EXPERIMENTAL INVESTIGATIONS ON GROUNDWATER FLOW IN COASTAL AQUIFERS

S.-H. HONG[1], H.-D. KIM[2], N. KUMAR, J.-H. KIM[2], N. PARK[1,] ✉

[1] Water Resources Systems Group,
[2] Geo-exploration Laboratory,
School of Civil & Ocean Engineering, Dong-A University, Korea
E-mail: wghsh72@smail.donga.ac.kr

Abstract

Experiments were conducted using laboratory models to study salt water intrusion phenomena in coastal aquifers. Two model tanks filled with sand were used. The smaller model tank could produce steady-state cross-sectional flow in a reasonably short time. The bigger tank model produced a more interesting three-dimensional flow field compared to the smaller one, but it also took much more time to reach a steady state condition, and posed difficulties in observing results. A cross-sectional model was used to investigate ëfreshwater lensí phenomena. A few pumping scenarios were tested. Contamination of the pumping well due to excessive withdrawal was observed. The effectiveness of a scavenger well was studied. The bigger model was used to study the steady-state lateral intrusion problems. Various attempts were made to measure the interface position in the sand.

Keywords: Sand tank experiments, cross-sectional flow, three-dimensional flow, saltwater intrusion

Introduction

Variable density fluid flow and transport in porous ground media occur in many cases of groundwater hydrology (i.e., seawater intrusion in coastal aquifers, natural or artificial saltwater up-coning in aquifers, vertical seepage of brackish water from open ocean canals, movement of brine solutions in salt domes that had been targeted as possible nuclear waste repositories, infiltration of dense aqueous (miscible) or non-aqueous (immiscible) phase liquids, etc...). The main focus of the present work is saltwater intrusion and the paper discusses the laboratory investigation carried out on this topic.

✉ Corresponding author

Agricultural development and urbanization in the coastal areas of Korea had led to an increasing demand for water. This demand has, in turn, increased groundwater pumping enormously in recent years. As a result of the over-pumping of coastal aquifers, groundwater levels in the main part of the irrigated and populated areas have significantly dropped below sea level, often leading to an intrusion of seawater. Additionally, adverse effects such as subsidence of strata are reasons for concern.

The objective of this on-going study was the acquisition of experimental data for the validation of a sharp-interface numerical model for simulating freshwater-saltwater groundwater flow. Preliminary experiments on an unconfined sandy single-layer aquifer have been carried out using laboratory sand tanks.

The first results of the experiments on the hydrodynamically steady-state salt and freshwater interface were presented for the discussion and review of project progress. The purpose of this study was to ascertain the nature and extent of the freshwater-saltwater interface and to learn the details of the extent of the salt wedge for an unconfined sandy aquifer.

Sand tank experiments

Recently, several laboratory model studies of saltwater ingress were carried out using sand tanks of suitable size. In most cases, these laboratory models were used to validate numerical models of variable density transport for saltwater intrusion in coastal regions.

Zhang, et al. (2000) investigated the migration of a contaminant plume in an unconfined aquifer using a sand tank under the realistic conditions of tides and beach face. This plume consisted of a salt solution with density varying from 995.2 g/L to 1025.0 g/L. The dimensions of the sand tank are 1650 mm long, 600 mm high and 100 mm wide. The steady state experimental results were used to calibrate the numerical model 2DFEMFAT, which was used to compare numerical predictions of contaminant plume transport. This experimental study concluded that seaward boundary conditions can be simplified as a constant freshwater head by neglecting seawater density and tidal variations to gain great savings in computing effort. However, this has resulted in underestimations of solute mass transport existing around the shoreline and unrealistic migration paths under the seabed. The experimental results showed that the contaminant moves upward, towards the coastline when it approaches the saltwater interface and exits around the coastline.

Panteleit et al. (2002) studied geochemical aspects of seawater intrusion into a porous coastal aquifer system in a 2D sand tank (200 x 50 x 5 cm) experiment. The sand tank was filled with natural aquifer material and, after a conditioning phase with artificial groundwater, a density-driven saltwater intrusion against the hydraulic head was induced. Geochemical processes were recorded by intense sampling at 100 monitoring points at different depths throughout the tank. These studies concentrated on exchange reactions during saltwater intrusion. Variations in the concentration of sodium and chloride with depth were measured using a soil moisture sampler (porous polymer tube; diameter 2.5 mm, pore width 1.1 µm) at different depths. It was concluded that the exchange processes are dominated by a linear rising of the total cation equivalent concentration.

Thorenz (2002) used sand tank experiments for validating a numerical model (RockFlow software – FEM simulation package). A sand tank (0.96 x 0.48 x 0.11 m) with two perforated walls was used to conduct the experiments. Through these perforations, 16 tubes of 1 mm inner diameter were inserted for tracer injection and sample extraction. Model accuracy and speed against a standard procedure were evaluated using these experimental results.

A rectangular sand tank (170 cm x 100 cm x 10 cm) was used by Jalbert et. al (2000) to verify the validity of a non-dimensional solution for the case of a moving interface during the displacement of water by saltwater. The agreement with experimental data showed weak influence of the boundary conditions on the general trend of the density-affected flow. The solution allowed for a simplified general view of the influence of density differences upon values of velocity, permeability, or dispersivity obtained in conservative tracer experiments.

Using a plexiglass sand tank (10.0 m x 1.2 m x 0.1 m), Koch and Starke (2001) analyzed the effect of density stratification and stochastic properties of medium on steady state macro-dispersion. Experiments were conducted with saltwater concentrations varying from 250 ppm (freshwater) to 35000 ppm and with two inflow velocities of 1 and 4 m/day. For calibration and validation purposes, the experiments were accompanied by a numerical simulation using the SUTRA density-dependent flow and transport model. These studies found, for the same concentration contrast, a larger sinking of the mixing layer with decreasing inflow velocity and, at the same time, an apparent increase of the lateral dispersion coefficient.

Inouchi et al. (2000) compared the results from sand sank (0.9 m x 0.45 m x 0.1 m) experiments with the predictions of salt and freshwater interface by the Boundary Element Method (BEM). They observed that experimental visual interfaces are below the interface predicted by the analytical solution.

In the present research work, sand tank experiments were planned to validate a simulation model of saltwater intrusion for various cases such as pumping and no-pumping conditions, tide level variations, and island conditions. Further, experiments were planned for the validation of an optimization model to study the decision variables such as the locations of the pumping wells and pumping rates. Control of the freshwater-saltwater interface by means of pumping saltwater was evaluated. Some of the preliminary results obtained from these sand tank experiments are discussed in this paper.

Experimental setup

Cross-sectional sand tank

A small sand tank was set up to study the freshwater-saltwater flow in a vertical cross section (Figure 1). At both ends of the sand, constant-level water reservoirs were located. Sidewalls were made of plexiglass so that flow phenomena can be observed when the dye tracer is used.

Three-dimensional sand tank

A larger tank was prepared to study three-dimensional flow. Two reservoirs at both ends of the sand were equipped with an overflow device which could change overflow elevations within the pre-specified limits at a constant rate to simulate the tidal fluctuation commonly observed in the sea. The drawing containing the details and the photograph of the sand tank are shown in figures 2 and 3.

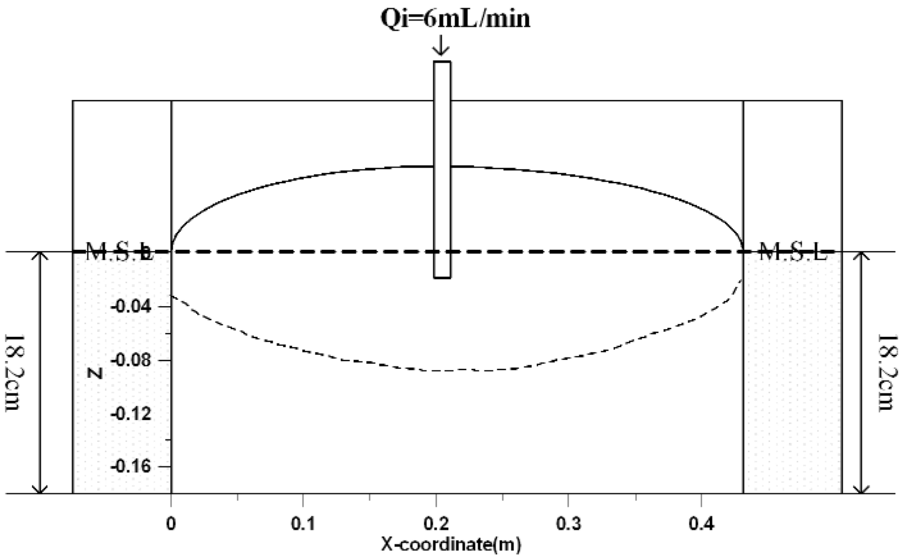

Figure 1. Sand tank for the cross-sectional experiment.

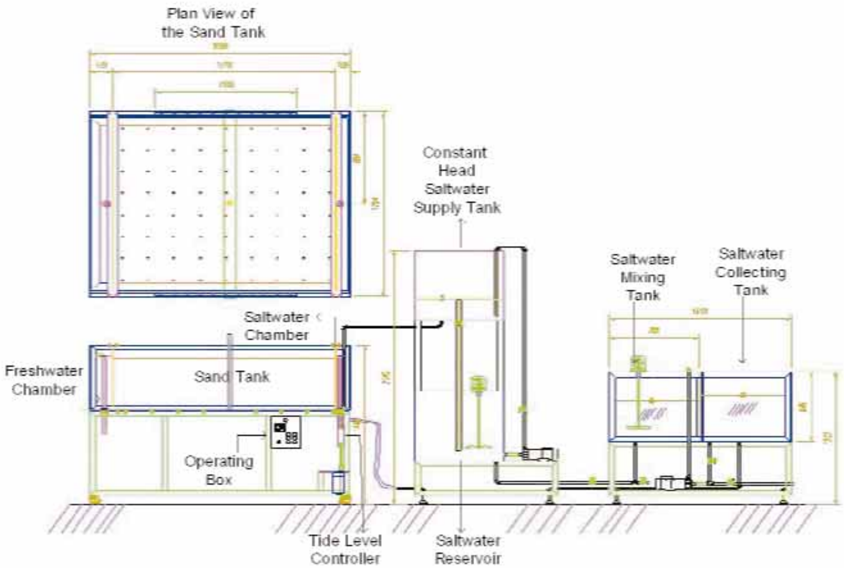

Figure 2. Drawing of the sand tank for the three-dimensional experiments.

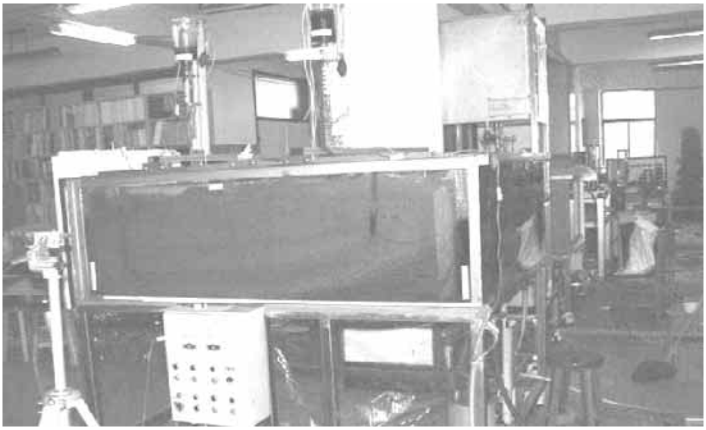

Figure 3. Sand tank for the three-dimensional experiments.

Materials and methodology

Both tanks were filled with sand, whose characteristics are given in Table 1. In the smaller tank the thickness of sand layer was 25 cm and approximately 50 cm in the larger tank. Tap water presenting a total salinity of ~90 mg/L was used as freshwater. Industrial salt was used to make the saltwater. Target specific gravity of the saltwater was set to 1.04 $g \cdot L^{-1}$. At that specified gravity value, the salinity was 46.7‰.

Table 1. Sand tank-aquifer properties.

Grain Size	Intrinsic Permeability
D_{50} = 0.47 mm D_{60} = 0.49 mm D_{10} = 0.28 mm C_u = 1.75 Well sorted sand	$k = 1.09 \cdot 10^{-10}\ m^2$

To identify the size of the salt-wedge, saltwater is mixed with textile dye (Red H-E3B). The streamlines of pore fresh water flow have been visualized by injecting Rhodamine – B dye. Attempt has been made to visualize the streamlines in the salt-wedge with Uranine (sodium fluorescein).

Measurements

The variables of primary interest are water level and the thickness and elevation of the transition zone. In this study we used three approaches to identify the transition zone. First, we used a dye to distinguish freshwater and saltwater. The transition zone could be seen through transparent sidewalls and the bottom plate. In all cases the saltwater zone was clearly visible. However, due to the color of the sand, the transition zone, which would presumably be indicated by a diluted color, could not be identified.

The second method was electrical resistivity. Two different types of sensor arrays were used: Schlumberger and Lee. The method was able to identify the sharp interface prepared in a sample tube or a box made of electrically non-conductive material. However, when the method was applied to the prototype sand tank, the result was not satisfactory. It was suspected that the stainless steel interfered the flow of electricity.

The third method was the sampling of columns of water in the observation wells. Glass tubes of 4 mm inner diameter were used. Two advantages were expected: first, the variation of color could be observed; secondly, the water table elevation could also be measured. The sampling method was tested on a sharp interface prepared in a 100 mL flask. Although the sample had a sharp interface, the interface in the column of water sampled in the glass tube was dispersed (Figure 4). Two causes were identified: dispersion occurred while the tube was lowered to sample, and also while the tube was pulled out with the water inside. A number of tests were conducted to estimate the thickness of the dispersed zone due to the sampling method. The thicknesses ranged from 5 mm to 12 mm, averaging 7 mm.

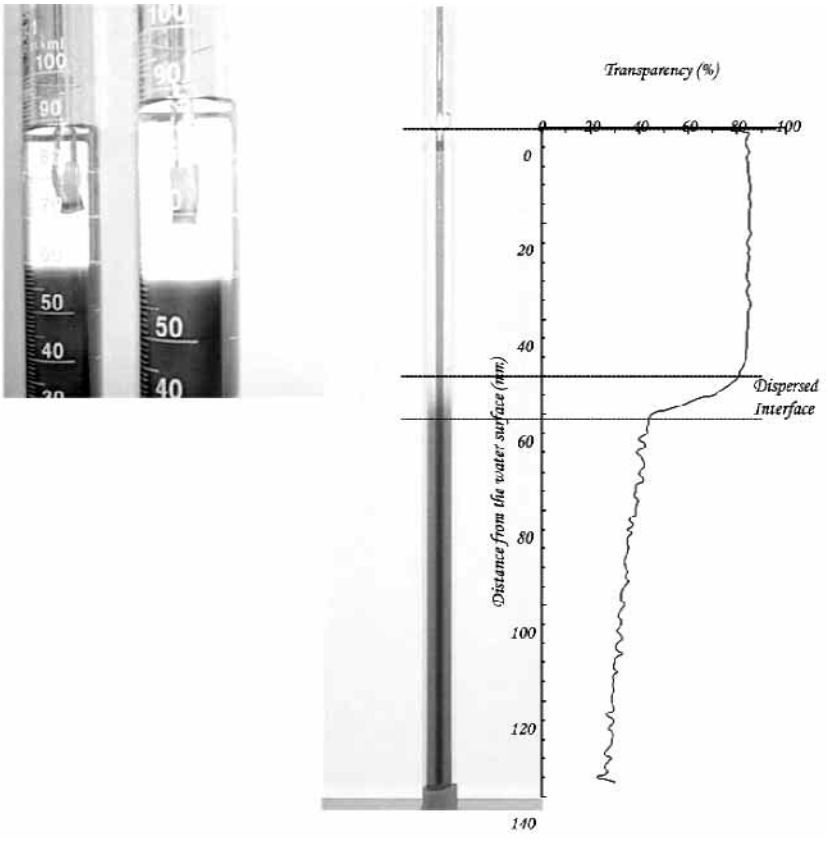

Figure 4. Detection of the interface using a sample column of water.

Experiments

Cross-sectional flow and freshwater lens

Pre-development condition

The smaller tank was used to study cross-sectional flow. Both constant-water-level reservoirs were filled with a saltwater salinity of 46.3 ‰. The corresponding specific gravity was 1.04 g·L^{-1}. Freshwater was recharged at the center of the sand at a rate of 6 mL/min. After several hours, a steady-state freshwater ëlensí floating on the saltwater was formed. At the center part, the lens extended 8.5 cm below the saltwater level in the reservoir (Figure 5). This data was used to calibrate the intrinsic permeability of the sand layer. It was estimated to be 1.092 · 10^{-10} m^2.

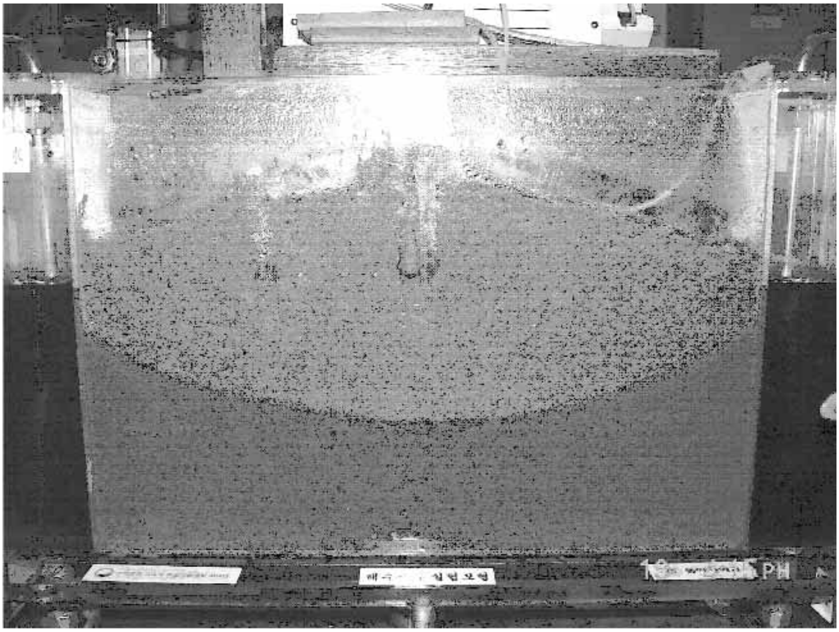

Figure 5. Development of a freshwater lens.

Groundwater withdrawal

To investigate the effect of groundwater pumping on the shape of the lens, a pumping well was installed at 12 cm from the left saltwater reservoir. The length of the screen of the pumping well was 3.5 cm and the well was installed in such a way that the bottom part of the screen was 3.5 cm below the saltwater level in the reservoir. Water was pumped from the well at a rate of 2.4 mL/min (Figure 6). After the flow reached a new equilibrium state, the interface rose by 1.5 cm below the well, and the salinity of the pumped water was 115 mg/L.

The pumping rate was raised to 3.5 mL/min to investigate the impact of excessive pumping. The interface rose by 1.69 cm from the pre-pumping position (Figure 6). In addition to the shift in the interface position, the well was intruded with saltwater. The salinity of the pumped water was measured at 1.69‰. The volumetric percentage of saltwater was evaluated using the following equations:

$$C_sQ_s + C_fQ_f = C_pQ_p$$

$$Q_s + Q_f = Q_p$$

It was found that about 3.4 % of pumped water was saltwater.

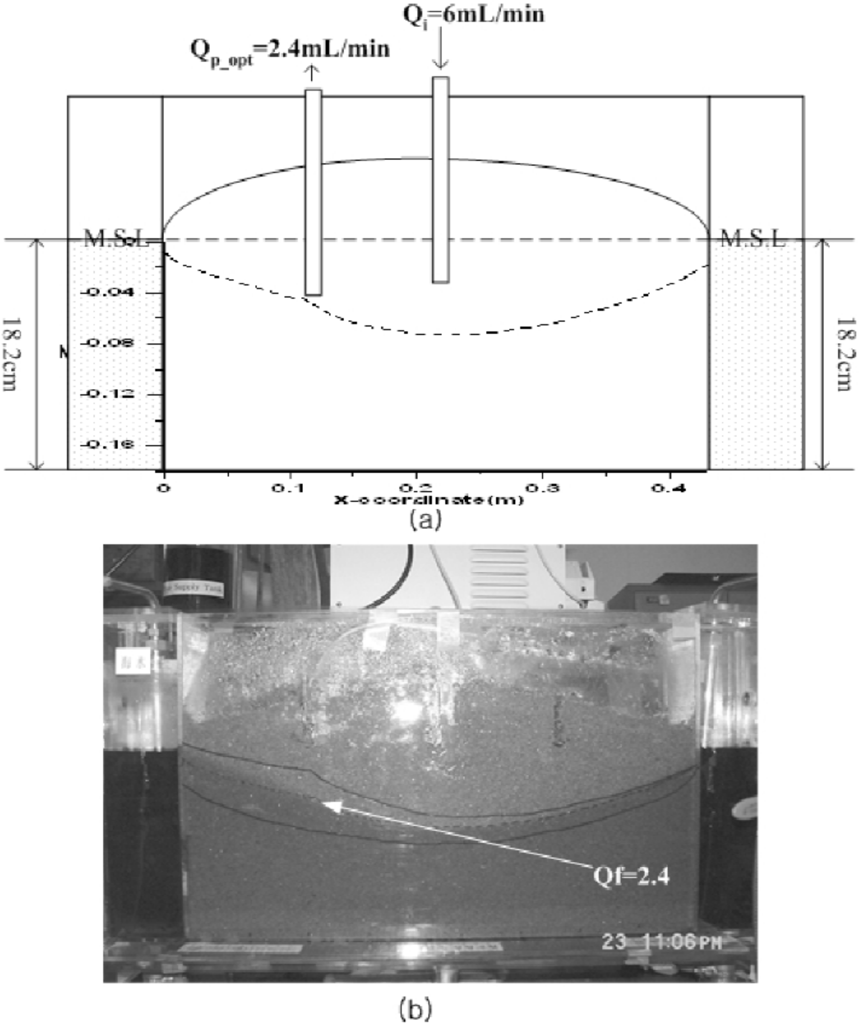

Figure 6. (a) Schematic diagram of the pumping scenario. (b) Shift in the interface position due to pumping.

Control of saltwater wedge

It was shown in the previous section that the pumping well was contaminated when water was withdrawn at a rate of 3.5 mL/min. In this section, the possibility of lowering the interface so as to make the well fresh was tested while maintaining the pumping rate. At the same location as the freshwater pumping well, a deeper well was added to extract saltwater (Figure 7). After several hours of pumping saltwater at a rate of 3.0 mL/min, a steady state was reached. The interface was lowered by 1.09 cm, while the salinity of the pumped water was lowered to 128 mg/L, practically freshwater. Thus, saltwater pumping was effective in lowering the interface for the sake of keeping the freshwater well fresh, while pumping freshwater at a higher rate would be otherwise advisable.

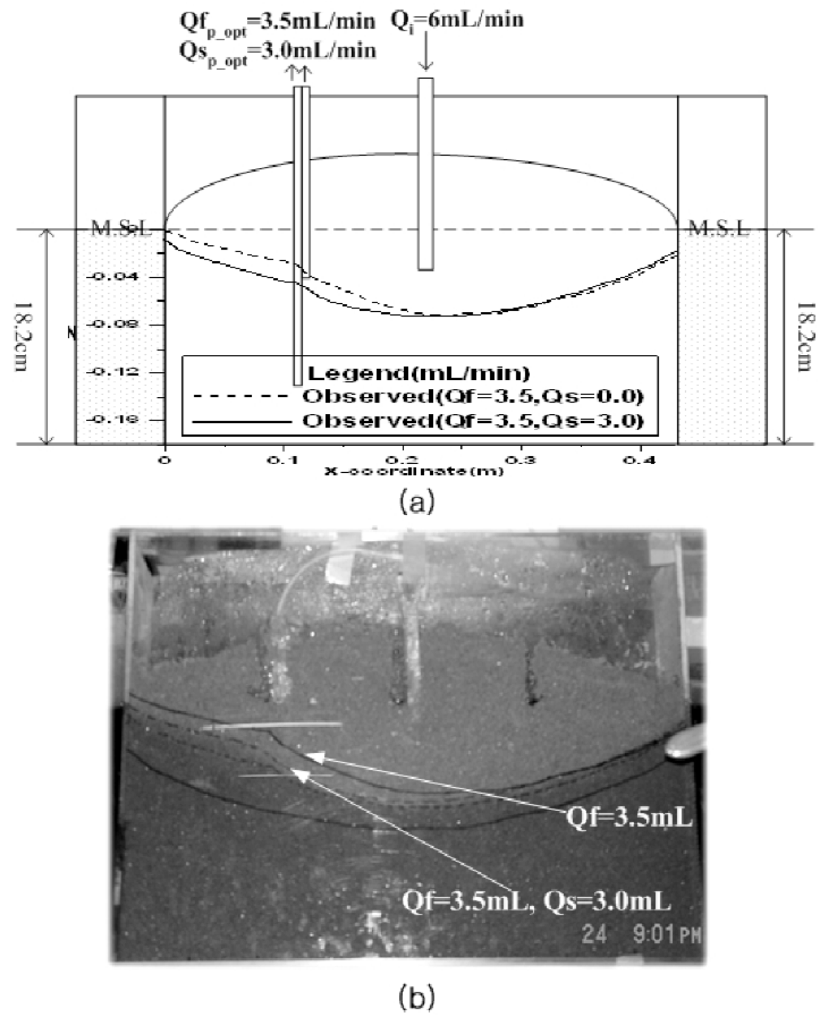

Figure 7. (a) Schematic diagram of the pumping freshwater and saltwater scenario. (b) Shift in the interface position due to pumping both waters.

Three dimensional saltwater intrusion

A three dimensional saltwater intrusion experiment was conducted with the big sand tank. The water level in the freshwater reservoir was 1.8 cm higher than the saltwater level in the corresponding reservoir. For the head difference, the toe of the interface was located at 75 cm from the freshwater chamber and the freshwater flow rate was 270 mL/min.

Pumping was started at two wells. The withdrawal rate at Well A, located at the coordinate (0.9 m, 0.8 m), was 15 mL/min and the withdrawal rate at well B, located at (1.2 m, 0.5 m) was 27.6 mL/min (Figure 8). The interface responded to pumping by advancing towards the freshwater reservoir. After several days, it reached a new equilibrium position. The maximum intrusion length was 68.8 cm, indicating 6.2 cm of additional intrusion due to pumping.

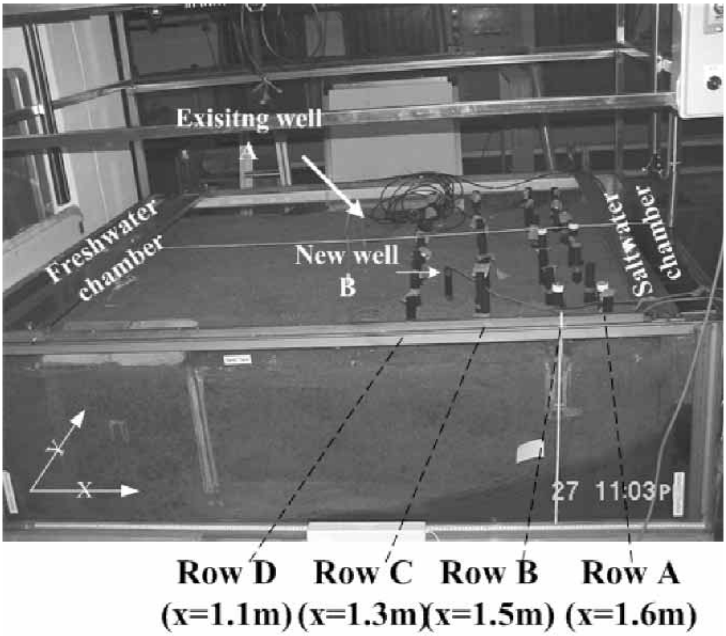

Figure 8. Well locations for the three dimensional experiment.

The interface was measured using the glass tubes. A total of 28 samples were obtained (Figure 9). The photographs of the samples were analyzed. Fifty percent were taken arbitrarily as the relative transparency value for the fresh-side limit of the transition zone, and twenty percent were used for the other limit of the transition zone. Thirty five percent were used for the middle part of the transition zone.

The resulting interface positions along rows A, B, C, and D of the observation wells are given in Figure 10. The effect of pumping well B could be clearly seen in the profile of the transition zone measured along row C. The effect of pumping well A is not clear from the interface measurement. The pumping rate is probably not high enough to cause changes in the position of the interface in the observation wells.

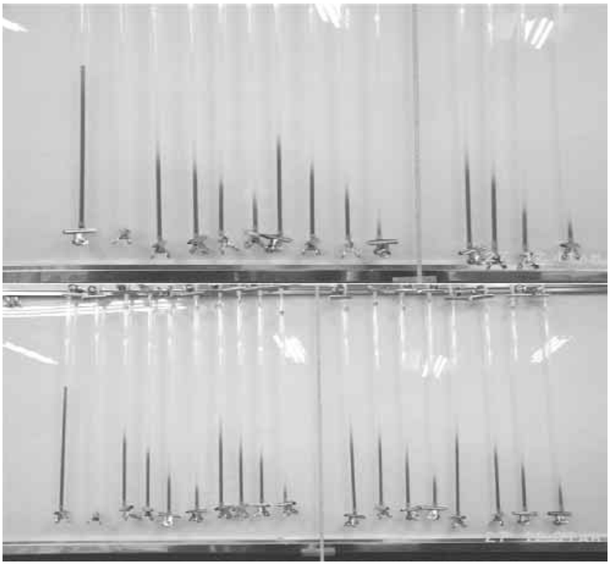

Figure 9. Water-column samples obtained from observation wells.

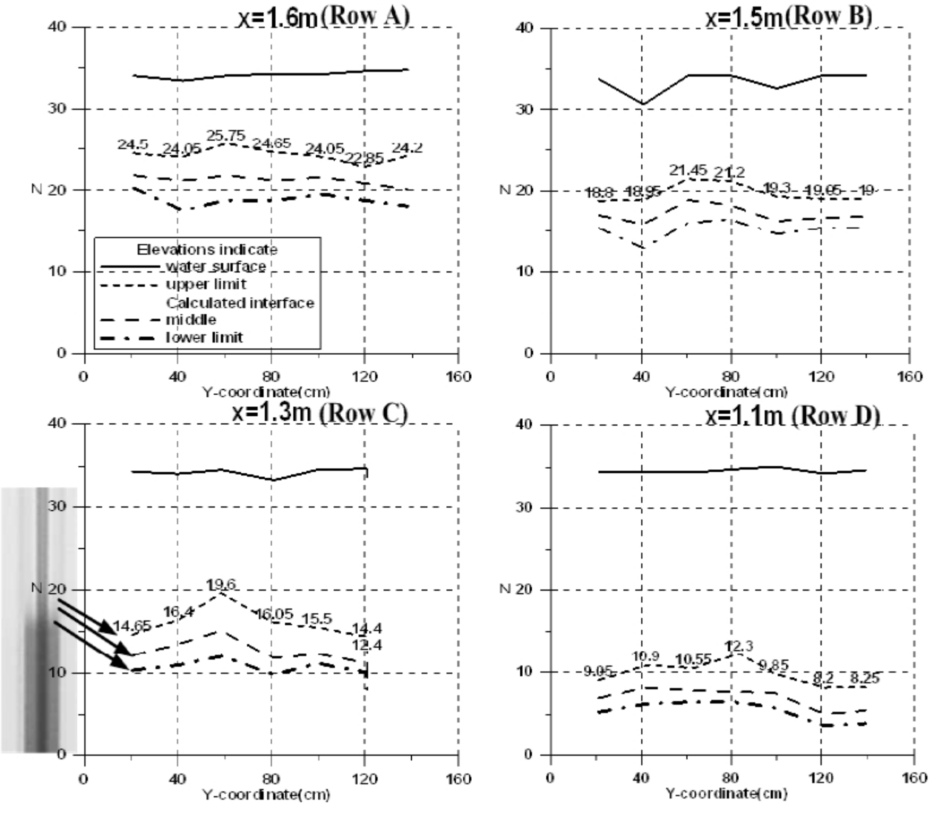

Figure 10. Calculated and observed interface positions.

Concluding remarks

Experiments were conducted using laboratory models to study saltwater intrusion phenomena in coastal aquifers. Two physical models were used. The smaller model was designed to study cross-sectional flows while the larger model was designed to study three-dimensional flows. The smaller model had the advantage of reaching steady states much faster than the bigger model.

The smaller cross-sectional model was used to study the behavior of a freshwater lens floating on top of salt water. The impact of a pumping well was studied and was found to produce steady-state cross-sectional flow in a reasonably short time. Various pumping scenarios were tested. Contamination of the well with excessive withdrawal was observed and the effectiveness of a scavenger well was studied.

The bigger three-dimensional model produced a more interesting flow field compared to those from the smaller one, but it took much more time to reach steady states and posed difficulties in observing results. Various attempts were made to measure the interface positions in the observation wells. The image analysis was most successful.

Acknowledgements

This research was supported by a grant (3-3-1) from the Sustainable Water Resources Research Center of 21st Century Frontier Research Program (Korea).

References

INOUCHI, K., SAKAMOTO, H., and KAKINUMA, T. (2000). Steady-state behavior of coastal and insular ground waters: Sand tank experiments. *Japanese Journal of Limnology*, 61: 1-10.

JALBERT, M., DANE, J.H., ABRIOLA, L.M. and PENNELL, K.D. (2000). A non-dimensional evaluation of tracer sensitivity to density effects. *Ground Water*, 38(2): 226-233.

KOCH, M. and STARKE, B. (2003). Experimental and numerical investigation of macrodispersion of density dependent transport in stochastically heterogeneous media: Effects of boundary conditions and at high concentration. Proc. of *Second International Conference on Saltwater Intrusion and Coastal Aquifers-monitoring, Modeling and Management.* Mexico, March 30- April 2, 2003.

PANTELEIT, B., KESSELS, W. and SCHULZ, H.D. (2002). Geochemical processes in the salt-freshwater transition zone – Preliminary results of a 2D sand tank experiment. Proc. of *17th Salt Water Intrusion Meeting*, Delft, The Netherlands, 6-10 May 2002.

THORENZ, C. (2002). Application of a model adaptive approach to the simulation of density driven flow in unsaturated laboratory system. Proc. of *17th Salt Water Intrusion Meeting*, Delft, The Netherlands, 6-10 May 2002.

ZHANG.O, VALKER.R.E. and LOCKINGTON, D.A. (2000). Influence of seaward boundary condition on contaminant transport in unconfined coastal aquifers. *Journal of Contaminant Hydrology*, 49: 201-215.