Journal of Hydrology 377 (2009) 227–236

Contents lists available at ScienceDirect

Journal of Hydrology

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

# Laboratory-scale saltwater behavior due to subsurface cutoff wall

Roger Luyun Jr. [a,*,1], Kazuro Momii [b], Kei Nakagawa [b]

[a] *United Graduate School of Agricultural Sciences, Kagoshima University, 890-0065, Japan*
[b] *Department of Environmental Sciences and Technology, Kagoshima University, 890-0065, Japan*

ARTICLE INFO

*Article history:*
Received 17 March 2009
Received in revised form 30 July 2009
Accepted 16 August 2009

This manuscript was handled by Prof. P. Baveye, Editor-in-Chief, with the assistance of Prof. Renduo Zhang, Associate Editor

*Keywords:*
Cutoff wall
SEAWAT model
Saltwater intrusion
Subsurface dam

SUMMARY

Artificial subsurface barriers are among several countermeasures proposed to control seawater intrusion into coastal aquifers. We performed experimental and numerical studies to investigate the dynamics of residual saltwater trapped in the storage area upon installation of cutoff walls. Experimental results showed that after wall installation, the residual saltwater wedge initially flattened causing its toe to advance, and then gradually retreated before being completely removed from the reservoir behind the cutoff wall. The SEAWAT model predicted the behavior of the advancing saltwater intrusion wedge and the retreating residual saltwater after cutoff wall installation. Flow patterns showed that dispersed saltwater flowed with the freshwater discharge along the mixing zone and over the cutoff wall. Eventually all remaining saltwater in the storage area was flushed out. Experimental and numerical results showed that a shorter cutoff wall achieved a faster removal rate of residual saltwater than a higher wall. Simulations of shorter cutoff wall heights show that a minimum height limit on the cutoff wall is needed to achieve complete removal of residual saltwater. Residual saltwater will be flushed if the wall height exceeds the thickness of the saltwater wedge at that position.



## Introduction

Seawater intrusion is often a major constraint to optimal utilization of fresh groundwater from coastal aquifers. Excessive groundwater abstraction, in response to deteriorating quantity and quality of available surface water resources, has led to large-scale lowering of groundwater tables. Coupled with a continuing sea level rise due to global warming, coastal aquifers are even more under threat. With about 70% of the world's population living in coastal zones, the challenges are for the optimal exploitation of fresh groundwater and the control of seawater intrusion (Bear and Cheng, 1999).

Several strategies have been proposed to prevent or minimize saltwater intrusion in coastal aquifers (e.g., Todd, 1959; Dam, 1999; Oude Essink, 2001). These may be summarized into the following methods: (1) reduction or rearrangement of the pattern of groundwater extraction; (2) artificial recharge from spreading basins or recharge wells; (3) development of a pumping trough by saltwater extraction adjacent to the coast; (4) maintenance of a freshwater ridge by freshwater injection along the coast; (5) construction of artificial subsurface barriers; and (6) land reclamation. Abarca et al. (2006) grouped these countermeasures into demand actions, recharge actions, relocation of pumping wells, and additional engineering solutions. Among these countermeasures, artificial subsurface barriers have found use in Japan, particularly on small islands and in archipelagos. In these areas, geological conditions not only limit the construction of conventional water supply systems but also favor the construction of subsurface dams for alternative water sources. Accordingly, subsurface dams are planned and constructed to store and control groundwater for effective use and to ensure a consistent extraction of freshwater without causing intrusion of seawater into coastal aquifers. There are now about 15 subsurface dams in Japan, seven of which were specifically constructed to prevent saltwater intrusion into coastal aquifers (Japan Green Resources Agency, 2004). Advanced construction procedures such as the soil mixing wall (SMW) or trench-cutting remixing deep wall (TRD) methods were employed for the cutoff walls.

Hanson and Nilsson (1986), Nishigaki et al. (2004), and the Japan Green Resources Agency (2004) have reviewed subsurface dam technology and developments worldwide. Other studies (e.g., Nagata et al., 1994; Osuga, 1997) have been site-specific and more focused on the design criteria, construction, and environmental impacts of individual dams. This prior research has identified specific benefits of subsurface dams including sustained irrigation supplies for various crops and prevention of seawater intrusion due to increased freshwater groundwater levels in areas where dams have been constructed. However, there is a dearth of information on

* Corresponding author.
*E-mail address:* k5891192@kadai.jp (R. Luyun Jr.).
[1] Land and Water Resources Division, University of the Philippines Los Baños, 4031, Philippines.

0022-1694/$ - see front matter © 2009 Elsevier B.V. All rights reserved.
doi:10.1016/j.jhydrol.2009.08.019

the behavior of residual saltwater trapped in the storage area after construction of a cutoff wall. After dam construction, the movement and removal of this residual saltwater is usually not investigated. Because cutoff walls are installed underground and their components and hydraulic properties are site-specific, groundwater behavior after dam construction is amenable to study by numerical simulation and laboratory experiments.

Numerous investigators have performed experimental and numerical studies to understand the dynamics of saltwater intrusion into coastal aquifers (e.g., Ataie-Ashtiani et al., 1999; Zhang et al., 2001; Thorenz et al., 2002; Momii et al., 2005; Nakagawa et al., 2005; Illangasekare et al., 2006; Goswami and Clement, 2007). However, these studies do not directly reference saltwater dynamics in cutoff walls. Part of the saltwater intrusion wedge that is trapped as residual saltwater in the storage area of the cutoff wall has been assumed to remain stagnant (Fig. 10 of Oude Essink, 2001) but relevant experimental and numerical studies have been conducted to show that saltwater can migrate out of an enclosing barrier. Oswald et al. (2002) and Oswald and Kinzelbach (2004) described results from saltpool experiments that showed saltwater of different densities migrating from a closed system due to freshwater flow from the top. It has been presented as a three-dimensional benchmark problem and results have been reported by Diersch and Kolditz (2002), Johannsen et al. (2002) and Oswald and Kinzelbach (2004). The saltdome problem (HYDROCOIN Level 1 Case 5) was proposed for intercomparison of numerical solutions (OECD, 1988) and also involves salt migration as groundwater flows over a constant-concentration salt source in a closed system. It has been widely used and discussed (Herbert et al., 1988; Oldenburg and Pruess, 1995; Konikow et al., 1997; Kolditz et al., 1998; Holzbecher, 1998; Youness et al., 1999, among others) for the different boundary condition treatments applied. Both problems offer insights on migration patterns of saltwater but they have different boundary conditions from the classic saltwater intrusion problem represented in our case.

The objective of this study is to investigate the dynamics of the residual saltwater trapped in the storage area upon installation of cutoff walls. First, we performed flow tank experiments to model saltwater intrusion in a coastal unconfined aquifer. After the steady state saltwater intrusion wedge was achieved, we installed cutoff walls of different heights and examined the behavior of residual saltwater. We then used the model SEAWAT to numerically simulate the experiments and use the model results to analyze the dynamics involved. We then performed additional simulations to examine the effect of cutoff wall height on the behavior and removal of the residual saltwater.

## Laboratory approach

### *Experimental setup*

We conducted our experiments in a flow tank with internal dimensions 90 cm length, 60 cm height, and 8 cm width (Fig. 1). To model an unconfined aquifer we packed the middle section of the tank with homogenous glass beads with a nominal diameter of 1.2 mm. To each side of the bead section, separated by fine mesh screens, were freshwater and saltwater reservoirs. The heads in the reservoirs were controlled by adjustable drainage pipes. We measured drainage pipe outflow to estimate hydraulic conductivity and freshwater flux through the system. Freshwater and saltwater were supplied at constant flow rates to the respective reservoirs from large constant-head tanks positioned above the experimental setup.

We prepared saltwater in several 40 L barrels by dissolving commercial salt in tap water. To distinguish it from freshwater,

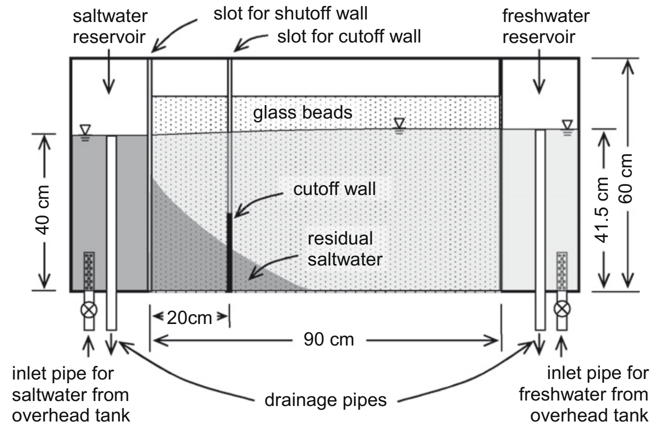


**Fig. 1.** Schematic diagram of the experimental setup.

the salt water was dyed with a red food color [New Coccine Acid Red 18 (C.I. Number 16255), Kiriya Chemical Co., Ltd.] at a concentration of 20 g dye per 40 L saltwater solution. The suitability of the dye was demonstrated by consistently similar breakthrough curves of NaCl and dye in our one-dimensional column test. We maintained saltwater solution density at 1.025 g ml$^{-1}$ as measured with an Akanuma hydrometer (JIS certified, Yokota Keiki Mfg., Co., Ltd.) and measured saltwater concentration with a WTW-LF330 conductivity meter. We used a small pump and several siphon tubes to circulate and homogenize the saltwater solution in the overhead constant-head tank, the constant-head saltwater reservoir, and the barrels, and monitored saltwater density and concentration at these locations. We used tap water for our freshwater source.

The slot for installing the cutoff wall is located in the main tank 20 cm from the saltwater reservoir (Fig. 1). Perforated acrylic sheets and fine mesh screens separate the cutoff wall slot from the main tank and prevent the entry of glass beads inside. A slot for insertion of a shutoff wall between the main flow tank and the saltwater reservoir was constructed to separate the saltwater solution from the freshwater-filled porous tank at the start of each experiment. The cutoff and shutoff walls were made of 4 mm thick acrylic sheets. Rubber seals attached to the sides of these walls prevented leakage. A grid of perpendicular lines at 10 cm spacing was etched on the flow tank and standard metallic rulers (cm and mm scales) were pasted along the bottom and sides of the flow tank to facilitate direct measurement of the saltwater wedge profile, and the freshwater and saltwater levels. Recorded data were cross-checked with photographs taken at various intervals with a high resolution digital camera.

Because the cutoff wall slot effectively divided the flow tank volume, we packed each section with glass beads separately but successively between each section. Beads were packed in 5 cm layers under fully saturated conditions to prevent air entrapment. Each layer was homogenized with those below using a mixing rod to disrupt any possible layering. To ensure homogeneity of the porous medium, the glass beads were carefully compressed after each layer was filled. We used clamps to prevent expansion of the tank sides during packing and ensure a fixed width for the flow tank. We estimated the hydraulic conductivity ($k$) of the porous medium using Darcy's law, based on the preset hydraulic gradient and the measured volumetric drainage discharge. We used the in situ approach applied by Oostrtom et al. (1992) to estimate the average $k$ of the flow tank. There was a long time lag between experiments and the porous medium was repacked for each experiment, causing different flow field conditions and, consequently, different hydraulic conductivity values. The $k$ values measured for the 40- and 20-cm cutoff wall height experiments were 1.18