltwater intrusion completely.

1. Introduction

The management of freshwater quality is a vital issue due to the increasingly water demand. Freshwater of the coastal aquifers is mostly vulnerable for dilapidation by saltwater due to its contact with seawater (Werner et al., 2013). Contamination of fresh groundwater by salt intrusion becomes a worldwide alarming problem that threatens many countries depending on groundwater in the coastal areas. The initial alarm of saltwater intrusion (SWI) is the reduction in the available freshwater due to contamination of the production wells. The considerable threat of SWI on freshwater has been well documented in many studies (e.g. Post, 2005; Barlow and Reichard, 2010).

SWI refers to the subsurface movement of seawater underneath the surface of fresh water bodies such as rivers, canals, wetlands or groundwater aquifers. Coastal aquifers, in particular, are complex environments characterised by variable salinities and water density distributions, transient water levels and heterogeneous hydraulic properties. Groundwater pumping and fluctuating sea levels due to tides and weather differences impose dynamic hydrologic conditions, which maximize SWI (Werner et al., 2013). Mixing of only 2% saltwater in a freshwater aquifer exceeds allowable objectives for the upper limit of chloride, as water begins to taste salty. Whereby, more than 250 mg/l chloride renders freshwater unfit for drinking as stated by World Health Organization (WHO, 2011). Mixing exceeds 4% leads to the water becomes unusable for many uses, and if mixing exceeds 6% water becomes unusable except for cooling and flushing purposes (Darnault and Godinez, 2008; Klassen et al., 2014).

In different coastal regions around the world, the problem of SWI has been investigated. Seckin et al. (2010) studied SWI in a costal aquifer in Turkey located close to the Mediterranean. They observed the degradation of the water quality in the areas

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neighboured the sea due to SWI and interpreted this manner as a result to intense use of groundwater for irrigation in these areas. Kouzana et al. (2009) investigated the salinization development in Korba aquifer in Tunisia. Results showed high TDS values especially chloride concentrations in the tested area. They also noted a strong relation between sample composition and marine water composition, which gives an indication about SWI in the aquifer. Sherif et al. (2011) studied the quality of the coastal aquifer water at Wadi Ham located in north eastern part of UAE. They categorized the salinity hazard in this aquifer water as a very high degree. They also reported that SWI extended up to 8 km away from the coast of Oman Gulf to inland. Ahmed and Askri (2016) investigated the water quality of groundwater located in northern costal of Sultanate of Oman. Their study confirmed the freshwater contamination by salt and they stated that the groundwater in the coastal strip of this region neither suitable for drinking nor for irrigation. Their study also referred to the possibility of the reversal process of cleaning the freshwater and pushing the saltwater back in the seaward.

Many researchers studied methods for prevention and remediation of the SWI problem and, hence, several control strategies have been early suggested (Todd, 1959; Van Dam, 1999; Oude Essink, 2001). These control strategies may be summarized into two main methods: the first strategy is using hydraulic barriers by recharging freshwater into aquifers to compensate the freshwater head loss; and secondly, subsurface physical barriers are used to reduce the intrusion or prevent it. Subsurface physical barriers can be defined as underground semi-impervious or impervious structures constructed in a coastal aquifer in seaside to retain groundwater, prevent SWI, and increase the groundwater storage capacity. There are two types of physical barriers, depending on the opening for fresh groundwater flow towards the coast. The first type is the subsurface flow barriers, which are physical barriers inserted across the flow direction to modify the flow field. Flow barriers have openings at the lower aquifer boundary and penetrate the aquifer in a part of its depth. The other type is the sub water dams, which are storage dams with a base imbedded on the aquifer bedrock and an open crest at the upper part of the aquifer (Luyun, 2010). Hanson and Nilsson (1986) reported from field study that areas with 1–5% slope are the most feasible for using sub water dams. They concluded that subsurface barriers are preferably constructed in high hydraulic conductivity sites such as sand and gravel riverbeds, weathered zones, and deep alluvial layers. For using the dam as a remediation tool for SWI in homogenous aquifers, Luyun (2010) concluded that more effective saltwater prevention can be achieved with barrier penetration in deep and at locations closer to the coast. Conversely, when the barrier is installed upstream of the original toe position, freshwater flow towards the sea is impeded and SWI will be exacerbated.

Many experimental and numerical research works were conducted on homogenous aquifers. However, heterogeneity aspect is not yet fully analysed and remains an important topic for future studies. Heterogeneity properties, especially the hydraulic conductivity, has a significant effect on the groundwater flow, and consequently solute transport and SWI. In flow systems with variable-density, heterogeneity can disturb flow over many length scales, ranging from slight differences in the pore geometry to the larger heterogeneities at the regional scale (Abarca, 2006). Some researchers investigated the impact of the multiple hydraulic conductivity layers on the thermal convection and solute transport (Mc Kribbin and O'Sullivan, 1980; Mc Kribbin and Tyvand, 1983). These studies and others examined heterogeneous layers, focused on the solute migration and instabilities caused by dense fluids overlying on the light ones and not on SWI process. Few investigations have been devoted to the study of the effect of heterogeneity on SWI in the coastal aquifers. Schwarz (1999) investigated the impact of the aquifer heterogeneity for typical benchmarks problems of density-dependent flow, such as Henry's problem on SWI.

Reviewing the literature shows an extensive array of field, laboratory and computer-based techniques for SWI investigation spanning for decades. Despite this, knowledge gaps exist in understanding the SWI process associated with transient processes and timeframes particularly, in highly heterogeneous settings (Werner et al., 2013). Few studies have yet focused on evaluating the impact of heterogeneity on SWI. The best of our knowledge, there is no research that has been conducted yet on using subsurface dam in heterogeneous aquifers, In addition, all previous works adopted visual observation to characterise SWI parameters, which is labour intensive, limits the spatial and temporal resolutions of the data, and is prone to human error. In this work, a new automated imaged analysis method presented by Robinson et al. (2015) for SWI measurements was used.

The main objective of this study was to investigate the use of sub water dams as protection tools to control SWI in the layered coastal aquifers. This has been achieved via laboratory experiments and numerical simulation models. The experiments were carried out in the lab scale by using a sandbox having different sizes of glass beads. The numerical simulations were conducted using SEAWAT, a variable-density groundwater flow coupled with heat transport and multi-species solute model. This has followed by sensitivity analysis to examine the effect of different locations, heights of the dam and the impact of different heterogeneous configurations of the layered soils.

2. Materials and methods

2.1. Experimental tests

A perspex tank having central viewing chamber of dimensions 38 × 15 × 1 cm for length, height and depth respectively was adopted in the experiments. The tank was flanked by two circular chambers at either side to provide the hydrostatic pressure boundary conditions. The left and right chambers were filled with fixed head freshwater and reddish dyed saltwater respectively as shown in Fig. 1. The figure shows the whole equipment components and test setup, which include sandbox having glass beads, two attached circular chambers, two electrical level sensors, two drainpipes, two feeding pipes from elevated tanks and finally the

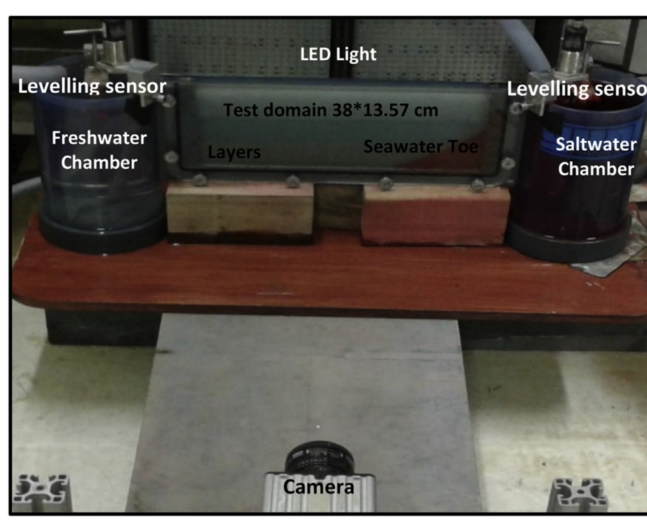

Fig. 1. Test equipment set up.