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ARTICLE

Quantification of the effect of rice paddy area changes on recharging groundwater

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Abstract This study quantifies the effects of paddy irrigation water on groundwater recharge. A numerical model of groundwater flow was conducted using MODFLOW in a 600 ha study site in an alluvial plain along the Chikugo River, located in southwestern Japan. To specify the surface boundary condition, data on the land use condition stored in the GIS database were transferred into a numerical model of groundwater flow. The simulated results were consistent with the observed yearly changes of groundwater level. Thus, it was appropriate to use the model to simulate the effects of paddy irrigation on groundwater. To quantify these effects, the groundwater level was simulated during the irrigation period when all farmlands in the study site were ponded. In this situation, the groundwater level was 0.5 to 1.0 m higher, the ground water storage 20% larger, and the return flow of the groundwater to the river 50% larger than in the present land use condition.

Keywords Numerical model · GIS application · Land use condition · Groundwater storage · Return flow to river

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Introduction

Paddy irrigation has multiple functions. It is used not only to supply water, but also to create various environmental effects including groundwater recharge, flood mitigation, nitrogen cycle control, mitigation of local climate, carbon sequestration, etc. Ground water recharge is one of the most significant contributions of irrigation to the environment.

The area of the paddy field has drastically decreased due to rice production regulation in Japan. Approximately 40% of regulated fields are used primarily for upland crop production. Additionally, about 10% of total agricultural fields are now residential areas, factories, or roads. These drastic changes of the land use condition have affected groundwater level formation.

Researchers have studied the relationship between groundwater and irrigation. Effects of irrigation on the groundwater quality were reported by Knisel and Leonard (1989). A simulation model to analyze the effects induced by different rice irrigation management schemes on groundwater levels was created by Saleh et al. (1989). An integrated water management model for decision-making in irrigation water management, used to maintain the groundwater table, was developed by Kumar and Singh (2003). The groundwater flow and recharge under paddy areas was examined by Walker and Rushton (1984), Bouman et al. (1994), Tuong et al. (1994), Elhassan et al. (2001), Chen and Liu (2002), and Chen et al. (2002). These studies revealed significant effects of irrigation on groundwater; however, the effect of the land use condition on the groundwater recharge was unclear.

The objectives of this study are the quantification of groundwater recharge created by paddy irrigation water and

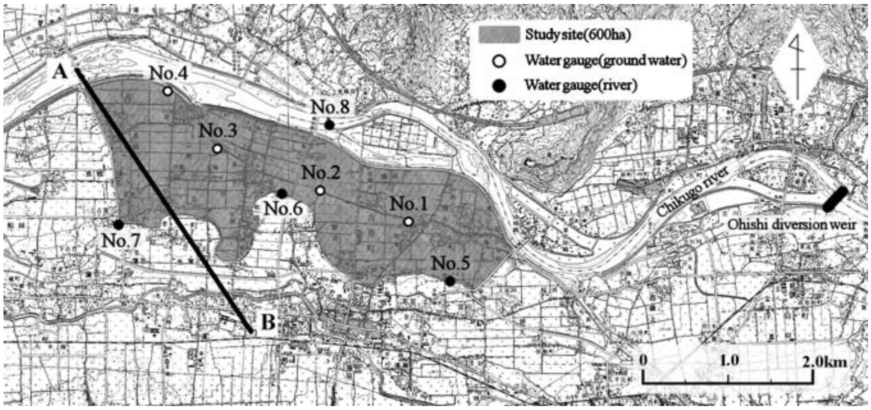


Fig. 1 Map of study site (Line A-B shows geological section in Fig. 2)

evaluation of the influence of the land use condition on the groundwater recharge. The groundwater analysis was conducted using MODFLOW (McDonard and Harbaugh 1988). MODFLOW is one of the most frequently used models in groundwater hydrology (Anderson and Woessner 1992; Lieuallen-Dulam and Sawyer 1997). A numerical model of groundwater flow using MODFLOW was conducted in a study site to quantify the groundwater recharge by paddy irrigation. To specify the surface boundary condition, data on the land use condition stored in the GIS database were transferred into the groundwater model.

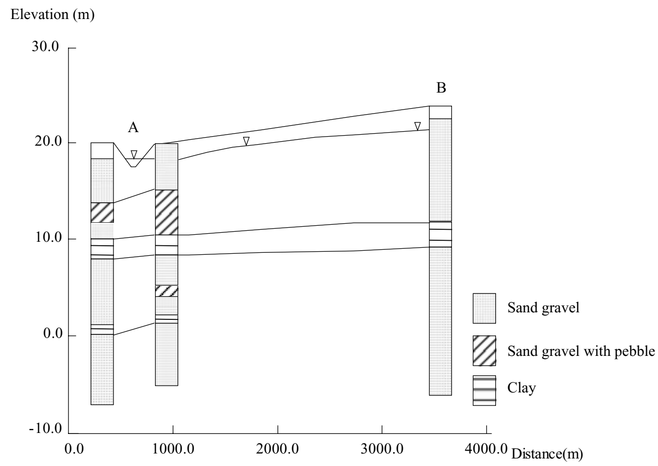


Fig. 2 Schematic view of the geological conditions across the study site (Line A-B in Fig. 1)

Study site

Geography and geological feature

A groundwater analysis was conducted in a 600 ha study site located on the left bank of the Chikugo River (Fig. 1). The Chikugo flows in Kyushu island (southwest of Japan). The basin area and length of the Chikugo are about 2860 km^2 and 143 km, respectively. About 60,000 ha paddy fields are supplied with irrigation water by this river. The south border of the study site is formed by the Mitsuru river, which is used as a drainage canal. Irrigation water in the study site is supplied from Ohishi diversion weir. Following the permitted water right, a maximum 16 m^3/s of water is allowed to be diverted during the irrigation period.

The study site is located between two mountain ranges. The alluvial plain, around 6 km width, was formed along the river about five million years ago. The schematic view of the geological condition around the study site is shown in Fig. 2. The study site is classified as a flood plain, resulting from the frequent flooding of the Chikugo. A relatively shallow layer is composed of gravel and sand; unconfined groundwater is formed in this layer. As shown in Fig. 2, there is an impermeable layer of clay at about 10 m to 13 m below the ground surface.

Observation of water levels

There were four groundwater level gauges (No. 1 to No. 4) and four river water level gauges (No. 5 to No. 8) in the study site, as shown in Fig. 1. (The type of the water level gauge used in this study was SS-202-2M-30.) The diameters and depths of the observation wells were 0.15 and 5.5 m, respectively. Water levels were recorded automatically in the data logger at 1-h intervals during the entire year. The distance between the wells and the river was 500 to 700 m, except for the downstream well, which was 50 m from the Chikugo river.

Historical changes of agricultural conditions

Table 1 shows the land use condition changes for the past thirty years in Yoshii town, including the study site (Ministry of Agriculture, Forestry and Fisheries 1971, 1981, 1991, 2001). Agriculture has been the main industry in Yoshii town; most of the farmlands have been used as paddy fields (Table 1). The paddy fields in the nonirrigation period were used as upland fields. Table 1 indicates that the land use

Table 1 Land use changes in Yoshii Town during the past 30 years

Unit: ha

	Paddy field	Fallow paddy field	Upland field	Residence
1970	1,111	187	79	166
1980	1,061	193	60	264
1990	910	246	62	285
2000	708	218	55	317

condition has drastically changed in this area following the administrative policy of rice production during the last 30 years. The paddy field areas have decreased, and the percentage of (paddy) fields used for producing upland crops, such as soybean, eggplant, and various vegetables during the summer irrigation period, has been gradually increasing. Some paddy fields lie fallow because of the agricultural labor shortage; fallow fields have been gradually increasing. Additionally, the residential area has increased during the past 30 years, so there is a large demand for domestic water in this area. The uses of irrigation water have also been affected by the change of the land use conditions.

The investigated land use condition of the study site in 2001 is shown in Fig. 3. Using the geographic information system software (GIS), the land use conditions were estimated with a resolution of 100 m squares. The land uses were classified into four categories: paddy fields, upland fields, residential areas, and roads. Farmland areas in the study site accounted for about 380 ha. The paddy field, upland field, and fallow field areas were about 240, 110, and 30 ha, respectively. The remaining areas were used for residences, roads, and other urban uses.

Methodology

Governing equation

MODFLOW was used for groundwater analysis. In this model, groundwater flow can be described using a three-dimensional equation as

$$S\frac{\partial H}{\partial t} = \frac{\partial}{\partial x}\left(k_x h\frac{\partial H}{\partial x}\right) + \frac{\partial}{\partial y}\left(k_y h\frac{\partial H}{\partial y}\right) + \frac{\partial}{\partial z}\left(k_z h\frac{\partial H}{\partial z}\right) + Q + L \quad (1)$$

where S is the effective porosity ($-$); H is the hydraulic head (m); t is the time (d); k is the hydraulic conductivity (m/d); h is the sectional length of the groundwater flow or the saturated thickness (m); x, y, and z are the rows, columns, and layers of the modeled system, respectively; Q is the infiltration of water from surface (m/d); and L is the outflow rate from the region (m/d) (McDonard and Harbaugh 1988).

Initial condition and boundary conditions

The initial groundwater levels at all nodes are given as the initial condition. These values were estimated from groundwater levels measured in the observation wells (Fig. 1) and from the contour map, interpolating between the known levels.

Figure 4 shows a schematic of the boundary conditions. Northern and southern boundaries are specified by the water levels of the Chikugo and Mitsuru rivers, respectively. Using observed river water levels with four gauges and longitudinal slopes of the riverbeds, the river water levels at nodes

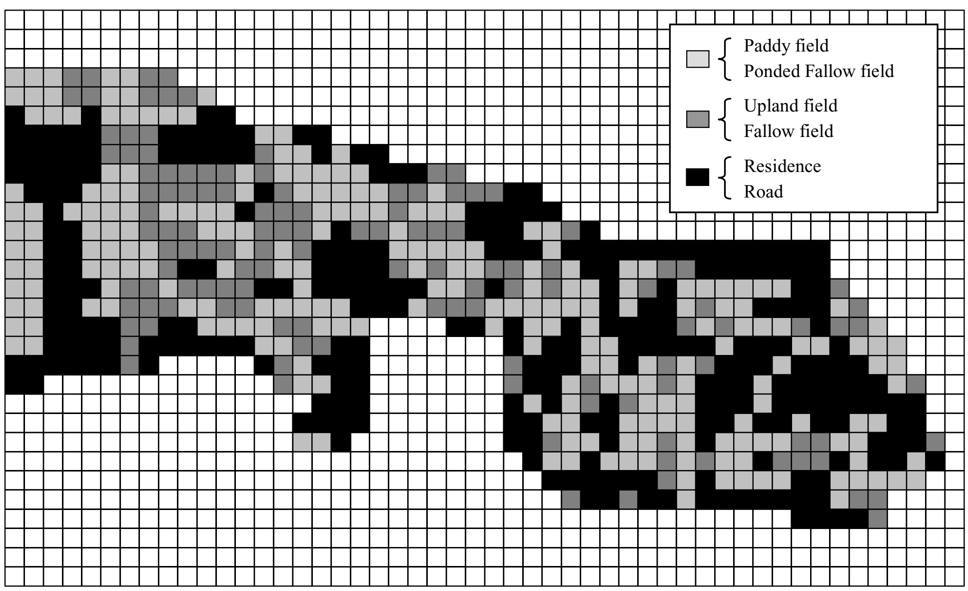


Fig. 3 GIS grid map of present (2001) land use in the study site

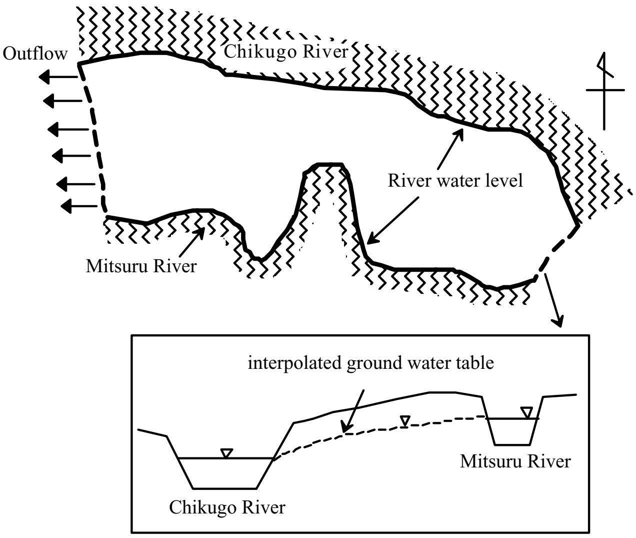


Fig. 4 Schematic view of the boundary conditions

were estimated and used as specified head boundaries. At the eastern ends, the groundwater tables were interpolated by the water levels of the Chikugo and Mitsuru rivers. At the western ends, the flow boundary was specified as the general head boundary.

Recharge boundary condition

The water balance at the ground surface can be described as

$$\sum (R + A) - \sum (E + O + Q) = 0 \tag{2}$$

where R is precipitation (m/d), A is irrigation (m/d), E is evapotranspiration (m/d), and O is runoff (m/d). Infiltration of water from surface Q (m/d) can be calculated by substituting R, A, E, and O for Eq. (2).

In the calculation, the land use conditions are classified as paddy fields, upland fields, residential areas, and road areas. Most of the fallow fields were classified as upland fields. The ponded fallow fields used for weed control were classified as paddy fields. When rainfall was less than 5 mm/d, the infiltration of water Q in the upland field was set as 0 because the rainfall or irrigation water was consumed by the evapotranspiration. Also, the infiltration is assumed as 0 in the residential and road areas.

During the irrigation period (from June 1 to September 30), the amount of the irrigation water A was set as 30 mm/d, which was observed as the lot water requirement reported by Anan et al. (2002). The irrigation water demand was great because the amount of paddy field infiltration was significant. As the study site was in the flood plain originating from the Chikugo river, the ground surface layer was classified as the sand gravel or gravel (Fig. 2), and the soil water conductance was high. Like the paddy fields in the nonirrigation period, the other land during one year did not take in water, so irrigation water A was assumed to be 0.

Evapotranspiration E in Eq. (2) was calculated as

$$E = K_c ET_p \tag{3}$$

where K_c is the crop coefficient and ET_p is the reference evapotranspiration.

The K_c of the rice paddy in Kyushu island, including the study site, was estimated during the paddy growth period by National Agricultural Research Center for Kyushu Okinawa Region (1999). ET_p was estimated by the Penman method as

$$ET_p = \frac{\Delta}{\Delta + \gamma}\frac{R_{\text{net}}}{l} + \frac{\gamma}{\Delta + \gamma} f(u_2)(e_{sa} - e_a) \tag{4}$$

where R_{net} is the net radiation (MJ/m^2), l is the latent heat of vaporization of water (MJ/kg), Δ is the rate of change of saturated vapor pressure with temperature (hPa/deg), γ is the psychrometer constant (hPa/deg), e_a is the partial pressure of water vapor in air (hPa), e_{sa} is the saturation vapor pressure of water vapor (hPa), and $f(u_2)$ is the wind function described using the wind velocity at 2 m height u_2 (m/s). The meteorological data stated as above is obtained from Amagi weather station.

Runoff O was calculated as a fraction of rainfall by the following equation:

$$O = aR \tag{5}$$

where a is the runoff coefficient. The average values of a in paddy, upland, residence, and road areas are assumed as 0.7, 0.52, 0.9, and 0.85, respectively (Japan River Association 1997). During the nonirrigation period, a of paddy fields was replaced by 0.52. The precipitation R was obtained from the weather station database.

Figure 5 shows the simulation model introduced by coupling the ground water analysis and the land use information. To specify the surface boundary conditions at all nodes, data on the land use condition stored in the GIS database were transferred into the groundwater model using MODFLOW by two dimensional.

Results and discussion

Model accuracy

Simulation of the groundwater level was conducted in an area 5.0 by 3.0 km. The MODFLOW mesh for the study site consisted of 50 columns and 30 rows. Each cell was

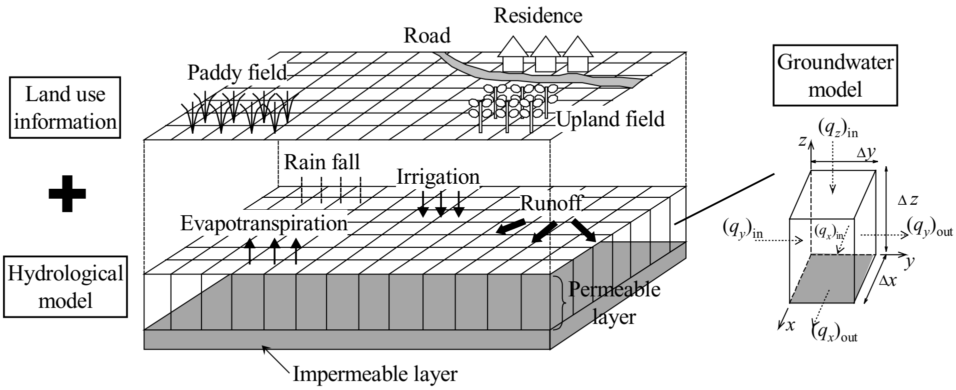


Fig. 5 Schematic view of simulation model for ground water analysis coupled with land use information

100 m^2. The finite difference method was used to solve the governing equation in MODFLOW. The calculation was pursued with the Bi-Conjugate Gradient Stabilized method. The initial conditions were set using data from 1 January 2001. Boundary conditions were specified by daily average data from 1 January to 31 December. The size of time step (Δt) was reduced any time during the simulation, computed by MODFLOW code as the simulation progressed (McDonard and Harbaugh 1988). This code computes the initial time step using the number and the multiplier of time step specified by the users.

As calculation groundwater levels agreed with those observed at four points, the model's parameters, which were hydraulic conductivity and effective porosity, were in accordance with the observed boundary conditions.

Figure 6 shows the comparison between observed and simulated groundwater levels during one year. The groundwater levels at wells No. 1, No. 2, and No. 3 increased abruptly when irrigation began. The maximum increases were from 2 to 2.5 m during the irrigation period. When the irrigation period was complete, the groundwater level gradually decreased. The change in the groundwater level at well No. 4 between the irrigation and the nonirrigation periods was unremarkable. This well was affected by the river water level because of its proximity to the Chikugo river at 50 m. The root mean squared error in this estimation was 12%; there were some errors in the irrigation period as to the peak of groundwater levels. Possible causes of these errors were the geologic features, which were too complicated to capture completely. These results indicated that it was appropriate to use this model to simulate the contribution of paddy irrigation to groundwater.

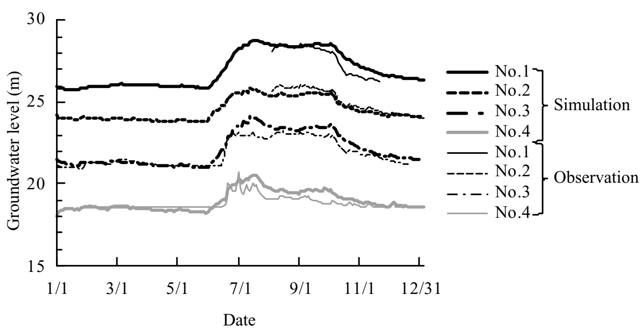


Fig. 6 Comparison of simulated and observed daily groundwater levels at the four observation wells

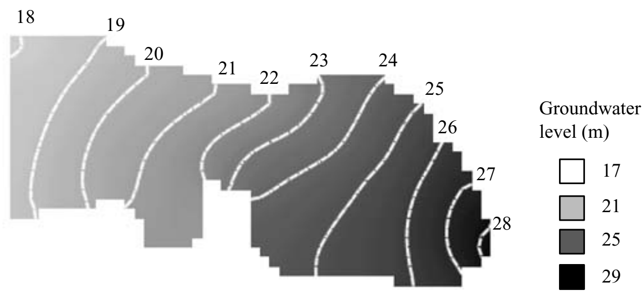
Groundwater movement during one year

Figure 7 shows the changes of the spatial distribution of the groundwater level with the paddy irrigation schemes. During the nonirrigation period, contours crossed the river boundary at a right angle (Fig. 7a). Figure 7b shows the spatial distribution of the groundwater level at the beginning of the irrigation period. The bended contours indicate that the groundwater flow was obviously affected by the irrigation water. The groundwater level was higher at the upward fields than at the downward fields. Figure 7c shows the groundwater contours of the middle irrigation period. The densely formed contours indicate that the hydraulic gradient was high. In the irrigation period, the groundwater level rose rapidly and was higher than river water level. As a result, the groundwater flows to the river decreased. Thus, a large amount of groundwater returned to the Chikugo and Mitsuru rivers.

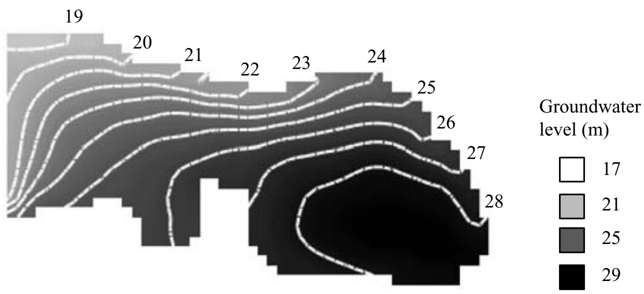
Contribution of paddy fields to groundwater storage

Groundwater recharge

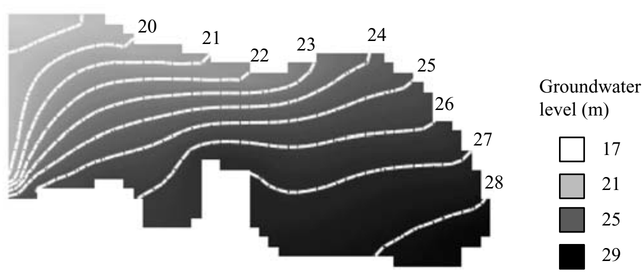
All of the fields in this site were originally paddy fields. However, 40% of these became well-drained fields, such as upland fields or fallow lands, because of the governmental set-aside system or a dearth of farmers. To quantify groundwater recharge by paddy irrigation and clarify the effect of the land use condition on groundwater, the groundwater level, assuming that all farmlands (about 380 ha) were ponded during the irrigation period, was simulated.



(a) March 1st



(b) June 1st



(c) September 1st

Fig. 7 Spatial distribution of the groundwater level with the paddy irrigation schemes

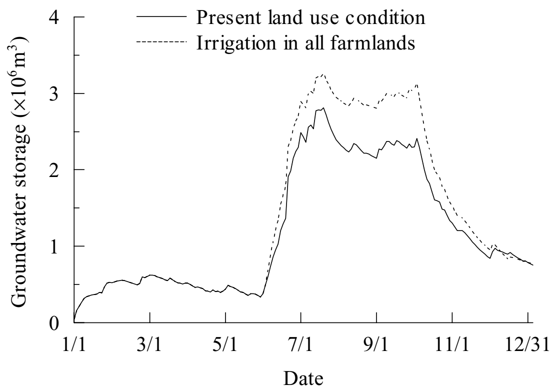


Fig. 9 Groundwater storage for the present land use condition. All farmlands were ponded during the irrigation period

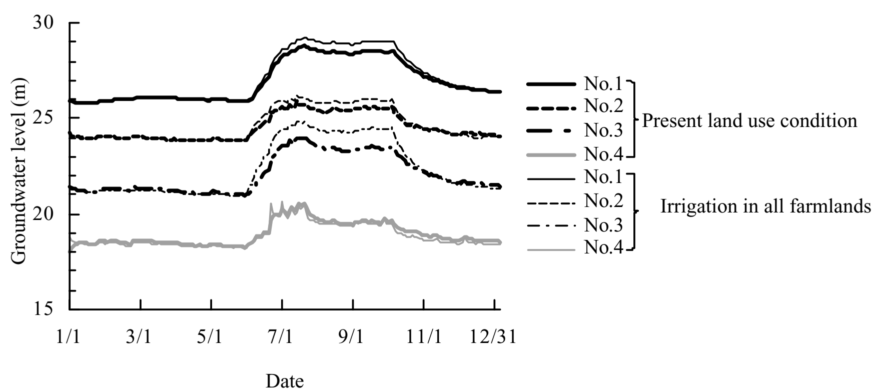
Figure 8 shows the groundwater levels when the present land use condition was maintained and all farmlands were ponded during the irrigation period. As shown in Fig. 8, differences in the groundwater level between both situations occurred in wells No. 1 and 3 as soon as irrigation began. The maximum difference of the groundwater level ranged from 0.5 to 1.0 m. The difference in the groundwater level was greater at the downward well because the groundwater inflow from the upward fields increased. The difference was not apparent in the No. 4 well. This indicates that the groundwater at the No. 4 well was recharged by water from the nearby Chikugo river. Figure 9 shows the total amount of groundwater retained in the permeable layer. The volume of storage was transformed from the saturated thickness calculated daily. In the present land use condition, about 2.5 million m^3 water was stored as groundwater. When all farmlands were irrigated, the storage groundwater was estimated at about 3.0 million m^3.

Considering that the residential area has increased around the study site, the additional storage water could supply the domestic water demand. Additionally, storage water could be used for rural life, fire fighting, snow clearing, amenity, and recreation.

Return flow of groundwater to the river

Figure 10 shows the return flow from groundwater to the Chikugo and the Mitsuru rivers, or the amount of water flowing out in the north and south sides, calculated when the

Fig. 8 Groundwater levels at the four observation wells for established land use. All farmlands were ponded during the irrigation period



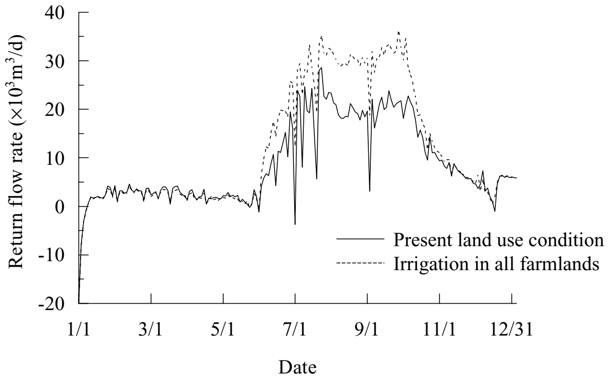


Fig. 10 Return flow rate of groundwater from the study site to the river. Established land use condition was maintained and all farmlands were ponded during the irrigation period

present land use condition was maintained and all farmlands were irrigated.

At present, 20,000 m^3/d water flows to the rivers in the irrigation period. This is equal to 20% of the water requirement of 240 ha paddy fields in the study site, assuming that the water requirement is 30 mm/d. The return flow to the rivers increases up to 30,000 m^3/d water when all farmlands are irrigated. To the south of this site is a mountain chain; the topography slants to a south–north direction. Some small rivers and canals flow from the mountain to the Chikugo river. Therefore, almost all of the groundwater would stream toward the Chikugo river. Increased return water to the river could be used for irrigation or domestic and industrial use.

Conclusions

To evaluate the effect of the land use condition on groundwater recharge, the simulation model was introduced by coupling the groundwater analysis using MODFLOW and the land use information using GIS. Model accuracy was gauged by the groundwater levels observed at four observation wells. The results calculated with present land use condition during one year were relatively consistent with the observed data. The groundwater levels increased abruptly when irrigation began. The maximum increases were from 2 to 2.5 m during the irrigation period. When the irrigation period ended, the groundwater levels gradually decreased. This indicates that the paddy field irrigation affected the groundwater level. The simulation model introduced here was appropriate for simulating the effects of paddy irrigation on groundwater.

Using this model, the groundwater level was simulated, assuming that all farmlands in the study site were paddy fields. The groundwater level in this situation was about 0.5–1.0 m higher than established conditions. After 40% of the fields became upland fields or wild lands, the groundwater storage increased by about 20%. Additionally, the return flow of the groundwater to the rivers increased by about 50% when all farmlands in the study site were irrigated. These results indicate that the paddy irrigation water was an important local water resource. Because the number of fallow fields in Japan is increasing, ponding could significantly contribute to groundwater recharge. Paddy irrigation should be planned with regard to not only paddy production, but also to water resource conservation.

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