

Simulation of groundwater flow and environmental effects resulting from pumping

Nguyen Cao Don · Hiroyuki Araki · Hiroyuki Yamanishi · Kenichi Koga

Abstract In coastal lowland plains, increased water demand on a limited water resource has resulted in declining groundwater levels, land subsidence and saltwater encroachment. In southwestern Kyushu, Japan, a sinking of the land surface due to over pumping of groundwater has long been recognized as a problem in the Shiroishi lowland plain. In this paper, an integrated model was established for the Shiroishi site using the modular finite difference groundwater flow model, MODFLOW, by McDonald and Harbaugh (1988) and the modular three-dimensional finite difference groundwater solute transport model, MT3D, by Zheng (1990) to simulate groundwater flow hydraulics, land subsidence, and solute transport in the alluvial lowland plain. Firstly, problems associated with these groundwater resources were discussed and then the established model was applied. The simulated results show that subsidence rapidly occurs throughout the area with the central prone in the center part of the plain. Moreover, seawater intrusion would be expected along the coast if the current rates of groundwater exploitation continue. Sensitivity analysis indicates that certain hydrogeologic parameters such as an inelastic storage coefficient of soil layers significantly contribute effects to both the rate and

magnitude of consolidation. Monitoring the present salinization process is useful in determining possible threats to fresh groundwater supplies in the near future. In addition, the integrated numerical model is capable of simulating the regional trend of potentiometric levels, land subsidence and salt concentration. The study also suggests that during years of reduced surface-water availability, reduction of demand, increase in irrigation efficiency and the utilization of water exported from nearby basins are thought to be necessary for future development of the region to alleviate the effects due to pumping.

Keywords Coastal lowland · Groundwater overdraft · Integrated numerical models · Land subsidence · Salinity encroachment · Sensitivity analysis · Shiroishi in the Saga lowland plain · Kyushu Island · Japan

Introduction

The Shiroishi coastal lowland area is one of the most productive and intensely farmed agriculture areas in Saga, Kyushu Island (in southwestern Japan). Water supplied to agriculture has traditionally been a high priority for water managers in this region. Due to the monsoon climate, about 1,900 mm of precipitation falls in the area. However, this rainfall water is run off quickly because rivers are rapid and short. Groundwater is therefore regarded as an important water resource for drinking water and the primary source of irrigation water for agriculture because its properties of purity and constant temperature are superior to surface water. The extent of groundwater overdraft, which is the withdrawal of potable water from an aquifer system in excess of replenishment from natural and artificial recharge, varies throughout the region. Such excessive pumping over the years since the late 1950s has led to undesirable effects such as a continual decline in potentiometric levels, seawater intrusion, and land subsidence over the alluvial plain. Previous studies related to groundwater and geotechnical aspects in the Shiroishi Plain include articles published by a number of authors and institutions. Tanaka (1990) studied the optimal pumping volume of groundwater for

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minimizing land subsidence in the Saga and Shiroishi areas based on the correlation between pumping volume and settlement volume. Miura and others (1988) investigated land subsidence and its influence on geotechnical aspects in the Saga Plain. Sakai (2001) studied land subsidence due to seasonal pumping of groundwater in the Saga Plain. These studies mainly aimed at finding some operating policies on pumpage and describing the effects due to pumping, by considering the effects of varying groundwater levels on land subsidence. On the other hand, a some literature has been written about modeling the link between groundwater and land subsidence and the mechanism of saltwater encroachment in the Shiroishi aquifers.

Understanding of the groundwater movement will ensure its proper utilization. In this paper, the model MODFLOW (McDonald and Harbaugh 1988) combined with the IBS-1 package (Leake and Prudic 1991) and the MT3D (Zheng 1990) were adopted to simulate transient groundwater flow, ground consolidation, and predict solute transport. Aquifer parameters were estimated by calibrating the model against the observed data. The simulated and the observed groundwater levels, ground settlement and chloride concentration were then compared to examine the performance of the numerical model. Sensitivities of the hydraulic and mechanical properties of the clayed layer due to gradual consolidation in response to excessive pumping were examined, and the impact on the groundwater of the deep confined aquifer was determined.

Description of the study area

The Shiroishi plain is situated on Kyushu Island, Japan, as shown in Fig. 1. The plain is bounded on the north, the south and the east by mountain ranges and on the west by the Ariake Sea. The plain is relatively flat and the altitude is about 1.5 m above mean sea level. The important Rokkaku River flows across this plain to the Ariake Sea from which it is, however, subject to tidal fluctuations and affected by salinity intrusion.

The subsurface strata of Shiroishi Plain is underlain by lowland quaternary soft deposits around the inland Ariake Sea. According to conventional classification, the sediments can be separately divided into several layers based on their geologic and hydrogeologic characteristics. Below the ground surface is a soft marine clay layer which is known as the Ariake clay (Miura and others 1988; Shimoyama and others 1994; Hachiya and others 1988; Onitsuka 1988), and has a 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 diluvial deposits dominated by sands, gravels, and pumices of various sizes, and are 5-m thick or less in both the vertical and lateral directions. Underlying that are volcanic ash soils deposited in two gravel layers. The Aso-4 volcanic ash appears at an altitude of about 20 m below sea level. This layer is a thin one but the Aso-3 volcanic ash sediment is of very thick develop-

ment. Both the diluvium and volcanic ash layers form a highly permeable and excellent aquifer in this region. Figure 2a depicts a typical geological profile along section A-A nearby the Rokkaku River, and Fig. 2b sketches a typical soil column at Arian-1 near the shoreline of the town of Ariake, as well as the modeled layers. The aquifer system was three-dimensionally 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 of 30 to 200 m below sea level. Layer 5 is assumed to extend to a depth of 200–250 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 bedrock is above the defined layer bottom, the layer bottom is equal to the depth of the bedrock.

Since 1957, prior to the arrival of surface water, large-scale groundwater development for agricultural supply had already been in use. With the rapid expansion of cultivable and urban areas, pumpage increased from 32,300 m³ in 1970 to 17.5 million m³ in 1978 and to 19.9 million m³ in the droughty year 1994 to meet the ever-increasing water demand for agriculture, industry, and domestic use. As a result, groundwater levels started to fluctuate with a great magnitude in response to varying climatic and pumping conditions. The subsidence zone, resulting in cracks in the ground, appeared in 1960 (Tanaka 1990). The accumulated subsidence has reached 123 cm over the past 38 years from 1960 to 1998, and the affected area has extended to 324 km² (Sakai 2001). Since 1985, analysis of the groundwater quality data from wells has revealed that saltwater encroachment has occurred in the area.

Mathematical model

Groundwater flow model

The three-dimensional movement of ground water of constant density through porous earth material may be described by the partial differential equation:

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

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 is the potentiometric head (L); W is a volumetric flux per unit volume and represents sources and/or sinks of water (T⁻¹); S_s is the specific storage of the porous material (L⁻¹); and t is time (T). Equation (1) describes groundwater flow under non-equilibrium conditions in a

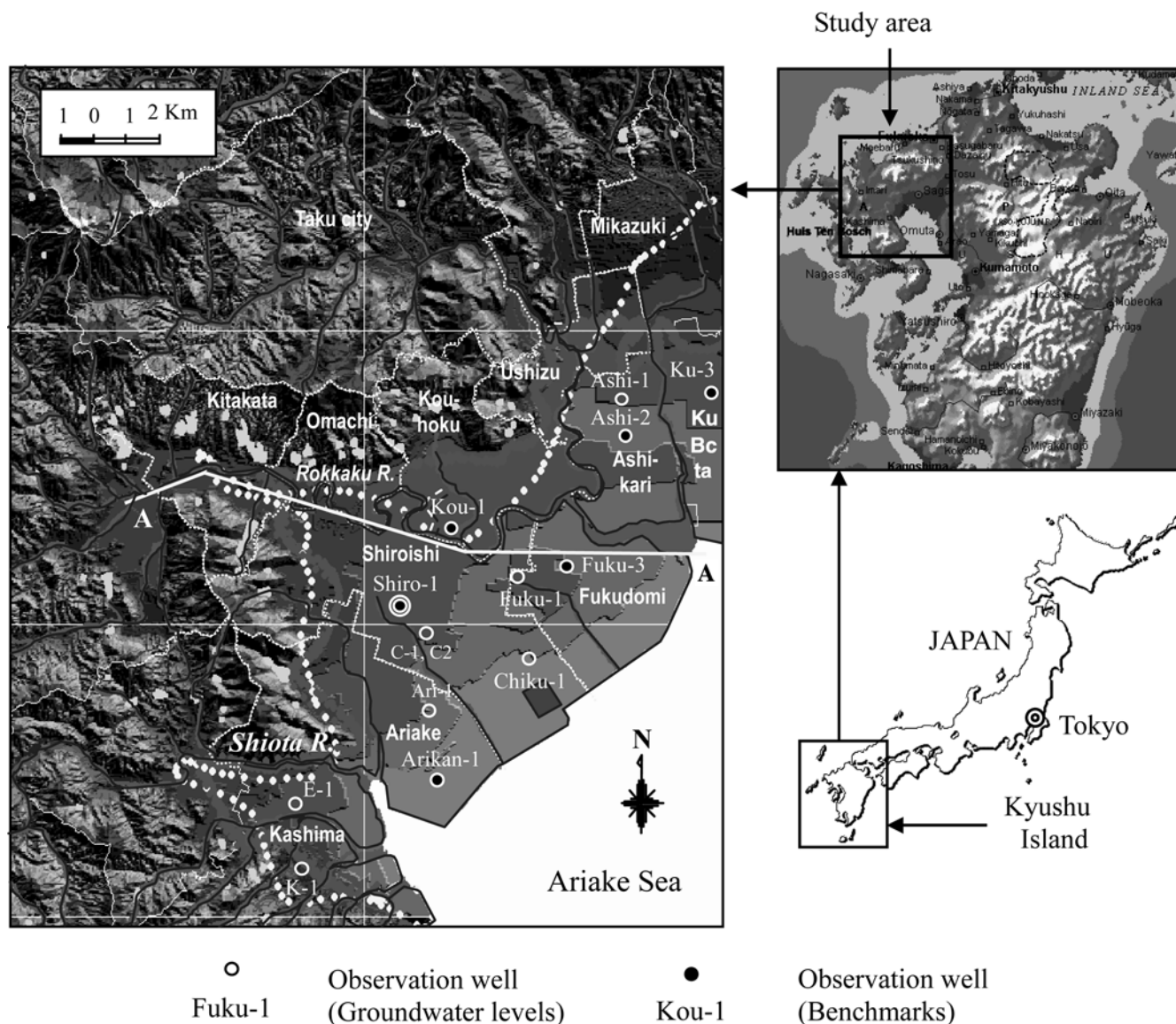


Fig. 1

Study area showing the Shiroishi site

heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

Except for very simple systems, analytical solutions of Eq. (1) are rarely possible; therefore various numerical methods must be employed to obtain approximate solutions. One such approach is the finite-difference method, wherein the continuous system described by Eq. (1) 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 of the time-varying head distribution that would be given by an analytical solution of the partial-differential equation of flow (McDonald and Harbaugh 1988).

Land subsidence model

The relation between groundwater head change and sediment compaction is based on the principle of effective stress developed by Terzaghi (1925), where effective stress (σ_e) is expressed as the difference between total stress (σ_T), which is the total overburden load or geostatic pressure, and fluid or pore pressure (p_p):

$$\sigma_e = \sigma_T - p_p \quad (2)$$

Figure 3 depicts the principle of effective stress as applied to land subsidence. Vertical displacement of land surface, Δb , is a result of a decrease in pore fluid pressure and a resultant increase in effective stress exerted on a horizontal plane located at a depth below land surface in fine-grained material under conditions of total stress in a one dimensional fluid saturated geologic medium.

The geostatic pressure or total overburden load of the sediments and water at a given depth equals the product of the unit weight of moist sediments and the thickness of the unsaturated zone plus the product of the unit weight of

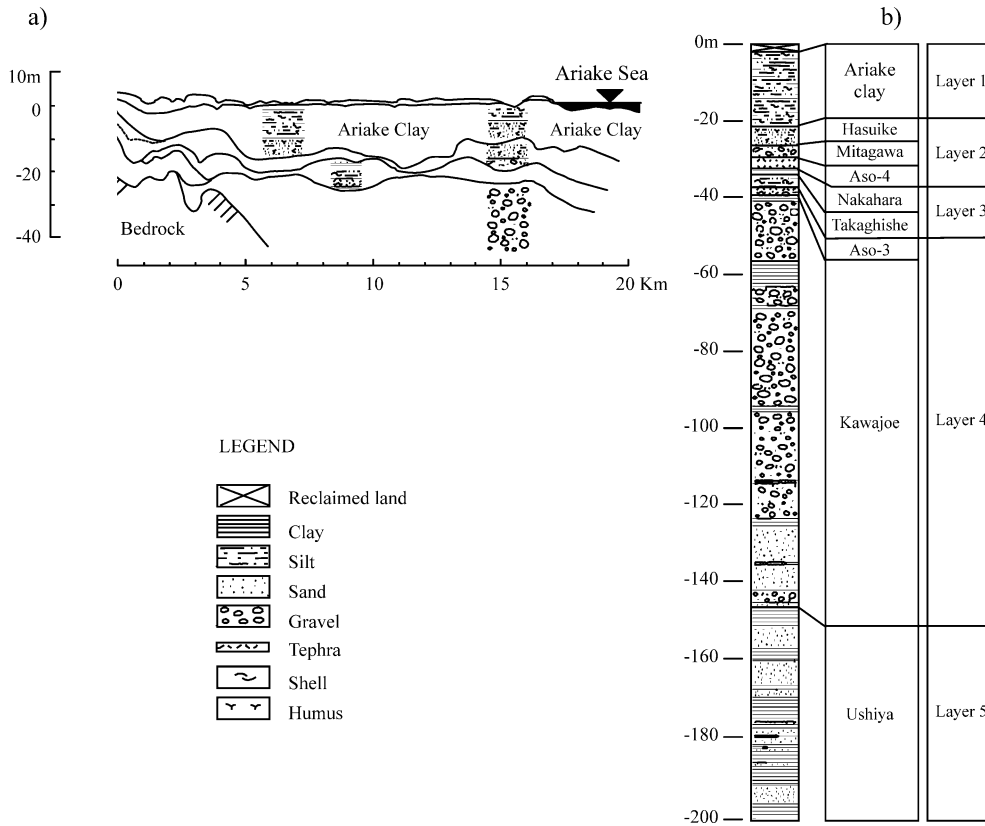


Fig. 2
a Simple geological profile along the section A-A near by the Rokkaku River, and **b** soil column (at Arikan-1, town of Ariake) and modelled layers

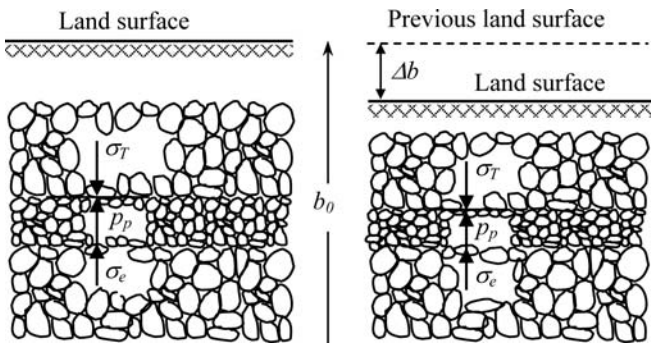


Fig. 3
 Principle of effective stress

saturated sediments below the water table and the thickness of the saturated sediments overlying that depth. Because of the dependency of geostatic stress on the position of the water table, a change in effective stress from a given head change generally is different in confined and unconfined aquifers. If the water table is raised or lowered in an unconfined aquifer, the geostatic pressure will change (Leake and Prudic 1991).

The principle of effective stress provides the link between ground water withdrawal and subsidence. Within an aquifer, pore water pressure is equivalent to pressure head. As water is withdrawn from the aquifer and the piezometric head drops, the effective stress on the aquifer increases even though the total stress remains constant. It is the increase in effective stress that causes the compression

of the soil leading to subsidence (Larsen and others 2001). When the hydraulic head drops below the previous lowest head, compaction will be inelastic. Inelastic compaction results from a non-reversible rearrangement of skeletal grains, and when the head rises above the previous lowest head, elastic rebound will take place due to elastic expansion of skeletal grains (Wilson and Gorelick 1996). The product of elastic skeletal specific storage and thickness is the skeletal component of elastic storage coefficient S_{ske} . For sediments in confined aquifers in which geostatic pressure is constant, the compaction of each model layer can be calculated as:

$$\Delta b_e = S_{ske} b_0 \Delta h \tag{3}$$

Compaction per unit increase in effective stress in the inelastic range is considerably greater than in the elastic range. When effective stress of sediments compacting in the inelastic range is reduced, the sediments again expand and compact with the elastic characteristics until effective stress increases beyond the new maximum effective stress. For confined aquifers in which geostatic pressure is constant, the expression analogous to Eq. (3) is:

$$\Delta b_i = S_{skie} b_0 \Delta h \tag{4}$$

in which Δb_e and Δb_i are the elastic and inelastic compaction, (L), respectively; Δh is the change in head at the center of the layer, (L); b_0 is the original thickness of the layer, (L); and S_{ske} and S_{skie} are the elastic and inelastic storage coefficients, (L^{-1}), respectively.

Saltwater intrusion model

Simulation of ground-water flow is performed by numerically solving the ground-water flow and solute-transport equations. The partial differential equation describing the three-dimensional transport of dissolved solutes in the groundwater can be written as follows:

$$\frac{\partial}{\partial x_i} \left(D_i \frac{\partial C}{\partial x_i} \right) - \frac{\partial}{\partial x_i} (v_i C) \pm \frac{q_s}{\theta} C_s + \sum_{k=1}^N R_k = \frac{\partial C}{\partial t} \quad (5)$$

where C is the concentration of contaminants dissolved in groundwater, (ML^{-3}); t is time, (T); x_i is the distance along the respective Cartesian coordinate axis, (L); D_i is the hydrodynamic dispersion coefficient, ($\text{L}^2 \text{T}^{-1}$); v_i is the seepage or linear pore water velocity, (LT^{-1}); q_s is the volumetric flux of water per unit volume of aquifer representing sources (positive) and sinks (negative), (T^{-1}); C_s is the concentration of the sources or sinks, (ML^{-3}); θ is the porosity of the porous medium, dimensionless;

$\sum_{k=1}^N R_k$ is the chemical reaction term ($\text{ML}^{-3}\text{T}^{-1}$).

The integrated groundwater model in this study, which we call the Shiroishi Model, was developed for the Shiroishi site to simulate the groundwater flow, refine estimates of aquifer-system hydraulic parameters controlling compaction, predict possible compaction, and predict salinity intrusion into the aquifer system. A three-dimensional, finite-difference model that simulates coupled ground-water flow and aquifer system compaction was developed using MODFLOW (McDonald and Harbaugh 1988) and the Interbed Storage Package-1 (IBS1) package (Leake and Prudic 1991). The term interbed refers to as a poorly permeable bed within a relatively permeable aquifer. Such interbeds are assumed to be of significantly lower hydraulic conductivity than the surrounding sediments considered to be aquifer material, yet porous and permeable enough to accept or release water in response to head changes in adjacent aquifer material, and of insufficient lateral extent to be considered a confining bed (or confining unit) that separates adjacent aquifers, and of relatively small thickness in comparison to lateral extent. The interbeds are also assumed to consist primarily of highly compressible clay and silt beds from which water flows vertically to adjacent coarse-grained beds (Leake and Prudic 1991). The modular structure of MODFLOW consists of a main program and a series of highly independent subroutines called modules. The modules are grouped into packages. Each package deals with a specific feature of hydrologic system which is to be simulated with a specific method of solving linear equations that describes the flow system. The division of the program into modules permits the examination of specific hydrologic features of the model independently. This also facilitates the development of additional capabilities because new modules or packages can be added to the program without modifying the existing modules or packages. The input and output systems of the computer program are also designed to permit maximum flexibility.

The Transient Specified-Flow and Specified-Head Boundaries (FHB1) package (Leake and Lilly 1997) was used to

specify head boundaries using measured and estimated values of groundwater levels. The model parameters were adjusted within moderate ranges and available constraints to provide the best between measured and simulated compaction. In addition to IBS1 and FHB1, other MODFLOW packages used in the Shiroishi site model include Basic 5 (BAS5), Block-Centered Flow 5 (BCF5), and Strongly Implicit Procedure Solution 5 (SIP5; McDonald and Harbaugh 1988). The MT3D, a modular three-dimensional finite-difference groundwater solute-transport model based on dispersion approach, coded by Zheng (1990) was applied to solve the solute-transport equation. This model uses a mixed Eulerian-Lagrangian approach to solve the solution of the three-dimensional advection and dispersion transport equation, or Eq. (5). The model is based on the assumption that changes in the concentration field do not significantly effect the flow field. This allows the user to construct, calibrate and validate a flow model independently. The calculated hydraulic heads and various flow terms from the current MODFLOW solution are used to set the basis for simulating and predicting the land subsidence and solute transport behaviors of the groundwater system.

Moreover, for a variable density system, in order to simulate saltwater intrusion in this study, SEAWAT model coded by Guo and Langevin (2002) was applied, which uses variable-density flow in terms of freshwater head. SEAWAT is a coupled version of the Modular Groundwater Flow MODFLOW model and the solute-transport model MT3D. During the simulation, MT3D runs for a period of time, and then MODFLOW runs for the same period of time using the last concentrations from MT3D to calculate the density terms in the flow equation. For the next time frames, velocities obtained from the MODFLOW are used to solve the transport equation.

Results and discussions

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 was 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 total 176 pumping wells located in the study area was taken into consideration. A finite-difference grid was developed to adequately discretize the model domain. One of the objectives for grid development was to sufficiently discretize the model domain while minimizing the total number of model cells. For the Shiroishi site, the groundwater system of interest is approximately $28.0 \times 20.0 \text{ km}^2$ and is covered with a three-dimensional grid. The sizes of each cell are $\Delta x=500 \text{ m}$, $\Delta y=500 \text{ m}$. The three-dimensional grid contains 13,440 cells: $n_x=56$, $n_y=40$, $n_z=6$, where n_i denotes the number of cells in the 'i' direction. Due to mountainous parts of the groundwater system, only 68.2% of the cells are considered as active ones.

Boundary conditions are assigned to all four sides. At the sea's side, a general head boundary is implemented. The general head boundary is typically a MODFLOW feature which models the in or outflow to an element through the difference between the head in the element itself and an external fixed head. The Rokkaku and Shiota Rivers in the study area appear to intersect the groundwater system. The river package is applied to account for this feature. In addition, the drain package is used to take into account the features of drained agricultural areas. The average recharge amount from paddy fields to groundwater was estimated to be 7.0 mm/day during the growing season of crops from June to September as a result of a surface water balance model by Zhou and others (2003), which balance the available amount of surface water supply to irrigation from rainfall, groundwater, river, pond and creek, and the consumed amount by evapotranspiration, runoff, and infiltration. At the uphill parts, a constant fixed head is inserted in the model. 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 in consideration and adjacent active cells. The specified heads were interpolated based on water level data from near by wells. Calibration of the model focused on choosing parameters for the layer such that their effect on land subsidence is equivalent to the composite effect of the actual interbeds. 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 material properties of the layered aquifer systems are summarized in Table 1.

Groundwater flow and land subsidence

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 (head distribution) at different time periods under different stresses (pumping and recharge) to simulate the aquifer (under stresses like pumping and

recharge) for a long period of time. The transient simulation was divided into 209 stress periods. A time increment of one day was used for a 20-year simulation, from 1979 to 1998.

Four monitoring wells indicated in Fig. 1 were randomly chosen among the monitoring wells for comparison of observed and simulated heads. As seen in Fig. 4, for all wells, the match between the observed and simulated heads is acceptable. The contour maps of simulated water levels were constructed and compared with the observed groundwater contour maps. It is believed that the overall features of the spatial water level distribution such as the maximum drawdown and its location, are well reproduced by the numerical model. To provide information on the overall match of all the monitoring wells, the performance statistics of the model were examined. The computed relative mean square error, $RMS=3.38$; mean error, $ME=2.45$; mean absolute error, $MAE=2.95$ m, indicating that a good estimation had been obtained; although the peaks of the head curves were over estimated. This error should stem from the complexity when assigning the model parameters in the calibration process. These parameters, however, should be specified as typical zonal values. It also stems from the fact that the hydraulic properties of the aquifer system are also affected by land subsidence. Compactions often result in a permanent loss of storage; most of the loss occurs in the compressible fine-grained units. Compaction also can result in a permanent decrease in the ability of the compacted unit to transmit water. It is noted that the forecast values of heads would be useful when they are modeled for short time-intervals. In practice, however, monthly data are the most popular; therefore, instantaneous and low peaks may not be obtained as they were forecasted by the model.

As shown in Fig. 4, water levels in the aquifers in this area follow a natural cyclic pattern of seasonal fluctuation, typically rising during the winter and spring due to greater precipitation, and recharge, as well as smaller discharge, then declining during the summer and fall due to less recharge and greater evapotranspiration, and greater discharge. The magnitude of fluctuations in water levels can vary greatly from season to season and from year to year in response to varying climatic conditions and pumping periods. Changes in groundwater recharge and storage caused by climatic variability commonly occur over years, and water levels in aquifers generally have a delayed response to the cumulative effects of drought. Because the clay does not easily transmit water, the shallow aquifer zone exhibits a relatively muted response to a seasonal increase in recharge that typically occurs at this location during the late winter and spring. In contrast, the more permeable sand and gravel in the deeper aquifer zone transmits water very easily, and the deeper aquifer zone exhibits a much greater response to the seasonal decline in discharge. On the hydrographs, piezometric heads decline sharply from the beginning of summer then recover gradually at the beginning of winter.

Figure 5 plots the contour map of the simulated head at the end of the time stress 1994, and the corresponding cone of depression is in Fig. 6. It can be seen that

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

K_H Horizontal hydraulic conductivity, K_V Vertical hydraulic conductivity, α_T The longitudinal dispersivity, α_L The transversal dispersivity

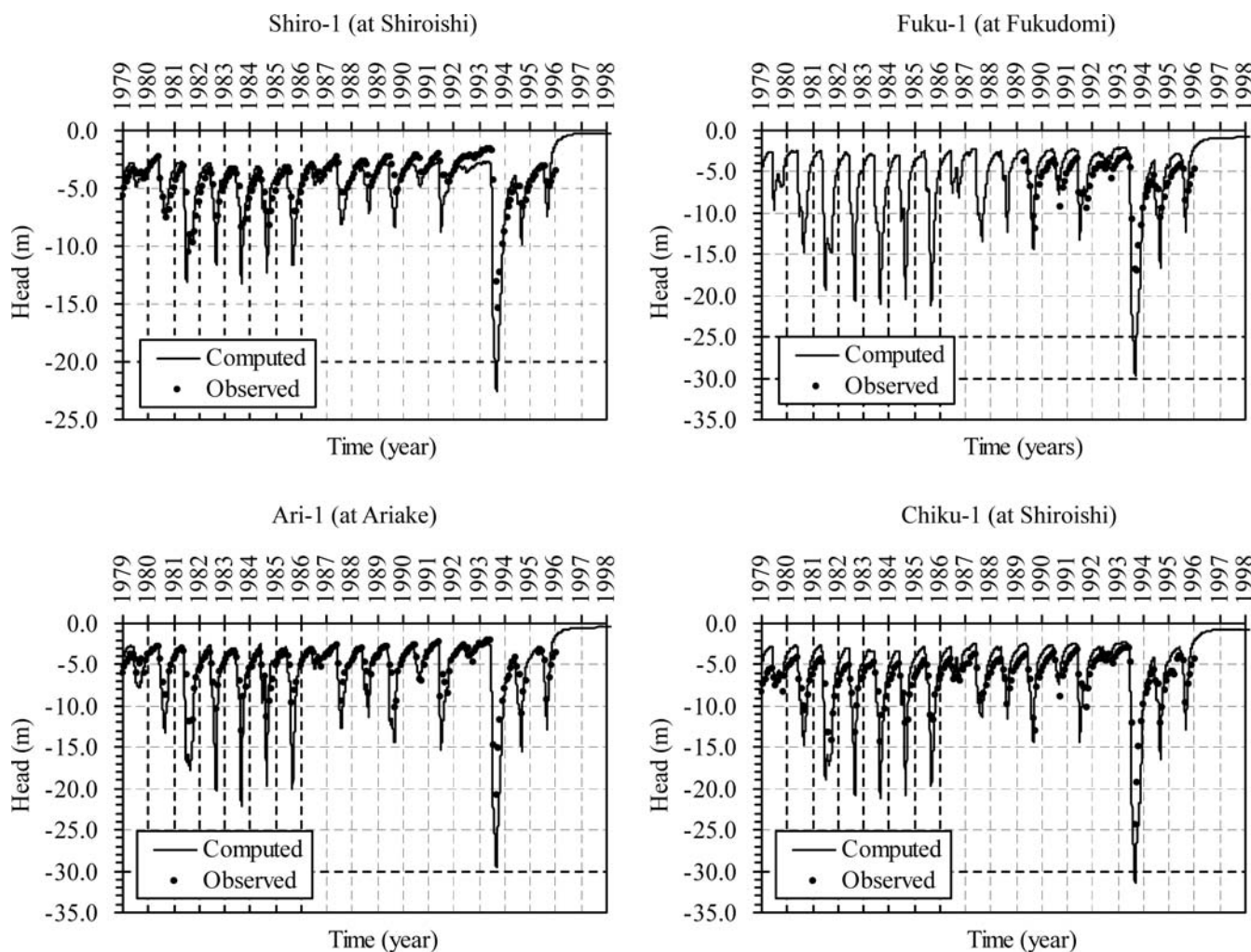


Fig. 4
Comparison of computed and observed heads at 4 chosen observation wells

groundwater pumping has caused the water level in the aquifer to greatly fluctuate throughout the entire coastal area, locally resulting in the development of cones of depression in areas of heavy, concentrated pumpage, especially in Shiroishi and Fukudomi areas. Subsidence due to the compaction of aquifer systems in response to excessive decline of water levels had affected about 200 km², which means that the area at the land surface lying directly over the cone of depression, or the zone of influence is rather large. As groundwater storage is depleted within the radius of influence of pumping, water levels in the aquifer decline. The size of the cone is controlled by the rate and duration of pumping, the storage characteristics of the aquifer, and the ease with which water is transmitted through the geologic materials to the well. Development of the cone of depression could result in an overall decline in water levels over a large geographic area, change the direction of groundwater flow within an aquifer, reduce the amount of base flow to streams, and capture water from a stream or from adjacent aquifers.

For simulation of land subsidence, in this model, it was assumed that compaction mainly occurs in layer 3 because layer 3 contains fine sediments which are of significantly lower hydraulic conductivity than the surrounding sediments, while little pumping occurs in layers 2 and 5. Moreover, layer 4 contains very coarse material so that there is little potential for compaction of this layer. Table 2 summarizes local values of hydraulic parameters derived from the best history matches between simulated aquifer system compaction and measured compaction. Figure 7 shows the model results plotted against the observed values of land subsidence at four chosen benchmarks. The simulated subsidence closely matched the measured one at all of the benchmarks. Simulated results show that the abrupt increase at benchmark Shiro-1 in Shiroishi where a large water level decline had occurred. Although water level had declined more than 20 m, the abrupt subsidence greater than 15 cm was documented only in the central part of the area. It can be seen that a drought as occurred in 1994 has substantial influence on the rate and magnitude of land subsidence.

Contours of measured and simulated subsidence accumulated from 1971 to 1998 are constructed and shown in Figs. 8 and 9, respectively. The measured 1998 contours were assumed to be representative and were used to

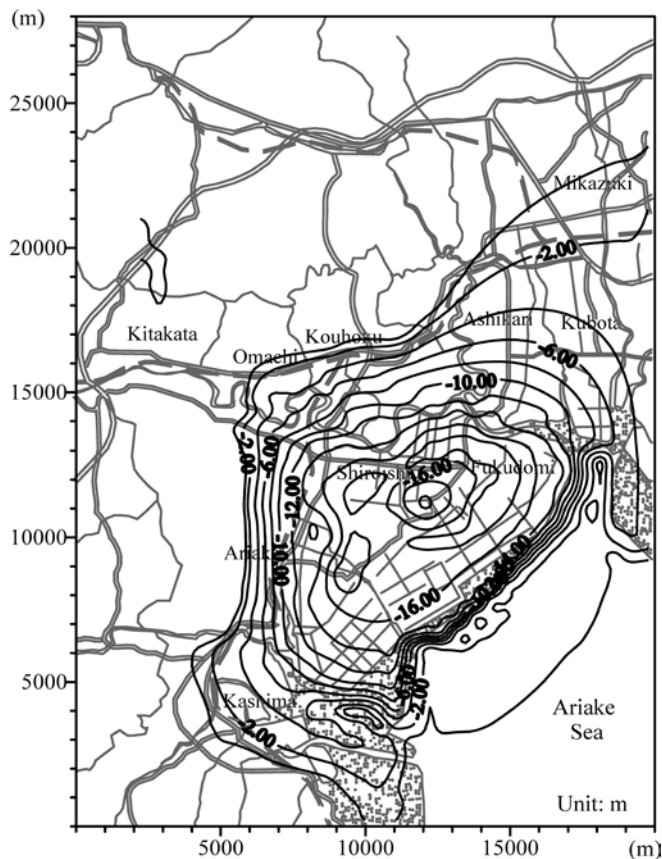


Fig. 5

Contour map showing the computed head at the end of time stress 1994

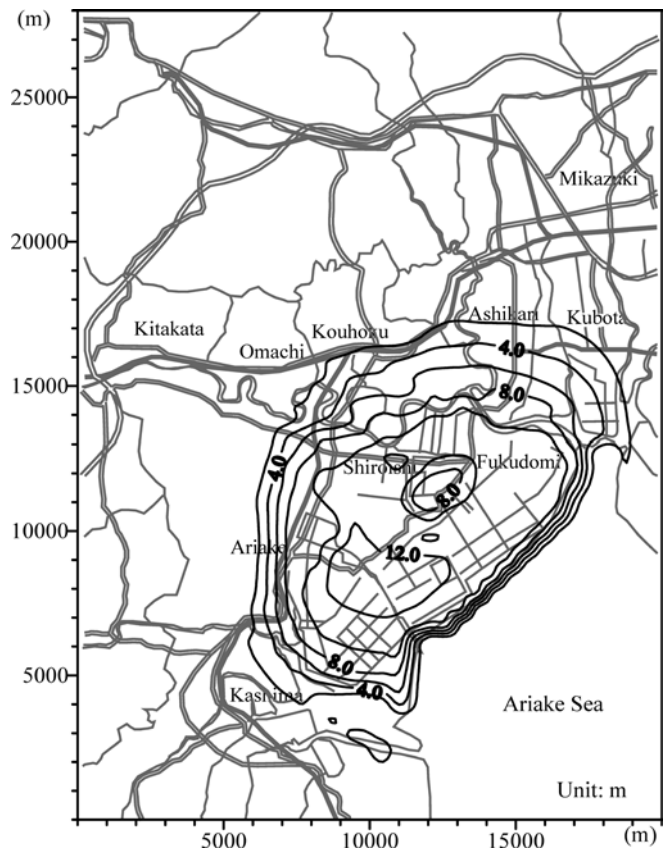


Fig. 6

Cone of depression at the end of time stress 1994

qualitatively evaluate the transient-state simulation. Although the measured data points were not dense enough for direct comparison, the subsidence trend and the affected area for each period are similar. There appears that there is a small shift in the peak of subsidence to the north-east of the study area. The seriously affected area was estimated to be about 210 km².

Figure 10a and b illustrate the subsidence predicted in Shiroishi and Fukudomi areas, respectively, based on a scenario that assumes 20% reduction of current pumping rate. It is clear that the predicted subsidence under 80% intensity is much lower than that under 100% intensity of pumping. This figure suggests a significant reduction of the future subsidence if the pumping rate is restricted in locations where pumping has been intensive.

Sensitivity analysis

A sensitivity analysis was done in order to investigate the effects of the sensitivity of the model to changes in model input parameters. This procedure was made by changing only one input parameter at a time while keeping all others fixed. The response of the model could be found after each run by observing the change in the shape of the graph. Sensitivity analysis can help determine which model parameters have the greatest effect on a model. The sensitivity of the model was evaluated by comparing

Table 2

Local hydrogeologic properties of interbed layers

Coefficient (unit 10^{-3} m^{-1})	Location					
	1	2	3	4	5	6
Elastic coefficient	0.10	0.75	0.35	0.35	0.60	0.40
Inelastic coefficient	3.5	9.9	7.5	9.5	12.5	120.0

1 Kubota, 2 Ashikari, 3 Kouhoku, 4 Fukudomi, 5 Shiroishi, 6 Ariake

subsidence from the sensitivity simulations with that from the calibrated transient-state model. In this study, two parameters effected subsidence were analyzed during the calibration process, which are inelastic storage and elastic storage coefficients.

Figure 11a shows the model results obtained for the cases of 200% increase and 25% reduction in inelastic storage coefficient, and Fig. 11b corresponds to the cases of 400% increase and 75% reduction in elastic storage coefficient. It can be seen that the rate and magnitude of consolidation is highly dependent on inelastic storage coefficient, while elastic storage coefficient has a smaller effect in the rate of subsidence.

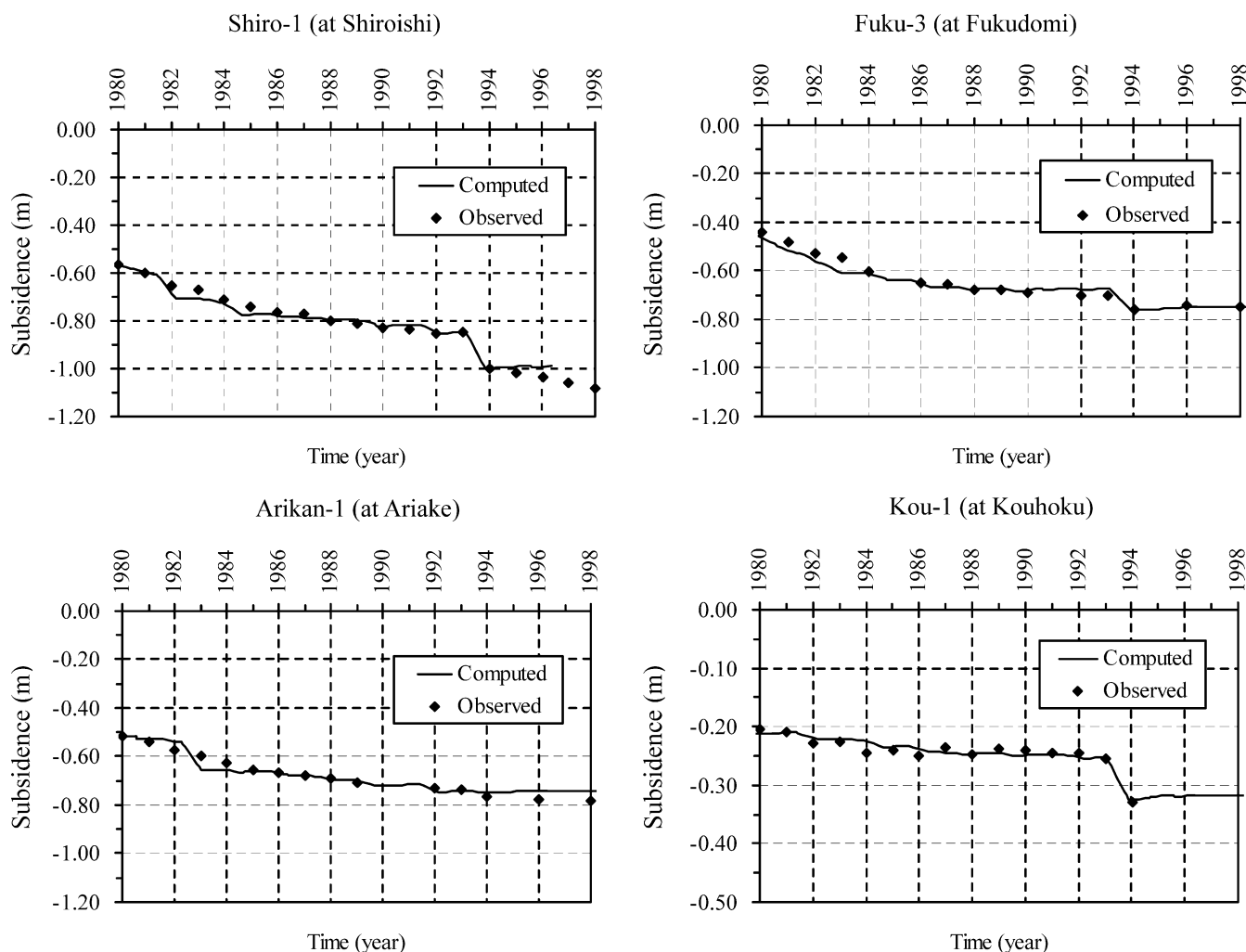


Fig. 7

Comparison of computed and observed subsidence at 4 chosen observation wells

Saltwater contamination

The Ariake Sea of Japan is a typical water body surrounded by lowlands as shown in Fig. 12 a. The sea is bounded by surroundings prefectures of Nagasaki, Saga, Fukuoka and Kumamoto. It has the biggest difference of tidal level in Japan, which is about 6 m at a spring tide in the gulf inner part. This tidal flat evidencing such a large tidal range is the greatest in Japan. The area of the tidal flat is about 207 km² or about 40% of the total tidal flat area in Japan. The Ariake Sea is a shallow and semi-closed gulf connected to the open sea by only one small place at the Hayasaki Strait. In addition, this shallow and semi-closed sea can be considered as a big salt lake.

The intrusion phenomena of saltwater in this study can be considered as those in the salt lake problem suggested by Simmons and others (1999). In this study area, saltwater, via the sea and existing rivers, initially encroaches from the top of the thick and soft Ariake clay layer and laterally leaks downward through this confining unit.

In this study, chloride concentration is used as a proxy for salinity. For purposes of this discussion, saline water

consists of varying dilutions of seawater up to 100%. The principal ion in seawater is chloride and it is the usual indicator of seawater intrusion. Since in coastal groundwater chloride (Cl⁻) is the predominant negative ion, the interest is often focused on the distribution of this ion. Seawater contains about 19,000 mg/L (milligrams per liter) chloride and about 34,500 mg/L dissolved solids (Goldberg 1963). A classification by Stuyfzand (1986) on chloride concentrations into three main types of fresh, brackish or saline groundwater is as follows: fresh Cl⁻ ≤ 300 mg/L, brackish 300 < Cl⁻ < 10,000 mg/L and saline Cl⁻ ≥ 10,000 mg/L. The drinking water standard in the European Community has been 150 mg Cl⁻/L (Stuyfzand 1986), while a convenient chloride concentration limit is 250 mg Cl⁻/L (Bakker 2000). Several conversion formulas relating density to chloride concentration, total dissolved solids, temperature and pressure can be found in Sorey (1978), Weast (1982), Voss (1984) and Holzbecher (1998). The boundary conditions for the transport simulation are dependent on the flow boundary conditions. The Cl⁻ 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⁻. Solute may neither disperse nor advect across the no-flow boundary. Salinity measurements were available for two observation

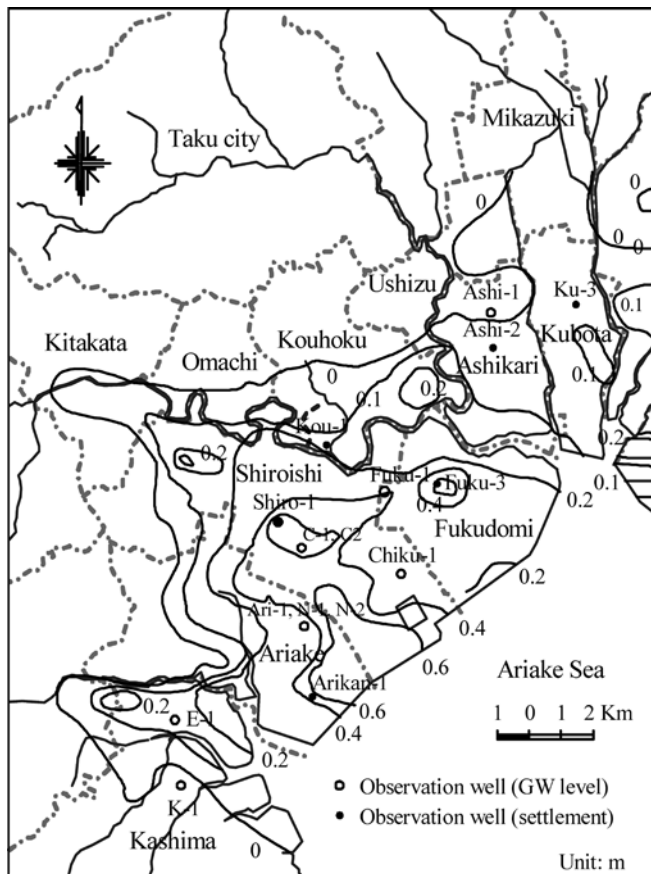


Fig. 8

Land subsidence observed in Shiroishi in 1998

wells (indicated as W1 and W2 in Fig. 12b showing the reclamation stages of the Shiroishi Plain, which has been reclaimed from the Ariake Sea throughout the past several hundreds of years via the gradual construction of dikes). The initial condition of the groundwater is ascertained from a few of the inspection wells. 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 the seawater intrusion that would be expected along the Ariake seacoast. Calibrated parameters such as the effective porosity (θ), the longitudinal dispersivity (α_L), and the ratio of transversal to longitudinal dispersivity α_T/α_L for the solute transport model are summarized in Table 1. In an effort to simulate the transport process in areas of high concentrations, an attempt was made to adjust the initial concentration distribution in those areas. After several trial runs, an improvement in model output was obtained as shown in Fig. 13, which plots the simulated chloride concentration distribution in selected wells against the observed one. As can be observed from this figure, 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 390 mg/L by 1997 in Shiroishi (W2). Toward the end of the simulation,

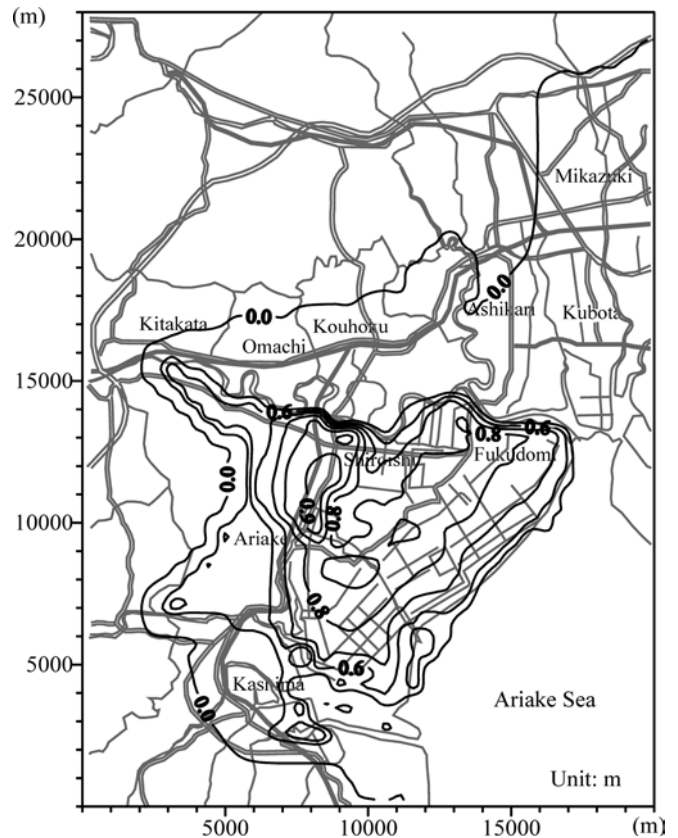


Fig. 9

Contour map showing the simulated land subsidence in 1998

it appears that the model approaches a steady state with respect to chloride in the model domain. The plot of chloride concentration suggests that the groundwater salinities simulated by the model are approaching equilibrium with the hydraulic stresses and aquifer parameters used in the model. It is suggested that locations with chloride concentrations in excess of 250 mg/L be considered undesirable for domestic use.

A chloride-concentration map shown in Fig. 14 illustrates the down-gradient migration of saltwater in the deep aquifer (-120 to -150 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. Lines of cross-sections are shown on this figure. Figures 15 and 16 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 and 1998, respectively, for section B-B.

Similarly, Figs. 17 and 18 are of section C-C. It can be seen from these figures that, after 20 years of pumping, the salinity plume appears to extend at least 1.2 km in the direction normal to the shoreline, far inland from the coast. The plume of liquid brine extends down-gradient to a few wells located about 1.5 km from the coast. Wells in the vicinity of pumping centers in Shiroishi may not be contaminated. The model results suggest that saline groundwater intrudes the system with an average velocity

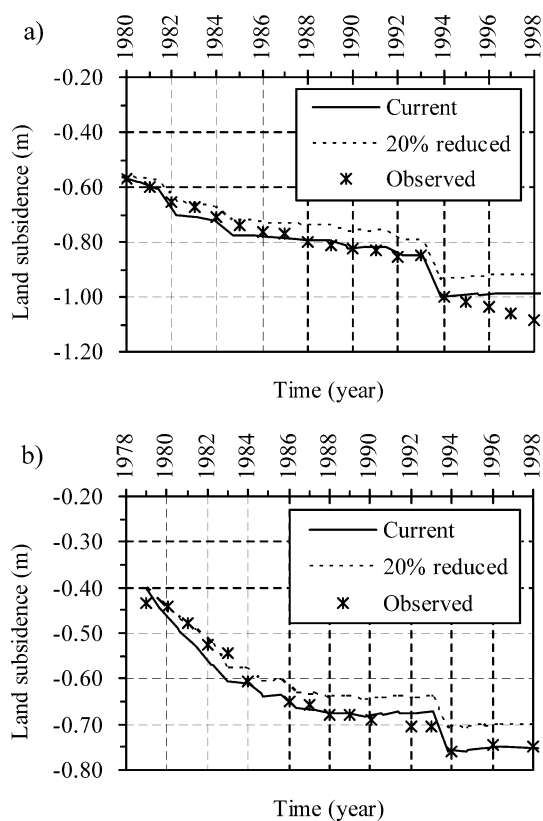


Fig. 10
Prediction of land subsidence under reduced pumpage

in the order of 30 m/year, and even enters the clay layer at a rate of 0.6 m/year. This conclusion is deduced from a straightforward calculation using streamlines based on the present velocity field in a vertical plane. As the Shiroishi Plain was reclaimed in 1860s, sea water has already intruded the system for some hundreds years.

The model is very sensitive with respect to changes in hydraulic conductivity and recharge. Higher values of hydraulic conductivity facilitate intrusion of seawater, whereas increased recharge has the opposite effect, diluting saline water within the aquifer. The model is also sensitive to changes in porosity, anisotropy and dispersivity but less sensitive to changes in molecular diffusivity. 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. Therefore, any groundwater development activity in the region needs to be carefully planned with remedial measures in order to contain the further intrusion of seawater. Salt water intrusion in the subsurface may not only be a threat for the public and industrial water supply but also for agriculture and horticulture.

Concluding remarks

This study has presented the development of an integrated groundwater model, which we call the Shiroishi Model.

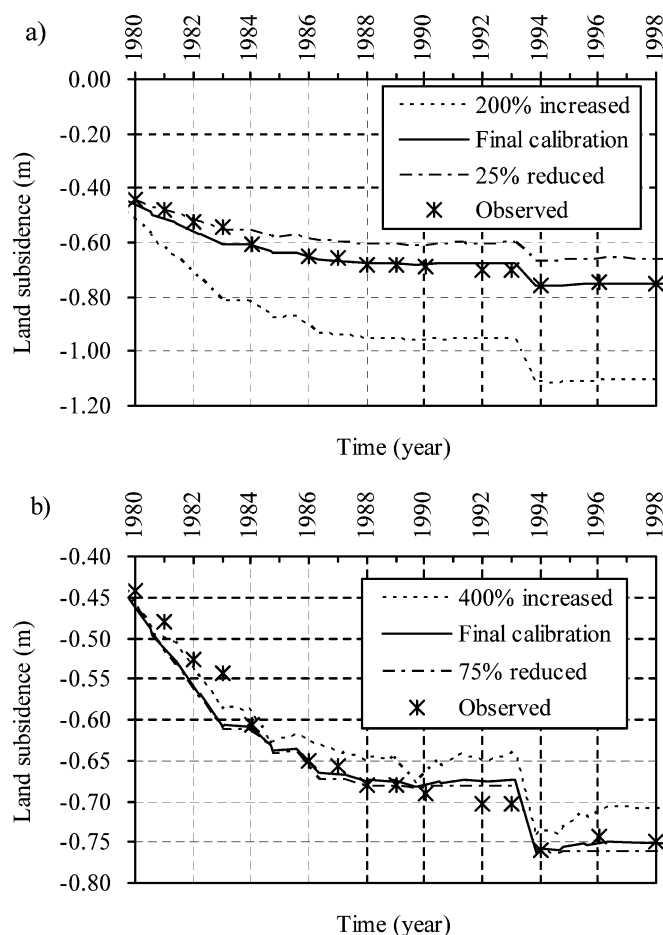


Fig. 11
Sensitivity analysis for well Fuku-3 in Fukudomi with respect to a inelastic storage coefficient, and b elastic storage coefficient

The model is a three-dimensional numerical model which combines the flow and consolidation and solute transport models to simultaneously simulate water level and investigate the mechanisms of land subsidence due to groundwater overdraft as well as predict transient solute transport. By calibrating the model with groundwater level, land subsidence and chloride concentration observed data, the aquifer parameters of the system were estimated. The model outputs agreed well with the observed results, which indicate that the numerical model can reproduce the dynamic processes of groundwater flow and soil consolidation and chloride concentration over the simulation period. Sensitive analysis shows that inelastic storage coefficient significantly contributes effects to both the rate and magnitude of consolidation. This provides a useful guideline on adjusting the model's parameters. The excessive groundwater extraction may not only cause ground settlement but also have adverse effect on sustainable water resources of the deep aquifer.

Numerical modeling can be considered to be a tool to enhance the knowledge of salt water intrusion and anticipate the salinization process. Despite less information on groundwater quality available for the study area, as a result of the present simulations on the aquifer system in Shiroishi site, seawater intrusion would be expected along

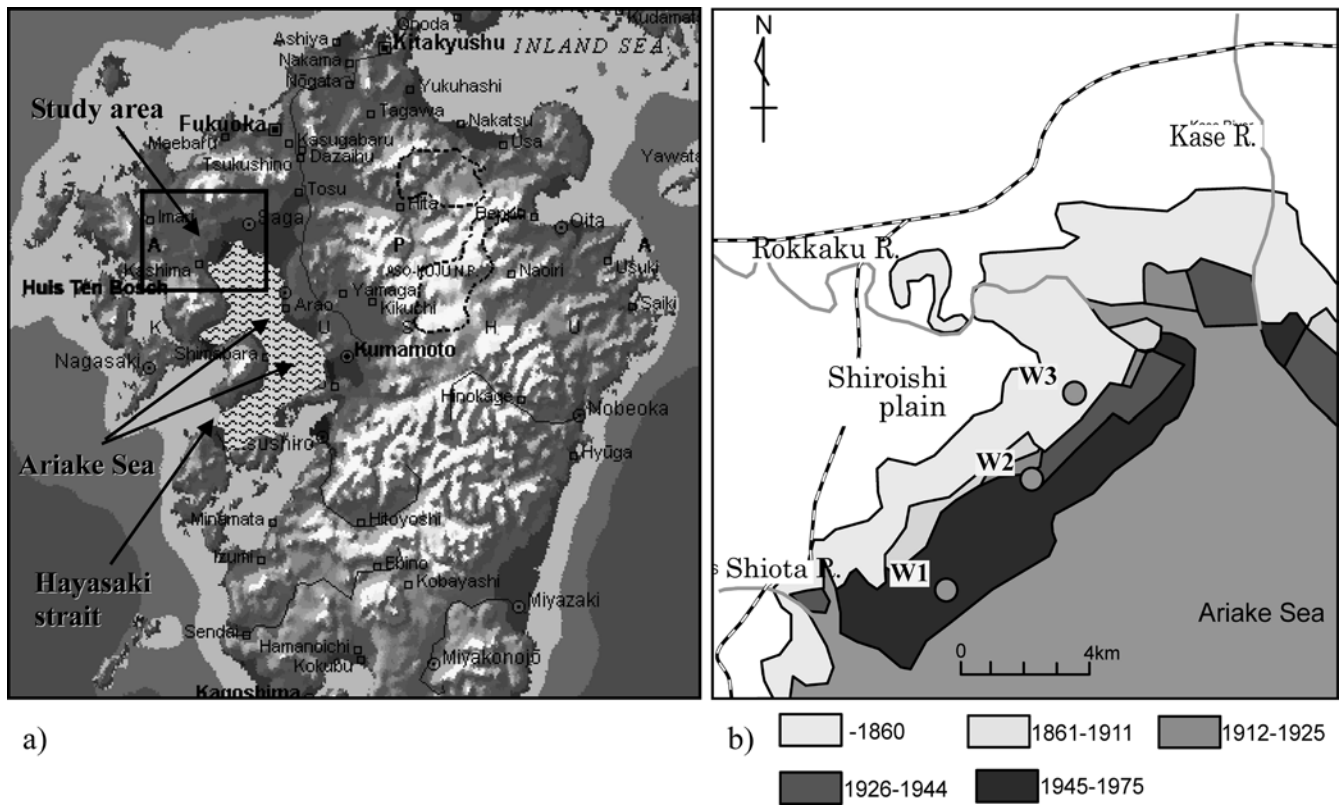


Fig. 12
 a Map showing the Ariake Sea in Kyushu Island, Japan; b reclamation stages of the Shiroishi Plain

the coast if the current rates of groundwater exploitation continue. Instead, an alternative to eliminate pumpage in the intruded area, and a reduction in pumpage rate could limit seawater intrusion significantly. This alternative is of practical value when considering the importance of the groundwater resources in the area. Moreover, monitoring the present salinization process is useful in contributing possible answer to those threats to fresh groundwater supplies in the near future.

Moreover, the model could be used to predict the future changes in groundwater levels, aquifer compactions and chloride concentrations of the groundwater when

controlling measurements of land subsidence and seawater intrusion are taken into account, because decreased pumpage in the area has been considered as the main measure for controlling the effects resulting from groundwater withdrawal. The model results also indicate that droughts contribute substantial influence in both the rate and magnitude of land subsidence and salinity intrusion as well. It is thought that during years of reduced surface water availability, reduction of demand, increase irrigation efficiency and exported water from nearby basins will be necessary for the future development of the region in mitigating the effects of ground water overdraft.

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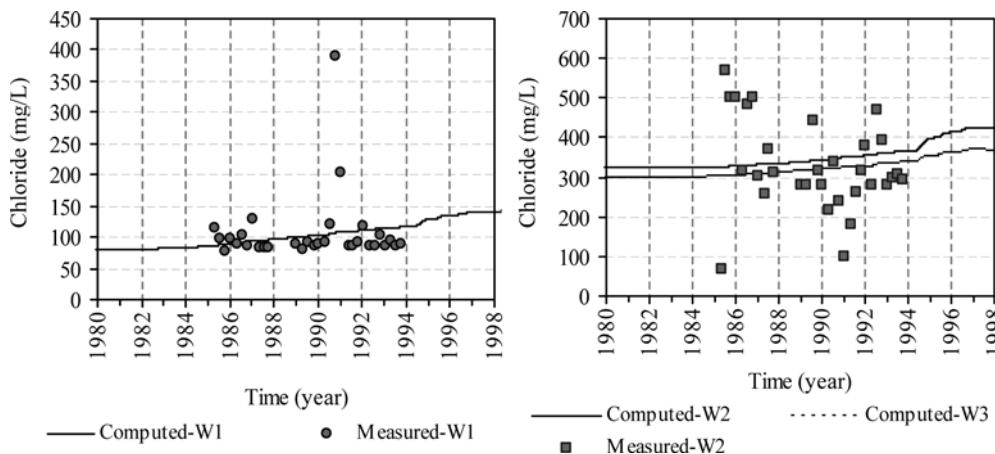


Fig. 13
 Chloride concentration in wells

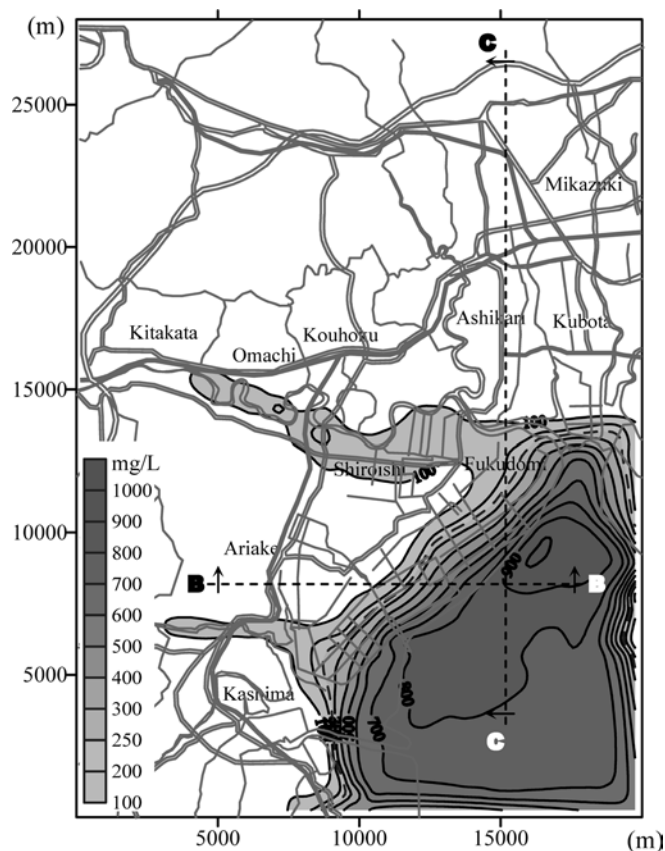


Fig. 14 Contour of simulated chloride concentration in a deep aquifer (–120 to –150 m)

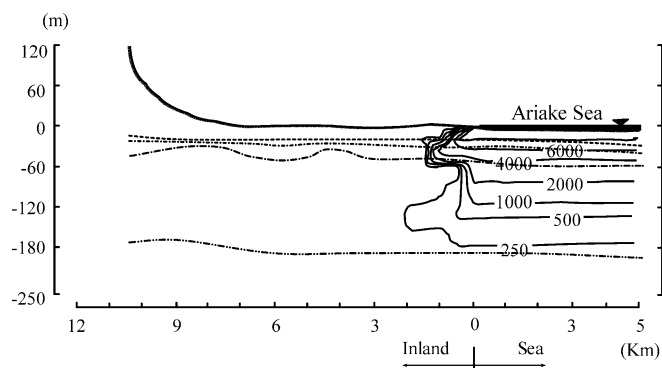


Fig. 15 Simulated chloride concentration (mg/L) in 1981, section B-B

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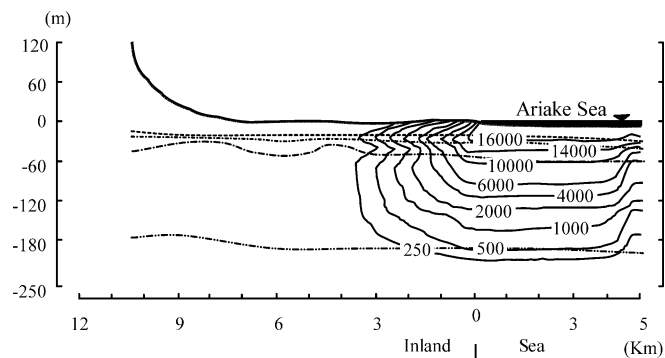


Fig. 16 Simulated chloride concentration (mg/L) in 1998, section B-B

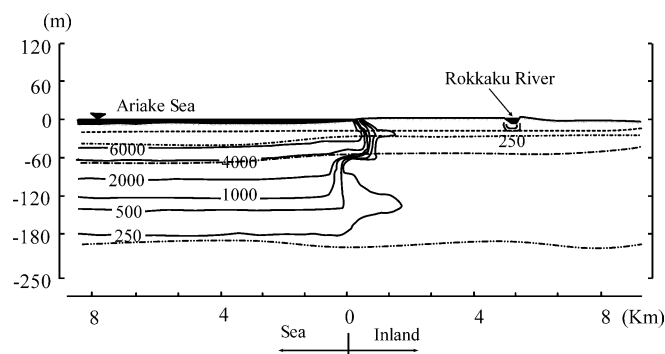


Fig. 17 Simulated chloride concentration (mg/L) in 1981, section C-C

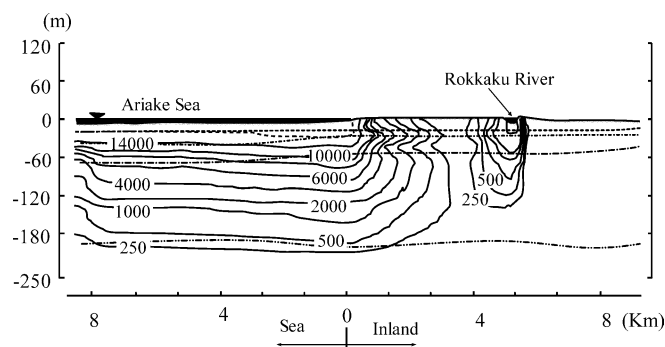


Fig. 18 Simulated chloride concentration (mg/L) in 1998, section C-C

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