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ORIGINAL ARTICLE

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Salinization processes in an alluvial coastal lowland plain and effect of sea water level rise

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Abstract In coastal areas, groundwater and aquifer systems are easily prone to pollution and contamination. Moreover, sea level rises also threaten the viability of many coastal zones and small islands. In the Shiroishi lowland plain, southwestern Kyushu Island of Japan, some environmental problems such as land subsidence and salinity intrusion due to over pumping of groundwater have long been recognized as water problems and become causes for public concern. In this study, an integrated surface and groundwater model was established and applied to the Shiroishi site to simulate groundwater flow hydraulics and predict the salinity intrusion process in the alluvial lowland plain. The simulated results show that groundwater levels in the aquifer greatly vary in response to varying climatic and pumping conditions. It is also found that sea water intrusion would be expected along the coast if the current rates of groundwater exploitation continue. Furthermore, sea water intrusion with a relative rise in sea water level due to aquifer compression and global climatic change was also considered. As a result, sea water intrusion appears to extend much farther in land from the coast compared to a reference case. The study also suggests a possible alternative to mitigate the inverse effects by pumping groundwater.

Keywords Coastal lowland plain · Groundwater over-withdrawal · Integrated surface and groundwater modeling · Salinity encroachment · Relative sea water level rise · Shiroishi plain · Kyushu Island · Japan

Introduction

In many countries, coastal lowlands are often convenient and attractive locations for human settlement, transportation, agriculture, industry, and economic activities. At the dawn of history, human settlements were associated with agriculture—an activity requiring plentiful water and fertile soils, elements found in river deltas and other lowland areas. The concentration of human activities in lowland areas intensifies local competition for all types of resources, such as for food, energy and natural resources with water amongst the most vital. These areas therefore become more and more important to the growth of human civilization and the development of their activities. However, under the natural process of the water cycle and human interferences such as mining of natural resources and land reclamation, water environment problems in these areas have become causes for social concern.

In coastal areas, groundwater and aquifer systems are easily prone to pollution and contamination, especially with an increase in development in these areas. The aquifers of these areas may be contaminated as a result of seepage of pollutants through the soils and into the groundwater. Heavily developed coastal areas increase the demand for a limited water resource from the aquifer, which results in declining groundwater levels, causing compression of the ground surface resulting in a sinking of the ground level, which induces a relative rise in sea water level, and the phenomena of saltwater intrusion.

In addition, coastal aquifers within the zone of influence of mean sea level are threatened by an accelerated rise in global mean sea level. Sea water level is subject to change in both long-term and short-term rise and fall from a variety of effects. A significant change in relative sea level can have adverse impact on both economic and social implications. A fall in sea level can affect operating difficulties in ports and harbors as well as have adverse effects on access to the coast and ocean. On the other hand, a rise in sea level can cause coastal flooding, loss of wetlands, loss of fresh water supplies due to possible saltwater intrusion into the coastal aquifer.

Although the sea level has been rising, worldwide the measured rise along the east coast has been greater, because of local subsidence usually taking place. In Japan, many lowland areas would be at risk if the sea level does rise due to sea water level change. Not only would large numbers of the population be at risk, but the impact on the economy would be very significant. One dramatic example is Osaka city with a population of over 2.5 million and an annual industrial production of approximately 500 billion US dollars. This city is highly vulnerable to sea level rise (Tamai and Ninomya 1991).

As discussed earlier, sea level rises would threaten the viability of many coastal zones, especially lowland areas. In this study, an integrated surface and groundwater model (Don et al. 2005a) was applied to simulate transient groundwater flow and solute transport in an alluvial coastal lowland area in southwestern Japan, taking into account the effect of sea water level to compare with the normal sea level, the reference case. The model is a three-dimensional numerical model that combines a surface water balance model, a groundwater flow model and a solute-transport model. The model results indicate that groundwater levels in the aquifer greatly vary in response to varying climatic and pumping conditions. As a result, sea water intrusion would be expected along the coast if the current rates of groundwater exploitation continue. Moreover, the salinity plume appears to extend at least a kilometer further inland from the coast compared to the reference case.

Description of the study area

The Shiroishi plain, one of the productive and intensely farmed agriculture areas, is situated in Kyushu Island, southwestern Japan, as shown in Fig. 1. Under the climate of the Asian monsoon, about 1,900 mm of precipitation falls in the area. However, this rainfall water runs off quickly because rivers are rapid and short. In the plain, the Rokkaku River basin is the largest with the total catchment area of 341 km^2. The river flows to the Ariake Sea and it is subject to tidal fluctuations and affected by salinity intrusion from the sea. An increased demand is placed on the aquifer during the summer months, not only because of droughts but also because of agricultural cultivation. Groundwater is, therefore, regarded as an important water resource of irrigation water for agriculture (Don et al. 2005), and it plays a significant role in irrigation water supply at more localized scales. As a result, there is a seasonal variation of high-water and low-water conditions in the aquifer. Due to the decline in water level from the reduction of paddy fields, water shortages in droughty years have

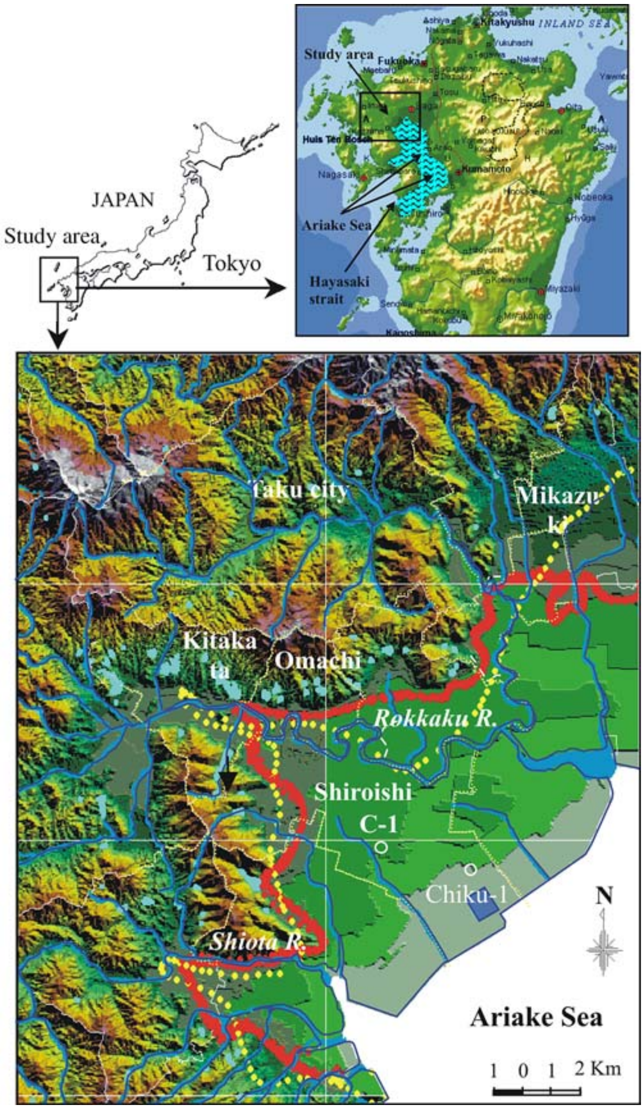


Fig. 1 Map showing the study area and the Ariake Sea, Japan

also become a growing concern. The contribution of surface water has, therefore, declined over this period.

Excessive pumping over the years since the late 1950s has led to undesirable effects, such as a continual decline in potentiometric levels, sea water intrusion turning large quantities of fresh water to brackish, and land subsidence over the alluvial plain. Rapid subsidence in 1994 occurred during the drought as a result of the severe depletion of the aquifer due to the extreme level of pumping. The accumulated subsidence has reached 124 cm over the past 50 years, from 1960 and the affected area has extended to 324 km^2. The link between withdrawals of groundwater and land consolidation in this study area has been widely studied using numerical models to simulate land subsidence and test management strategies to minimize subsidence (Don et al. 2003, 2005, Don et al. 2005a).

Since 1985, extensive sampling of the groundwater and coastal marine water analysis of the groundwater quality data from wells has revealed that saltwater encroachment has occurred in the area. With increased exploitation of the groundwater and the resulting intrusion of saltwater, the chloride in solution in the aquifer has increased due to the interaction with chloride from sea water.

Over the past two decades, some other studies related to geotechnical aspects in the plain have been performed to describe the dynamic behavior of the lowland plain, with the works of Miura et al. (1988), Tanaka (1990), and the most recent Sakai (2001). In general, the whole area of the Shiroishi plain is underlain by lowland quaternary soft deposits around the inland Ariake Sea. 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. Its 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 5 m thick or less, in both vertical and lateral directions. The underlain are volcanic ash soils deposited in two gravel layers. The volcanic ash (Aso-4) appears at an altitude of about 20 m below sea level. In general, this layer is a thin one but the Aso-3 volcanic ash sediment is a very thick development. Both diluvium and volcanic ash layers form a highly permeable and excellent aquifer in this region.

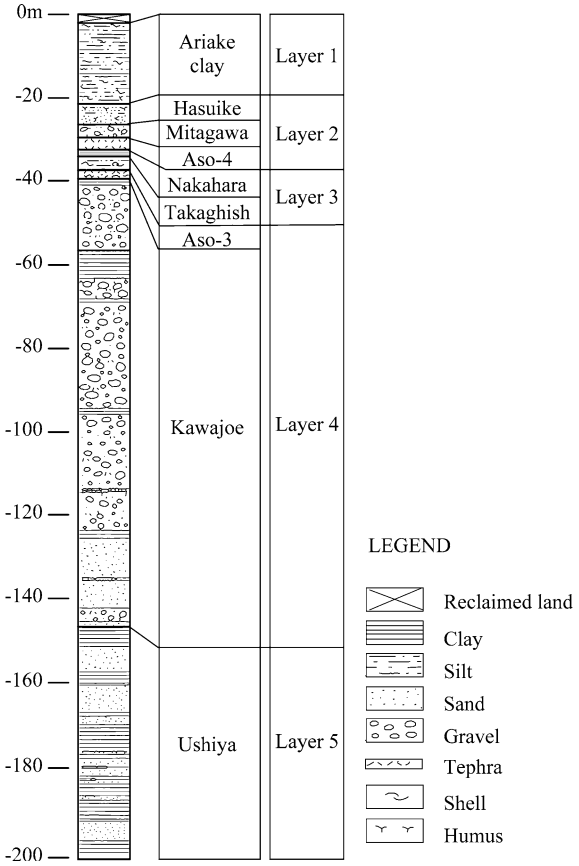


Fig. 2 A soil column and modeled layers

Figure 2 sketches a typical soil column at Arikan-1 near the shoreline in Ariake town, as well as the modeled layers. The aquifer system was 3D discretized vertically into five layers. Layer 1 is unconfined throughout most of the ground-water basin. Layer 2 was simulated as confined or unconfined, depending on the water level. The upper boundary of layer 2 is the bottom of the confining clay. Layer 3 is confined and extends from 20 to 70 m below sea level. Layer 4 is confined and represents the lower aquifer, ranging in depth from 30 to 200 m below sea level. Layer 5 is assumed to extend from an altitude of 200 to 250 m below sea level. The deposits in each aquifer are included in the layers representing the aquifers. Alluvial material at depths below 250 m below sea level was assumed to be well indurated, impermeable, and not a significant part of the regional flow system. Where the altitude of the bedrock is above the defined layer bottom, the layer bottom is equal to the altitude of bedrock.

Numerical models

In this study, an integrated surface and groundwater management model (Don et al. 2005a) was applied. The model integrates three main components, which are a lumped surface-water balance model for estimation of groundwater recharge. The main inputs to this model include rainfall, irrigation supplies, tube-well pumpage, area under different crops, crop coefficient values, reference evapotranspiration, and growth periods of different crops. A groundwater flow model is a main module within the integrated modeling. This model takes the recharge calculated by the previous model as one of the inputs and simulates the ground-water movement in an aquifer system under all other applied stresses. Integrated with the ground-water flow model is a salinity intrusion model. In addition, supporting models can be used to work on the base map and finally for analysis and presentation of simulated results.

Surface water balance model

The basic concept of the surface water hydrological cycle is as follows. The inflow of fresh water, consisting of rainfall and the available water supply from groundwater, ponds, creeks, reservoir dams, and water of rivers, should balance with the outflow, which consists of runoff, evapotranspiration and infiltration to the groundwater system. This lumped hydrologic model is very simple in structure yet a convenient tool to answer the key question of how much surface water is infiltrating to the groundwater system.

The surface water hydrological cycle simulation equation can be expressed as follows:

$$P(t) + S(t) = Ro(t) + ET(t) + I(t) \tag{1}$$

where $P(t)$ is precipitation, [LT^{-1}]; $S(t)$ water available from groundwater, ponds, creeks, reservoir dams and rivers, [LT^{-1}]; $Ro(t)$ runoff, [LT^{-1}]; $ET(t)$ evapotranspiration, [LT^{-1}]; $I(t)$ infiltration, [LT^{-1}], that recharges the groundwater system and t time, [T].

The surface water balance model can be applied to specify the temporal and spatial distribution of infiltration water from the surface water system recharged to the groundwater system. The components of the hydrological cycle consist of rainfall, evaporation, runoff discharge, and infiltration. Factors effecting this water cycle are land use, water consumption, agriculture and storage facility.

Groundwater flow model

The three-dimensional movement of groundwater of constant density through porous earth material may be described by the partial differential equation in the MODFLOW model (McDonald and Harbaugh 1988):

$$\frac{\partial}{\partial x}\left(K_{xx}\frac{\partial h}{\partial x}\right) + \frac{\partial}{\partial y}\left(K_{yy}\frac{\partial h}{\partial y}\right) + \frac{\partial}{\partial z}\left(K_{zz}\frac{\partial h}{\partial z}\right) - W = S_s\frac{\partial h}{\partial t} \tag{2}$$

where K_{xx}, K_{yy} and K_{zz} are values of hydraulic conductivity along the x, y, and z coordinate axes, which are assumed to be parallel to the major axes of hydraulic conductivity [LT^{-1}]; h the potentiometric head [L]; W a volumetric flux per unit volume and represents sources and/or sinks of water [T^{-1}]; S_s the specific storage of the porous material [L^{-1}] and t time [T].

Solutions to Eq. 2 can be obtained by applying the finite-difference method, wherein the continuous system described by Eq. (2) is replaced by a finite set of discrete points in space and time, and the partial derivatives are replaced by terms calculated from the differences in head values at these points. The process leads to systems of simultaneous linear algebraic difference equations; their solution yields values of head at specific points and times. These values constitute an approximation to the time-varying head distribution that would be given by an analytical solution of the partial-differential equation of flow (McDonald and Harbaugh 1988).

The groundwater flow model can be utilized for predictions of groundwater levels, drawdowns, gradients, and velocities, and can also be used as a basis for particle tracking to illustrate groundwater flow-paths and capture zones. The input data for the model include information on topography, geology, geo-hydrology of the aquifer system; time series data of pumping and recharge; initial, boundary conditions, and so on.

Saltwater intrusion model

The salinity intrusion model can be applied to simulate the salinity intrusion over time from the sea into the fresh aquifer system due to pulsed or continuous pumping of groundwater. Simulation of groundwater flow is performed by numerically solving the groundwater 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:

$$\nabla(D\nabla C) - \nabla(\bar{v}\,C) - \frac{q_s}{\theta}C_s + \sum_{k=1}^{N} R_k = \frac{\partial C}{\partial t} \tag{3}$$

where: $\nabla = \frac{\partial}{\partial x} + \frac{\partial}{\partial y} + \frac{\partial}{\partial z}$ is the spatial gradient operator; C the concentration of contaminants dissolved in groundwater, [M/L^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; $\sum_{k=1}^{N} R_k$ a chemical reaction term, [$ML^{-3}T^{-1}$].

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. 2005). For supporting the model, SURFER (Golden Software 2002) can be used for mapping, contouring, and analyzing the model input and outputs.

Results and discussion

The basic input data to the model are the aquifer parameters, including topography, geometry, elevation, and 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 include pumping wells and evapotranspiration. A well field consisting of a total of 176 pumping wells located in the study area was taken into consideration. A finite-difference grid was developed to adequately discretize the model domain. For the Shiroishi site, the groundwater system of interest is approximately 28.0×20.0 km^2 and is covered with a 3D grid. The sizes of each cell are $\Delta x = 500$ m, $\Delta y = 500$ m. The 3D grid contains 11,200 cells; $n_x = 56$, $n_y = 40$, $n_z = 5$, where n_i denotes the number of cells in the i direction.

Boundary conditions are assigned at all four sides. Water levels along the eastern model boundary were designated as a time varying specified head boundary as water entering or leaving the system depends on the water-level gradient between cells under consideration and adjacent active cells. The specified heads were interpolated based on water level data from near by wells. The average recharge amount from paddy fields to groundwater was estimated to be 7.0 mm per day during the growing season of crops from June to September.

Calibration of the model focused on choosing parameters for the model layers. The final choices for model parameters were achieved through trial and error. During the calibration, the hydraulic characteristics of the modeled layers were adjusted until a satisfactory correspondence between model results and observed field data was obtained. Calibrated hydraulic parameters of the material properties of the layered aquifers are summarized in Table 1.

Table 1 Material properties of the layered aquifer systems

Parameters	Layered aquifer				
	1	2	3	4	5
K_H (m/day)	0.01	50.1	0.518	103.7	0.13
K_V (m/day)	0.002	10.4	0.104	19.9	0.026
Effective porosity	0.45	0.25	0.25	0.45	0.01
Specific storage (m^{-1})	0.03	0.0002	0.001	0.0001	0.0001
α_T (m)	2.0	20.0	5.0	50.0	50.0
α_T/α_L	0.1	0.1	0.1	0.1	0.1

Notes K_H horizontal hydraulic conductivity, α_T the longitudinal dispersivity, K_V vertical hydraulic conductivity, α_L the transversal dispersivity

Groundwater hydraulics

Transient-state analysis was conducted to observe the aquifer response at different periods 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 C-1 in Shiroishi. As seen in Fig. 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 stem from the complexity when choosing the model parameters in the calibration process. As shown in Fig. 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). The water levels in shallow aquifers also fluctuate with irrigation, which are higher during the growing season.

Saltwater contamination

In this study area, the reclamation of sea embayment came into perspective with the introduction of sea dikes in the eighteenth century. Reclamation of these areas essentially meant drainage, which caused a lowering of the ground surface by compaction and disintegration of the peat. This subsidence eventually brought the area below sea level and created an irregular surface by differentiated compaction due to the variation in soil properties and dewatering intensity. This variation in

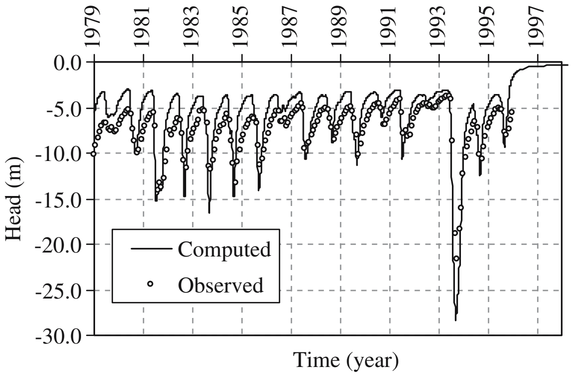


Fig. 3 Computed and observed heads at well C-1 (in Shiroishi)

land surface made it necessary to separate the different areas hydrologically from each other by dikes, dams, and other hydraulic structures, forming a network of creeks with ponds. In this way, large areas were regained that previously were lost by sea encroachment and river flooding. The ongoing change in topography through these land and water management measures has set in motion a complicated pattern of groundwater recharge and discharge systems.

The study area is bounded by the Ariake Sea to the southeastern part. The Ariake Sea of Japan is a typical water body surrounded by lowlands as shown in Fig. 1. The sea, an inland sea, is bounded by the surrounding prefectures of Nagasaki, Saga, Fukuoka, and Kumamoto. The Ariake Sea is a shallow and semi-closed gulf connected to the open sea by only one small place at the Hayasaki strait (Fig. 1). In this study, this shallow and semi-closed sea was modeled as a big salt lake problem (Don et al. 2005) as saltwater can initially encroach from the top of the thick and soft Ariake clay layer where the sea and existing rivers occupy and laterally leak downward through this confining unit. The principal ion in sea water is chloride (Cl) and it is the usual indicator of sea water intrusion. Since in coastal groundwater chloride (Cl-) is the predominant negative ion, interest is often focused on the distribution of this ion. Sea water contains about 19,000 mg/L chlorides and about 34,500 mg/L dissolved solids (Goldberg 1963).

The boundary conditions for 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. However, less information on groundwater quality is available and data are lacking to reasonably describe the chloride distribution in groundwater. Therefore, rather than compare simulated results with measured data, the model tries to predict sea water intrusion that would be expected along the Ariake Sea coast. Calibrated parameters such as the effective porosity, the longitudinal dispersivity and the ratio of transversal to longitudinal dispersivity of the aquifer layers are also summarized in Table 1.

Figure 4 plots the simulated chloride concentration distribution in an observation well (Chiku-1) against the observed one. As can be observed from this figure there is a slightly 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 420 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 Fig. 5a illustrates the down-gradient migration of saltwater in a deep aquifer (−80 to −120 m) after a 20-year simulation. 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.

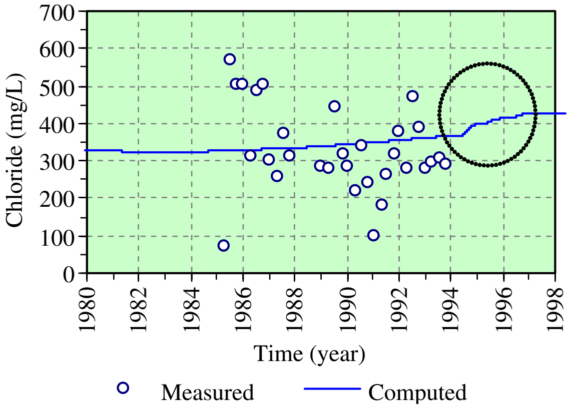


Fig. 4 Chloride concentration in an observation well Chiku-1

Figures 6 and 7 depict irregular contours of a plume of high-chloride water (greater than 250 mg/L) encroaching on the aquifer in response to pumping in 1981 (Figs. 6a, 7a; after 3-year pumping) and in 1998 (Figs. 6b, 7b; after 20-year pumping), for sections A–A and B–B (shown in Fig. 5a), respectively. It can be seen from these figures that, saline water intrusion into the aquifer is clearly indicated, and after a 20-year pumping, the salinity plume appears to extend at least 1.2 km far inland from the coast. Moreover, the plume of liquid brine extended down-gradient to few wells located about 1.5 km from the coast (Don et al. 2005). Based on the above observation, it is apparent that sea water intrusion would worsen in the confined aquifer along the coast if the current scheme of groundwater pumping continues. Simulation of sea water intrusion for the cross section considered in the study shows that the sensitive zone with chloride more than 500 mg/L in this area is between 400 and 2,000 m from the high tide line. As the Shiroishi plain has been reclaimed in 1860s, sea water may have intruded into the system for some hundreds of years.

Effect of relative sea water level rise

Sea level rise will accelerate the salinisation of the subsurface. Groundwater flow is slow, however, the effects of this rise on the groundwater system will not be very noticeable in the short to medium term. In the long term, the effects in terms of the amount of seepage, average salt content and salt load could be considerable. In this study, a relative sea water level rise of 0.6 m (2 ft) was taken into the simulation for a number of reasons. The phenomena of sea water level rise may include the

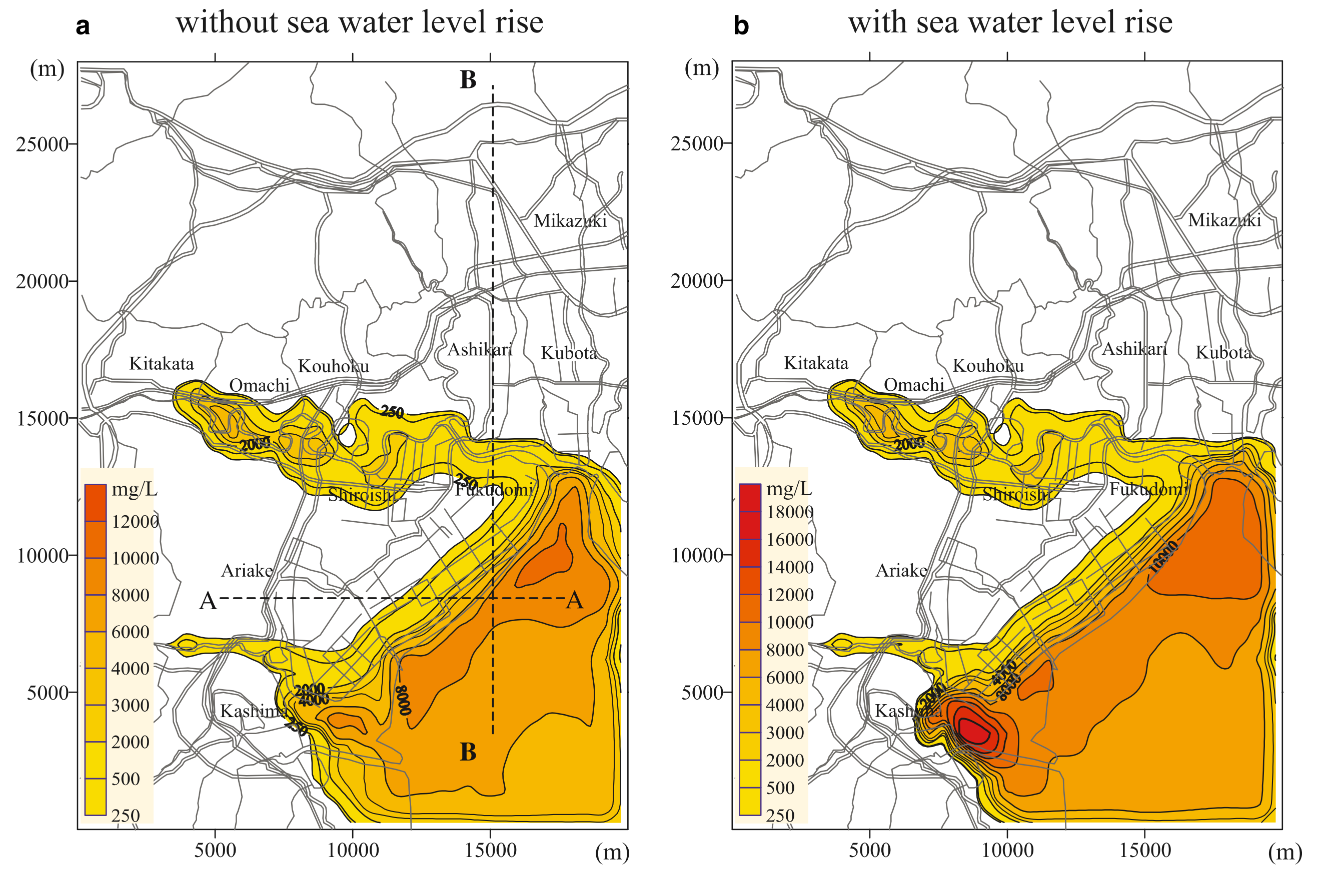
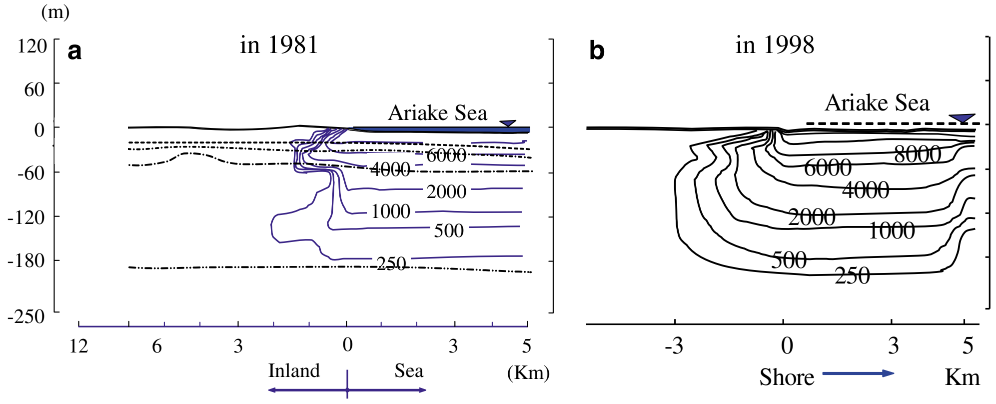


Fig. 5 Simulated chloride concentration in a deep aquifer

change due to change in global climate and land subsidence. Land subsidence also contributes to the relative rise in sea level because the ground level sinks from its original level to a lower level due to aquifer compression.

The chloride-concentration map shown in Fig. 5b also illustrates the down-gradient migration of saltwater in the deep aquifer after a 20-year simulation. Inspection of Fig. 5a, which is the normal sea water level as the baseline case, and Fig. 5b (with sea water level rise) reveals that the salt load increases substantially. Figures 8 and 9 draws irregular contours of a plume of high-chloride water (greater than 250 mg/L) encroaching on the aquifer in response to pumping in 1998, for the sections A–A and B–B, respectively, in both cases of simulation without (Figs. 8a, 9a) and with sea water level rise (Figs. 8b, 9b). By considering the contours of the high-chloride plumes shown in

Fig. 6 Simulated chloride concentration (mg/L) (Section A–A)



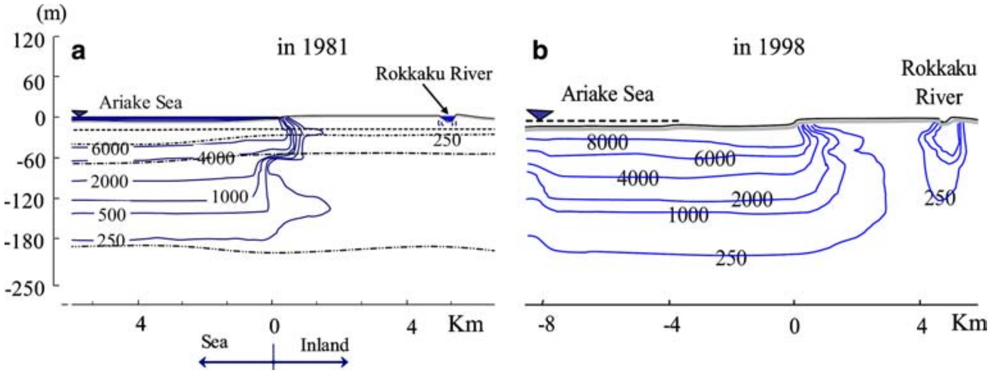


Fig. 7 Simulated chloride concentration (mg/L) (Section B–B)

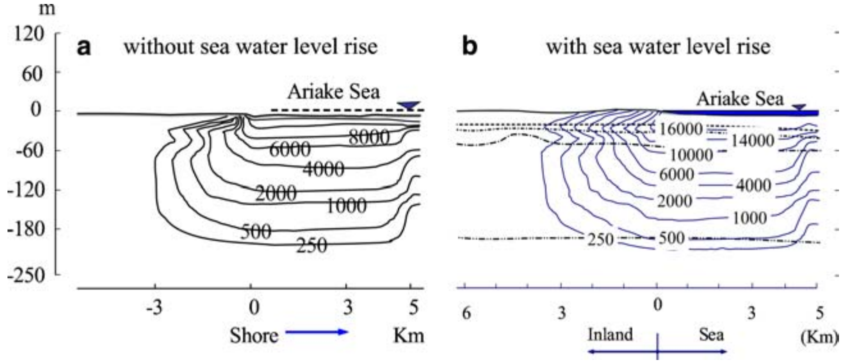


Fig. 8 Chloride concentration (mg/L) in 1998 (Section A–A)

Figs. 8a and 9a (the reference case) and those in Figs. 8b and 9b, it is clear that in case of relative rise of sea level, the salinity plume appears to extend further inland, at least a kilometer, compared to the normal sea level, the reference case.

The chloride concentration increase due to the simulated sea level rise was most pronounced in the south area and near the river mouths. A recurrence of the 1994's drought with a higher sea level would cause increased chloride levels in locations along the coast. These increased levels would persist for long periods as the high-chloride water dispersed and propagated toward pumping wells. For many years, some wells would experience elevated sodium levels that could make the water unfit for many purposes, including human consumption, in which case, water from alternate sources could be required.

Sea water intrusion caused by pumping of wells also occurs locally within some coastal towns in the plain where pumping well density is high but not extensive. Upconing of brackish groundwater into wells completed into upper freshwater zones underlain by saline waters occurs in many areas as evidenced by seasonal groundwater quality deterioration in pumped wells during the summer months and irrigation times. Reduced pumping demands and groundwater recharge from infiltration of precipitation in the irrigation periods generally should improve groundwater quality.

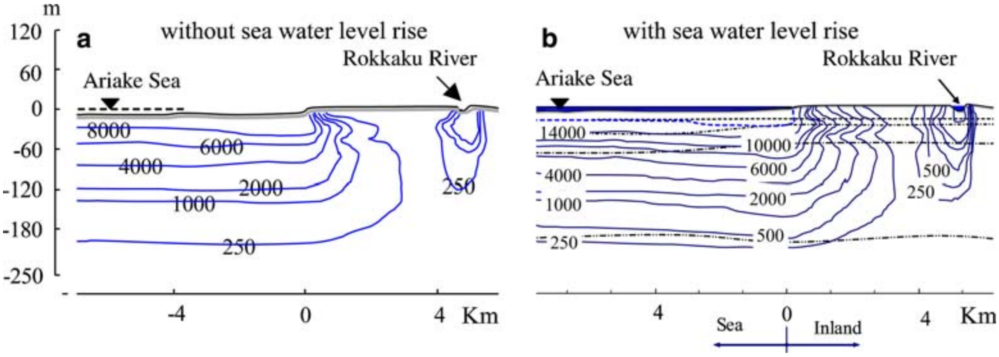


Fig. 9 Chloride concentration (mg/L) in 1998 (Section B–B)

Based on the above observation, it is apparent that sea water intrusion would worsen in the confined aquifer along the coast if the current scheme of groundwater pumpage continues. Therefore, any groundwater development activity in the region needs to be carefully planned with remedial measures in order to contain the further intrusion of sea water. Some of remedial measures include freshwater injection; extraction of saline and brackish waters; modifying pumping practices, such as lowering rates of extraction, relocation of extraction wells, and usage of shallow water wells; land reclamation; increase of the upland recharge areas; and creation of physical barriers, such as sheet piles, clay trenches, and chemical injections (Essink 2001). Some of these countermeasures may have environmental consequences as well as economic limitations.

Concluding remarks

In this study, the water environment in coastal lowland areas such as land subsidence and salinity intrusion and the effect of sea water level rise are discussed. It implies that sea water level rise may include the change in global climate and may be due to land subsidence. Sea water level rises also threaten the viability of many coastal zones. In order to examine the effect of this change, an integrated surface and groundwater model was developed and applied to an alluvial coastal lowland area, namely Shiroishi plain in southwestern Japan. The model is a three-dimensional groundwater flow model integrated with a surface water balance model and a solute-transport model to simultaneously simulate dynamic groundwater flow and predict transient solute transport in the aquifer system.

The model outputs matched well the observed results, indicating that the numerical model can simulate the dynamic processes of groundwater flow and chloride concentration over the simulation period. The results reveal that sea water intrusion would be observed along the coast if the current rates of groundwater exploitation continue. The model results also indicate that, in case of sea water level rise, the salinity plume with high-chloride concentration appears to extend at least a kilometer further inland compared to the reference case.

In order to mitigate the environmental effects due to groundwater exploitation, a legal restriction on groundwater and the conversion to surface water from groundwater and some of the remedial measures should be implemented in the areas where pumping has been intensive. The conceptual model, along with other results obtained in the study, will be used to more fully model the exchange processes and provide greater confidence in the transport processes that may occur where groundwater discharges to sea environments.

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