# Effect of high permeable layer on hydraulic system in a coastal aquifer

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## ABSTRACT

The sea-level rise due to climate change could potentially induce the encroachment of saline seawater to coastal aquifers, resulting in the deterioration of water quality in drinkable water resources adjacent to coastal aquifers. The process of seawater intrusion into coastal aquifers is site-specific and often depends upon the geometry of the coastal aquifer systems, hydraulic properties, and the discharge rate to the sea. The Jeju Island in Korea comprises extensive lava flows and its complex geology including high permeable layer such as clinkers and hyalocalstites plays a major role on fresh /saline water interactions in coastal aquifer. In this study, we developed a vertical two-dimensional model, representing the hydrogeologic characteristics of the Jeju Island, to assess the effect of high permeable layer on the coastal groundwater system. A series of sensitivity studies using SEAWAT-2000 were conducted to understand the effect of the horizontal length and vertical depth of high permeable layer on the spatial location of the fresh / seawater interface toe and the thickness of dispersion zone. In addition, each model case has also been simulated with the rising sea-level. Although there were some differences with the depth and length of high permeable layer, the interface toe, in general, encroached about 6-8 m toward inland with 1 cm rise of the sea-level. The simulated results provided the major factors that influence the interactions between fresh groundwater and seawater in coastal zone.

## INTRODUCTION

Coastal aquifers serve as major resources for the supply of freshwater in many countries. Consequently, to exploit and assess the drinkable groundwater resources, and prevent the potential seawater intrusion in coastal aquifers, it is critical to understand the dynamic interactions between freshwater and sea water in coastal aquifers. In this work, we investigated the seawater intrusion in Jeju Island located 140 km south of the Korean Peninsula. The Jeju Island is a volcanic island and, its coastal zone, seawater intrusion is a generalized phenomenon. Kim *et al*. (2006) proposed a conceptual model describing the fresh / saline water interactions in the eastern part of Jeju Island by interpreting the multiple results from electrical conductivity (EC), temperature log, and the flowmeter tests. On the extension of the study, Kim *et al*. (2008, 2009) analyzed the mutual interaction of fresh / saline water influenced by tidal fluctuations using EC data and end-member mixing analysis. The purpose of this paper is two-fold. First, it aims to examine the effect of hydrogeological characteristics of the Jeju Island on fresh / saline water interaction in coastal area. The second is to investigate the impact of sea-level rise on seawater intrusion in coastal aquifer. For these purposes, we developed a vertical two-dimensional model, representing the hydrogeologic characteristics of Jeju Island in Korea. A series of sensitivity studies were conducted to understand the effect of the horizontal length and vertical depth of high permeable layer on the interface toe of fresh / seawater and the thickness of dispersion zone. In addition, each model case has been simulated with rising sea-level. Our study did not tend to reproduce the field observation on the numerical model; rather, the objective was to understand the dynamic nature of coastal system in the Jeju Island using the hypothetical model. The simulations were performed with SEAWAT-2000 (Guo and Langevin, 2002; Langevin *et al*., 2003) which is a computer program for simulation of three-dimensional, variable-density, transient groundwater flow in porous media.

## METHODS

Simulations presented were carried out to illustrate the occurring processes observed at coastal zone in Jeju Island. In this way, a basic understanding of the behavior of saline water intrusion in the subsurface can be gained. Although the numerical model in this study is not aimed to reproduce the real world, the dimensions of the subsurface system used in this study are similar to coastal system in the eastern part of Jeju volcanic island. A vertical two-dimensional model was constructed (Figure 1). The dimension of the model was 5,000 m in length and 100 m in depth. The domain consists of 250 columns with 20 m grid spacing. The model has 57 layers with grid size of 1-3 m. The left-side boundary representing the inland was set as a constant head boundary with 4 m. Sea water hydrostatic conditions were applied to the right boundary with constant concentration of 35 kg m$^{-3}$. Later, right-side boundary was increased to 0.5 m and 1.0 m to simulate the rising sea-level. Finally, the high permeably layer representing clinker or hyaloclastite is assigned to understand its effect on the saltwater intrusion.

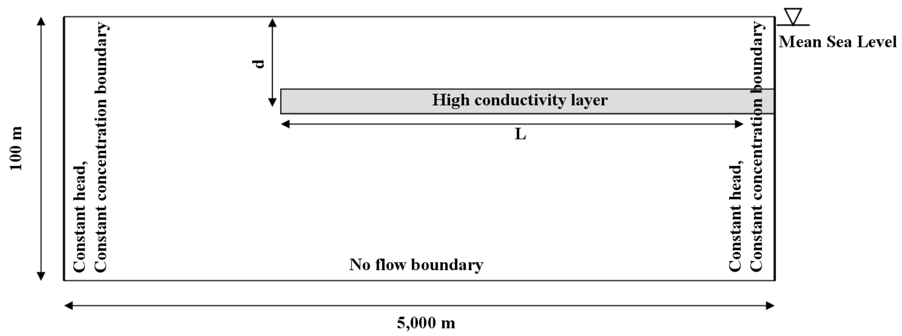


**Figure 1. Basic model setting used in this study.**

## RESULTS

### *Effect of high permeable layer*

Figure 2 illustrates the streamlines of groundwater that flows from the inland to the coast with the presence of high permeable layer adjacent to the coast. In case of the existence of high permeable layer in the aquifer, the groundwater flow pattern is similar to homogeneous case at inland part. However, as the fresh water approaches near high permeable layer, the groundwater tends to flow through this permeable zone. Due to this intensive flow through high permeable layer, there is a decrease of fresh water flow underneath the high permeable layer. Since the lack of groundwater flow beneath the high permeable layer, more seawater encroaches into the inland here, resulting that the interface toe of the saltwater front reaches about 2600 m. The other characteristic with the presence of high permeable layer is that the dispersion zone becomes thicker under the high permeable layer. We could infer that the presence of the high permeable layer in coastal aquifer could control the spatial configuration and thickness of dispersion zone. To investigate further, we set the depth as 30 m consistently and changed the horizontal length from 1,500 m to 2,500 m, and 3,500 m. A simple criterion to determine the extension of saltwater intrusion is to examine the interface toe location. The toe location was 1,920 m when the aquifer was homogeneous, but the toe was at 2,580 m with L=1,500 m, 3,050 m with L=2,500 m, and 3,450 m with L=3,500 m. The next simulation was carried out to investigate the effect of vertical depth of high permeable layer. The horizontal length was set to be 1,500 m consistently, and the depth of high permeable layer was changed with the value of 30 m, 40 m, and 50 m. The simulation results predicted that the toe position was recessed to coast as the depth of high permeable layer was increased. For example, it was 2,580 m with d=30 m, 2,960 m with d=40 m, and 2,380 m with d=50 m. The high permeable layer at lower part of the aquifer enables high flux of fresh groundwater toward coast and effectively resists the intrusion of seawater.

### *Effect of sea-level rise*

We also performed a series of numerical simulations to investigate the effect of sea-level rise on coastal aquifer. Three scenarios were developed for homogeneous aquifer with different sea-level rises such as 0 m, 0.5 m and1.0 m. Simulation results show that the interface toe was 1,920 m when sea level was set to be 0 m. As sea-level rose to 0.5 m and 1.0 m, the interface toe approached to 2,360 m and 3,000 m, respectively. The results showed that the seawater encroachment progress toward inland was about 11 m with 1 cm sea-level rise in this aquifer system. To see the effect of high permeable layer with rising sea-level on fresh / saline water interaction each model case has been simulated with different head boundary conditions. For case the high permeable layer has a length of 2,500 m at depth of 30 m, the simulation results show that the interface toe was 3,050 m when sea level was set to be 0 m. As sea-level rose to 0.5 m and 1.0 m, the interface toe approached to 3,310 m and 3,700 m, respectively. Although there are some differences with the depth and length of high permeable layer, the interface toe encroached about 6-8 m toward inland with 1 cm sea level rise. This result also shows that the seawater encroaching rate toward inland is higher in homogeneous aquifer than in the aquifer with high permeable layer. This indicates that high permeable layer play a major role in coastal aquifer.

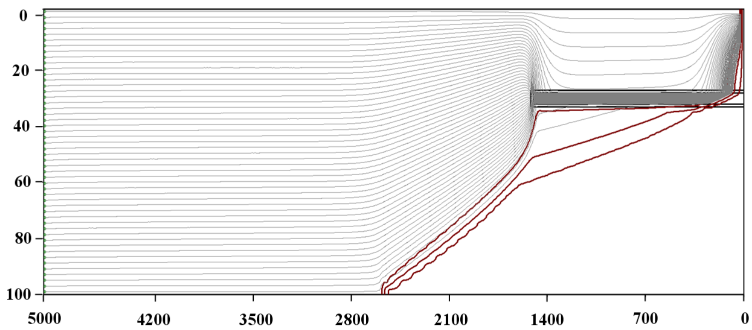


**Figure 2. Groundwater streamline with the presence of high permeable layer.**

## CONCLUSIONS

The interface toe of fresh / saline water was assessed to evaluate the degree of seawater intrusion. In addition, the thickness of dispersion zone was also investigated with the dispersion index to determine the spatial characteristics of dispersion. The simulation results showed that the presence of high permeable layer in coastal aquifer allows an intensive fresh groundwater flow from the inland toward coast and causes to develop a thick dispersion zone immediately underneath the high permeable layer. Various case studies showed that more seawater intruded toward inland as the horizontal length of high permeable layer is increased and its vertical depth is decreased. Lowering the position of high permeable layer effectively curbed the seawater intrusion underneath the high permeable layer but we were able to observe that the thickness of dispersion zone above the high permeable layer is increased. The effect of sea-level rise on the coastal aquifer was evaluated. The simulation results predicted that the seawater intrudes about 11 m with 1 cm increase of sea-level in homogeneous aquifer. In case of model with high permeable layer, the seawater encroached about 6-8 m with 1 cm sea-level rise. This result suggests that the intrusion rate proportional to sea-level rise is more sensitive in homogeneous aquifer than in the aquifer where high permeable layer exists.

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