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Evaluation of Effect of the Upland Field on the Groundwater Recharge

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The objectives of this study are quantification of the upland field effect on the groundwater recharge and evaluation of the influence of the land use condition on the groundwater recharge. The groundwater analysis is conducted using MODFLOW in a 1540 ha study site, Izena Island, which is located in southwestern Japan. To specify the initial and surface boundary condition, data on the elevation and use condition in the study site stored in the GIS database is transferred into the numerical model of groundwater flow, respectively. To quantify the upland field effect on the groundwater recharge, the groundwater analysis is conducted in 2 cases. First, the groundwater storage is calculated under the present land use condition. Next, the groundwater analysis is conducted when all forests in the study site are converted into the upland field. Simulation results indicated that groundwater storage, when all forests are converted into the upland field, is larger than the groundwater storage under the present land use condition. This result is caused that the irrigation water in the upland field contributes to the ground water recharge and the water loss by the rainfall runoff and the evapotranspiration at the upland field is less than amount of the forest.

INTRODUCTION

In the upland fields, the irrigation water and rainfall are consumed as the evapotranspiration and surface runoff. The surplus water infiltrates into the ground, and is stored in the permeable layer as the groundwater. The groundwater is the indispensable water resource for the crop growing. Additionally, it contributes to the microorganism living in the ground.

The groundwater analysis, considering the land use condition, has been studied by many researchers. A simulation model to analyze the impacts induced by different irrigation management schemes on groundwater levels was established by Saleh *et al.* (1989). An integrated water management model for decision–making in irrigation water management to maintain the groundwater table was developed by Kumar and Singh (2002). These studies clarified the significant effects of irrigation on the groundwater; however, the upland field effect on the groundwater recharge has not been yet evaluated quantitatively.

The objectives of this study are quantification of the upland field effect on the

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groundwater recharge and evaluation of the influence of the land use condition on the groundwater recharge. The groundwater analysis is conducted using MODFLOW. MODFLOW is one of the most frequently used codes in groundwater hydrology (Anderson and Woessner, 1992; Lieuallen–Dulam and Sawyer, 1997). A numerical model of groundwater flow using MODFLOW is conducted in a study site for quantifying the upland field effect on the groundwater storage.

STUDY SITE

A groundwater analysis was conducted in Izena Island (N24°55', E127°56'), which is located in Okinawa Prefecture (southwest of Japan), as shown in Fig. 1. The study site is relatively plain, and the soil of the study site is classified as the Maaji soil. The Maaji soil is acid, and the hydraulic conductivity of this soil is rather high. At the study site, the water resource for the agriculture is groundwater. The drought occurs frequently and agricultural product has had large impact at the study site. To cope with the water resource problem, the development of the underground dam is conducted at the study site.

Figure 2 shows the land use condition in the study site. Using the geographic information system software (TNT lite), the land use conditions are specified with a resolution of 100 m squares. The land uses are classified into three categories: upland field, forest,

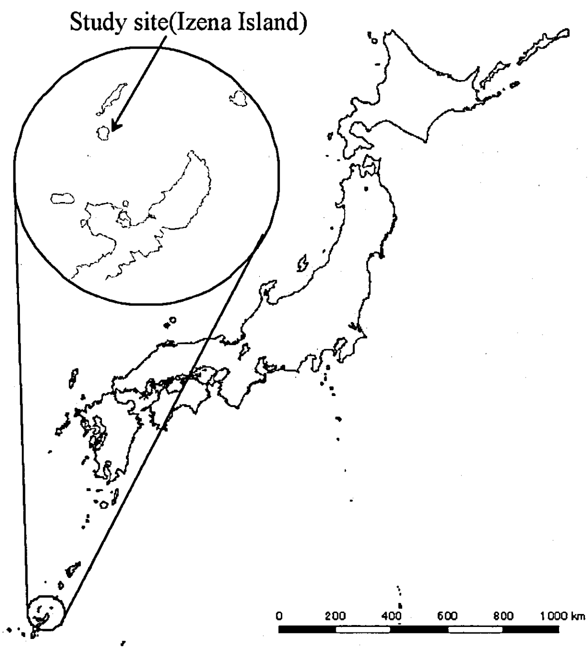

Fig. 1. Location of the study site.

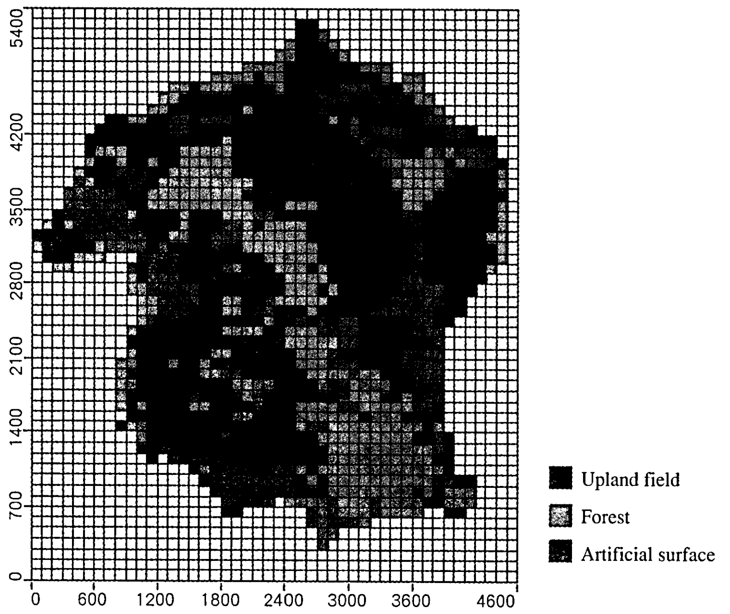

Fig. 2. Land use condition in the study site (1993).

and artificial surface. The total area of the study site is about 1540 ha. The farmland and the forest is about 52% and 29% of the total area, respectively. The staple product in the study site is the sugar cane.

METHODLOGY

Governing equation

MODFLOW was used for groundwater analysis. In this code, groundwater flow can be described with a three–dimensional equation as follows:

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

where S is effective porosity, H is hydraulic head (m), t is time (day), k is water conductivity (m day^{-1}), h is sectional length of the groundwater flow (m), x, y, and z is rows, columns, and layers of modeled system, respectively, Q is percolation of water from surface(m day^{-1}), and L is outflow rate from the region (m day^{-1}) (McDonard and Harbaugh, 1988).

Initial condition and boundary conditions

The boundary condition is specified using the measured seawater level, which is given by the Japan Meteorological Agency (Fig. 3). Figure 4 shows the schematic view of the specification of the initial conditions. Elevations at the all nodes are given by geographic

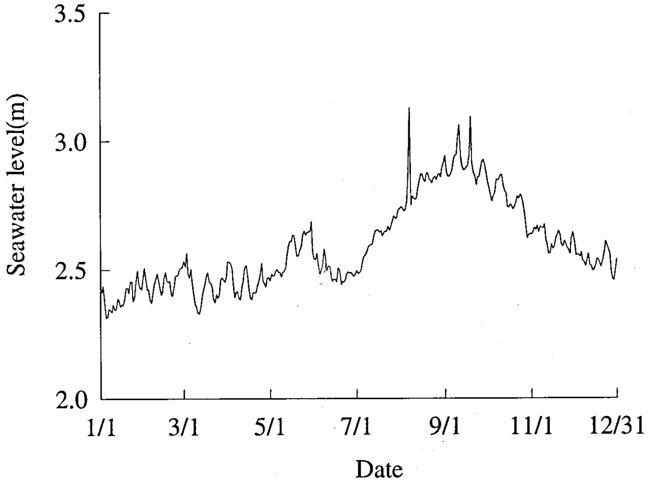

Fig. 3. Daily change of the seawater level in the study site.

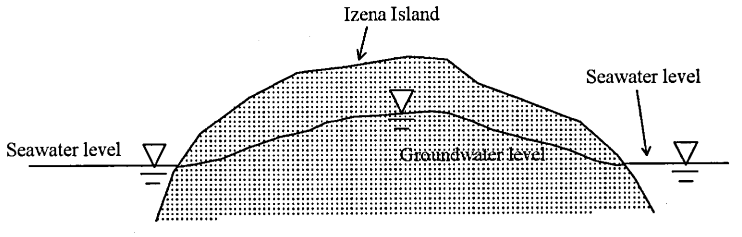

Fig. 4. Schematic view of the specification of the initial condition.

information system software (TNT lite) as shown in Fig. 5. Using the seawater level and elevations of the study site, the initial heads at all nodes are specified with interpolation as shown in Fig. 4.

Surface boundary condition

The water balance at the ground surface can be described as follows:

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

where R is precipitation (m day^{-1}), A is irrigation (m day^{-1}), E is evapotranspiration (m day^{-1}), and O is runoff rate of rainfall (m day^{-1}) . Percolation of water from surface Q (m day^{-1}) can be calculated by substituting R, A, E, and O for eq. (2).

Evapotranspiration E in eq. (2) was calculated as follows:

$$E=K_cET_0 \tag{3}$$

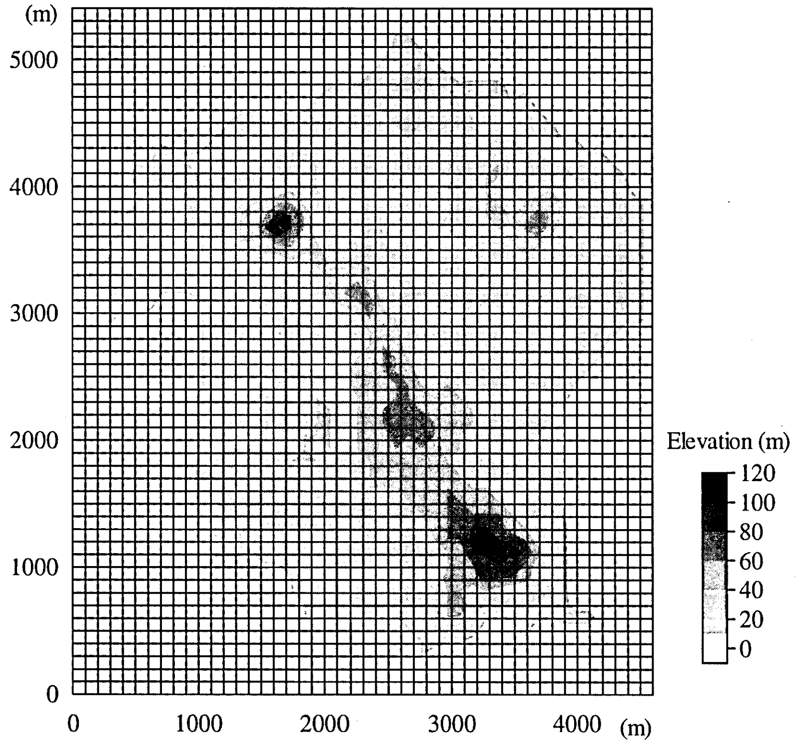

Fig. 5. Elevation of the study site.

where K_c is crop coefficient, and ET_0 is reference evapotranspiration (m day^{-1}). ET_0 was estimated by the FAO Penman–Monteith method as follows:

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \dfrac{900}{T_a + 273} u_2(e_s - e_a)}{\Delta + \gamma(1 + 0.34u_2)} \tag{4}$$

where R_n is the net radiation at the crop surface (MJ m^{-2} day^{-1}), G is the ground heat flux (MJ m^{-2} day^{-1}), T_a is the air temperature (°C), u_2 is the wind velocity (m s^{-1}), e_s is the saturation vapor pressure (kPa), e_a is the actual vapor pressure (kPa), γ is the psychrometric constant (kPa °C^{-1}), Δ is the slope vapor pressure curve(kPa °C^{-1}).

Runoff rate of rainfall, O, can be calculated by the following equation:

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

where a is the runoff coefficient.

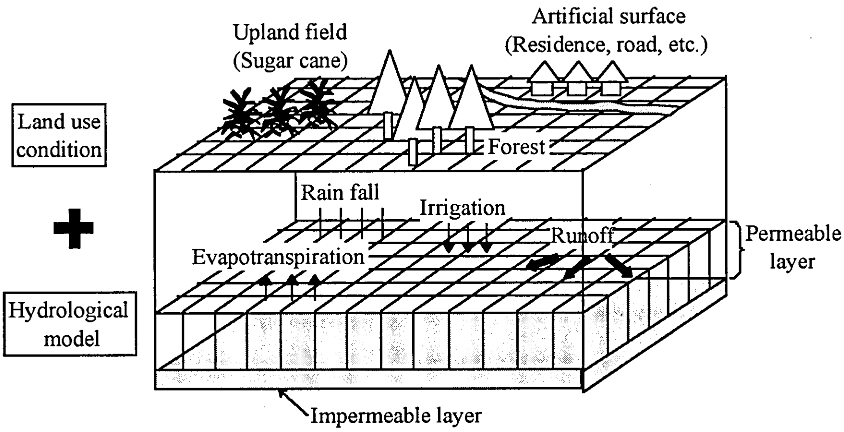

Fig. 6. Simulation model for groundwater analysis coupled on the land use condition.

Fig. 6 shows the simulation model introduced by coupling the groundwater analysis and the land use information. For specifying the surface boundary conditions at all nodes, data on the land use condition stored in the GIS database is transferred into the groundwater model using MODFROW.

RESULTS and DISCUSSION

Simulation of the groundwater level was conducted in the area of 5400 m times 4600 m. The MODFLOW mesh for the study site has 54 columns and 46 rows. Each cell is 100 m square. The finite difference method is used to solve the governing equation in MODFLOW. The calculation was pursued with the SOR (Successive over–relaxation) method. The initial conditions were set using data in 1 Jan. 2003, and boundary conditions were specified by daily data from 1 Jan. to 31 Dec.

In the calculation, as the land use conditions are categorized as the upland field, the forest, and the artificial surface, the parameters in eq. (2) should be estimated, considering the land use condition.

The amount of the irrigation water A at the upland fields is given, assuming that all upland fields are used for cultivating the sugar cane. The value of A can be specified, considering the growth stages of the sugar cane, as shown in Table 1. Irrigation at the upland field of the sugar cane is conducted until late in September, and irrigation interval is 7–8 days. As at the forest and the artificial surface are specified as 0.

The parameters for estimating the evapotranspiration E by eq. (4) are estimated using the method suggested by Allen *et al.* (1998) with the meteorological data of the weather station.

To estimate the evapotranspiration, considering the sugar cane growth stage, K_c of the upland field is given as shown in Fig. 7 (Allen *et al.*, 1998). The growth stages of the sugar cane are estimated using the cultivation guideline of the sugar cane (Okinawa

Prefecture, 1999). K_c of the forest is set as 1.5 throughout the year. E of the artificial surface is set as 0.

The values of a in the upland field, the forest, and the artificial surface are assumed as 0.45, 0.5, and 0.9, respectively (Yoshikawa, 1966).

To evaluate the effect of the upland field irrigation on the groundwater storage, the groundwater level is simulated. First, the groundwater storage is calculated under the present land use condition. Next, the groundwater analysis is conducted, assuming that all forests, shown in Fig. 2, are used as the upland field.

Figure 8 shows total amount of groundwater retained in the permeable layer. Under the present land use condition, the groundwater storage increase during the growth period of the sugar cane. However, after the end of the growth stages, the groundwater storage decrease gradually, and in December, the amount of the groundwater storage reaches 0 m^3. The groundwater storage, calculated on the assumption that all forest is used for the upland field, is larger than the storage under the present land use condition as shown in Fig. 8. This result is caused that the irrigation is conducted in the upland field as shown in Table 1, and the runoff rate of the rainfall and the evapotranspiration at the forest is larger than at the upland field.

Table 1. Irrigation schedule of the sugar cane.

	Irrigation water (mm)
Seeding	30–35
Germinating	15–20
Tillering	20–25
Mid–season	35–40

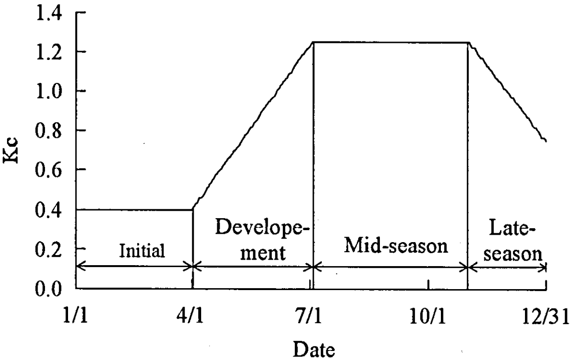

Fig. 7. Crop coefficient of the sugar cane.

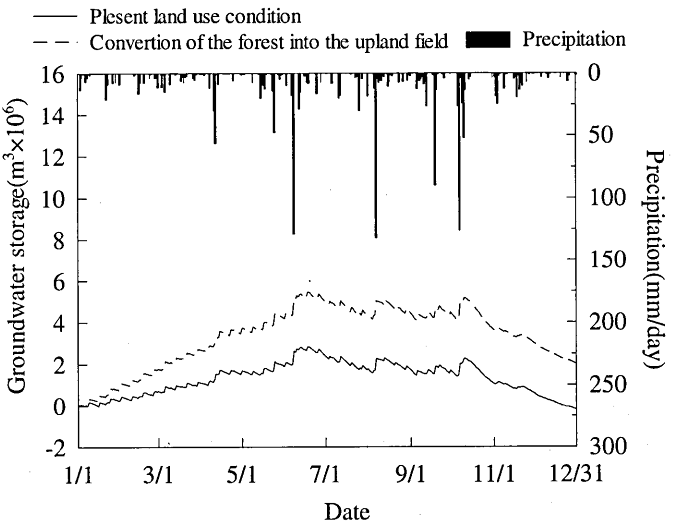

Fig. 8. Groundwater storage when the present land use condition is maintained and all forests are used as the upland fields.

CONCLUSIONS

To evaluate the effect of the upland field on the groundwater recharge, the groundwater analysis is conducted in Izena Island. A numerical model of groundwater flow using MODFLOW is conducted in a study site for quantifying the upland field effect on the groundwater storage. To specify the initial groundwater level using the seawater level as the initial condition of the numerical model, the elevation data at the study site stored in GIS database are transferred into the model. Additionally, to set the surface boundary condition, data on the land use condition in the study site stored in the GIS database is transferred into the groundwater model. Using this model, the groundwater storage are calculated under the present land use condition. To quantify the groundwater recharge of the upland field, the groundwater analysis is conducted, assuming that all forests are converted into the upland field.

Simulation results indicated that groundwater storage, when all forests are converted into the upland field, is larger than the groundwater storage under the present land use condition. This result is caused that the irrigation water in the upland field contributes to the ground water recharge and the water loss by the rainfall runoff and the evapotranspiration at the upland field is less than amount of the forest.

The method introduced here is effective for prediction of the groundwater storage, assuming that the land use condition changes variously.

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