Effect of Groundwater Pumping on Saltwater Intrusion in a Coastal Plain

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ABSTRACT

Salinity intrusion due to groundwater over-pumping has been recognized as an environmental issue in the Shiroishi area, a coastal lowland plain in Kyushu, Japan. In this study, an integrated numerical model was established and applied to the Shiroishi site, using a groundwater flow model and a solute transport model to simulate groundwater flow hydraulics and solute transport in the alluvial lowland plain. The simulated results reveal that groundwater levels in the aquifer greatly vary from season to season in response to varying climatic and pumping conditions. Consequently, seawater intrusion has hapenned along the coast. The study suggests that monitoring the present salinisation process is useful to participate in time possible threats to fresh groundwater supplies in the near future.

Keywords: Coastal aquifer, groundwater withdrawal, groundwater hydraulics, salinity intrusion

1. INTRODUCTION

Groundwater is an important water resource and its management is vital for integrated water resources development in coastal plains. Situated in Kyushu Island of Japan, the Shiroishi plain is one of the productive and intensely farmed agriculture areas as shown in Figure 1. Prior to the arrival of surface water, a large scale groundwater development for agricultural supply has begun since the late 1950s. With rapid expansion of the cultivable and urban areas, a large amount of groundwater has been exploited to meet the ever-increasing water demand for agriculture, industry and domestic use. Such excessive pumping over the years has led to undesirable effects, such as a continual decline in potentiometric levels, seawater intrusion, turning large quantities of fresh water to brackish and land subsidence over the alluvial plain (Don *et al.*, 2003). Since 1980s, analysis of the groundwater quality data from wells has revealed that saltwater encroachment has occurred in the area. The water resources engineers or the environmental scientists need to consider such impacts and plan for reducing the adverse effects.

2. MATHEMATICAL MODEL

The model is a three-dimensional groundwater flow model integrated with a solute transport model. Groundwater level for the study area was modeled using MODFLOW (McDonald and

Harbaugh, 1988). The three-dimensional movement of groundwater of constant density through porous earth material can be described by the partial differential equation:

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right)-W=S_s\frac{\partial h}{\partial t} \quad (1)$$

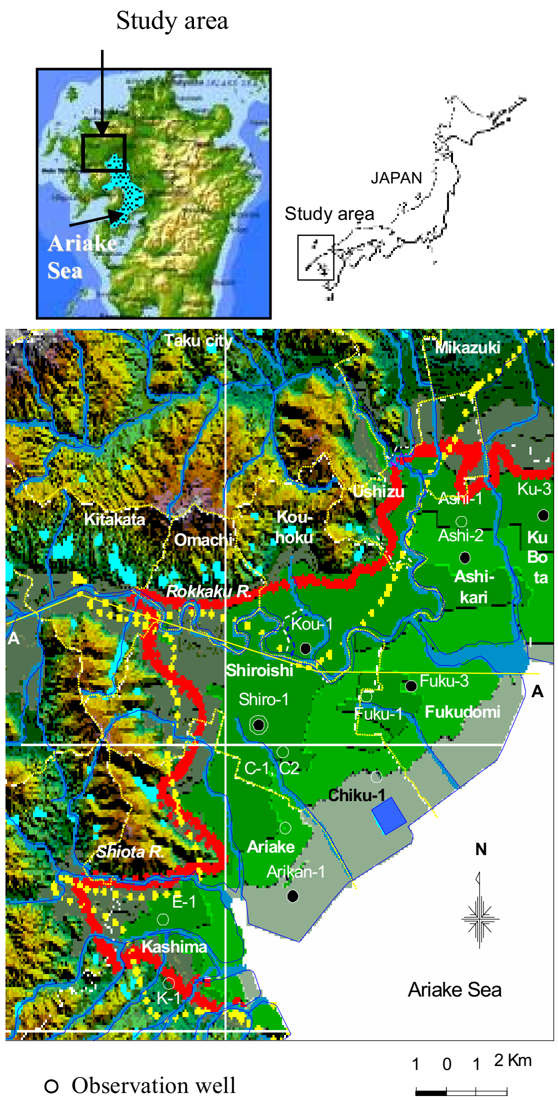

Figure 1. Map showing the Ariake Sea and the Shiroishi plain.

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, [LT^{-1}]; h is the potentiometric head [L]; W is source and/or sink of water [T^{-1}]; S_s is the specific storage of the porous material [L^{-1}]; and t is time [T].

On the other hand, simulation of ground-water flow is performed by numerically solving the ground-water flow and solute-transport equations. For a variable density system, in order to simulate saltwater intrusion in this study, SEAWAT model (Guo and Langevin, 2002) was applied, which uses variable-density flow in terms of freshwater head. The transport of solute mass in ground water can be described by the following partial differential equation:

$$\nabla\left(D\nabla C\right) - \nabla\left(\bar{v}C\right) - \frac{q_s}{\theta}C_s + \sum_{k=1}^{N} R_k = \frac{\partial C}{\partial t} \qquad (2)$$

where: ∇ is the spatial gradient operator; C : the concentration of contaminants dissolved in groundwater, [ML^{-3}]; t : time, [T]; D : the dispersion coefficient [L^2/T]; $\bar{v}$ is velocity [L/T]; q_s : the volumetric flux of a source or sink [T^{-1}]; C_s : the concentration of the source or sink [M/L^3]; θ : the porosity of the porous medium, dimensionless.

Solution to equation (1) can be obtained by applying the finite-difference method (McDonald and Harbaugh, 1988). During the simulation, the solute-transport model runs for a time step, and then MODFLOW runs for the same time step using the last concentrations from the solute-transport model to calculate the density terms in the flow equation. For the next step, velocities obtained from the MODFLOW are used to solve the transport equation (Don *et al.*, 2003).

3. RESULTS AND DISCUSSION

3.1 Model Setting

Figure 2 sketches a geological profile along a section A-A near by the Rokkaku River. In general, the whole area of Shiroishi plain is underlain by lowland quaternary soft deposits around the inland Ariake Sea. The aquifer system was 3-D discretized vertically into 4 layers based on their geologic and hydrogeologic characteristics. Below the ground surface is a soft marine clay layer which is locally known as the Ariake Clay. It is a confining bed with thickness varying from 10 to 20 m. The thickness becomes greater as it approaches the coastal zone and spreads far and wide under the plain area. Below this Ariake clay are dilluvial deposits dominated by sands, gravels, and pumices of various sizes, and are of 5m thick or less, in both vertical and lateral directions. The underlain are volcanic ash soils deposited in two gravel layers. The Aso-4 volcanic ash appears at an altitude of about 20m below sea level. In general, this layer is a thin one. The Aso-3 volcanic ash sediment is very thick development. Both diluvium and volcanic ash layers form a highly permeable and excellent aquifer in this region.

The basic input data to the model are the aquifer parameters including topography, geometry, elevation, soil properties of each soil layer in the aquifers. Bedrock is modeled as no-flow boundary. Recharges to the system are precipitation and rivers. Discharges from the system

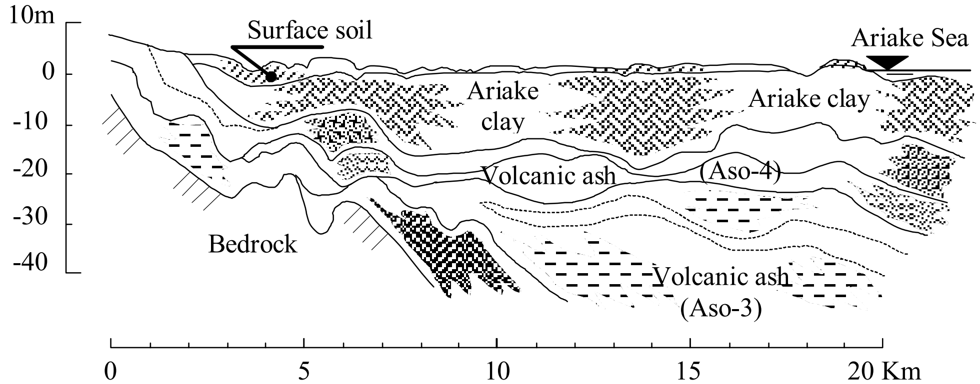

Figure 2. A typical geological profile.

include pumping wells and evapotranspiration. A well field consisting of total 176 pumping wells located in the study area was taken into consideration. A finite-difference 3-D grid was developed to adequately discretize the model domain of 28.0 x 20.0 km^2. The sizes of each cell are Δx = 500m, Δy = 500m.

Boundary conditions are assigned at all four sides. Water levels along the eastern model boundary were designated as a time varying specified head boundary. Calibration of the model focused on choosing parameters for the model layers. The hydraulic conductivities of the model layers were found in the order of 0.01 to 50.0 m/day.

3.2 Groundwater Flow

The steady-state analysis was first done to get the initial head values for transient-state simulation. The transient-state analysis was then conducted to observe the aquifer response at different period under different stresses and to simulate the aquifer for a long period of time. The transient simulation was divided into 209 stress periods. A time step of one day was used for a 20-year simulation, from 1979 to 1998.

Figure 3 plots the observed heads against simulated ones at a selected monitoring well, namely Shiro-1 in Shiroishi. As seen in Figure 3, overall the match between the observed and simulated heads is acceptable, indicating that a good estimation has been obtained. However, the peaks of the head curves were over estimated. This error may stern from the complexity when choosing the model parameters in the calibration process. As shown in figure 3, water levels in the aquifers in this area follow a natural cyclic pattern of seasonal fluctuation. The magnitude of fluctuations in water levels greatly varies from season to season and from year to year in response to varying climatic conditions and pumping periods (Don *et al.*, 2003). Figure 4 shows the annual groundwater level from 1980 to 1996. On average, groundwater declines at a rate of 0.07m per year.

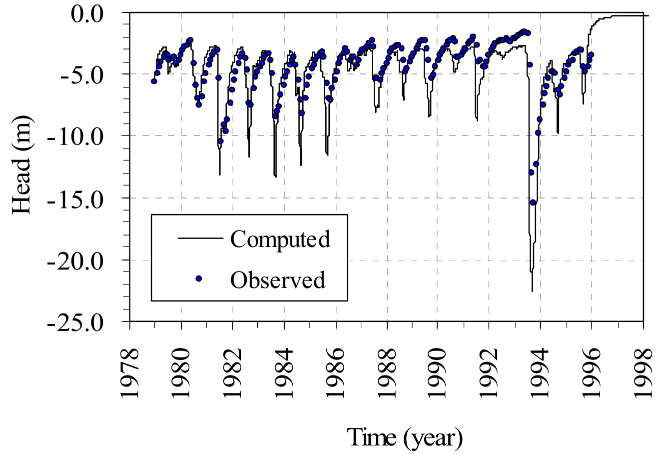

Figure 3. Computed and observed heads at well Shiro-1 (Shiroishi).

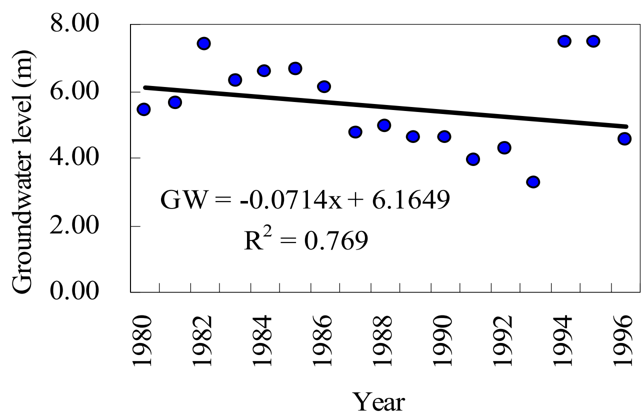

Figure 4. Average annual groundwater level from 1980 to 1996.

3.3 Saltwater Intrusion

The Ariake Sea of Japan is a typical water body surrounded by lowlands as shown in figure 1. This shallow and semi-closed sea can be modeled as a big salt lake problem suggested by Simmons *et al.* (1999). The boundary conditions for the transport simulation are dependent on the flow boundary conditions. The concentration of recharge due to rainfall is zero. Any inflow, occurring through the general head boundary, has a sea water concentration of 19,000 mg/L Cl. Because of less information on groundwater quality, rather than compare simulated results with measured data, the model tries to predict seawater intrusion that would be expected along the Ariake Sea

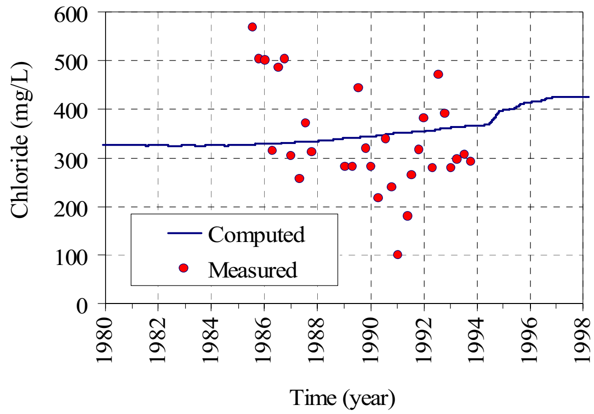

Figure 5. Chloride concentration in an observation well, Arikan-1 (Ariake).

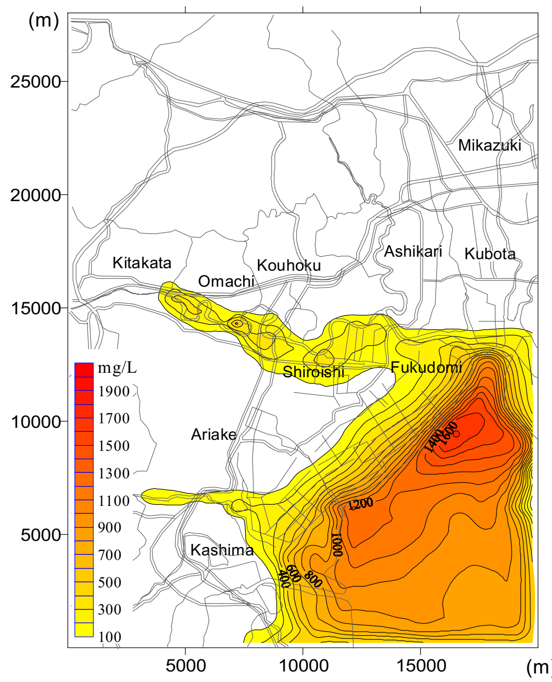

Figure 6. Simulated chloride concentration in a deep aquifer.

coast. After several trial runs, an improvement in model output was obtained. Figure 5 plots the simulated chloride concentration distribution in an observation well (Arikan-1) against the observed one. There is a slight increasing trend in chloride concentrations at all the observation wells located along the coast. An abrupt chloride concentration locally appears as a result of the 1994 drought and increases to more than 400 mg/L by 1997. Moreover, toward the end of the simulation, it appears that the model approaches a steady state with respect to chloride in the model domain.

A chloride-concentration map shown in Figure 6 illustrates the down-gradient migration of saltwater in a deep aquifer after a 20-year simulation. It can be seen that the saltwater initially flowing from offshore and existing rivers has mixed with fresh water and laterally leaked downward through the confining unit, and apparently across the aquifer unit toward pumping centers. It is also found that, after a 20-year pumping, the salinity plume appears to extend far inland from the coast. Based on the above observation, it is apparent that seawater intrusion would worsen in the confined aquifer along the coast if the current scheme of groundwater pumpage continues.

4. CONCLUDING REMARKS

In this study, the environment impact due to groundwater over pumping was examined by applying an integrated groundwater model. The model is a three-dimensional numerical model integrated with a solute transport model to simultaneously simulate water level and predict transient solute transport in the study area. The model outputs were well agreed with the observed results. The results reveal that seawater intrusion has happened along the coast under the current rates of groundwater exploitation. Instead, an alternative to eliminate pumpage in the intruded area, and a reduction in pumpage rate could significantly limit the inverse effects induced by groundwater pumping.

5. REFERENCES

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