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ESTIMATING THE POTENTIAL FOR CONJUNCTIVE WATER MANAGEMENT IN COASTAL PLAINS

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ABSTRACT: This paper presents the development and application of a conjunctive water management model for lowland catchments. The model incorporates a simulation model and a management model to simulate groundwater movement, ground consolidation and to search for the potential pumping amount of groundwater without violating physical and environmental constraints. The results reveal that groundwater levels in a coastal aquifer greatly vary in response to pumping. Consequently subsidence rapidly occurs throughout the area. The study also suggests that conjunctive water management can be used to improve water supply reliability, to reduce groundwater overdraft and land subsidence and to improve environmental conditions.

Keywords: Coastal lowland plain, groundwater pumping, groundwater hydraulics, land subsidence, conjunctive water management, optimization model

INTRODUCTION

Conjunctive water management is considered as the coordinated operation of surface water, groundwater, and conveyance facilities to meet water management objectives (CWP, 2005). It involves the systematic use of groundwater and surface water to optimize the combined yield from both sources. In its most common form, surface water is used to conserve groundwater so that it is available during dry seasons. Although surface water and groundwater are sometimes considered separate resources, they are connected by the hydrologic cycle. Conjunctive water use of surface water and groundwater plays an important role in the hydrology of coastal lowland areas as it helps to improve water supply reliability, to reduce groundwater overdraft and land subsidence, to protect water quality, and to improve environmental conditions. Moreover, conjunctive water management allows surface water and groundwater to be managed in an efficient manner by taking advantage of the ability of surface storage to capture and temporarily store storm water and the ability of aquifers to serve as long-term storage. Therefore, reliable estimate of potential for conjunctive water management is critical in many alluvial lowland plains. In general, where surface water and groundwater are

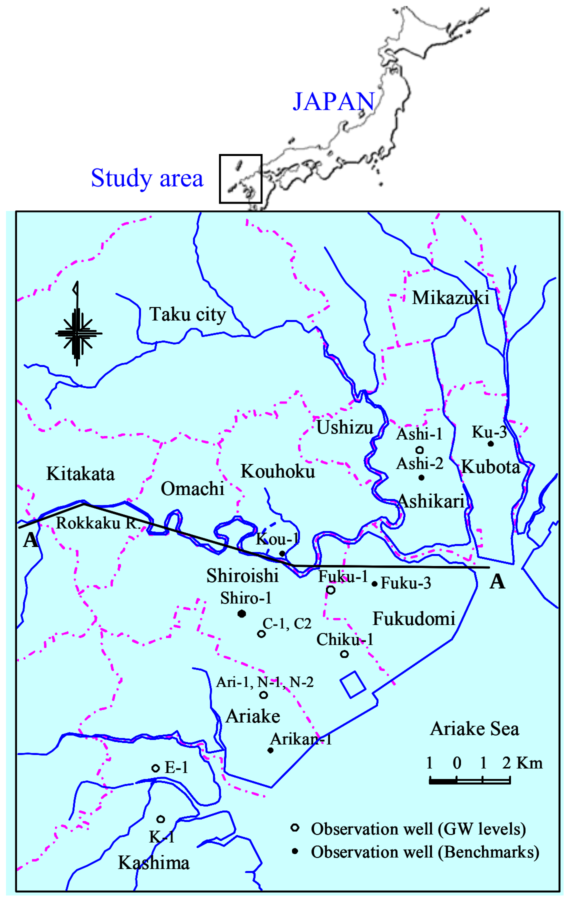

Fig. 1 Map showing the study area in the Shiroishi plain

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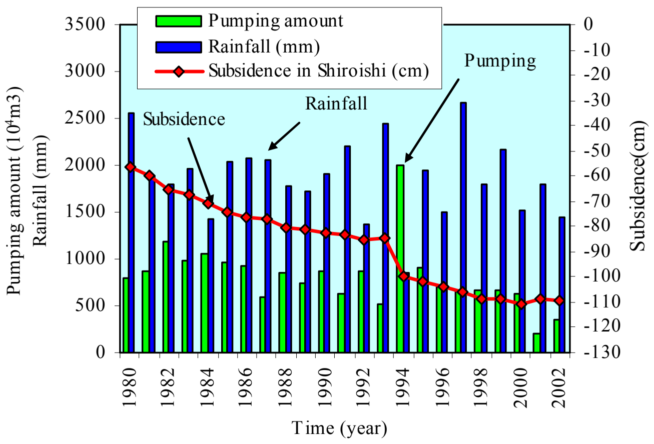

Fig. 2 Annual pumping, rainfall and subsidence

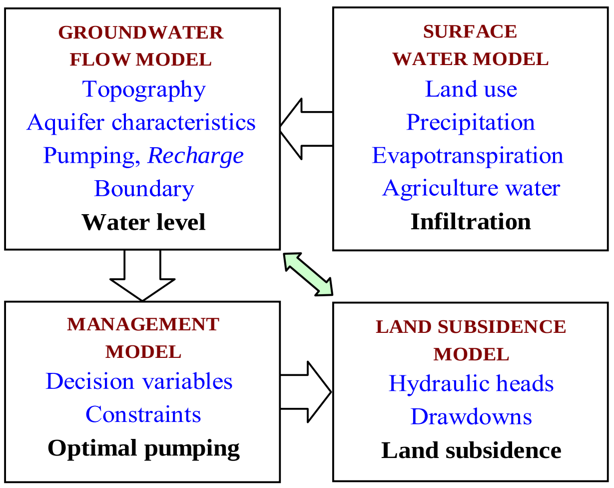

Fig. 3 Modeling framework

managed as part of a conjunctive scheme, a decrease in the rate pumping groundwater is possible.

As in a case study, Shiroishi region is one of the productive and intensely farmed agriculture areas in the Saga plain, southern Kyushu Island of Japan (Fig. 1). Water supplied to agriculture has traditionally been a high priority for water managers in this region. As surface water resource is very limited because of no water storage facility while as rainfall is runoff quickly, groundwater is, therefore, regarded as the primary source of irrigation water for agriculture. However, intense withdrawals of groundwater in excess of natural recharge have resulted in land subsidence in this area. Land subsidence is the lowering of the land surface elevation from changes that take place underground.

Figure 2 shows the annual groundwater pumping, rainfall and land subsidence in Shiroishi. It indicates that on an average an amount of water as large as 9.2 million m^3 is pumped up annually, especially in 1994, it was about 20 million m^3. In the droughty year 1994, the amount of rainfall was rather small, even though, the groundwater exploitation amount was about 6.3 million

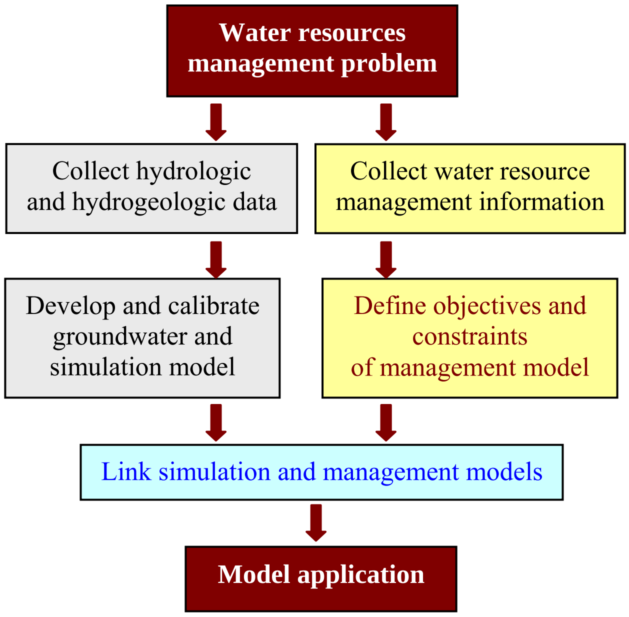

Fig. 4 Steps in development and application of model

m^3, resulting in the most abrupt settlement to occur in the area. This steady increase in the demand for surface water and groundwater resources since the late 1950s has resulted in seawater intrusion, inter-aquifer flow land subsidence. So far, conjunctive water management has not been practiced in many coastal areas. Although many researches have been done on groundwater separately, study of groundwater in combination with land subsidence and groundwater management still has been very limited. Moreover, there is no comprehensive data on the planning and implementation of conjunctive water management at the local agency level.

MODEL DEVELOPMENT

Conjunctive use of groundwater and surface water often occurs by default. It is the coordinated operation of surface water, groundwater and conveyance facilities to meet water management objectives. Using groundwater in conjunction with surface water is a very important aspect of water resources management. When water resources are a limiting factor in the development of a region, then optimum utilization is a main concern to society. The aim of the groundwater-surface water conjunctive use scheme is to use water from both surface and groundwater in a combined manner, taking advantage of the complementarities in hydrologic, hydrogeologic, environmental and socioeconomic features of utilizing from each source to achieve the given objective. Figure 3 shows the modeling framework. The conjunctive water management model is the linkage of two models, a simulation model and a management model. The simulation model consists of a surface water balance model, a groundwater model and a land subsidence model. As shown in Fig. 4, the use of linked simulation and optimization models greatly enhances the utility of simulation models alone by directly incorporating management goals and constraints into the modeling process.

Simulation Model

The groundwater recharge is computed using a lumped surface water balance model. The basic concept of the surface water hydrological cycle is as follows. The inflow of fresh water that consists of rainfall and the available water supply from groundwater, ponds, creeks, reservoir dams and water of rivers should balance with the outflow that consists of runoff, evapotranspiration and infiltration to the groundwater system.

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

$$P(t) + S(t) = Ro(t) + ET(t) + I(t) \qquad (1)$$

where $P(t)$: 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}]; $I(t)$ is infiltration, [LT^{-1}], and t: time period, [T].

Groundwater flow movement in the study area was modeled using MODFLOW (McDonald and Harbaugh 1988). The governing equation of 3-D movement of groundwater through porous can be described as:

$$\frac{\partial}{\partial x}\left(K_x \frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(K_y \frac{\partial h}{\partial y}\right)+\frac{\partial}{\partial z}\left(K_z \frac{\partial h}{\partial z}\right)-W=S_s \frac{\partial h}{\partial t} \qquad (2)$$

where K_x, K_y and K_z are values of hydraulic conductivity along the x, y, and z coordinate axes, [LT^{-1}]; h is the potentiometric head, [L]; [T^{-1}]; S_s is the specific storage, [L^{-1}]; and t is time, [T].

In Eq. 2, W is a volumetric flux per unit volume and represents sources or sinks of water. W can be the infiltration rate that is the movement of surface water from the land surface, through the topsoil and subsurface, and into de-watered aquifer space. W is also pumping and evapotranspiration rate from the groundwater system.

Moreover, land subsidence was modeled using the Interbed Storage Package-1 (Leake and Prudic, 1991). For sediments in confined aquifers in which geostatic pressure is constant, the compaction of each model layer can be calculated as:

$$\Delta b_e = S_{ske} b_0 \Delta h \qquad (3)$$

When effective stress of sediments compacting in the inelastic range is reduced, the sediments again expand:

$$\Delta b_i = S_{skie} b_0 \Delta h \qquad (4)$$

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, respectively.

Management Model

The management model developed for the system was formulated and solved by use of optimization techniques. Formulation of the model refers to the process of defining the conjunctive management problem mathematically by a set of decision variables, an objective function, and a set of constraints. The decision variables of the model were monthly withdrawal rates at each of the public water-supply wells; values for each decision variable were calculated by the optimization solution technique.

The objective function of the conjunctive model was to maximize the total groundwater withdrawal at all production wells during forecast periods and is expressed as:

$$Max\ Z = \sum_{p=1}^{M} \sum_{q=1}^{NT} Q(u,v) \qquad (5)$$

The objective function must satisfy the following constrain set, Eqs. (6) to (8):

- Total pumping needs to meet the normal year demand, Q_d, [L^3T^{-1}]:

$$\sum_{p=1}^{M} \sum_{q=1}^{NT} Q(u,v) \geq Q_d \qquad (6)$$

- Pumping rates at production wells u^{th} during time period v^{th} must not exceed the maximum permissible pumping rate at well u^{th}:

$$Q(u,v) \leq Q_{max}(u) \qquad (7)$$

The maximum withdrawal rate for each well was assumed to be the larger of the well's yield based on the aquifer test done when the well was first installed.

- Drawdown constraint: Drawdown should not exceed the permissible one, s_p, [L]:

$$s(p,q) \leq s_p(p,q) \qquad (8)$$

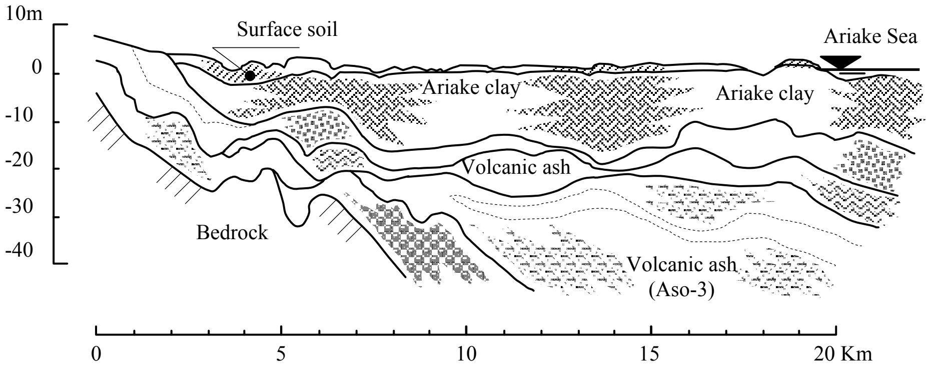

Fig. 5 A typical geological profile

Response Matrix Technique for Solution

The optimization method used to solve the management model is based on a widely applied technique for solving many types of groundwater management problems called the *response matrix technique* to couple the groundwater levels with the optimization constraints. In this system, linear response theory based on the principle of linear superposition is applied. The principle of linear superposition is that drawdown induced by more than one well is equal to the sum of drawdown induced by each individual well.

The drawdown *s(p,q),* [L], at the well p^{th} at the end of time period stress q^{th} related to groundwater withdrawals is given by the following respond equation:

$$s(p,q) = \sum_{u=1}^{NT} \sum_{v=1}^{M} \alpha(p,u,q-v+1) Q(u,v) \qquad (9)$$

in which $\alpha(p,u,q-v+1)$ is respond functions that is the change in drawdown at the well p^{th} at the end of time period stress q^{th} due to a unit quantity of water pumped from the well u^{th} during the time period v^{th}. $Q(u,v)$ is pumping volume, $[L^3T^{-1}]$, from the well u^{th} during the time period v^{th}. *M* is the total number of wells withdrawing water from the aquifer. *NT* is the number of pumping stress periods. In the modeling process, the response functions in Eq. (9) are generated using the groundwater flow model and the objective function in Eq. (5) can be solved using an optimization solver, LINGO (Kenvin and Linus, 1988).

MODEL APPLICATION AND DISCUSSION

For geologic setting, in general, the whole area of Shiroishi plain is underlain by lowland quaternary soft deposits around the inland Ariake Sea. Figure 5 sketches a geological profile along a section A-A (shown in Fig. 1) near by the Rokkaku River. The aquifer system was 3-D discretized vertically into four 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. It is a confining bed with thickness varying from 10 to 20 m. The thickness becomes greater as it approaches the coastal zone and spreads far and wide under the plain area. Below this Ariake clay are dilluvial deposits dominated by sands, gravels, and pumices of various sizes, and are of 5m thick or less, in both vertical and lateral directions. The underlain are volcanic ash soils deposited in two gravel layers. The Aso-4 volcanic ash appears at an altitude of

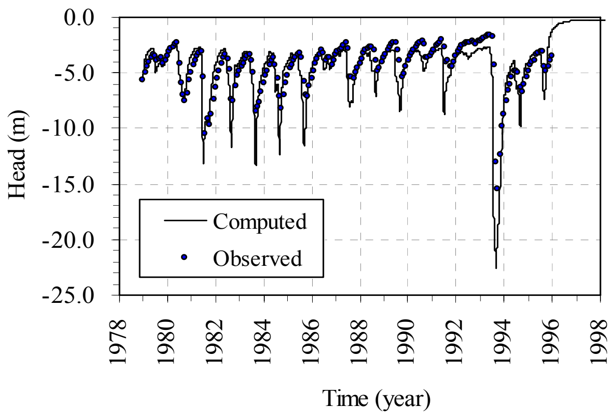

Fig. 6 Comparison of computed and observed heads

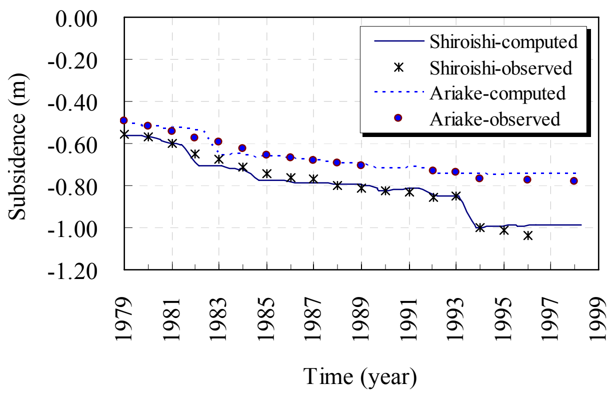

Fig. 7 Computed and observed subsidence

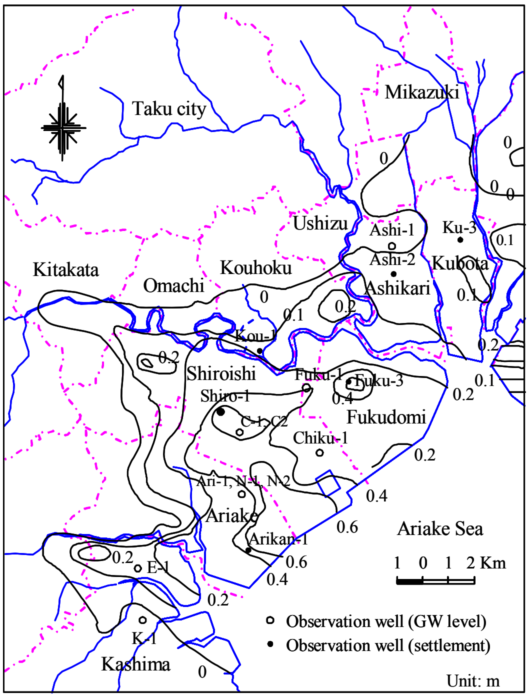

Fig. 8 Land subsidence observed in Shiroishi in 1998

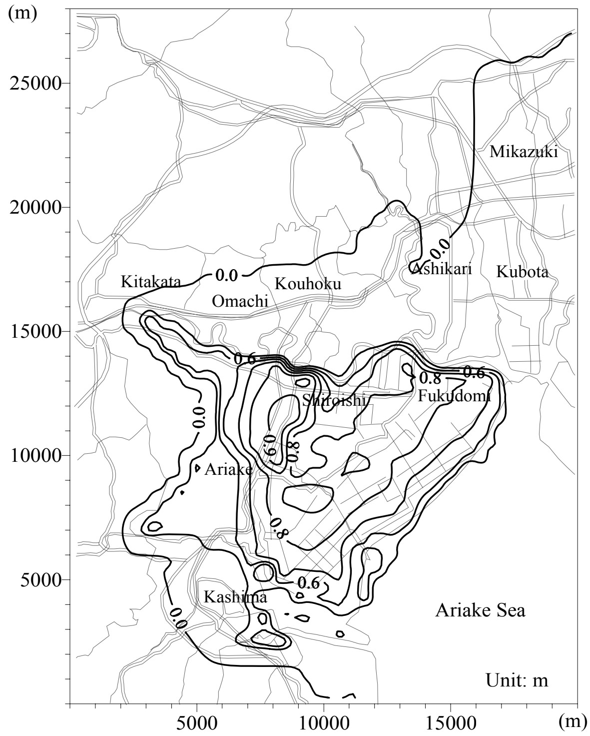

Fig. 9 Simulated land subsidence in 1998

about 20m below sea level, and becomes shallow near Takeo. In general, this layer is a thin one. The Aso-3 volcanic ash sediment is very thick development. Both diluvium and volcanic ash layers form a highly permeable and excellent aquifer in this region.

The basic input data are the aquifer parameters including topography, geometry, elevation, soil properties of each soil layer in the aquifers. Bedrock was modeled as no-flow boundary. 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, and during the other months less than 1.0 mm/day. Other recharges are flow discharging from uphill areas, precipitation and rivers.

The groundwater system of interest is approximately 28.0 x 20.0 km^2 and is covered with a 3-D grid. The sizes of each cell are Δx = 500m, Δy = 500m. Boundary conditions are inputted at all four sides of the model. Time step Δt = 1 day was used for a 20-year simulation, from end of 1979 to 1999. Calibration of the model was achieved through trial and error, focusing on choosing parameters for the layer such that their effect on land subsidence is equivalent to the composite effect of the actual interbeds. The hydraulic conductivities of the model layers were found in the order of 0.01 to 100.0 m/day and of 0.001 to 20.0 m/day for horizontal hydraulic conductivity and vertical hydraulic conductivity, respectively.

Figure 6 plots the observed heads against simulated ones at a monitoring well (Shiro-1) in Shiroishi. As seen in Fig. 6, overall the match between the observed and simulated heads is acceptable, although the peaks of the head curves were over estimated. The overall match between the observed and simulated heads at other monitoring wells also show the same outcome, indicating that a good estimation has been obtained. Water levels in the aquifers in this area follow a natural cyclic pattern of seasonal fluctuation in response to varying climatic conditions and pumping periods (Don et al., 2005).

Figure 7 is the model results plotted against the observed values of land subsidence at benchmarks Shiro-1 (in Shiroishi) and Ari-1 (in Ariake). Simulated subsidence closely matched measured subsidence at all of the benchmarks. Simulated results show an abrupt increase at benchmark Shiro-1 in Shiroishi where large water level declines had occurred in the droughty year 1994. Such a drought has substantial influence on the rate and magnitude of land subsidence. However, there is a small difference between the observed data and the simulated ones during the last two-year simulation. This may stern from using recharge values obtained from the lumped surface water balance model.

Contours of measured and simulated subsidence accumulated from 1971 to 1999 were constructed and shown in Figs. 8 and 9, respectively. The measured 1999 contours were assumed representative and were used to qualitatively evaluate the transient-state simulation. Although the measured data points were not dense

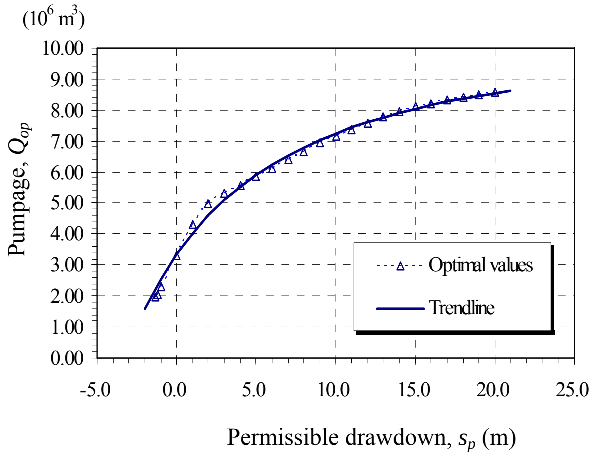

Fig. 10 Optimal pumping under varying drawdown

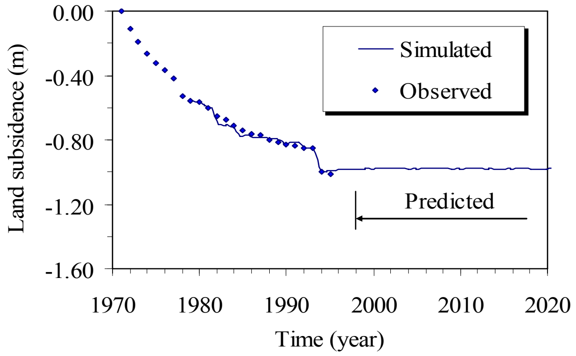

Fig. 11 Predicted land subsidence when pumping with the optimal yield

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 east-north of the study area (Don et al., 2005).

For estimating the potential for conjunctive water management, the management model was run to search for pumping amounts (Eq. 5) that satisfy the constraint sets shown in Eq. (6) through (8). After each run, a pumping amount corresponding to each constraint set was obtained. Figure 10 plots the predicted relationship between the pumping amount (Q_{op}) and its corresponding permissible drawdown (s_p).

Pumping amounts were then regenerated as the input data and returned to the simulation model to predict land subsidence over the 23-year planning horizon, from 1998 to 2020 in Shiroishi. The pumping amount that induces less land subsidence rate will be considered as the optimal potential pumping amount for conjunctive water management. It is found that the total maximum groundwater withdrawal without causing land subsidence for the entire area is estimated to be five million cubic meters. It means that pumping with amounts greater than the optimal value will produce more subsidence. Figure 11 plots the predicted land subsidence in Shiroishi area under pumping the potential optimal yield. It is apparent that when pumping rate is less than the optimal amount, land subsidence will not occur in the entitle area.

CONCLUSIONS

This study presents the development and application of a conjunctive water management model for coastal lowland areas. The model is a simulation model integrated with a management model to simultaneously simulate water level and land subsidence and to search for the potential pumping amount. The aquifer parameters of the system were well estimated through model calibration. The model outputs reveal that groundwater levels in the aquifers greatly vary from season to season. Results obtained from the management model show that conjunctive water management will virtually minimize the land subsidence process caused by heavy groundwater pumping in the study area. To sustain groundwater use in pumped areas, enhancing recharge from precipitation and surface water imports is necessary.

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