

## HYDRAULICS OF GROUNDWATER FLOW AND MECHANICAL PROPERTIES AFFECTING AQUIFER SYSTEM COMPRESSION IN SHIROISHI, SAGA PLAIN

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**ABSTRACT:** Land subsidence in Shiroishi area in the Saga plain, Japan, has become noticeable since 1960s. Water supplied to agriculture has traditionally been a high priority for water managers in this region. Intense withdrawals of groundwater in excess of natural recharge have resulted in land subsidence in this region. Land subsidence can have several negative economic and social implications. Many problems associated with land subsidence can be observed in this area. In this paper, a numerical model that incorporated 3-D groundwater flow and 1-D ground consolidation was applied to simulate groundwater level and ground consolidation. It is found that subsidence rapidly occurs throughout the area with the central prone in Shiroishi basin. Certain hydrogeologic parameters such as inelastic storage coefficient, elastic storage coefficient, and hydraulic conductivity of soil layers contribute significantly effects to both the rate and magnitude of consolidation. Moreover, a considerable reduction in discharge is supposed necessary for future development of the region to alleviate the effects of groundwater overdraft.

**Key words:** Lowland, groundwater withdrawal, aquifer compaction, groundwater flow and land subsidence models, sensitivity analysis

### INTRODUCTION

Human activities mostly concentrate in lowland areas that are often convenient and attractive locations for settlement, transportation, agriculture, industries and economic activity, with many cities and economic centers. These areas therefore become more and more important to the growth of human civilization and the development of their activities. In Japan, Shiroishi region is one of the productive and farmed agriculture areas in the Saga plain. Water supplied to agriculture has traditionally been a high priority for water managers in this region. 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 basin. Overdraft is also dependent on climatic variability and associated increases in water use. However, there has been an increased amount of conjunctive use to compensate for the effects of the variability of surface water supplies and to mitigate the effects of ground water overdraft. Intense withdrawals of groundwater in excess of natural recharge have resulted in land subsidence. Land subsidence can have several negative economic and social implications. Problems associated with land subsidence include changes in ground water and surface water flow patterns, ground

water quality deterioration and saltwater intrusion, decline in storage capacity and restrictions on pumping in land subsidence prone areas, localized flooding, failure of well casings and changes in channel gradient, as well as damage to highways, buildings, and other structures (Miura and Sakai et al. 1988). Many of these problems can be observed in Shiroishi area. The link between withdrawals of groundwater and land consolidation has been widely study, and since the early 1970s, numerous investigators have used numerical models to simulate subsidence and test management strategies (Wilson and Gorelick 1996). In recent years, much effort that has been expended on numerical models and their usefulness in studying practical measures has now been reasonably well demonstrated and understood, facing with the need to come up with answers to design and plan pumping systems. Previous studies related to geotechnical aspects in Saga plain include articles published by a number of authors and institutions. Miura et al. (1988) investigated land subsidence and its influence to geotechnical aspect in Saga plain. A technique to cope with subsidence was introduced by utilizing reinforced raft foundation. Tanaka (1990) studied the optimal pumping volume of groundwater for minimizing land subsidence in Saga and Shiroishi areas, simply based on the correlation between pumping volume and settlement volume. Sakai,

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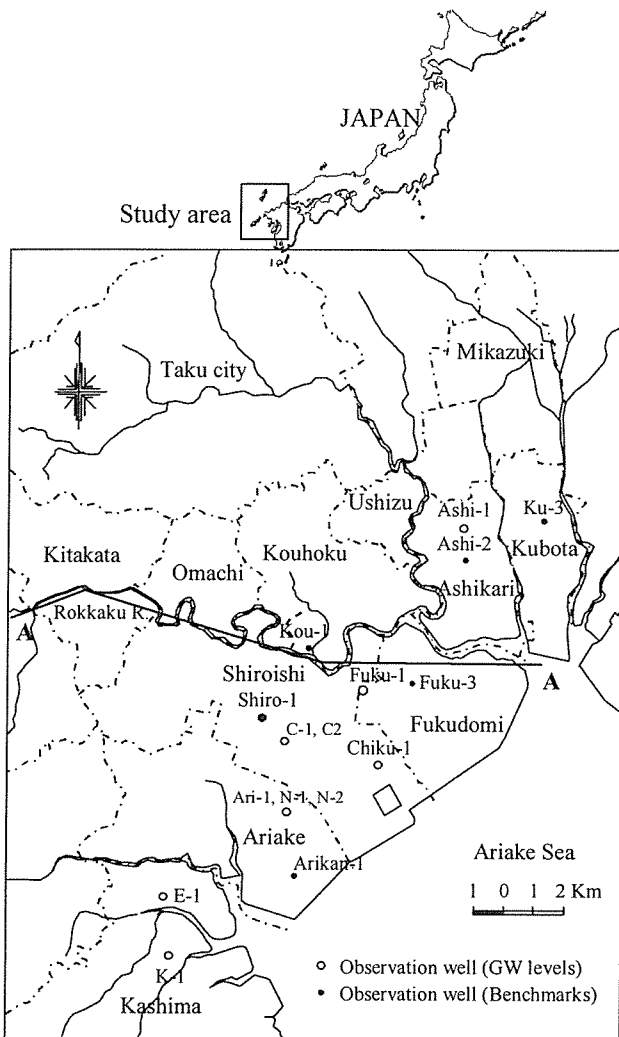


Fig. 1 Study area showing the Rokkaku River basin

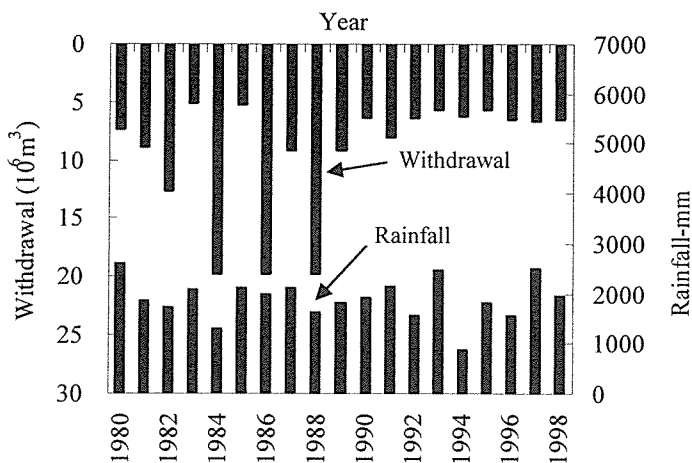


Fig. 2 Annual groundwater withdrawal vs. rainfall

2001, studied land subsidence due to seasonal pumping of groundwater in Saga plain. An analysis based on the finite element method was carried out to examine the settlement in Suko area, western part of the Saga plain. Furthermore, Saga Prefecture (1970-2003) annually publishes a report on

subsidence investigation in Saga plain. Although groundwater flow was not simulated, these researches and investigations have provided important insight into several aspect of this research. On the other hand, little literature has been written about basin-wide modeling the link between groundwater and effects resulting from groundwater withdrawal as well as groundwater management for the Shiroishi basin.

In this paper, a three-dimensional numerical model groundwater flow which couples 1-D soil consolidation model was applied to simulate water level and ground settlement. Aquifer parameters were estimated by calibrating the model against the observed water level and settlement data. The simulated and the observed groundwater levels and ground settlement were compared to examine the performance of the numerical model. Sensitivities of the hydraulic and mechanical properties of the clayey layer due to gradual consolidation in response to excessive pumping were examined, and the impact on the groundwater of the deep confined aquifer was evaluated.

#### LAND SUBSIDENCE IN THE SAGA PLAIN

The land subsidence in the Saga plain has been observed since 1957, and in Shiroishi town the subsidence zone resulting in crack of 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 km<sup>2</sup>. Soft clay layers, 10m to 30m thick with high water content and high compressibility, are present in the surface strata of the plain, making the area highly susceptible to land subsidence by the lowering of the groundwater level (Sakai, 2001). The study area is the lowland plain shown in Fig. 1. The Rokkaku basin is the largest one in the plain with the total catchment area of 341 km<sup>2</sup>. The Rokkaku River flows to the Ariake Sea and is the important river in the area. However, it is subject to tidal fluctuations and affected by salinity intrusion from the sea. Prior to the arrival of surface water, groundwater has been widely exploited. Figure 2 shows the annual amount of groundwater abstractions in Shiroishi region including Fukudomi and Ariake areas, from 1980 to 1998, in contrast with annual rainfall. It indicates that on an average an amount of water as large as 9.2 million m<sup>3</sup> is pumped up annually, especially in 1984 1986, and 1998, it was about 20 million m<sup>3</sup>. In the droughty year 1994, the amount of rainfall was rather small and as low as about half of the mean value, even though the groundwater exploitation amount was about 6.3 million m<sup>3</sup>, resulting in the most abrupt settlement to occur in the area.

#### Hydrogeologic Setting

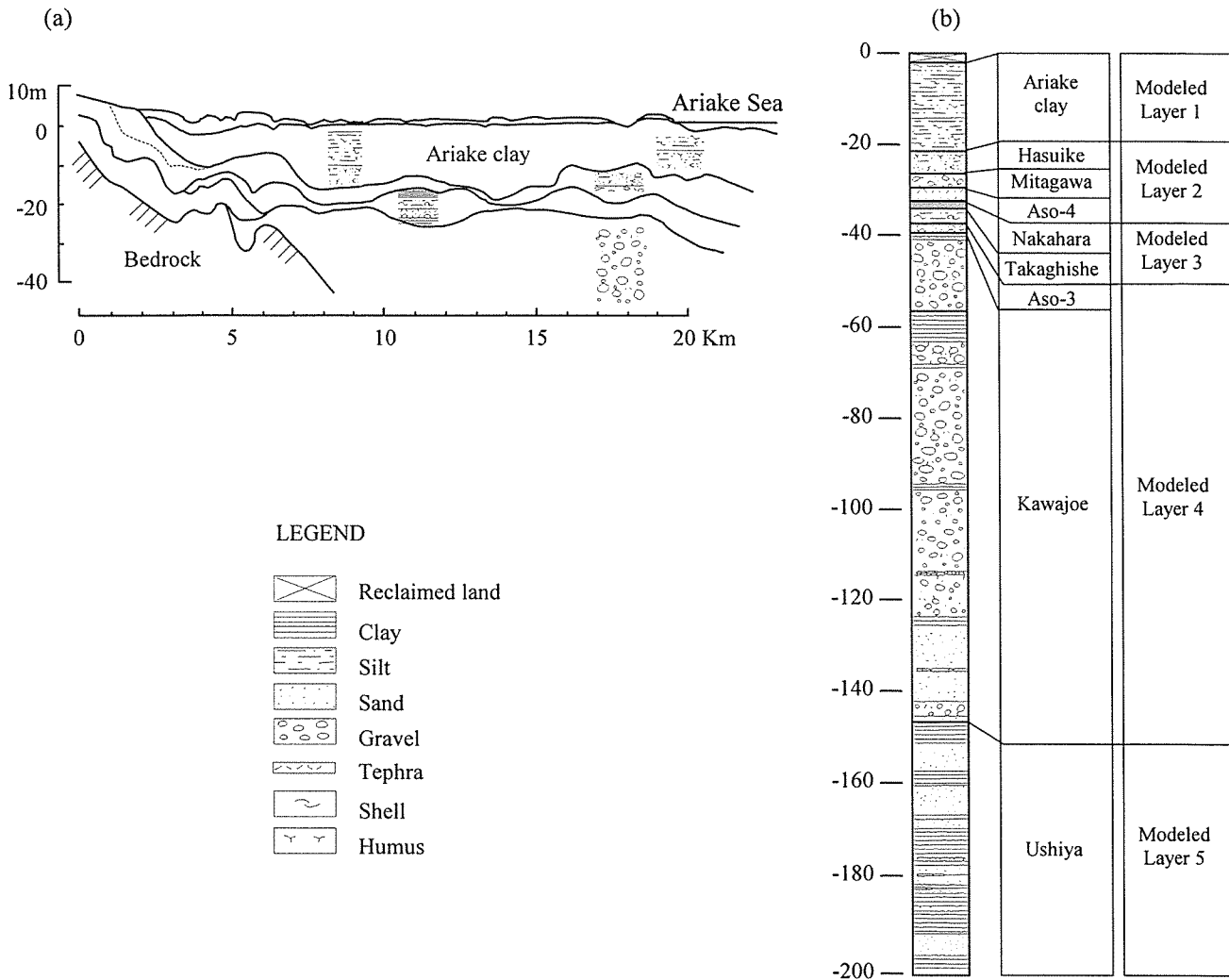


Fig. 3 (a) Simple geological profile along the section A-A near by the Rokkaku River, and (b) Soil column and modeled layers

The hydrogeology of the Saga plain was previously documented by Miura (1988), Sakai (1988), Onitsuka (1988), Tanaka (1990), Shimoyama et al. (1994). In general, the whole area of Shiroishi plain is underlain by lowland quaternary soft deposits around the inland Ariake Sea. The sediments can be separately divided into several layers based on their geologic and hydrogeologic characteristics. The layer below the ground surface is a soft marine clay layer which is well known as the Ariake clay. It is a confining bed with thickness varying from 10 to 20m. 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 of 5m or less in thickness, in both vertical and lateral directions. The underlain are volcanic ash soils deposited in two gravel layers. The Aso-4 volcanic ash appears at about elevation of -20m, and becomes shallow near Takeo. In general, this layer is a thin one. The Aso-3 volcanic ash sediment is very thick development, ranging in depth between 30 to 200m.

Both diluvium and volcanic ash layers form an excellent aquifer in this region.

Figure 3(a) depicts a simple geological profile along the section A-A near by the Rokkaku River and Fig. 3(b) draws a typical soil column at Ushiya near the shoreline in Ariake town and the modeled layers. The aquifer system was 3-D 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 30 to 200 m below sea level. Layer 5 is assumed to extend at altitude 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 bedrock is above the defined layer bottom, the layer bottom is equal to the altitude of bedrock.

## GROUNDWATER AND LAND SUBSIDENCE MODELS

## Groundwater Flow Model

Groundwater level for the study area was modeled using MODFLOW (McDonald and Harbaugh 1988). 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 [ $L T^{-1}$ ];  $h$  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 heterogeneous and anisotropic medium, provided the principal axes of hydraulic conductivity are aligned with the coordinate directions.

Solutions of Eq. 1 can be obtained by applying 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.

## Land Subsidence Model

Land subsidence was modeled using a modular called the Interbed Storage Package-1 (Leake and Prudic 1991). The interbed is 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. 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. The package is based on the one-dimensional consolidation theory of Terzaghi (1925). As a load is applied to a saturated, low conductivity soil, the pore water is unable to immediately escape and pore water pressure develops. No compression will occur until the pore pressure dissipates as the water flows out of the soil. Compression of the sediments is elastic if the lowering of fluid (pore) pressures does not

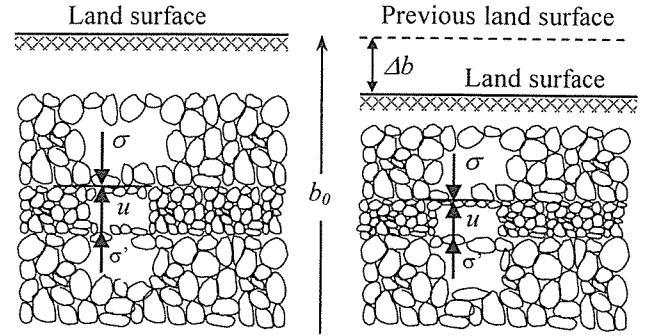


Fig. 4 Principle of effective stress

result in permanent rearrangement of the skeletal structure of the sediments and if water removed from storage can be replaced when fluid pressures increase. However, if the fluid pressures decrease beyond the interval where the sediments deform elastically, additional water is released from the clayey beds as the skeletal structure is rearranged and permanently compacted. This process is referred to as permanent deformation. Water removed from storage by permanent deformation cannot be returned after pumping decreases or ceases. Thus, water released during permanent deformation can be considered a one-time source that cannot be replaced.

The theory of hydrodynamic consolidation Terzaghi (1925), an essential element of the aquitard drainage model, describes the delay involved in draining aquitards when hydraulic heads are lowered in adjacent aquifers and the residual compaction that may continue long after aquifer heads are initially lowered. The drainage process is described well by a one-dimensional diffusion equation for groundwater flow:

$$\frac{\partial^2 h}{\partial z^2} = \frac{S_s}{K_v} \frac{\partial h}{\partial t} \quad (2)$$

where  $S_s$  is specific storage of the aquitard,  $K_v$  is vertical hydraulic conductivity of the aquitard. Depending on the thickness and vertical hydraulic diffusivity of an aquitard, the equilibration of pore fluid pressure and thus compaction-lags head declines in adjacent aquifers.

To account for the presence and effects of pore pressure, Terzaghi (1925) defined an effective stress which is expressed as the difference between total stress and pore pressure:

$$\sigma' = \sigma - u \quad (3)$$

where  $\sigma'$  is the effective stress;  $\sigma$  is the total stress; and  $u$  is the pore water pressure.

Figure 4 depicts the principle of effective stress as applied to land subsidence. Vertical displacement,  $\Delta b$ , of land surface is a result of a decrease in pore fluid pressure

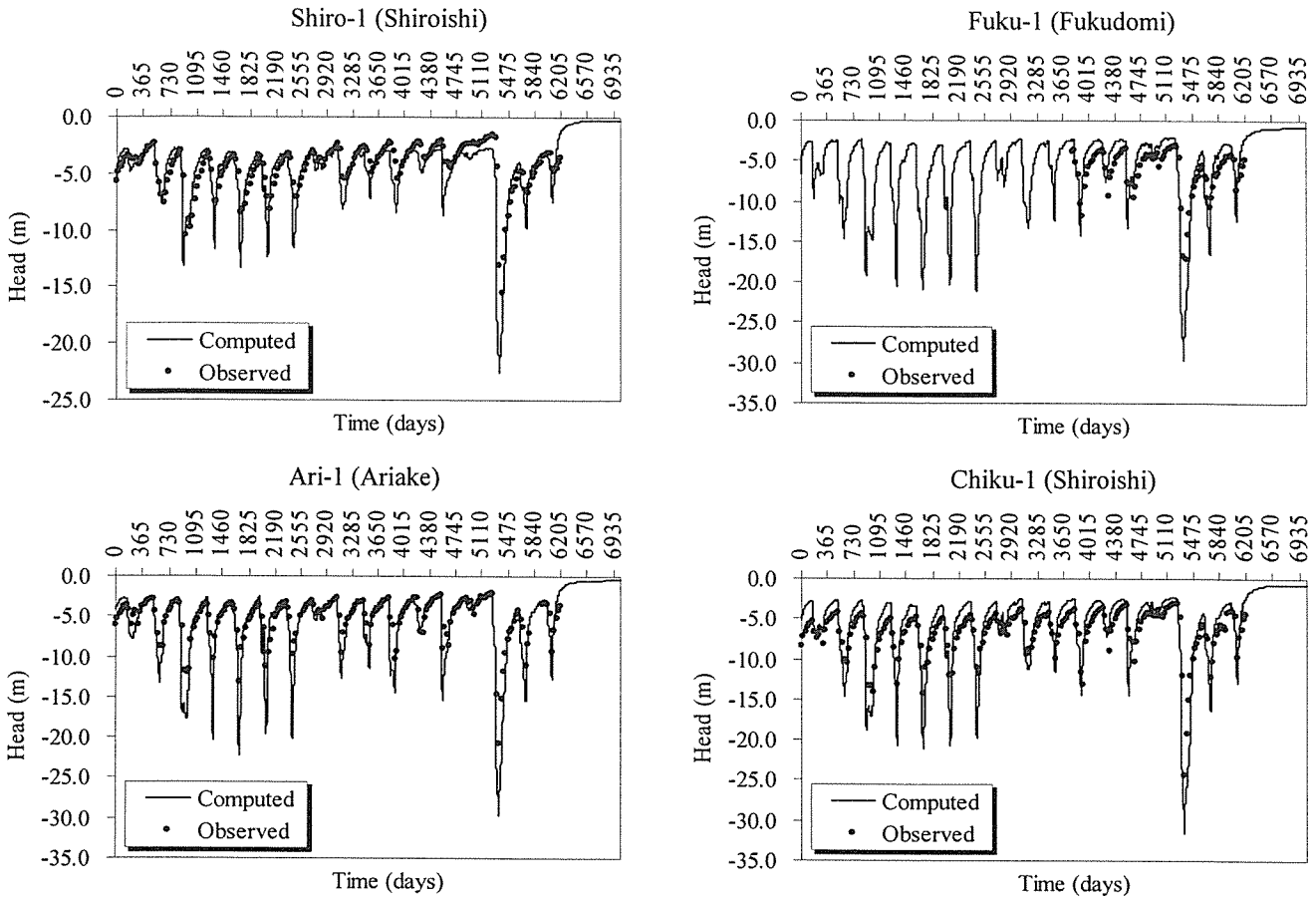


Fig. 5 Comparison of computed and observed heads at 4 chosen observation wells

and 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 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 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. The relationship between effective stress and the compression of clays is highly nonlinear. The past maximum stress is recorded in the soil's structure and is called its preconsolidation stress,  $\sigma'_p$ . Compression is elastic at stresses less than the preconsolidation stress while compression beyond the preconsolidation stress is inelastic. It is mainly the inelastic deformation of fine-grained aquifer interbeds to cause subsidence in the Shiroishi area. The package calculates deformation based on changes in effective stress. The package assumes that a change in piezometric head produces an equal but opposite change in effective stress in the aquifer, i.e. even as the piezometric head fluctuates, the total stress remains constant. This assumption introduces

error in shallow unconfined aquifers (Leake 1991), but holds for deep or confined aquifers. The package also assumes that the inelastic and elastic storage coefficients are constant. The values of these coefficients are actually functions of effective stress; however, the assumption introduces little error if changes in effective stress are small in relation to the overall effective stress. Again, this assumption is problematic for shallow aquifers, but satisfactory for deeper ones.

The compression of each model layer can be calculated as:

$$\Delta b_e = S_{ske} b_0 \Delta h \quad (4)$$

$$\Delta b_i = S_{skie} b_0 \Delta h \quad (5)$$

in which  $\Delta b_e$  and  $\Delta b_i$  are the elastic and inelastic compression, respectively;  $\Delta h$  is the change in head at the center of the layer;  $b_0$  is the original thickness of the layer; and  $S_{ske}$  and  $S_{skie}$  are the elastic and inelastic storage coefficients, respectively. For all layers included in the package, the preconsolidation stress is actually recorded as a preconsolidation head,  $h_p = \sigma'_p / \gamma_{water}$ . For each time step, the total elastic and inelastic compression is recorded and the amount of water released due to compression is returned

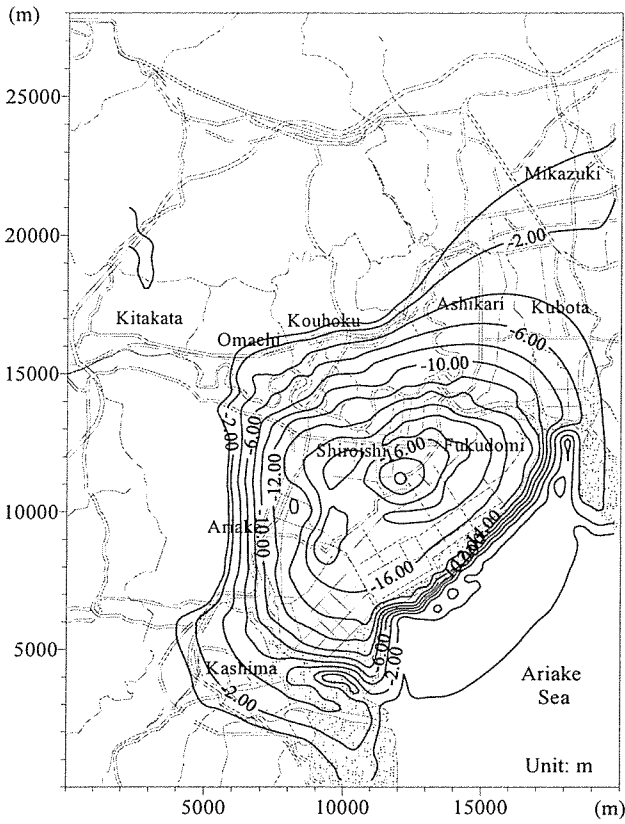


Fig. 6 Computed head contour map at the end of time stress 1994

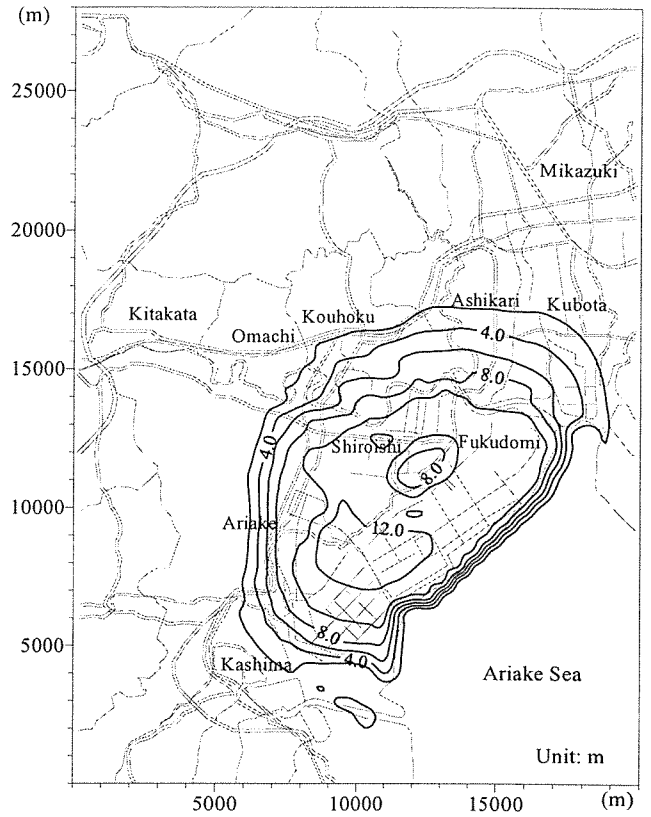


Fig. 7 Cone of depression at the end of time stress 1994

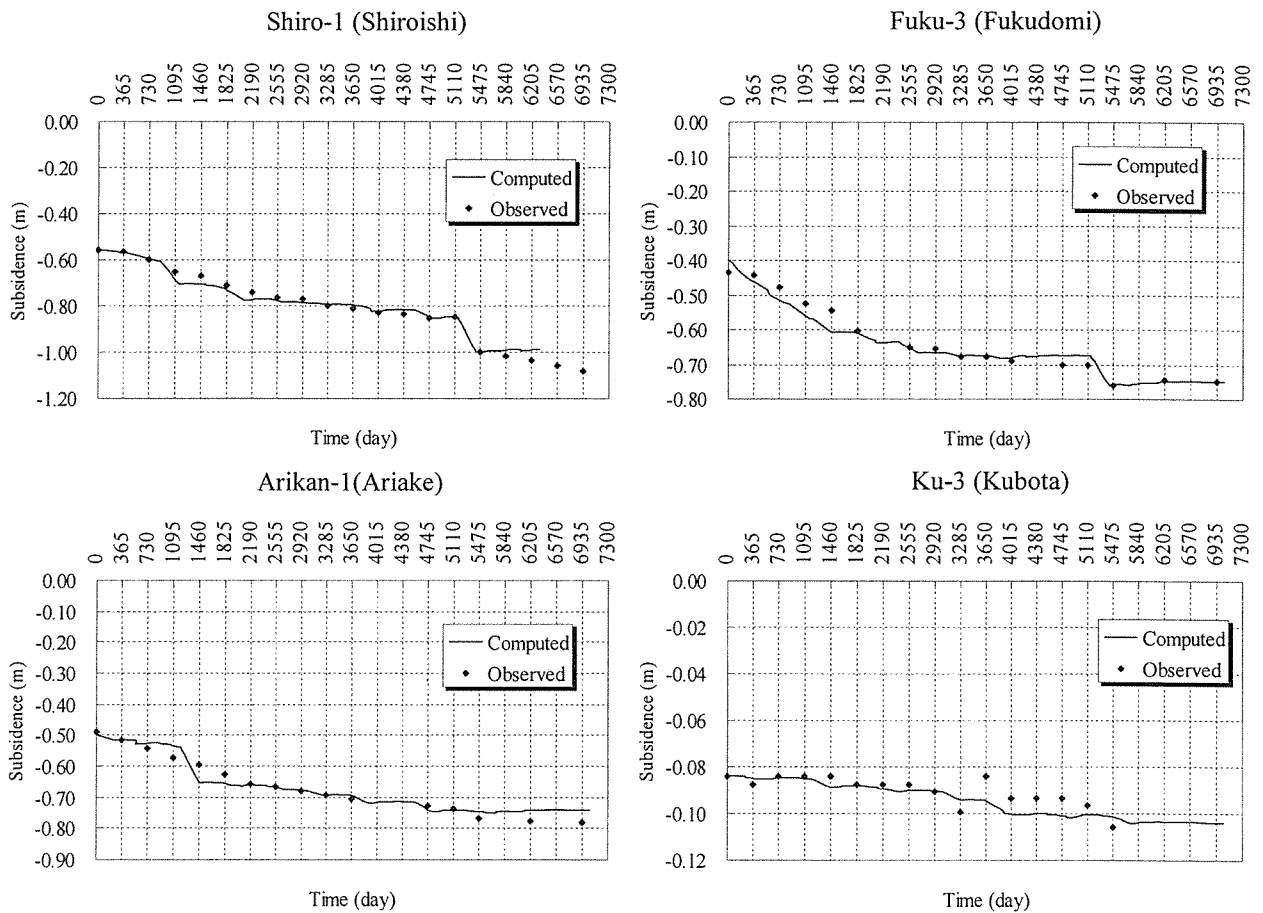


Fig. 8 Comparison of computed and observed subsidence at 4 chosen observation wells

Table 1 Material properties of the layered aquifer systems

| Parameters                           | Layered aquifer |        |           |        |        |
|--------------------------------------|-----------------|--------|-----------|--------|--------|
|                                      | 1               | 2      | 3         | 4      | 5      |
| $K_H$ ( $10^{-8} \text{ ms}^{-1}$ )  | 11.6            | 5790   | 600       | 12000  | 150    |
| $K_V$ ( $10^{-6} \text{ ms}^{-1}$ )  | 0.02<br>3       | 120    | 1.20      | 230    | 3.00   |
| Effective porosity                   | 0.45            | 0.25   | 0.25      | 0.45   | 0.01   |
| Specific yield                       | 0.06            | 0.32   | 0.20      | 0.10   | 0.20   |
| Specific storage ( $\text{m}^{-1}$ ) | 0.03            | 0.0002 | 0.00<br>1 | 0.0001 | 0.0001 |

Note:  $K_H$ : Horizontal hydraulic conductivity  
 $K_V$ : Vertical hydraulic conductivity

to the model water balance. Finally, if inelastic compression has occurred, a new value of preconsolidation head is recorded.

## RESULTS AND DISCUSSIONS

The basic input data 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 flow discharging from uphill areas, 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. The groundwater system of interest is approximately  $28.0 \times 20.0 \text{ km}^2$  and is covered with a 3-D grid. The sizes of each cell are  $\Delta x = 500\text{m}$ ,  $\Delta y = 500\text{m}$ . The 2-D grid contains 2240 cells:  $n_x = 56$ ,  $n_y = 40$ , where  $n_i$  denotes the number of cells in the  $i$  direction. Due to the rugged coastline of the groundwater system, only 58.2% of the cells are considered as active cells. Boundary conditions are inputted at all four sides. At the sea side, a general head boundary is implemented as outflow of fresh groundwater from the land to the sea is difficult to implement in the model. The general head boundary is typically a MODFLOW feature which models the inflow or outflow to an element through the difference between the head in the element itself and an external fixed head. The 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. At the uphill parts, a constant fixed head is inserted in the model. Water levels at the specific-head cells along the eastern model boundary are interpolated based on water level data from near by wells. Calibration of the model will focus on choosing

parameters for the layer such that their effect on land subsidence is equivalent to the composite effect of the actual interbeds.

The steady-state analysis was first done to check the mass balance of the discretized model domain; to calibrate the aquifer for adjustment of hydraulic conductivity; and 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 period under different stresses (pumping and recharge); to simulate the aquifer (under stresses like pumping and recharge) for a long period of time which will ensure the natural steady flow condition after that long period; and to determine the possible pumping amount of groundwater throughout the simulation period. The transient simulation was divided into 209 stress periods. A time step of day was used for 20 years simulation, from 1980 to 1999. Four monitoring wells indicated in Fig. 1 were chosen among the monitoring wells for comparison of observed and simulated heads. As seen in Fig. 5, overall the match between the observed and simulated heads is acceptable. Heads at other monitoring wells were also satisfactory simulated. 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,  $RMS = 3.38\text{m}$ ; mean error,  $ME = 2.45\text{m}$ ; mean absolute error,  $MAE = 2.95\text{m}$ , indicating that a good estimations have been obtained. Although the peaks of the head curves were over estimated. This error should stem from the complexity when choosing the model parameters in the calibration process. Table 1 summarizes the final calibrated properties of material in the layered aquifer systems. These parameters, however, should be specified as typical zonal values. It is also from the fact that the hydraulic properties of the aquifer system are also affected by land subsidence. Very few parameters were similarly found in documented data for direct comparison. Compressions often result in a permanent loss of storage; most of the loss occurs in the compressible fine-grained units. Compression 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 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 in the model.

As shown in Fig. 5, 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

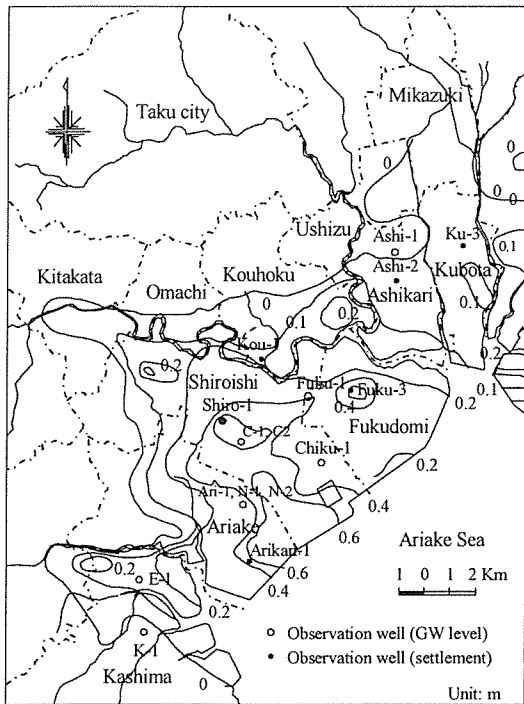


Fig. 9 Land subsidence observed in Shiroishi in 1999

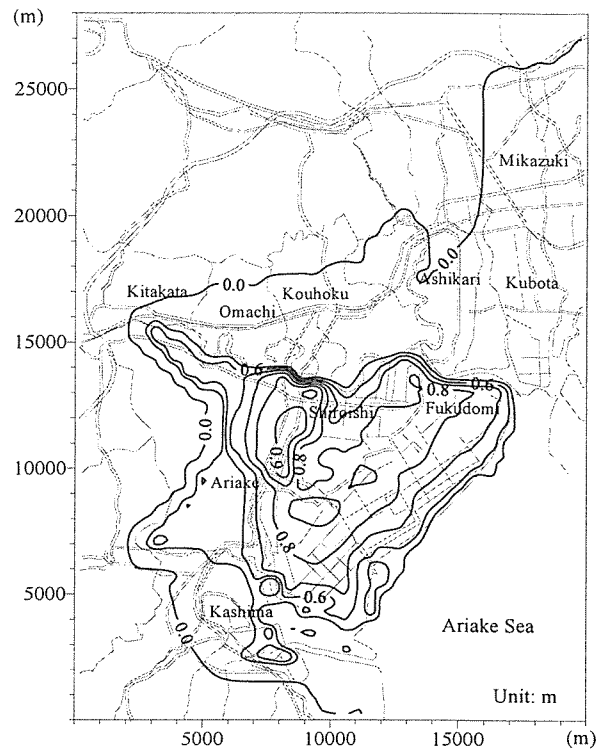


Fig.10 Contour map showing the simulated land subsidence in 1999

precipitation, recharge, and smaller discharge, then declining during the summer and fall owing 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. Changes in groundwater recharge and storage caused by climatic variability commonly occur over decades, 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 a water year then recover gradually at the end of the year.

Figure 6 shows the contour map of the simulated head at the end of the time stress 1994, and corresponding cone of depression shows in Fig. 7. It can be seen that the center of the cone is in Shiroishi and Fukudomi areas. This cone covers an area of about 200 km<sup>2</sup>. It 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

Table 2 Local hydrogeologic properties of interbed layers

| Parameter<br>(unit 10 <sup>-3</sup> m <sup>-1</sup> ) | Zone |      |      |      |      |       |
|---|------|------|------|------|------|-------|
|   | 1    | 2    | 3    | 4    | 5    | 6     |
| $S_{ske}$   | 0.10 | 0.75 | 0.35 | 0.35 | 0.60 | 0.40  |
| $S_{skie}$  | 3.5  | 9.9  | 7.5  | 9.5  | 12.5 | 120.0 |

Note:

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

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.

Table 2 summarizes zonal values of hydraulic parameters derived from the best history matches between simulated aquifer-system compression and measured compression. Figure 8 is the model results plotted against the observed values of land subsidence at four chosen bench-marks. Simulated subsidence closely matched measured subsidence at all of the bench marks. Simulated results show that the abrupt increase at benchmark Shiro-1



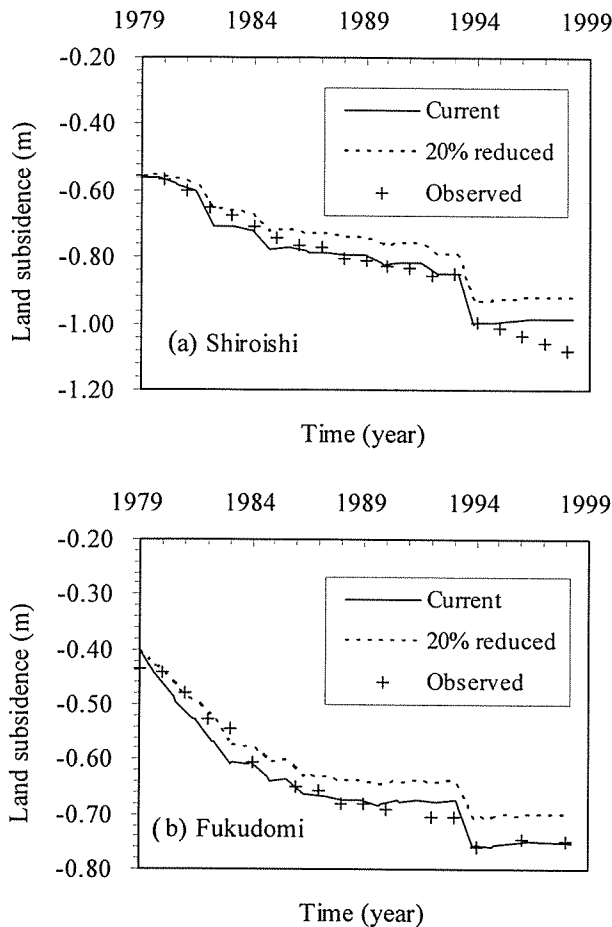


Fig. 11 Simulation of land subsidence under reduce pumpage

in Shiroishi where large water level declines had occurred in the droughty year 1994. Although water level was declined more than 20 m, the abrupt subsidence greater than 15cm was documented only in the central part of the area. It appears that droughts have substantial influence on the rate and magnitude of land subsidence.

Contours of measured and simulated subsidence accumulated from 1971 to 1999 are shown in Figs. 9 and 10, respectively. The measured 1999 contours were assumed to be representative and were used to 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 to be a small shift in the peak of subsidence to the east-north of the study area. The affected area was estimated about 210 km<sup>2</sup>.

Figures 11 (a) and 11 (b) plot the simulated subsidence in Shiroishi and Fukudomi areas, respectively, under a reduced pumpage 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

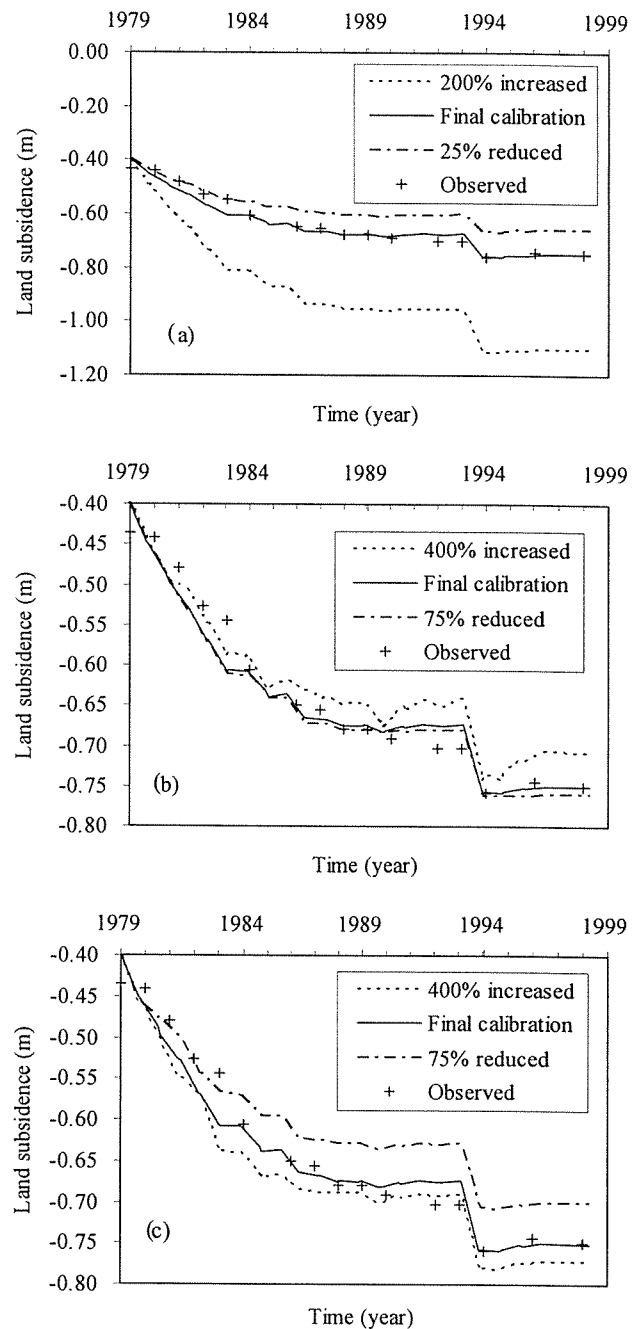


Fig. 12 Sensitivity analysis for Fuku-3 (Fukudomi) with respect to:

- (a) Inelastic storage coefficient;
- (b) Elastic storage coefficient; and
- (c) Vertical leakance

significant reduction of the future subsidence if the pumping rate is restricted in locations where pumping has been intensive.

As previously discussed, removal of groundwater by pumping from aquifers could result not only in compression of compressible soft clayey layers but also in compression of fine-grained beds that are within or adjacent to the aquifers.

## 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. For land subsidence analysis, the sensitivity of the model's parameters was evaluated by comparing subsidence from the sensitivity simulations with that from the calibrated transient-state model. In this study, three major effected subsidence's parameters were determined during the calibration process, which are inelastic storage coefficient, elastic storage coefficient, and vertical leakance.

### *Inelastic and elastic storage coefficients ( $S_{skie}$ and $S_{ske}$ )*

Figure 12 (a) shows the model results obtained for the cases of 200% increase and 25% reduction in inelastic storage coefficient, and Fig. 12 (b) 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.

### *Vertical hydraulic conductivity or vertical leakance*

The vertical leakage greatly affects the performance of the model because it determines the rate pore pressure leaves the fine-grained layers and hence, the rate of subsidence. Fig. 12 (c) shows the model results obtained to the cases of 400% increase and 75% reduction in the calibrated vertical leakance values for the interbed layers. As can be observed from Fig. 12 (c), this parameter also has a strong effect to the rate of subsidence. Vertical leakage values generally are for discrete thicknesses of sediments, usually aquitards that primarily govern the rate of land subsidence.

## CONCLUDING REMARKS

This study presents a method for evaluating land subsidence due to groundwater overdraft in Shiroishi, Saga plain. A three-dimensional numerical model which couples the 3-D groundwater flow model and 1-D soil consolidation model was applied to investigate groundwater hydraulics and the mechanisms of ground settlement. By calibrating the model with both groundwater level and ground settlement measurement data, the aquifer parameters of the system were estimated. The model outputs were well agreed with the observed results reasonably, which indicate that the numerical model can simulate the dynamic

processes of both groundwater flow and soil consolidation over the simulation period. Sensitive analysis shows that among three major parameters of inelastic storage coefficient, elastic storage coefficient, and vertical leakage, the first and the last parameters contribute significantly effects to both the rate and magnitude of consolidation. The excessive groundwater extraction may not only cause ground settlement but also have affect on sustainable water resources of the deep aquifer. It is supposed that a significant reduction in discharge is necessary for future development of the region to mitigate the effects of ground water overdraft. These problems have recently been improved by laws and the conversion to surface water from groundwater to reduce amount of groundwater withdrawals.

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