MODELING OF GROUNDWATER FLOW AND LAND SUBSIDENCE DUE TO PUMPING IN SHIROISHI, SAGA PLAIN

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1. INTRODUCTION

Land subsidence occurs in many areas where groundwater pumping lowers water levels within compressible aquifer systems. 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. 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^2. The study area is the lowland plain shown in Fig. 1, which plots the observed land subsidence in 1999. For hydrogeologic setting, the study area 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. Below this Ariake clay are diluvia 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. 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.

2. GROUNDWATER AND LAND SUBSIDENCE MODELS

Groundwater level for the study area was modeled using MODFLOW (McDonald and Harbaugh 1988). The governing equation of 3-D movement of ground water of constant density through porous can be described as:

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

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

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 was modeled using a modular called the Interbed Storage Package-1 (Leake and Prudic 1991). The package is based on the one-dimensional consolidation theory of Terzaghi (1925). 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, K_v is vertical hydraulic conductivity. 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.

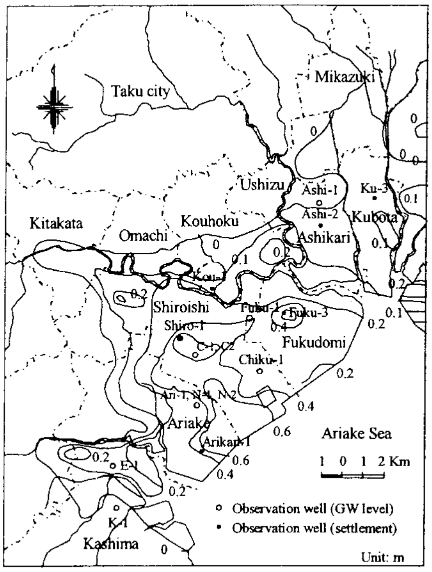

Fig. 1 Study area showing land subsidence observed in 1999

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 σ' is the effective stress; σ is the total stress; and u is the pore water pressure.

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 Δb_e and Δb_i are the elastic and inelastic compression, respectively; Δh 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.

3. MODEL APPLICATION

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. 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 at different period under different stresses; to simulate the aquifer 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. A time step of one day was used for 21 years simulation, from 1979 to 1999. As seen in Fig. 2, overall the match between the observed and simulated heads at Shiro-1 (Shiroishi) is acceptable. Heads at other monitoring wells were also satisfactory simulated. The contour maps of simulated water

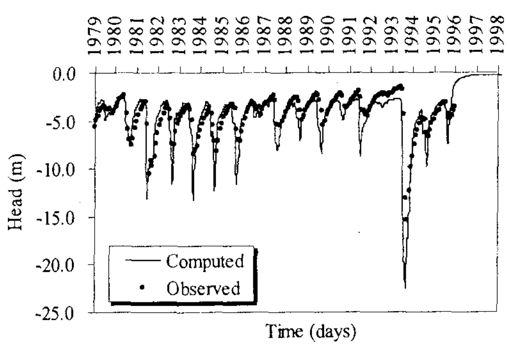

Fig. 2 Comparison of computed and observed heads

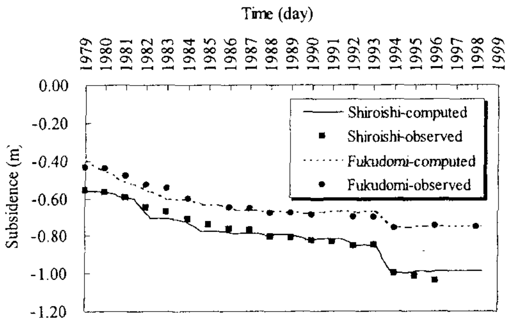

Fig. 3 Computed and observed subsidence

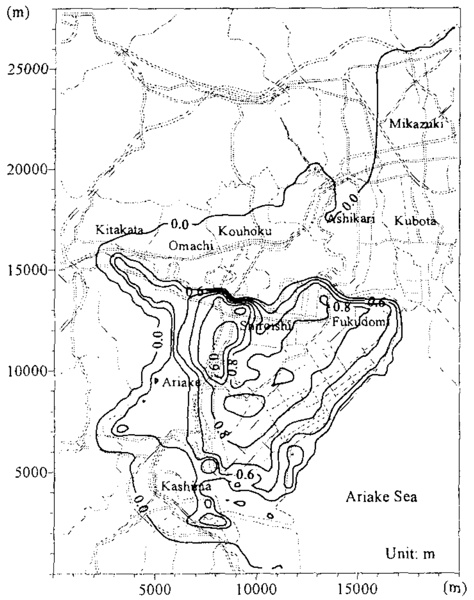

Fig. 4 Contour of simulated land subsidence in 1999

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. Figure 3 is the model results plotted against the observed values of land subsidence at bench-marks Shiro-1 (Shiroishi) and Fuku-3 (Fukudomi). Simulated subsidence closely matched measured subsidence at all of the bench marks. Simulated results show that the abrupt increase at benchmark Shiro-1 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. 1 and 4, 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^2. Figure 5 plots the simulated subsidence in Shiroishi 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 significant reduction of the future subsidence if the pumping rate is restricted in locations where pumping has been intensive.

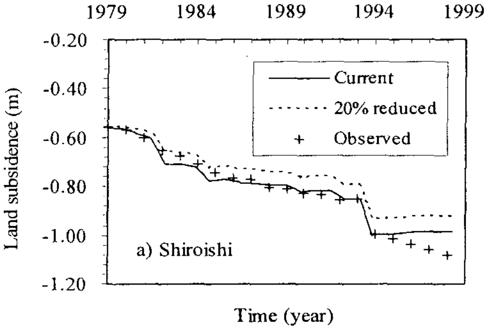

Fig. 5 Land subsidence under reduced pumpage

4. CONCLUSIONS

This study presents a method for evaluating land consolidation due to groundwater overdraft in Shiroishi, Saga plain. A three-dimensional numerical model which couples the groundwater flow and soil consolidation was applied to investigate groundwater hydraulics and the mechanisms of ground settlement. 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. 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 the conversion to surface water from groundwater to reduce amount of groundwater withdrawals.

REFERENCES

Leake, S.A. and Prudic, D.E. (1991). Documentation of a computer program to simulate aquifer-system compaction using the modular finite-difference groundwater flow model. USGS Open-file report, Book 6, Chapter 2.

McDonald, M.G. and Harbaugh, A.W. (1988). A modular three-dimensional finite difference groundwater flow model. USGS Open-file report 83-875.

Terzaghi, K. (1925). Principles of soil mechanics: IV settlement and consolidation of clay. Engineering News Record. McGraw-Hill, New York.