Effect of Conjunctive Use of Water for Paddy Field Irrigation on Groundwater Budget in an Alluvial Fan

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ABSTRACT

Conjunctive use of surface water and groundwater for irrigation plays an important role in the hydrology of alluvial fans, both as a source of recharge to the groundwater and as a cause of discharge by pumping. Therefore, reliable estimates of distributed groundwater recharge and discharge are critical in analyzing groundwater budgets in alluvial fans. Nasunogahara basin, Tochigi Prefecture, Japan, is an alluvial fan with abundant shallow groundwater, which is extracted and used for irrigation. In this study an integrated surface water- groundwater model, which combined a modified tank model with a finite difference model, was used to evaluate quantitatively groundwater recharge and discharge capacities of each recharge source and discharge route and to assess the effect of conjunctive use of surface water and groundwater for paddy field irrigation on the water balance of the shallow aquifer of Nasunogahara. The tank model calculated recharge by different recharge sources to the shallow aquifer and also calculated the amount of groundwater pumped for irrigation. Distributed groundwater recharge and discharge were estimated at each node in the groundwater flow model based on the paddy field area around the node. Results of the model indicate that the calculated water table elevations were able to describe the actual behavior of the shallow aquifer adequately. From the model simulation runs, it was found that although paddy fields are big users of groundwater by pumping, the irrigation water applied is used in a cyclic manner to recharge the shallow aquifer. The percentage of the recharge from paddy fields to the total net recharge is 21 %, which is mainly provided from paddy fields irrigated by canal water. These facts indicate the importance of the conjunctive use of surface water and groundwater for irrigation in maintaining the hydrologic system of the basin.

KEY WORDS: Conjunctive use, Paddy field irrigation, integrated surface water-groundwater model, Groundwater budget, Nasunogahara alluvial fan

1. INTRODUCTION

Substantial increase in water demand for municipal, agricultural and industrial uses, created primarily

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by rapid population growth, makes the optimal joint operation of surface water and groundwater supplies attractive (Basagaoglu and Marino, 1999).

Conjunctive use of surface water and groundwater resources for irrigation, which is a common practice in agricultural lands in alluvial fans, plays an important role in the hydrologic system of these alluvial fans. This is because irrigation water from both resources acts as a source of recharge to the shallow aquifer as well as a cause of discharge by pumping. In most of alluvial plains in Japan, the groundwater table rises up and remains elevated in the paddy fields during the irrigation season (Takase, 1999). Accurate simulation of water circulation in alluvial fan emphasized the need for reliable estimates of distributed groundwater recharge and discharge in analyzing groundwater budget in alluvial fans (Elhassan, et al., 2000).

Simulation models have been widely used to evaluate impacts of various irrigation practices on both water resources and to determine operation strategies for regional water supplies (Basagaoglu and Marino, 1999) and (Perkins and Sophocleous, 1999). This study proposes the use of a distributed, daily time step, integrated surface water- groundwater model to:

- Quantitatively evaluate groundwater recharge and discharge capacities of each recharge source and discharge route; and
- Assess the effect of conjunctive use of surface water and groundwater for paddy field irrigation on the water balance of the shallow aquifer of Nasunogahara alluvial fan, Japan.

2. OUTLINE OF NASUNOGAHARA

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 (**Fig. 1**). The basin is agrarian land, and is considered as one of the biggest groundwater consumers for irrigation purposes in Japan. 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.

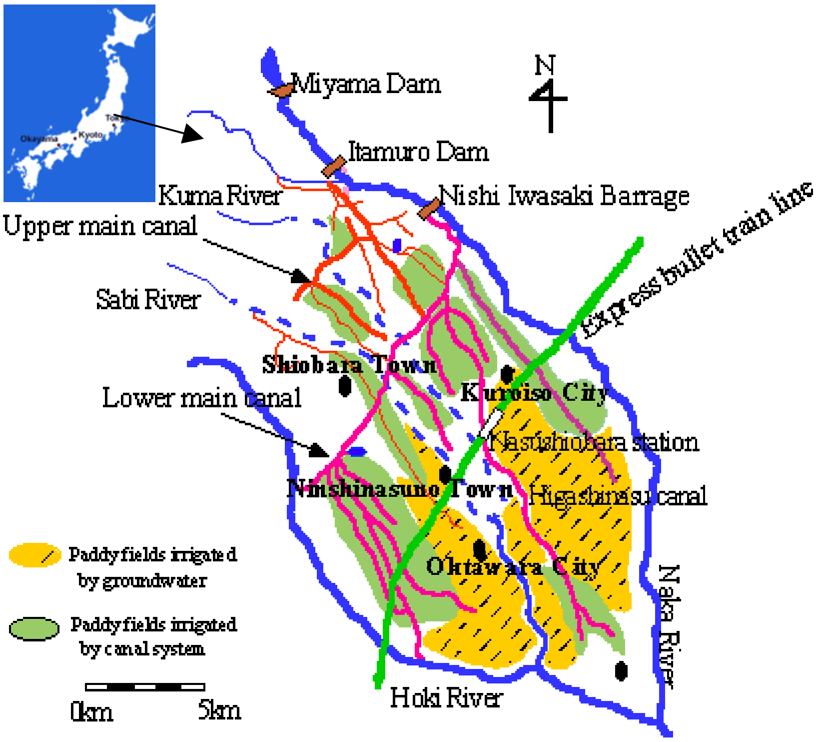

Figure 1 **Outline of Nasunogahara alluvial fan, Tochigi Prefecture, Japan, and its irrigation system**

The mean annual rainfall of the area is about 1500-mm. Nasunogahara canal irrigation system **(Fig. 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. 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. In recent years, a trend of lowering in the groundwater table and drying up of natural springs has been observed in the basin. The influences of the development of industrial and residential areas in the upper part, possibly associated with low precipitation, are considered to be the reasons for this trend.

3. 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).

3.1 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).

3.2 Combining Tank Model with the Groundwater Flow Model

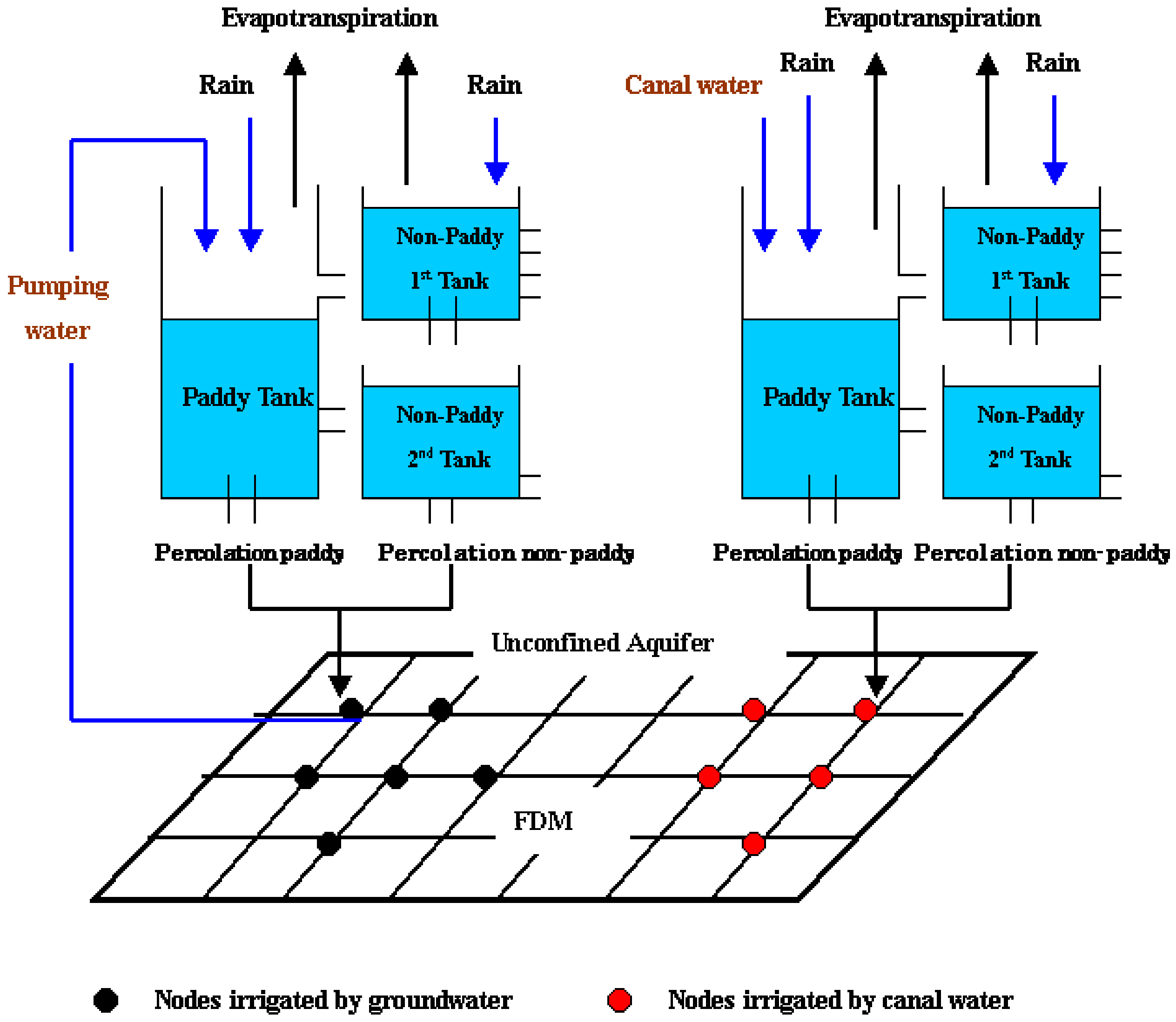

Figure 2 Combination of the modified tank model with the groundwater flow model

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 represents 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 to 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**.

3.2.1 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.

To calculate the distributed recharge rate at each node in the finite difference grid, the nodes of the grid were divided into irrigation nodes and pumping nodes based on the types of paddy fields surrounding the node. The paddy field area around each node was estimated and used together with the percolation rates calculated by the tank model to estimate the recharge using the following equations:

$$Rch_{pump} = (pp \times PRP_{pump} + (\Delta x\Delta y - pp) \times PRNP) / \Delta x\Delta y \qquad (2)$$

$$Rch_{canal} = (pp \times PRP_{canal} + (\Delta x\Delta y - pp) \times PRNP) / \Delta x\Delta y \qquad (3)$$

where Rch_{pump} is the recharge per unit area from fields irrigated by pumping (m.d^{-1}), Rch_{canal} is the recharge per unit area from fields irrigated by canals (m.d^{-1}), pp is the paddy field area around each node in the finite difference grid (m^2), PRP_{pump} is the percolation per unit paddy field area from paddy fields irrigated by groundwater (m.d^{-1}), PRP_{canal} is the percolation per unit paddy field area from paddy fields irrigated by canal water (m.d^{-1}), $PRNP$ is the percolation per unit non-paddy field area (m.d^{-1}), and Δx and Δy are the grid spacing (m).

3.2.2 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 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.

The daily amount of water pumped at each node in the finite difference grid where pumping occurred, was then calculated employing the paddy field area *pp* around the node as in equation (4)

$$W = Pump \times pp / \Delta x \Delta y \qquad (4)$$

where W is the amount of water pumped per unit aquifer area (m.d^{-1}), and $Pump$ is the amount of water pumped per unit area of paddy field area (m.d^{-1}).

4. RESULTS OF MODEL APPLICATION AND DISCUSSIONS

4.1 Model Calibration and Application

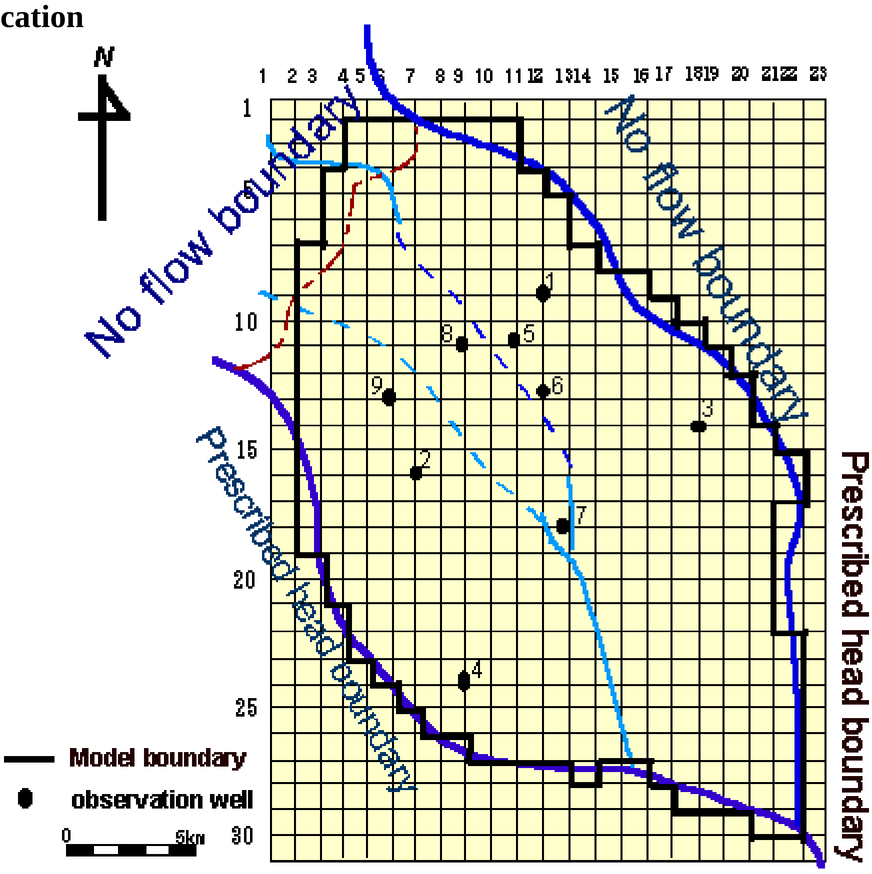

Figure 3 **Groundwater model grid, boundary conditions and locations of observation wells**

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 (**Fig. 3**). Prescribed head boundaries were assigned along Hoki River and the lower part of Naka River (**Fig. 3**). The upper part of Naka River and the boundaries between the mountainous area at the northern-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 Western side of Nasunogahara alluvial fan in order to calculate runoff discharges to rivers in the area (Goto and 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.

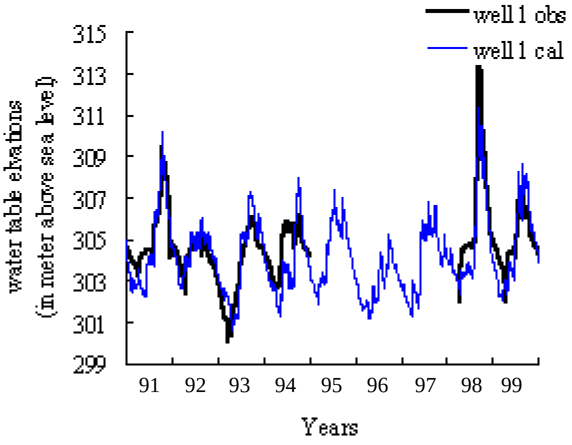

Figure 4. **Comparison between calculated and observed water table elevations at observation well 1 (1991-1999)**

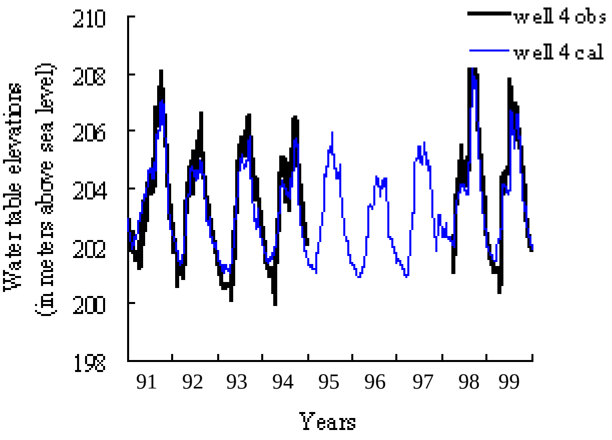

Figure 5. **Comparison between calculated and observed water table elevations at observation well 4 (1991-1999)**

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 discriminate between 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.

4.2 Groundwater Budget and the Effect of Conjunctive Use of Water for Irrigation

The integrated model was used to estimate the water balance of Nasunogahara basin. In this water balance analysis, 3 sources of recharge were considered: recharge from paddy fields which consists of recharge from paddy fields irrigated by canals and recharge from paddy fields irrigated by groundwater; recharge from non-paddy field areas; and recharge from the rivers' under ground flow. For discharge, 3 routes were considered: discharge to big rivers in the area; discharge by pumping; and discharge by natural springs and small rivers. Deep percolation to the confined aquifer was not simulated in this model because of lack of data. The water that percolates to the confined aquifer was assumed to flow to Naka River and Hoki River.

From model simulation runs for the years from 1991-1999, the average annual groundwater budget of the fan was calculated. The contribution of each recharge source to the total annual recharge and the portion of each discharge route to the total discharge are illustrated in **Figure 6**.

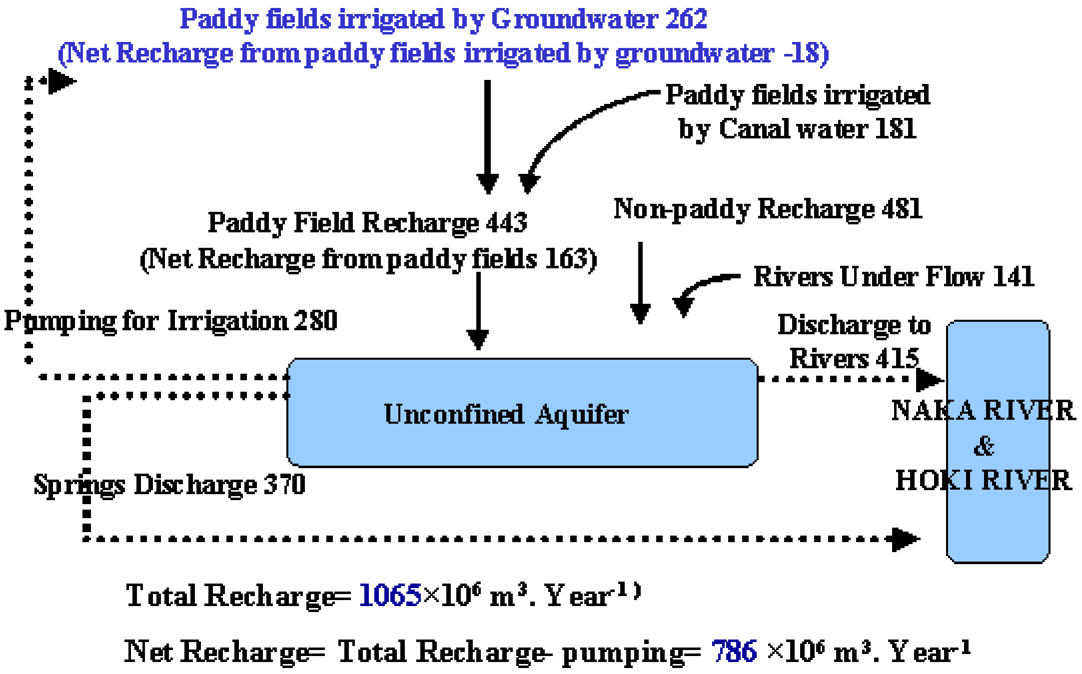

Figure 6 **Groundwater budget of the unconfined aquifer in Nasunogahara (million m^3. $year^{-1}$)**

According to the calculated results, the total recharge to the shallow aquifer is about 1065 million m^3 a year. Recharge from paddy fields occupies about 42% (443 million m^3.$year^{-1}$) of the total recharge to the shallow aquifer. While recharge from paddy fields irrigated by groundwater contributes to about 25% to the total recharge, a large amount of groundwater is extracted for paddy field irrigation (26% of the total groundwater discharge). Therefore, by subtracting the groundwater extraction, the result will be the total net recharge, which is about 786 million m^3 a year. The net recharge from paddy fields which is the sum of net recharge from paddy fields irrigated by groundwater and those irrigated by canal water becomes 163 million m^3 a year. The net recharge from paddy fields irrigated by groundwater is –18 million m^3 a year. The minus sign indicates that the amount discharged by pumping exceeds the recharge. The deficit is compensated every year by the recharge from paddy fields irrigated by canal water. These findings emphasize the hydrological influence of conjunctive use of surface water and groundwater for paddy field's irrigation on the water balance of the shallow aquifer of the basin.

Capacities of the different sources of groundwater recharge in Nasunogahara basin are shown in **Figure 7.** Generally, paddy field areas and non paddy field areas contribute equally to the total annual recharge of the shallow aquifer of the area. It is clear that recharge from paddy field areas contributes significantly to the total recharge especially in relatively dry years, as in 1996 and 1994 when it exceeded recharge from non paddy field areas, while a large amount of water from non paddy field areas recharges the aquifer in very wet years, as in 1998. The percentages of the different recharge sources to the total gross recharge are 42% from paddy fields in which 25% from paddy fields irrigated by groundwater, 17% from paddy fields irrigated by canal water, 45% from non-paddy lands and 13% from river's underflow.

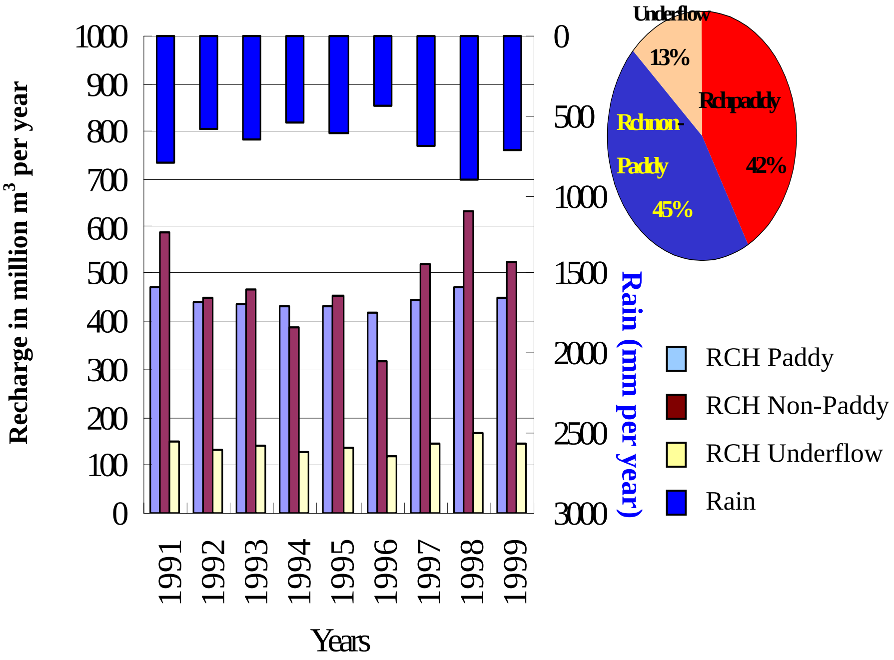

Figure 7 Comparison of precipitation and capacities of different recharge sources for the period 1991-1999

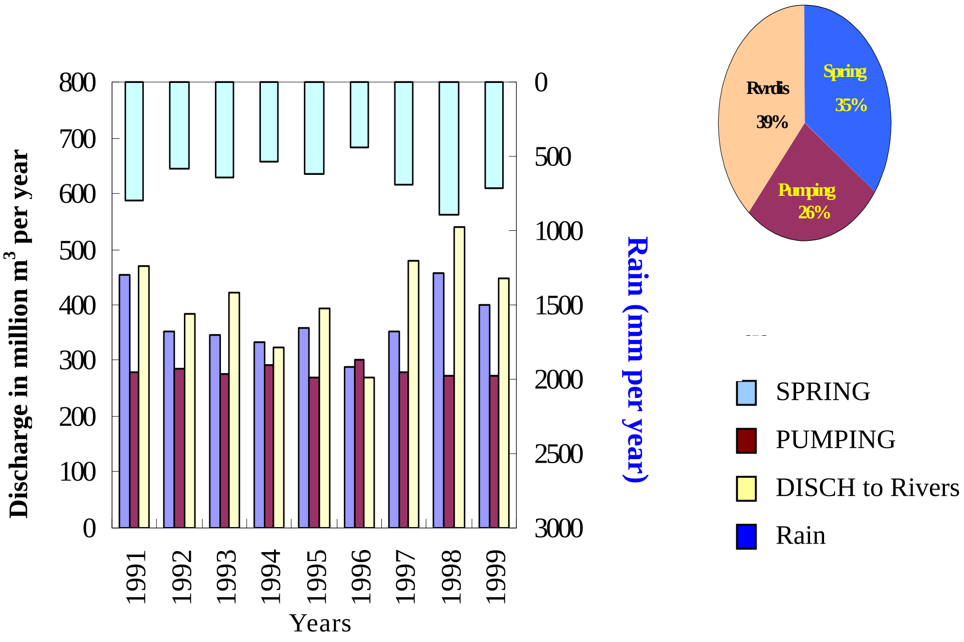

Figure 8 **Comparison of precipitation and contribution of different discharge routes to total gross discharge, for the period 1991-1999**

Contributions of the different routes of groundwater discharge to the total discharge in Nasunogahara basin are shown in **Figure 8.** Pumping for irrigation is a major source of groundwater discharge in the area, about 26% of the total discharge. The water pumped is added to the paddy fields irrigated by groundwater and again it contributes to the recharge from these fields. This fact indicates the cyclic use of irrigation water. Out of the total discharge from the aquifer, discharge by natural springs and small rivers occupies a significant portion, about 35%. This amount of water plays an important role in irrigating the paddy fields in the area especially in the eastern and southern parts of the fan. About 39% of the total discharge from the shallow aquifer is discharged to two main rivers in the area, Hoki and Naka Rivers, as base flow. The only year in which the pumping rate exceeded the other discharge components was in 1996 when the smallest amount of rain in the last ten years fell in Nasunogahara.

Although the discharged water through springs and small rivers is a major source of irrigation in the area, in the model it was assumed to flow to the big river systems in the area and do not be added to the paddy field tank of the area. The discharge to the big rivers was not compared to observed data because of the absence of gauge stations at the lower end of the fan.

From the water balance calculation of Nasunogahara basin, it is clear that the effect of paddy fields' irrigation on groundwater recharge is significant in spite of the fact that the portion of paddy fields to the total area is less than 40% and the irrigation period is limited in four months of the year. Although paddy fields are big users of groundwater for irrigation purposes, irrigation water applied to paddy fields is used in a cyclic manner as a source of recharge from paddy fields to the shallow aquifer. Recharge from paddy fields is more significant in years with less rainfall.

It is clear that paddy fields irrigated by canal water provide all the annual net recharge to the shallow aquifer from paddy fields. This indicates the importance of the conjunctive use of surface water and groundwater in the maintenance of the hydrologic system of Nasunogahara alluvial fan.

5. CONCLUSIONS

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 all over the fan area; hence the model ability to describe the actual behavior of the aquifer was confirmed. The model evaluated quantitatively groundwater recharge and discharge capacities of each recharge source and discharge route. Based on the model results, the following points were clarified regarding the water balance of the unconfined aquifer of Nasunogahara:

- While recharge from paddy fields irrigated by groundwater occupies about 25% of the total annual recharge, pumping for irrigation, which occupies a significant portion of the total groundwater discharge (26%), should be subtracted to determine net recharge from paddy fields. The water pumped is added to the paddy fields irrigated by groundwater and again it contributes to the recharge from these paddies. This fact shows the cyclic use of irrigation water.
- The percentage of the recharge from paddy fields to the total net recharge is 21% this is all provided by paddy fields irrigated by canal water. This fact indicates the importance of the conjunctive use of surface water and groundwater in the maintenance of the hydrologic system of Nasunogahara alluvial fan. It also indicates that the effect of paddy fields to net groundwater recharge is significant considering the portion of paddy fields to the total area and the limited period of cropping.
- Discharge by natural springs and small rivers occupies an appreciable portion of the total discharge; this amount of water plays an important role in irrigating the paddy fields in the area especially in the eastern and southern parts of the fan.

It can be concluded that the model can be used as a 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 the irrigation practices and land use.

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