Songklanakarin J. Sci. Technol.
34 (6), 679-687, Nov. - Dec. 2012

SONGKLANAKARIN JOURNAL OF SCIENCE AND TECHNOLOGY
http://www.sjst.psu.ac.th

Original Article

Physical model simulations of seawater intrusion in unconfined aquifer

Tanapol Sriapai, Chaowarin Walsri, Decho Phueakphum, and Kittitep Fuenkajorn*

Geomechanics Research Unit,
Suranaree University of Technology University Avenue, Mueang, Nakhon Ratchasima, 30000 Thailand.

Received 14 February 2012; Accepted 27 September 2012

Abstract

The objective of this study is to simulate the seawater intrusion into unconfined aquifer near shoreline and to assess the effectiveness of its controlling methods by using scaled-down physical models. The intrusion controlled methods studied here include fresh water injection, saltwater extraction, and subsurface barrier. The results indicate that under natural dynamic equilibrium between the recharge of fresh water and the intrusion well agree with the Ghyben-Herzberg mathematical solution. Fresh water pumping from the aquifer notably move the fresh-salt water interface toward the pumping well, depending on the pumping rates and the head differences (Δh) between the aquifer recharge and the salt water level. The fresh water injection method is more favorable than the salt water extraction and subsurface barrier method. The fresh water injection rate of about 10% of the usage rate can effectively push the interface toward the shoreline, and keeping the pumping well free of salinity.

Keywords: seawater intrusion, physical model, salinity, aquifer, groundwater pumping

1. Introduction

Seawater intrusion or encroachment is the movement of saltwater from the ocean into coastal aquifers (Freeze and Cherry, 1979; Fang, 1997; Todd and Mays, 2005). The problem of seawater intrusion has occurred in many cities that locate near shoreline. This problem has become increasingly more severe as the coastal population increases. The rise of sea levels due to the global warming, and the increasing demands of fresh water from the industries have recently contributed to the seawater intrusion problem. Several controlling methods have been proposed and implemented to minimize the seawater intrusion. These include the applications of saltwater extraction wells, injection of freshwater (artificial recharge) and subsurface barrier (Bear *et al.*, 1999; Luyun *et al.*, 2009; Bear and Cheng, 2010). Performance of these methods has been assessed by a variety of numerical models and by in-situ monitoring and measurements. Selection of the suitable methods depends primarily on the site-specific geology of the near-shore aquifers, groundwater recharge and usage, availability of the materials, performance requirements and economic constraints. Extensive studies have been carried out to understand the mechanisms of the seawater intrusion, particularly via numerical simulations (Aharmouch and Larabi, 2001; Bear *et al.*, 2001). Explicit observations and performance assessment of these controlling methods however have never been attempted particularly under a well-controlled condition in the laboratory scale.

The objectives of this study are to simulate the seawater intrusion into unconfined aquifers and to assess the effectiveness of the controlling methods by performing steady-state flow tests in a scaled-down physical model. The two-dimensional flow simulations include the dynamic equilibrium between the saltwater and freshwater under natural condition, the impact of groundwater pumping (freshwater usage), and the performance of saltwater extraction, freshwater injection and subsurface barrier techniques. The results can assess the performance of these commonly practiced controlling methods and can improve an understanding of the seawater intrusion mechanisms. Accuracy and validity

* Corresponding author.
Email address: kittitep@sut.ac.th

of the Ghyben-Herzberg mathematical relation will also be verified.

2. Test Frame

A test frame is developed to represent a vertical cross section of an unconfined aquifer across the shoreline. Figure 1 shows its main components and dimensions. To allow a visual inspection during the test, two transparent acrylic plates with 1.2 m high, 1.8 m wide and 1.5 cm thick are mounted in upright position between steel frames. All gaps and connections are water-tightly sealed with adhesive silicone. The space between the two plates is provided to fill with the test materials. In the mid-section of the frame the space is filled with clean sorted sand (0.6-0.8 mm in diameter)

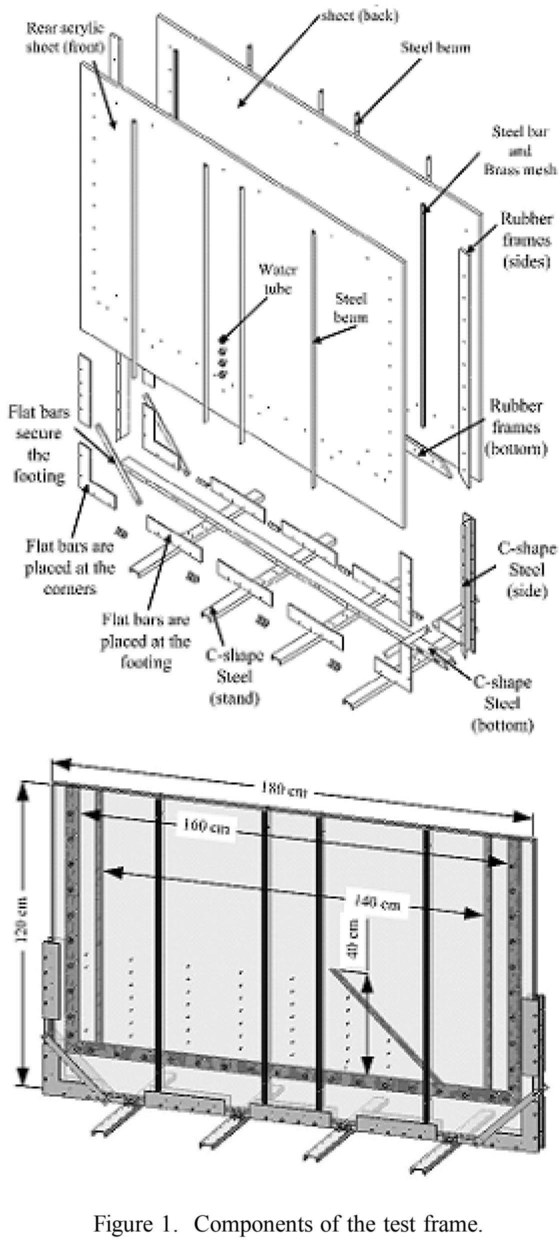

Figure 1. Components of the test frame.

to represent the unconfined aquifer (Figure 2). The shoreline with a slope face angle of 45° is formed by a porous steel strip with the pore spaces smaller than the sand particles. The left side of the frame is the reservoir of freshwater where its head can be maintained constant at any level by continuously supplying with distilled water. It is used to simulate the far-field groundwater table to supply freshwater to the sand aquifer. The saltwater reservoir is arranged in the right side of the frame to simulate the seawater which its levels can be controlled constant. The saltwater is saturated brine (100% salinity). It is prepared by dissolving pure sodium chloride with distilled water. The initial desired thickness of the aquifer, seawater level, and groundwater table can be specified and obtained by pre-calculating the volume of the materials before installing in the space of the frame. The simulated sand aquifer is 40 cm high and 140 cm long (Figure 2). The hydraulic conductivity of the sorted sand determined by the Darcy test method is 35×10^{-3} m/s. It is recognized that the permeability of simulated aquifer is relatively high compared to most actual in-situ aquifers. The use of sorted sand is to accelerate the testing time and hence obtaining the results within a practical period. There are outlet holes with 0.5-mm in diameter systematically drilled through the rear acrylic sheet, and hence allowing withdrawal of the fluid samples at various depths and locations within the sand aquifer.

Scaled-down or physical models have long been used to simulate the behavior and impact of the seawater intrusion (Christensen and Evan, 1974; Goswami and Clement, 2007; Brakefield, 2008; Luyun *et al*., 2009; Werner *et al*., 2009). They are an effective tool to study and visualize the interaction between fluids with different properties in the same domain. Unlike the actual in-situ condition the boundary conditions of the laboratory test models can be well controlled, and hence isolating some undesirable factors from the test results. Observations taken from the physical

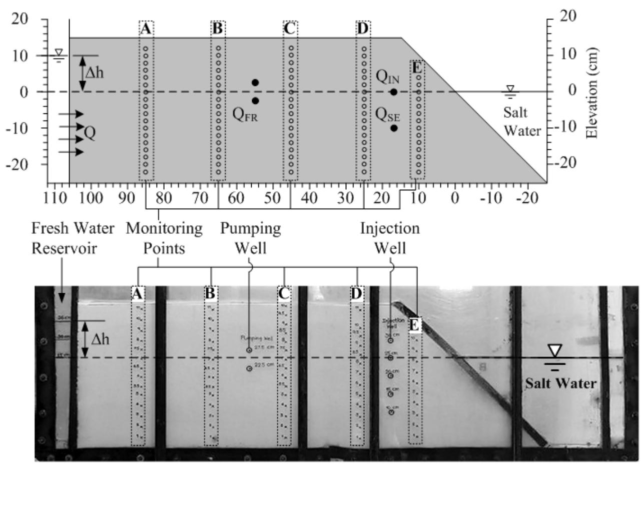

Figure 2. Test parameters and locations of monitoring points on rear acrylic sheet.

model simulation have widely been used to compare with or to verify the validity of the numerical simulations.

3. Ghyben-Herzberg Relation

The Ghyben-Herzberg relation (Todd and Mays, 2005) describes the mechanism of the seawater intrusion that salt water occurs underground, not at sea level but at a depth below sea level of about 40 times the height of the fresh water above sea level. This distribution is attributed to the hydrostatic equilibrium that exists between the two fluids of different densities. The equation derived to explain this phenomenon is generally referred to as Ghyben-Herzberg relation after its originators. For two segregated fluids with a common interface, the weight of a column of fresh water extending from the water table to the interface is balanced by the weight of a column of seawater extending from the sea level to the same depth as the point on the interface. Figure 3 shows the idealized Ghyben-Herzberg model of an interface in a coastal unconfined aquifer.

Recognizing the approximations inherent in the Ghyben-Herzberg relation more exact solutions for the shape of the interface have been developed from the potential flow theory (Todd and Mays, 2005). The depth to the interface (z) for this situation is determined by:

$$z^2 = \frac{2\rho_f qx}{\Delta\rho K} + \left(\frac{\rho_f q}{\Delta\rho K}\right)^2 \quad (1)$$

where x is the distance from shoreline, z is the thickness of the freshwater zone above sea level, $\Delta\rho$ is the difference between the density freshwater (ρ_f) and saltwater (ρ_s) which is about 0.23 g/cm^3, K is the hydraulic conductivity of the unconfined aquifer, and q is the freshwater flow per unit length of shoreline.

The corresponding shape of the water table is given by:

$$h_f = \left(\frac{2\Delta\rho qx}{(\rho + \Delta\rho)K}\right)^{1/2} \quad (2)$$

The width x_o of the submarine zone through which freshwater discharges into the sea can be obtained from Equation 2 by setting z equal to 0, yielding:

$$x_0 = \frac{\rho_f q}{2\Delta\rho K} \quad (3)$$

The depth of the interface beneath the shoreline (z_o) taking place where x is zero can be defined by:

$$z_0 = \frac{\rho_f q}{\Delta\rho K} \quad (4)$$

The freshwater above the sea level at z = 0 is

$$h_f = \left(\frac{2\Delta\rho qx}{\rho_f K}\right)^{1/2} \quad (5)$$

The above equations will be used in this study to determine the location and depth of the interface obtained from the scaled-down model simulation under the natural condition.

4. Physical Model Simulations

Series of steady-state flow tests are performed to represent seawater intrusion characteristics under various scenarios of groundwater usage and with the applications of the controlling methods. These include the freshwater-saltwater flow balance in unconfined aquifer under natural condition and assessments of the effects of groundwater pumping (usage) on the saltwater intrusion. Three controlling methods studied here are (1) injection of freshwater into the aquifer (artificial recharge), (2) extraction of the intruded saltwater, and (3) construction of subsurface barrier or low-permeability zone close to the shoreline. Table 1 describes the test parameters used in the simulations. The designated Δh is the head differences between the fresh groundwater table and the saltwater level, Q is the recharge rate of fresh water, Q_{FR} is the groundwater pumping rate representing the freshwater usage, Q_{SE} is the rate of saltwater extraction, Q_{IN} is the rate of freshwater injection, and D_B is the depth of subsurface barrier measured below the saltwater level. The water salinity (S_B) sampled from the predrilled holes in the rear acrylic plate is measured using a Refracto-Salinometer (Figure 4). It is a popular optical device used to measure the water salinity. The water salinity sampled from the sand aquifer is measured to the nearest 1%. The changes of the

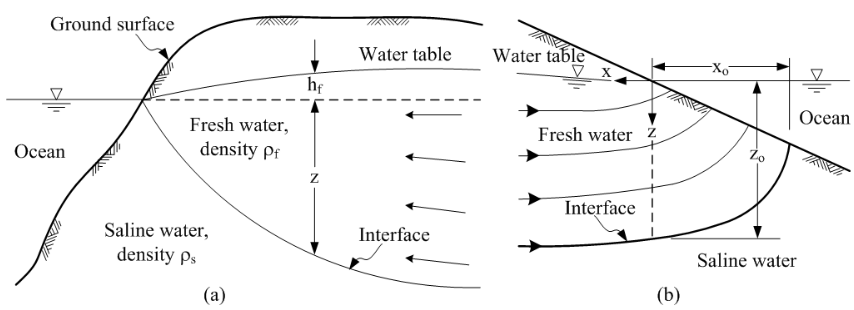

Figure 3. Idealized sketch of occurrence of fresh and saline groundwater (a) and flow pattern of fresh water (b) in an unconfined aquifer.

Table 1. Test parameters and results.

Testing series	Test Parameters						Results		
	Δh (cm)	Q (cc/min)	Q_{FR} (cc/min)	Q_{SE} (cc/min)	Q_{IN} (cc/min)	D_B (cm)	% salinity of pumping well	1 * (cm)	2 * (cm)
Natural Condition	10	62	-	-	-	-	-	-	-
	5	24	-	-	-	-	-	-	-
Water Pumping	10	62	0.2	-	-	-	0	<-25	<-25
		85	10	-	-	-	0	<-25	-22
		120	100	-	-	-	0	-23	-14
	5	25	5	-	-	-	0	-13	-11
		50	30	-	-	-	20	-10	-9
		96	70	-	-	-	45	-8	-7
Saltwater Extraction	5	75	70	15	-	-	20	-8	-5
		100	70	50	-	-	0	-15	-10
		150	70	100	-	-	0	-22	-13
Freshwater Injection	5	80	70	-	7	-	0	-18	-10
		80	70	-	15	-	0	-19	-11
		57	70	-	50	-	0	-23	-15
Subsurface Barrier	5	96	70	-	-	5	0	-17	-9
		96	70	-	-	10	15	-11	-7
		96	70	-	-	15	0	-15	-8

Explanations:
Δh = head differences; Q = flow rate of discharge
Q_{FR} = flow rate of freshwater pumping; Q_{SE} = flow rate of saltwater extraction
Q_{IN} = flow rate of freshwater injection; D_B = depth of subsurface barrier
1*, 2* = elevations of interface at pumping location and at half distance between shoreline and pumping location.

water salinity (or degree of brine saturation) at various points can also be monitored as a function of time. The salinity measurement results can be used to plot the profiles of the freshwater-saltwater interfaces under a variety of the boundary conditions described above. All simulation series are performed under room temperature (about 25°C).

5. Flow Tests under Natural Condition

The natural condition (no pumping and extraction wells) is simulated under two head differences: Δh = 10 and 5 cm. The groundwater recharge rates are 65 cc/minute for Δh = 10 cm, and 24 cc/minute for Δh = 5 cm. Immediately after the flow test is started, the freshwater flows from the left reservoir through the sand aquifer in the middle of the frame, and seeps out through the porous strip into the saltwater reservoir on the right. To obtain a steady-state flow the head differences are maintained constant at the pre-designed values, and the brine is maintained 100% saturated (100% salinity) during the test. The profile of the freshwater-saltwater interface can be determined by measuring the salinity of the fluid in the sand aquifer at various locations and depths. The transition zone where the fluid salinity is grading from 0 to 100% can be drawn from the test simulations. To ensure that the steady-state flow condition is achieved the measure-

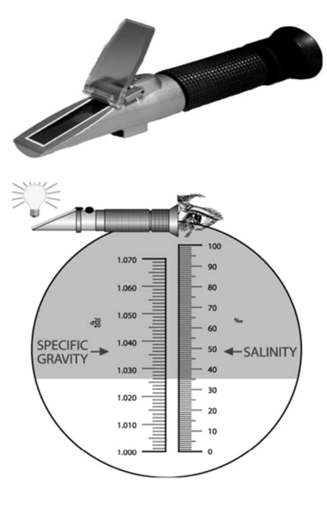

Figure 4. Refracto-Salinometer used to measure water salinity in this study.

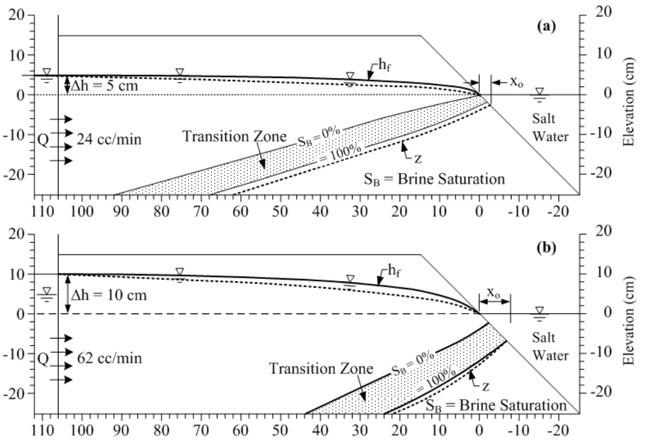

Figure 5. Interface profiles of groundwater and saltwater from physical model (solid lines) compared with the Ghyben-Herzberg solution (dash lines) for Δh of 5 cm (a) and 10 cm (b).

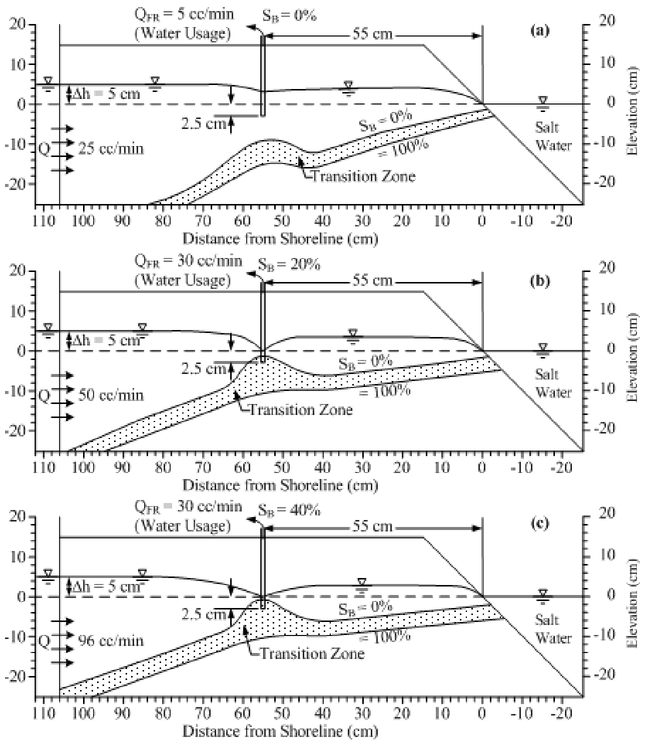

Figure 6. Simulation of groundwater pumping effect under Δh = 5 cm with pumping rates (Q_{FR}) = 5 cc/minute (a), 30 cc/minute (b), and 70 cc/minute (c).

ments are taken place every hour until no significant change in the salinity of the sampling fluid. The tests normally take about 12 hrs. The results are compared with those calculated by the Ghyben-Herzberg equations (described in Section 3). Figure 5 compares the interface profiles observed from the physical model and from the calculation. As shown in Figure 5 the measurements agree well with the calculations for both Δh values. The saltwater intruded into the aquifer and pushed the fresh groundwater away from the shoreline, about 60-65 cm for Δh = 5 cm, and about 25-45 cm for Δh = 10 cm. These indicate that the magnitude of saltwater intrusion is smaller for a larger head difference between the groundwater and seawater. The agreement between the measurements and the calculations implies also that the physical model and test procedure used here are sufficiently reliable for use to simulate the flow characteristics of the seawater intrusion under more complex boundary conditions.

6. Effect of Fresh Water Pumping

Six test simulations with Δh equal to 5 and 10 cm are performed to assess the effect of groundwater pumping rate on the characteristics of the saltwater intrusion. The groundwater pumping is simulated by withdrawing the freshwater from a drilled-hole on the rear acrylic plate located at depth of 2.5 cm below the saltwater level. The pumping rates (Q_{FR}) are maintained constant at 0.2, 10 and 100 cc/minute for Δh = 10 cm, and at 5, 30, and 70 cc/minute for Δh = 5 cm. The results indicate that soon after the freshwater pumping starts the interface moves toward the pumping well location. The lower Dh value shows the greater penetration of the salt-water into the aquifer (Figures 6 and 7). The toe of the interfaces moves 75-110 cm for Δh = 5 cm and 20-70 cm for Δh = 10 cm from the shoreline. The water withdrew from the pump location however remains fresh as long as the pumping rate (Q_{FR})

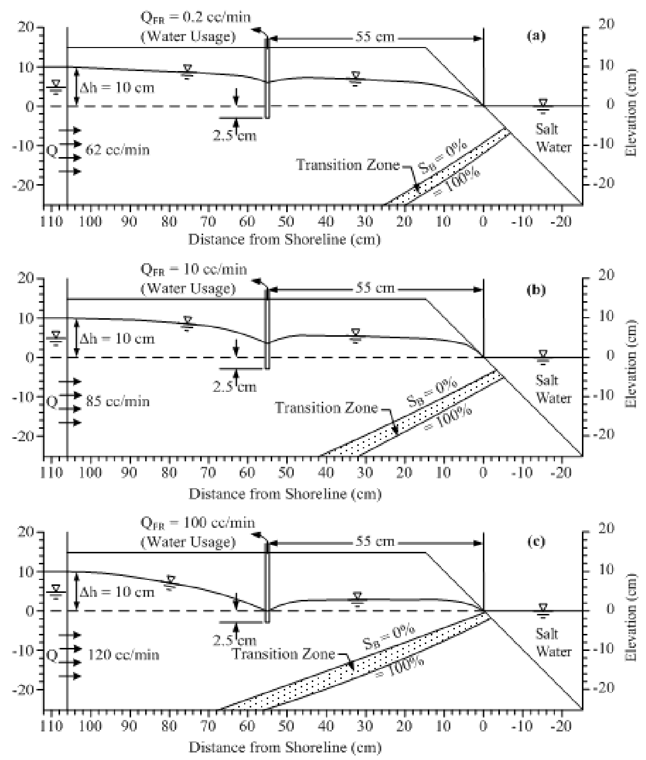

Figure 7. Simulation results of groundwater pumping effect under Δh = 10 cm with Q_{FR} = 0.2 cc/minute (a), 10 cc/minute (b), and 100 cc/minute (c).

is less than 50% of the recharge rate, Q (see Table 1). For the greater head difference (i.e. Δh = 10 cm) all pumping rates used here do not cause any salinity to the pumping well. At a higher pumping rate the up-coning characteristics of the interface can be observed, and eventually increases the salinity of the pumping water. The results suggest that the head difference and pumping rate are the key parameters governing the movement of the interface.

7. Performance of Controlling Methods

7.1 Salt water extraction

This method aims to reduce the volume of the intruded saltwater by extracting it from the near-shore aquifer and disposing it to the sea. It is simulated by withdrawing the saltwater from a pre-drilled hole at 10 cm below the saltwater level and 17 cm behind the shoreline. Here the Δh value and the groundwater pumping rate (Q_{FR}) are maintained constant at 5 cm and 70 cc/minute. Three rates of saltwater extraction are used: Q_{SE} = 15, 50 and 100 cc/minute. The resulting interface profiles are shown in Figure 8. The interfaces are located at 100-110 cm, 85-100 cm, and 65-85 cm, for the saltwater pumping rates of 15, 50 and 100 cc/minute, respectively. No salinity found in the freshwater pumping well for the extraction rates of 50 and 100 cc/minute. This means that this method is effective only if the saltwater extraction rate is greater than the groundwater usage rate (Q_{FR}).

7.2 Fresh water injection

This method (sometime called artificial recharge) aims to increase the head of the fresh groundwater close to the shoreline, and hence minimizing the saltwater intrusion. An injection well of freshwater is located in the sand aquifer and 17 cm from the shoreline. The bottom of the well is at the saltwater level. The injection rates (Q_{IN}) of 7, 15, and 50 cc/minute are used while the head difference is maintained constant at 5 cm with the groundwater pumping rate (Q_{FR}) at 70 cc/minute. Figure 9 shows the interface profiles obtained from the flow tests with different injection rates. For the injection rates of 7, 15, and 50 cc/minute the toes of the interface move away from the shoreline about 70, 68 and 65 cm, respectively. The results show that there is no salinity in the groundwater pumping well. This technique seems to be the most effective method compared to the other two methods described previously.

7.3 Subsurface barrier

This method involves construction of a subsurface barrier or low permeability zone to reduce the permeability of the aquifer close to the shoreline, and hence increasing the head (elevation) of the fresh groundwater. The subsurface barrier is simulated here by creating a low permeability zone by inserting a 0.6 mm diameter plastic rod into the aquifer.

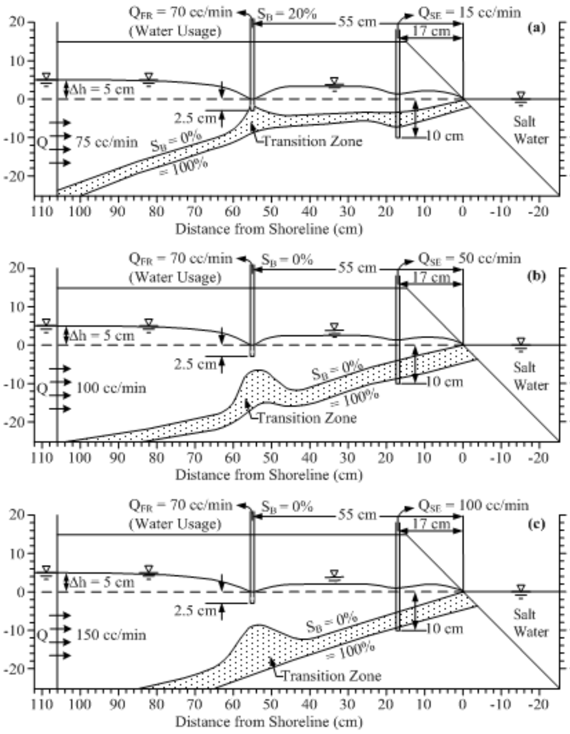

Figure 8. Simulation results of saltwater extraction method under 10 cm depth with extraction rates (Q_{SE}) = 15 cc/minute (a), 50 cc/minute (b), and 100 cc/minute (c).

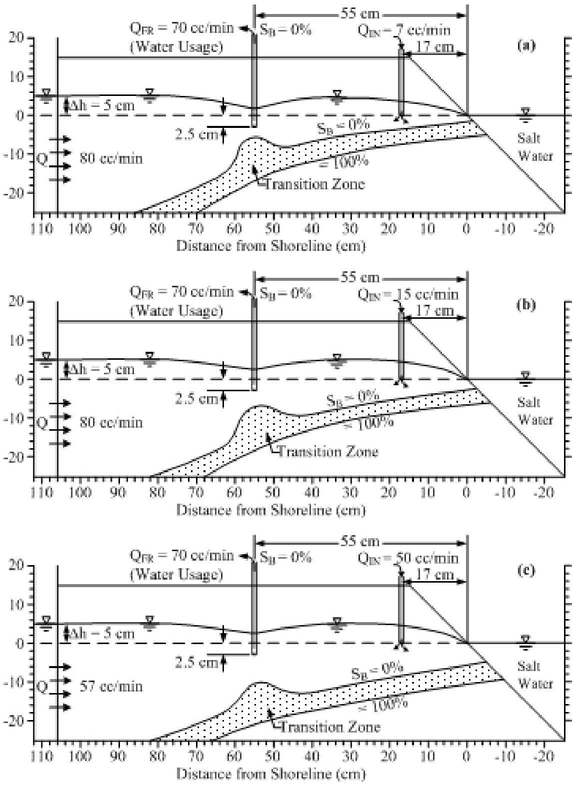

Figure 9. Simulation results of freshwater injection method with injection rates (Q_{IN}) = 7 cc/minute (a), 15 cc/minute (b), and 50 cc/minute (c).

Since the sand thickness in test space is 1.2 cm, this zone will reduce the amount of flow by 50%. The results suggest that there is an optimum barrier depth that can reduce the salinity of the groundwater well. Figure 10 shows the simulations for subsurface barrier depths (D_B) of 5, 10, and 15 cm below saltwater level. For the shallow barrier (5 cm below saltwater), the toe of the fresh-salt water interface is 70-90 cm from the shoreline and the pumping well is free of salinity. For the deep barrier (15 cm below saltwater level), the toe of the interface is 75-95 cm from the shoreline, and no salinity detected in the pumping well. However the barrier depth of 10 cm can not keep the pumping well fresh. The toe of the fresh-salt water interface moves up to 80-100 cm away from the shoreline.

8. Dye Testing

Dye testing is performed for all cases described earlier mainly to allow a visual inspection of the movement of the interface during the flow simulations. A red dye is dissolved in the saltwater stored in the right reservoir to observe its penetration into the sand aquifer. Since only small amount of the dye in used, the property of the salt water remains unchanged. The test for each series is started after the mixture is consistent. Figures 11 through 15 show the results observed by dye testing under various conditions. The interface between the saltwater and freshwater can be clearly seen. The observations agree well with the salinity profiles measured from the monitoring points for all cases (Figures 5 through 10).

The saltwater intrusion under natural condition for the lower Δh is clearly greater than that for the higher Δh value (Figure 11). For groundwater pumping condition the dye testing was performed on the model using Δh of 5 cm and freshwater pumping rate (Q_{FR}) of 70 cc/minute. The interface moves 95-110 cm away from the shoreline, and shows the up-coning characteristics, and eventually increases the salinity in the pumping well (Figure 12). For the fresh water injection method the dye testing is performed under the injection rate of 50 cc/minute, the fresh water pumping rate (Q_{FR}) of 70 cc/minute and the injection well is located at the salt water level. The toe of the interface moves toward the shoreline and the pumping well is free of salinity. This agrees with the salinity measurements performed earlier (Figure 13). The Dh value of 5 cm, Q_{FR} of 70 cc/minute and Q_{SE} of 50 cc/minute are used to simulate the effectiveness of the saltwater extraction technique. Here the extraction well is located at 10 cm below the saltwater level and the freshwater pumping well is set similar to the previous. The toe of the interface moves over 110 cm from the shoreline (Figure 14). The interface profile is pushed down below the pumping well depth. No salinity is detected in the groundwater well. For the subsurface barrier condition the dye testing is performed for the

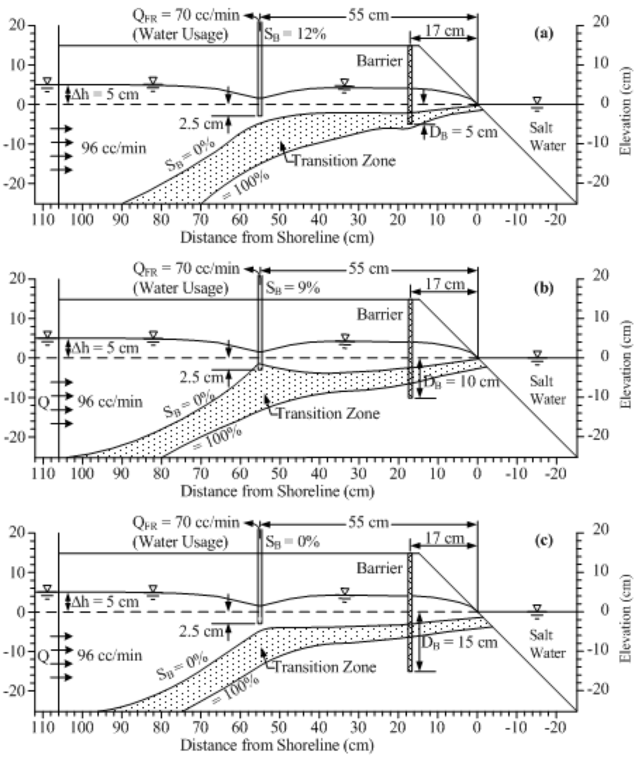

Figure 10. Simulation results of subsurface barrier method for 5 cm (a), 10 cm (b), and 15 cm (c) depth below salt water level.

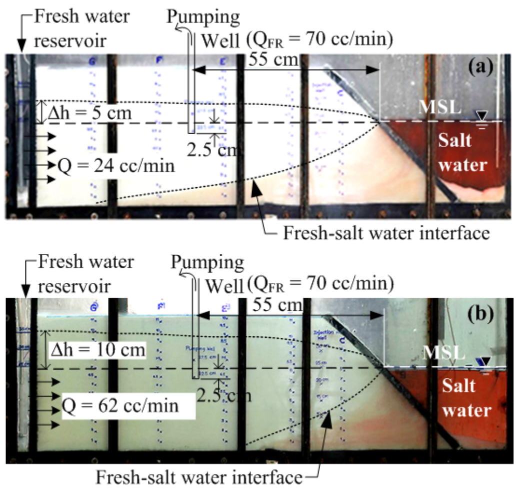

Figure 11. Dye testing under natural condition for Δh = 5 cm (a) and 10 cm (b).

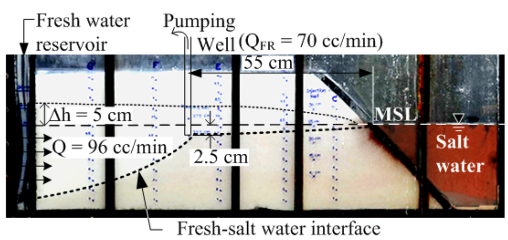

Figure 12. Dye testing for groundwater pumping effect with Δh = 5 cm and Q_{FR} = 70 cc/minute.

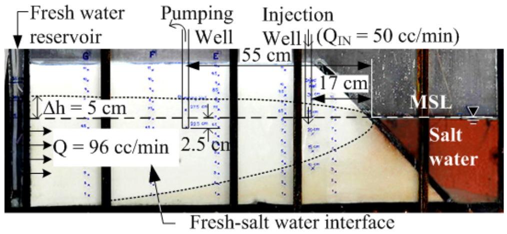

Figure 13. Dye testing for freshwater injection method with Δh = 5 cm and Q_{IN} = 50 cc/minute.

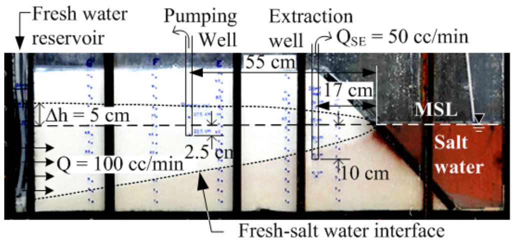

Figure 14. Dye testing for saltwater extraction method at 10 cm below salt water level with Q_{SE} = 50 cc/minute.

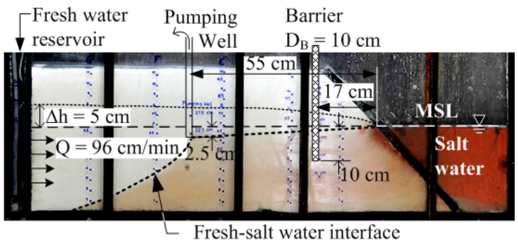

Figure 15. Dye testing for subsurface barrier method at depth (D_B) 10 cm below saltwater level.

barrier depth of 10 cm below the saltwater level. The interface rises up and reaches the pumping well. The toe of the interface is located at 100 cm from the shoreline (Figure 15). In summary the observations from the dye testing well agree with those measured from the flow simulations for all cases.

9. Discussions and Conclusions

The movements of fresh-salt water interface in unconfined aquifer near shoreline are simulated in this study. The results indicate that under natural dynamic equilibrium between the recharge of freshwater and the intrusion of saltwater the salinity measurements agree well with the solution given by Ghyben-Herzberg. This confirms that the scaled-down physical model used here is sufficiently reliable to simulate the locations and movements of the saltwater and freshwater near the shoreline. The freshwater pumping can move the interface toward the well, depending on the pumping rates and the difference between the far-field recharge (freshwater reservoir) and the saltwater level. To control the saltwater intrusion the freshwater injection or artificial recharge method near the shoreline is more favorable than the saltwater extraction method. The fresh water injection rate of about 10% of the discharge rate can effectively push the interface toward the shoreline, and keeping the pumping water free of salinity. The effectiveness of the subsurface barrier technique depends heavily on the depth of the barrier below the salt water level. The barrier depth that is equivalent to Dh can effectively press the interface lower, and keeps the pumping well free of salinity. The saltwater extraction is effective only if the extraction rate is greater than the groundwater usage rate.

It is recognized that the two dimensional flow in unconfined aquifer assumed here may not truly represent the actual conditions in many areas. The results obtained from these simplified conditions are very useful to qualitatively determine the effectiveness of the controlling methods. The conclusions drawn above are based purely on the simulation results. In actual practice however the selection and suitability of each method depends primarily on site-specific conditions. The subsurface barrier requires a high initial investment on geotechnical work but has an advantage over other methods in terms of the long-term maintenance. The saltwater extraction method requires continuous energy and may not be suitable in some areas. The freshwater injection method seems here the most suitable to control the salt water intrusion particularly in the areas where the head difference between the in-land fresh water and salt water is large.

Acknowledgements

This study is funded by Suranaree University of Technology and by the Higher Education Promotion and National Research University. Permission to publish this paper is gratefully acknowledged.

References

Aharmouch, A. and Larabi, A. 2001. Numerical modeling of saltwater interface upconing in coastal aquifers. Proceedings of the First International Conference on Saltwater Intrusion and Coastal Aquifers-Monitoring, Modeling and Management, Essaouira, Morocco, April 23-25, 2001, 1-12.

Bear, J., Zhou, Q. and Bensabat, J. 2001. Three dimensional simulation of seawater intrusion in heterogeneous aquifers: with application to the coastal aquifer of Israel. Proceedings of the First International Conference on Saltwater Intrusion and Coastal Aquifers - Monitoring, Modeling and Management, Essaouira, Morocco, April 23-25, 2001.

Bear, J. and Cheng, A.H.D. 2010. Modelling Groundwater Flow and Contaminant Transport, Springer, New York.

Bear, J., Chang, A.H.D., Sorek, S., Ouazar, D. and Herrera, I. 1999. Seawater Intrusion in Coastal Aquifers: Concepts, Methods, and Practices, Kluwer Academic

Publishers, The Netherlands.

Brakefield, L.K., Abarca, E., Langevin, C.D. and Clement, T.P. 2008. Physical and numerical modeling of buoyant groundwater plumes. Proceedings of the 20th Salt Water Intrusion Meeting, Naples, Florida, U.S.A., June 23-27, 2008, 26-29.

Christensen, B.A. and Evans, A.J.Jr. 1974. A Physical model for the prediction and control of saltwater intrusion in the Floridan aquifer. Florida Water Resources Research Center.27, A-022-FLA, Department of Civil & Coastal Engineering University of Florida, Gainesville, 101 p.

Fang, H.Y. 1997. Introduction to Environment Geotechnology, CRC Press LLC, New York.

Freeze, R.A. and Cherry, J.A. 1979. Groundwater, Prentice Hall, New York.

Goswami, R.R. and Clement, T.P. 2007. Laboratory-scale investigation of saltwater intrusion dynamics. Water Resources Research. 43, W04418, 1-11.

Luyan, R.Jr., Momii, K. and Nakagawa, K. 2009. Laboratory-scale saltwater behavior due to surface cutoff wall. Journal of Hydrology. 377, 227-236.

Oswal, S.E. and Kinzelbach, W. 2004. Three-dimensional physical benchmark experiments to test variable-density flow models. Journal of Hydrology. 290, 22-42.

Todd, D.K. and Mays, L.W. 2005. Groundwater Hydrology, John Wiley and Sons, New York.

Werner, A.D., Jakovovic, D. and Simmons, C.T. 2003. Experimental observations of saltwater up-coning. Journal of Hydrology. 373, 230-241.