IMPACTS OF CHANGING RICE IRRIGATION PRACTICES ON THE SHALLOW AQUIFER OF NASUNOGAHARA BASIN, JAPAN

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ABSTRACT

The challenge for water resources planners is how best to manage the surface water and groundwater resources of a region to prolong their usefulness for present and future generations. This study was carried out in Nasunogahara Basin Tochigi Prefecture, Japan to evaluate the effect of changing rice crop irrigation practices on managing the use of water from the shallow aquifer of the area. The basin is an alluvial fan where paddy fields occupy 40% of the area. 66% of these paddy fields are irrigated by groundwater and are located in the southern part of the basin. The current practice is to carry out rice transplanting and land preparation, which is a high demand period for water, in a short period of 15 days. This short period usually starts in the middle of April and lasts until the beginning of May with the highest water demand is at the end of April and beginning of May.

In the early 1990s a trend of lowering in the groundwater table and drying up of the natural springs was observed in the basin. The reasons for this trend are suspected to be low precipitation and the influences of various new developments for residential or industrial land use in the northern part of the basin. This trend and the relatively short duration of the high water demand period caused severe groundwater shortages during the transplanting period in the basin.

An integrated surface water- groundwater model was developed as a tool for management of regional groundwater resources and used to examine the effect of prolonging the high demand period. The model simulated the effects of two longer periods of transplanting and land preparation, 30 and 60 days. The simulation results showed that extending the high demand period eased the groundwater shortage significantly. There are no major differences between the effects of the two periods, 30 and 60 days, in improving the water supply. Present institutional and economic constraints make the 60-day alternative impractical.

INTRODUCTION

Substantial increase in water demand for municipal, agricultural and industrial uses, created primarily by rapid population growth, makes the optimal joint operation of surface water and groundwater supplies attractive (Basagaoglu and Marino, 1999). With continued population

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increases and economic development in many parts of the world, the stresses imposed on water resources consequently increase, resulting in undesirable impacts on both surface and groundwater systems. The challenge is how best to manage the interacting surface and groundwater resources of a region to prolong their usefulness for present and future generations. This study was carried out in Nasunogahara Basin Tochigi Prefecture, Japan to evaluate the effect of changing rice crop irrigation practices on managing the use of water from the shallow aquifer of the area. The basin is an alluvial fan where paddy fields occupy 40% of the area. The current practice is to carry out rice transplanting and land preparation, which is a high demand period for water, in a short period of 15 days. This short period starts in mid April and lasts until the beginning of May with the peak of water demand is at the end of April and beginning of May. In the early 1990s a trend of lowering in the groundwater table and drying up of the natural springs was observed in the basin. The reasons for this trend are suspected to be low precipitation and the influences of various new developments for residential or industrial land use in the northern part of the basin. This trend and the relatively short duration of the high water demand period caused severe groundwater shortages during the transplanting period in the basin.

In this study an integrated surface water- groundwater model was developed as a tool for management of regional groundwater resources in the basin and used to examine the effect of prolonging the high irrigation demand period. The model simulated the effects of two longer periods of transplanting and land preparation, 30 and 60 days. The simulation results showed that extending the high demand period alleviated the groundwater shortage.

OUTLINE OF NASUNOGAHARA BASIN

Nasunogahara Basin is an alluvial fan with a total area of about 40,000 ha. The basin is situated in the northern part of Tochigi Prefecture, Japan. The total paddy field area of the fan is 15,000 ha, out of which around two thirds are irrigated by groundwater. The paddy fields irrigated by groundwater are located in the lower part of the fan where abundant shallow groundwater is available. On the other hand Nasunogahara Canals Irrigation Scheme supplies irrigation water for the paddy fields in the upper area of the fan.

Nasunogahara Basin is surrounded by Hoki River to the west and Naka River to the east. Between these two rivers, Sabi River had mainly developed the fan (Figure 1). Sabi River and its tributary Kuma River usually have no water in their riverbeds in the upper area of their streams. Runoff water of these rivers flowing down from the mountains disappears from the riverbed surfaces to the subsurface because of the high permeability rates of the riverbeds' coarse gravel formation. River water can be seen in the upper part of the two rivers only after big storms. A part of the river's water that flows under the ground, appears again to their riverbeds in the lower part and the rest is believed to recharge the groundwater along the river. The mean annual rainfall of the area is about 1500-mm. Nasunogahara canal irrigation system (Figure 1) has an important role in the hydrologic regime of the fan. It supplies stable water, which is diverted from Naka River, for irrigating the paddy fields in the upper area of the fan. The water infiltrating from these paddy fields is an important source of groundwater recharge.

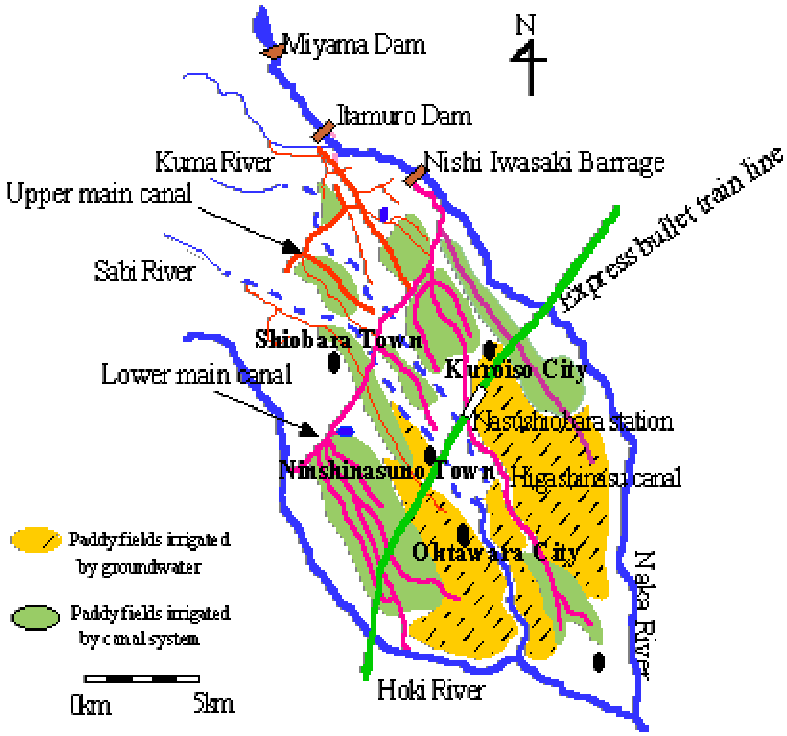

Figure 1. Outline of Nasunogahara alluvial fan, Tochigi Prefecture, Japan, and its irrigation system

On the other hand, in the lower area of the fan, water pumped from the unconfined aquifer is the major source of irrigation. The irrigation period for paddy fields in the area usually starts in April and ends in August, which is the rice-cropping season.

MODEL DEVELOPMENT

The integrated model simulated comprehensively the hydrologic processes in Nasunogahara Basin. The recharge processes, which were simulated in this model, include recharge from precipitation, infiltration from applied irrigation water and recharge from Sabi River's underflow. The discharge processes include pumping of groundwater and discharge by springs (Elhassan, et al., 2001).

Groundwater Flow Model

The groundwater flow model was developed assuming that the aquifer is single-layered, isotropic and heterogeneous. The flow was assumed to be transient and two-dimensional. The partial differential equation that governs the flow in the aquifer is Boussinesq equation for the two-dimensional, transient flow in an unconfined aquifer (Anderson and Woessner, 1991):

$$\frac{\partial}{\partial x}\left(kh\frac{\partial h}{\partial x}\right)+\frac{\partial}{\partial y}\left(kh\frac{\partial h}{\partial y}\right)=S_y\frac{\partial h}{\partial t}-R \qquad (1)$$

where h is the saturated thickness of the aquifer (m), k is the hydraulic conductivity ($m.d^{-1}$), x and y are the spatial coordinates, S_y is the specific yield of the unconfined aquifer, t is time (d), and R is the source-sink term ($m.d^{-1}$).

Equation (1) was solved using an implicit finite difference scheme namely the Crank-Nicolson scheme and Gauss-Seidel iteration technique (Wang and Anderson, 1982).

Combining Tank Model with the Groundwater Flow Model

Tank model, which is a conceptual rainfall-runoff model, is one of the applicable and widely used rainfall-runoff models in Japan (Sugawara et al., 1974). Goto and Sawata (1999) modified the ordinary tank model so as to express the property of paddy field irrigation in an alluvial fan and they used it to assess the water balance in Nasunogahara alluvial fan, Japan. In the modified tank model, the upper tanks, which represent the hydrologic processes on the ground surface, consist of a paddy field tank and non-paddy field tanks. The upper part of the modified tank model was combined with the groundwater model to calculate groundwater recharge to the shallow aquifer, by different recharge sources, as well as water pumped from the aquifer for irrigation as seen in Figure 2.

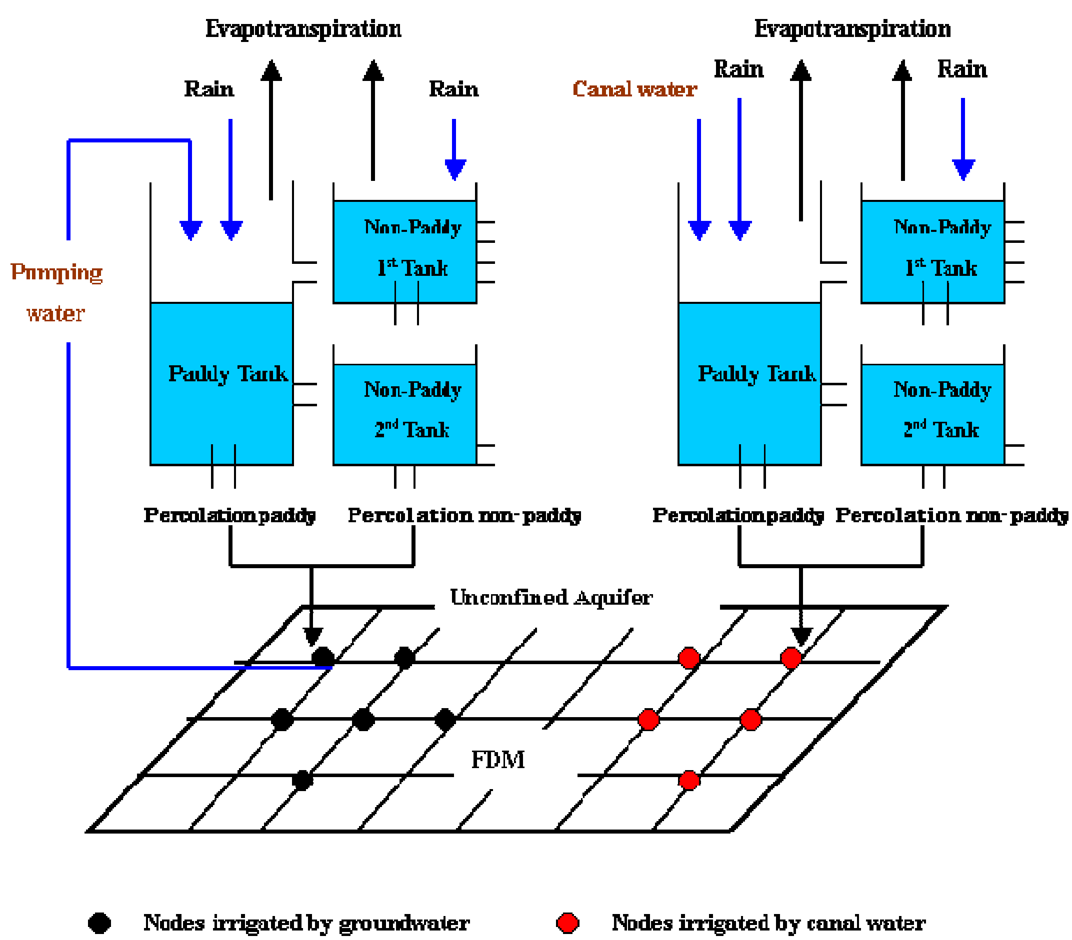

Figure 2. Combination of the modified tank model with the groundwater flow model

Calculation of groundwater recharge

The modified tank model calculated the percolation rate from the upper tanks to the shallow aquifer tank from both paddy field and non paddy field areas separately for irrigation and non-irrigation periods (Fig. 2). Percolated water from the ground surface tanks directly recharges the shallow groundwater. Furthermore, in the tank calculation percolation rates from paddy fields irrigated by groundwater were calculated separately from those irrigated by canal water. From the maps of beneficiary areas of Nasunogahara irrigation system, paddy fields were distinguished based on their source of irrigation water to paddy fields irrigated by groundwater, which are located mainly in the lower part of the fan and receive pumping water only, and paddy fields irrigated by canal water, which are located in the upper part of the basin where no pumping is practiced in those paddy fields.

Calculation of groundwater discharge by pumping

In many regions it is difficult to estimate the exact amount of distributed groundwater pumping from the aquifer, because exact locations of many users are unknown and they are pumping water by using small portable pumps without keeping water extraction records. Therefore, in this model the modified tank model was also used to calculate the amount of groundwater withdrawals from the aquifer.

To calculate the amount of water pumped, a certain ponding depth was assumed to exist in the paddy field tank during the irrigation period. The value of the ponding depth was estimated based on the agricultural practices of the area. Pumping from the shallow aquifer starts when the water level in the paddy tank becomes less than the assumed value and pumping stops when the ponding depth in the paddy tank reaches the assumed value.

MODEL CALIBRATION AND VALIDATION

The model was applied to Nasunogahara Basin to describe the seasonal variation of the groundwater table elevation throughout the fan, using a daily time step. The groundwater table elevations were calculated by adding the elevation of the upper surface of the impervious layer and the thickness of the water above the impervious layer (h) calculated by equation (1). A grid having a nodal spacing of 1-km divided the fan into 713 nodes, out of which 438 nodes are active nodes (Figure 3). Prescribed head boundaries were assigned along Hoki River and the lower part of Naka River (Figure 3). The upper part of Naka River and the boundaries between the mountainous area at the north-western part and the fan were treated as no-flow boundaries because of the presence of confining layers. A steady state water table configuration was computed and used as the initial conditions for the transient simulation.

Primary values of the groundwater flow model parameters and input data were obtained or estimated from existing records, topographic and hydro-geological maps and previous research studies.

In their research, Goto and Sawata applied the modified tank model to the area west of Kuma River in the alluvial fan in order to calculate runoff discharges to rivers in the area (Goto and

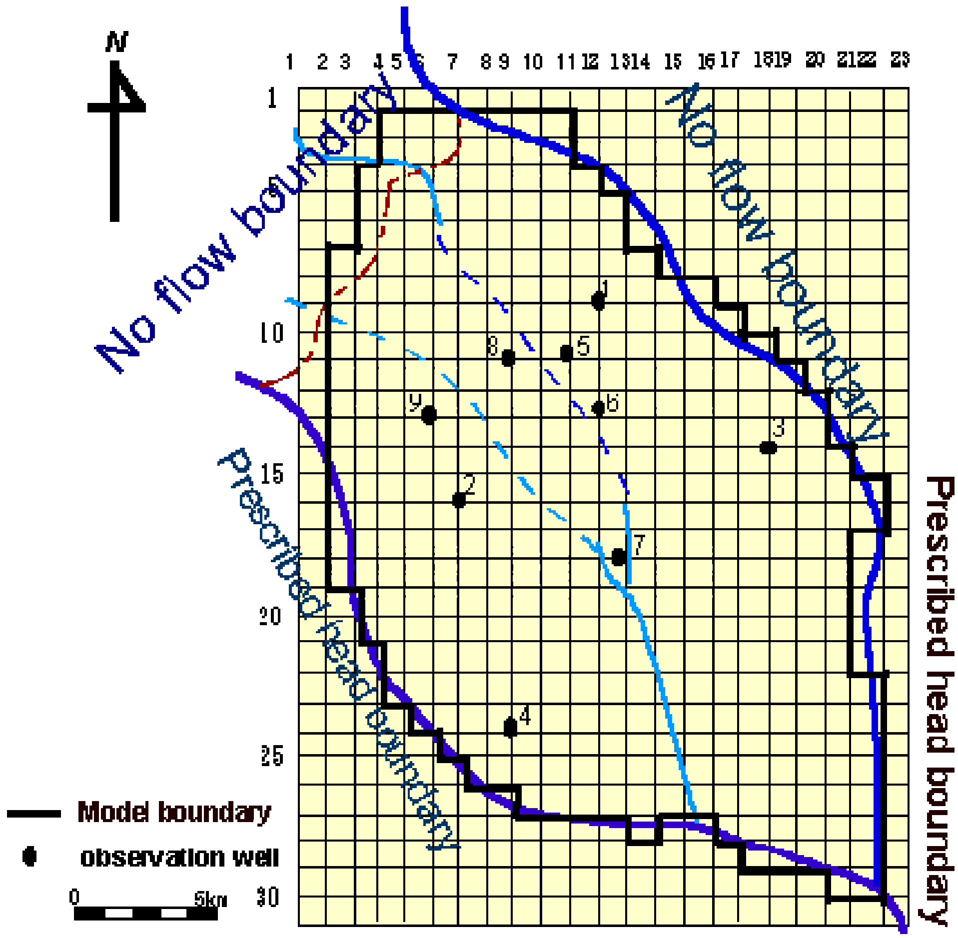

Figure 3. Groundwater model grid, boundary conditions and locations of observation wells

Sawata, 1999). Tank model parameters determined and input data used in their study were adjusted and used in this research where the area was simulated as one basin having a uniform set of parameters.

The calibration and validation of the transient two-dimensional groundwater flow model were based solely on the hydraulic-head distribution. Through trial and error calibration, groundwater model parameters, mainly k (355 ~ 650 m.d^{-1}) and Sy (0.07~0.15), prescribed head boundaries and areas of paddy fields irrigated by canal water and pumping in the tank calculation were adjusted to find the suitable set of parameters that makes the computed water table elevations agree satisfactorily with those observed in the field (Elhassan, et al, 2001).

The model was calibrated using daily water table elevation data from the nine observation wells shown in Fig. 3, for four years from 1991 to 1994. An independent set of data for 1998-1999 for only three wells, well 1, well 4 and well 9, was obtained and used to validate the calibrated model.

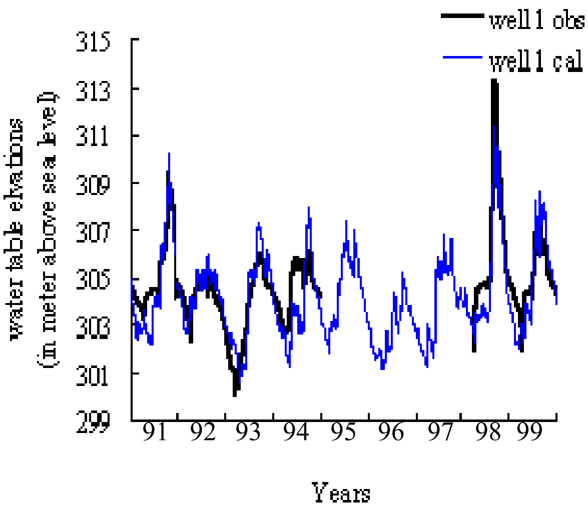

Figure 4. Comparison between calculated and observed water table elevations at observation well 1 (1991-1999)

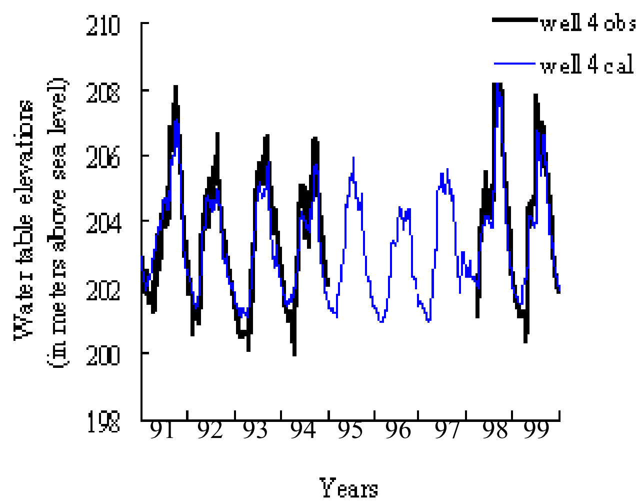

Figure 5. Comparison between calculated and observed water table elevations at observation well 4 (1991-1999)

Generally the comparisons between the calculated and observed water table elevations show a good correlation at most of the wells during the application period as can be seen in Figures 4 and 5. It indicates that the model is able to depict the seasonal variations in the water table elevations of the unconfined aquifer satisfactorily. It was noticed that the water table elevations in all observation wells rose during the irrigation period from April to August and dropped during the non-irrigation period. For detailed information about model structure, application and water balance of the area please refer to the paper titled: Effect of Conjunctive Use of Water for Paddy Field Irrigation on Groundwater Budget in an Alluvial Fan. (Elhassan, et al., 2003).

SIMULATION SCENARIOS OF DIFFERENT IRRIGATION PRACTICES

Japan is the only industrialized country whose agriculture is based on rice. Agriculture in Nasunogahara Basin is no exception where rice is the main crop. The irrigation period for paddy fields in the area usually starts in April and ends in August with the highest water demand being during the transplanting and land preparation. The current practice in the area is to carry out the transplanting and land preparation in a short period, 15 days, starting in the middle of April and lasting until the beginning of May. The highest demand period is at the end of April and beginning of May, which is a famous holiday in Japan known as the golden week. The reason for that is because farmers are part-time farmers who have permanent jobs other than rice farming; therefore they use these holidays to perform land preparation and transplanting activities.

In the early 1990s in Nasunogahara Basin, a trend of lowering in groundwater table and drying up of the natural springs has been observed. It has sometimes caused irrigation water shortages during the high demand season. Besides low precipitation, the influences of various developments for residential or industrial land use in the upper part are considered to be the reasons for the trend. This trend and short duration of high water demand caused severe groundwater shortages during the transplanting period in the basin, Figure 6.

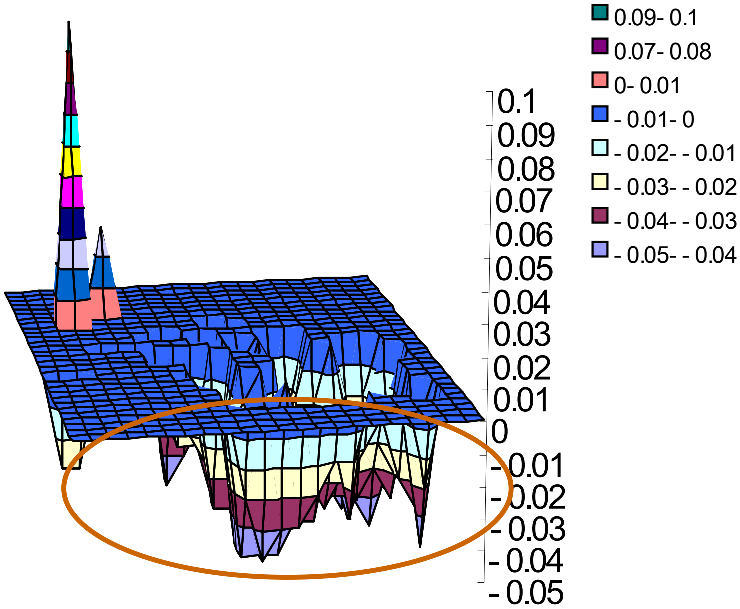

Figure 6. Distributed Source-Sink term (m.d^{-1}) on 15th of April 1993, excessive pumping at the beginning of irrigation season caused severe water shortage

The model was used to examine the effect of extending the length of the high demand period. The effect of two longer periods of transplanting and land preparation, 30 and 60 days, on shallow water supply was examined. The irrigation season was also lengthened so as to allow for the whole agricultural practices of rice farming to be completed. In the current model the irrigation season starts in mid-April and lasts until the end of August.

30-Day Transplanting Period Scenario:

For the 30-day scenario, the irrigation season starts at the beginning of April and ends at the end of September. Land preparations and transplanting period starts at the beginning of April and ends at the beginning of May. The simulation results showed that extending the high demand period to 30 days eased the groundwater shortage as indicated by the positive values of the source–sink term for that period (Figure 7).

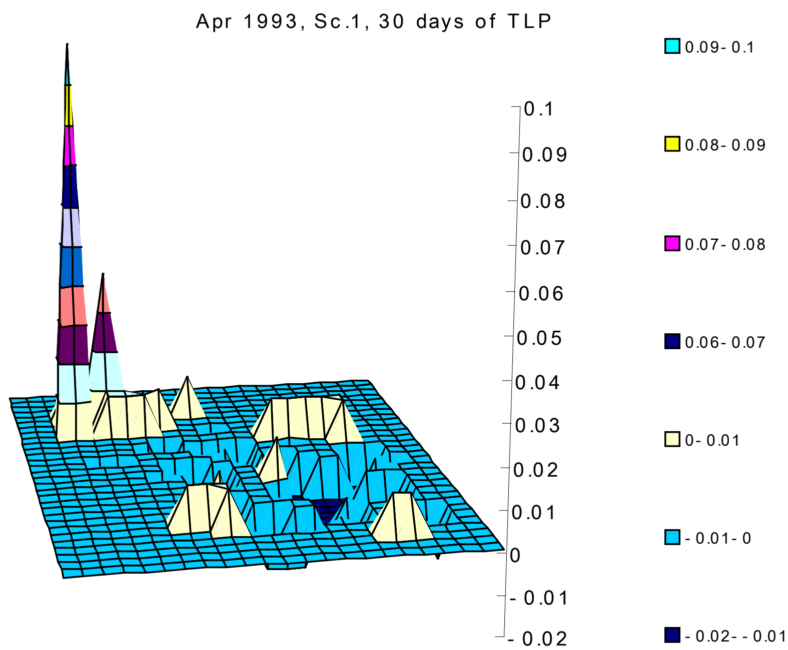

Figure 7. Simulated distributed Source-Sink term ($m.d^{-1}$) on 15th of April 1993, using a period of 30 days for transplanting and land preparations

60-Day Transplanting Period Scenario:

For the 60-Day scenario, irrigation commences at the end of March and ends at the beginning of October and the land preparations and transplanting period starts at the end of April and ends at the beginning of June. The simulation results showed that extending the high demand period to 60 days alleviated the groundwater shortage as indicated by the positive values of the source–sink term for that period (Figure 8). The practice of performing the land preparations and transplanting in 60 days was practiced in the area in the past. Although 60 days for transplanting and land preparation can alleviate the water shortage, this alternative is considered impractical. This is due to the present institutional and economic constraints mainly because the farmers are part-time farmers who have permanent jobs other than rice farming.

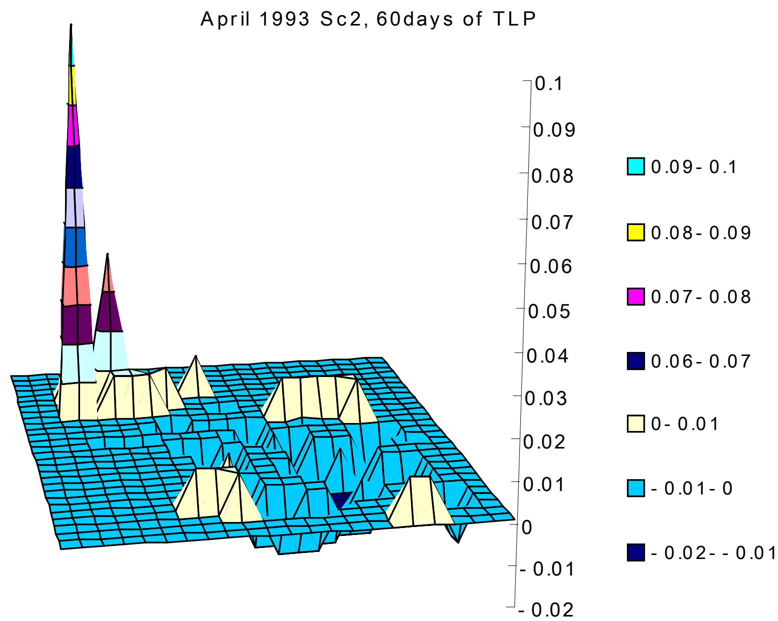

Figure 8. Simulated distributed Source-Sink term (m.d^{-1}) on 15th of April 1993, using a period of 60 days for transplanting and land preparations

CONCLUSION

An integrated surface water- groundwater model was applied to Nasunogahara alluvial fan, Japan. The model-calculated water table elevations during the application period show a fairly good correlation with field observation data. The model was able to simulate the daily changes in the water table elevations throughout the fan area; hence the model's ability to describe the actual behavior of the aquifer was confirmed. By using this model, hydrologic impacts on the shallow aquifer resulting from extending the length of the rice transplanting and land preparation period, which is a high demand period for water, were simulated and evaluated. Two scenarios were simulated:

30-Day Transplanting Period; and
60-Day Transplanting Period.

The simulation results showed that extending the high demand period alleviated the groundwater shortage. There are no major differences between the effects of the two periods, 30 and 60 days, in alleviating the water shortage. Present institutional and economic constraints make the 60-day alternative impractical; the 30-day option is preferable. It can be concluded that the model proved to be an effective tool for planners of the groundwater resources in alluvial fans. The model can assess the response of the water table to different hydrologic stresses resulting from changes in irrigation practices.

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