Hydrological Analysis of Interaction between Surface and Subsurface Water in the Middle Basin of the Obaru River, Western Fukuoka, Japan

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ABSTRACT

To reproduce an accurate hydrological cycle condition quantitatively with numerical analysis model, it is essential to incorporate hydraulic geological conditions of the investigated area as clearly as possible. In the previous research, although the river flow discharge was calculated by the TSUTSUMI-JINNO model as will hereinafter be described, the numerical value of the river flow discharge at the most downstream observation point was considerably higher than the observation value. Therefore, hydraulic geological conditions of the basin had to be reconsidered. In this paper, in order to reproduce the actual surface water-groundwater relationship, a new model is developed by adding the following the two conditions: 1)the existence of the former channel of the Obaru river, and 2)phenomenon of groundwater flow out to river as gaining river(stream) is also taken into account the phenomenon of river water flow in to groundwater as losing river(stream) as well. As the results, considering the two phenomena, the calculated river flow discharge and its observed value showed good correlation at the observation point. To reproduce real hydrological cycle condition quantitatively, it is important that evaluating the accurate hydraulic geological conditions in the investigated area are incorporated in the model.

INTRODUCTION

It is important to estimate the system of water circulation by using hydrological mechanism in term of restoration of water circulation and it is essential for hydrological cycle stabilization to produce natural condition quantitatively by reflecting hydraulic geological condition of the investigated area as clearly as possible.

River flow rate was calculated by the TSUTSUMI-JINNO model[1)] at S6 point in the Obaru river (Fig.1) is higher than that of observation. On the other hand, at S2 and S3 point, the calculated river flow rate and the observation values show good correlation, so it is assumed that there are unknown hydraulic geological conditions between S3 and S6.

In this study, the hydraulic geological conditions of the Obaru river middle basin are reconsidered for the purpose of grasp of the hydrological cycle between surface and subsurface water. So, the permeability is reconsidered by the geological condition as pre-improved channel confirmed by Hiroshiro *et al.*[2)]. In addition, the TSUTSUMI-JINNO model is reconsidered, since the phenomenon that groundwater flow out surface water was considered but the groundwater recharge that the phenomenon that surface water flow into groundwater was not considered. In this study, the two phenomena were considered to the new model.

OBSERVATION AREA

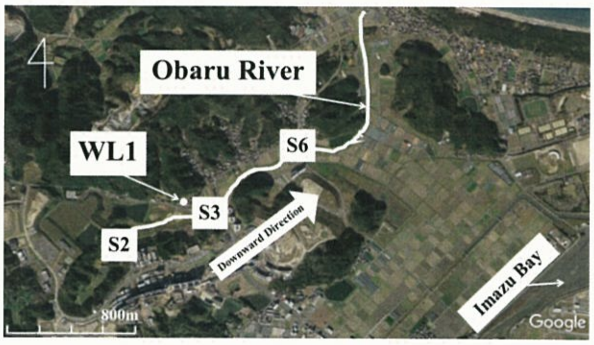

Fig.1 Observation area (The Obaru river basin)

The study area is around in Kyusyu University Ito campus. The study area divided by 12,750 meshes (50m by 25m). The Obaru river in this study area is located at west of Fukuoka city and is the provisional rank river. The river length is 3,780m and its basin area is 3.1km^2. Various dates such as permeability are set in each meshes. The calculation period is one year, 2002.

CALCULATION MODEL

TSUTSUMI-JINNO model shows the groundwater recharge model and the quasi 3dimension fresh-salt ground water flow model. The two models are described the flowing (a), (b).

(a)GROUNDWATER RECHARGE MODEL

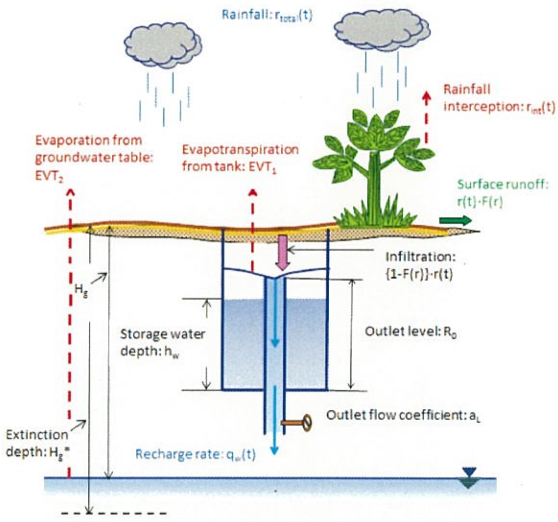

Fig.2 Groundwater recharge model[1)].

The conceptual groundwater recharge model is illustrated in Fig. 2. It functions as a vertical tank storage with an outlet at height R_0 and an outlet coefficient a_L. The R_0 corresponds to the field capacity of the soil and a_L controls the groundwater recharge rate $q_w(t)$ from the tank. The recharge induces a rise of the groundwater table. Further, the rainfall interception is denoted by $r_{int}(t)$ and rainfall that reaches the ground surface r(t) is calculated by $r(t) = r_{total}(t) - r_{int}(t)$, where $r_{total}(t)$ is the total rainfall intensity. For areas without trees, $r(t) = r_{total}(t)$.

The rainfall that reaches the ground surface is then separated into two components: the surface runoff, whose rate is given as F(r)·r(t) and the infiltration, with rate [1 – F(r)]·r(t), as shown in Fig. 2. Here, F(r) denotes the surface runoff coefficient as a function of rainfall intensity.

$$F(r)=\frac{r(t)}{r(t)+(r)_{1/2}}\cdot F_{\infty} \tag{1}$$

where $(r)_{1/2}$ is the value of r(t) when Fi(r) is equal to $F_{i\infty}/2$. If typical $F_{i\infty}$ values are adopted, such as exemplified in Table 1, then only $(r)_{1/2}$ is an undetermined parameter in the equation.

Evapotranspiration reduces water stored in the tank by $EVT_1(t)$. If the water in the tank is exhausted, evapotranspiration can still occur by water uptake denoted by $EVT_2(t)$ from the groundwater through the unsaturated zone and the root zone as explained by Bouwer (1978) [3]. This may occur if the vertical distance between the ground surface and the unconfined groundwater table is less than the extinction depth Hg*, which needs to be evaluated separately. A similar approach was introduced by Anderson & Woessner (1992) [4] who considered water uptake rate from the groundwater as a linear function of depth of the water table less than Hg*. The actual evapotranspiration can thus be estimated as the sum of $r_{int}(t)$, $EVT_1(t)$ and $EVT_2(t)$. It is obvious that the actual evapotranspiration by the present procedure varies over the region depending on tank properties and the groundwater level.

The following equations describe the change in water level stored in the tank as illustrated in Fig. 2. Equation (2) expresses the change in tank water level, $h_w(t)$, and equation (3) gives the recharge rate to the unconfined groundwater:

$$\frac{dh_w}{dt}=\{1-F(r)\}\cdot r(t)-q_w(t)-EVT_1(t) \tag{2}$$

$$q_w(t)=a_L\cdot\{h_w(t)-R_0\}\times Y[h_w(t)-R_0] \tag{3}$$

where $Y\{h_w(t) - R_0\}$ is a step function equal to 1 for $hw(t)>R_0$ and 0 for $h_w(t)<R_0$. The outlet coefficient a_L has the unit h-1, and $q_w(t)$ is the recharge rate to groundwater. The $q_w(t)$ divided by effective porosity n_e can be approximated as the groundwater table rising rate.

The parameters n_e, a_L, R_0, F_∞, $(r)_{1/2}$, were assigned values depending on land use (Table III) to represent its effect to direct runoff, infiltration, and groundwater recharge from a previous study by Tsutsumi *et al.* (2004) [5].

(b)QUASI-3DIMENSION FRESH-SALT GROUNDWATER FLOW MODEL

The quasi three-dimensional salt- and freshwater two-phase groundwater flow model was applied to the present simulation, since one of main interests was to calculate outflow from groundwater into river. Not only freshwater but also saltwater is taken into consideration in the model. The model employs basic groundwater flow equations for unconfined aquifer and confined aquifer. Figure.3 and 4 show the quasi three-dimensional two-phase groundwater flow model for unconfined aquifer and confined aquifer.

The basic groundwater flow equations in the unconfined aquifer are;

Freshwater phase

$$n_e\frac{\partial(h_f-h_s)}{\partial t}=-\frac{\partial\{(h_f-h_s)\cdot u_f\}}{\partial x}-\frac{\partial\{(h_f-h_s)\cdot v_f\}}{\partial y}-\sum_m Q_m(x,y,t)\delta(x-x_m)\delta(y-y_m)+q_w(x,y,t)-EVT_2(x,y,t) \tag{4}$$

Saltwater phase

$$n_e\frac{\partial h_s}{\partial t}=-\frac{\partial[\{h_s-b(x,y)\}\cdot u_s]}{\partial x}-\frac{\partial[\{h_s-b(x,y)\}\cdot v_s]}{\partial y} \tag{5}$$

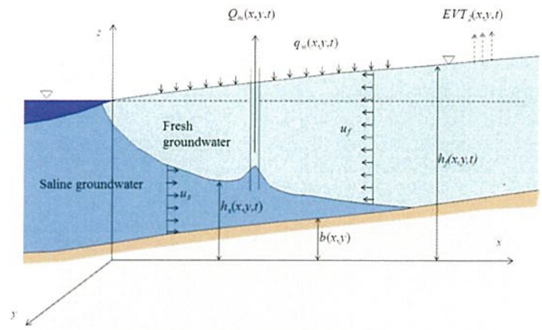

Fig.3 Quasi three-dimensional two-phase groundwater flow model for unconfined aquifer

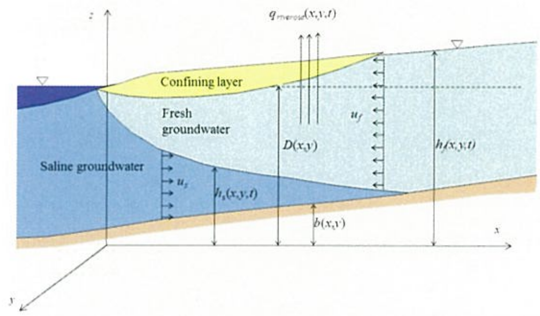

Fig.4 Quasi three-dimensional two-phase groundwater flow model for confined aquifer

The basic groundwater flow equations in the confined aquifer are;

Freshwater phase

$$S \cdot \frac{\partial h_s}{\partial t} - n_e \frac{\partial h_s}{\partial t} = -\frac{\partial[\{D(x,y) - h_s\} \cdot u_f]}{\partial x} - \frac{\partial[\{D(x,y) - h_s\} \cdot v_f]}{\partial y} - \sum_m Q_m(x,y,t)\delta(x - x_m)\delta(y - y_m) - q_{riverout}(x,y,t)\delta(x - x_{out})\delta(y - y_{out}) \quad (6)$$

Saltwater phase

$$n_e \frac{\partial h_s}{\partial t} = -\frac{\partial[\{h_s - b(x,y)\} \cdot u_s]}{\partial x} - \frac{\partial[\{h_s - b(x,y)\} \cdot v_s]}{\partial y} \quad (7)$$

where $h_f(x,y,t)$, $h_s(x,y,t)$, $b(x,y)$ and $D(x,y)$ are fresh groundwater elevation, two-phase interface elevation, impermeable base elevation taken from the reference level and the elevation of the base of the confining layer taken from the reference level, respectively. The term $Q_m(x,y,t)$ is the water extraction rate by pumping at location (x_m,y_m) at time t. The delta functions $\delta(x-x_m)$ and $\delta(y-y_m)$ represent the location of the pumping well. The term $q_w(x,y,t)$ represents the groundwater recharge. The term $q_{riverout}$ is the groundwater discharge into the river at location (x_{out},y_{out}).

Darcy's law gives the relationship as shown in equation 8.

$$u_f = -k\frac{\partial \phi_f}{\partial x}, v_f = -k\frac{\partial \phi_f}{\partial y}, \phi_f = h_f$$
$$u_s = -k\frac{\partial \phi_s}{\partial x}, v_s = -k\frac{\partial \phi_s}{\partial y}, \phi_s = \frac{\rho_f}{\rho_s}\cdot h_f + \frac{\Delta\rho}{\rho_s}\cdot h_s \quad (8)$$

where the terms u_f, u_s, and v_s, v_f represent the velocity components in x- and y- direction. The subscripts s and f denote saltwater and freshwater, respectively. The terms ϕ_f and ϕ_s are the piezometric heads, and the density difference is written as $\Delta\rho=\rho_s-\rho_f$ at the saltwater intrusion area. The permeability k varies spatially but is assumed uniform in the vertical direction.

RESULTS AND DISCUSSIONS

HYDROULIC GEOLOGICAL CONDITION OF S6 POINT

It was reported that a trace of pre-improved channel exists around S6 spot[2)]. So the difference between the calculation result and the observation flow rate in TSUTSUMI-JINNO model might form existence of this pre-improved channel wasn't being considered. The permeability was 1×10^{-4}cm/s ~ 1×10^{-5}cm/s around estimated pre-improved channel in TSUTSUMI-JINNO model On the other hand, the permeability in this study is about 1×10^{-3}cm/s in estimated pre-improved channel and is about 1×10^{-3}cm/s ~ 1×10^{-4}cm/s around estimated pre-improved channel. These values of permeability are within the range of permeability in sand[4)] from the report[2)] that sandy soil lay is in the pre-improved channel.

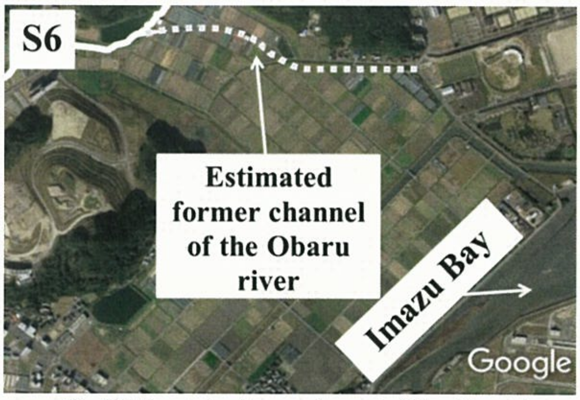

Fig.5 Estimated a former channel of the Obaru river

RERATION OF RIVER WATER AND GROUNDWATER IN TSUTSUMI-JINNO MODEL

The TSUTSUMI-JINNO model was considered the phenomenon that groundwater flow out surface water was considered but the groundwater recharge that the phenomenon that surface water flow into groundwater was not considered in case of calculate the flow rate. In this study, the amount of recharge from surface water to groundwater (Fig.6) is considered.

$$q_{riverin^{3)}} = \frac{k(h_r - b_r)}{d} \qquad (9)$$

where
k is permeability of semi-permeable layer, hr is the height of river surface from basis, br is the height of bed layer of river form basis, d is thickness of semi-permeable layer.

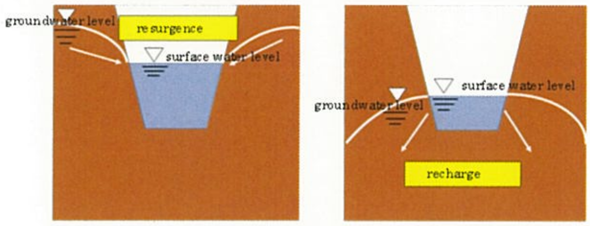

Fig.6 Image of gaining stream(left) and losing stream(right)

EVALUATION OF RESULTS

Table1 flow rate in S6 point

2002	flow rate in S6 point(m^3/year)	
	observation	calculation
before improvement	1,233,186	1,680,488
pre-improved channel		1,560,057
pre-improved channel +qriverin		1,323,298

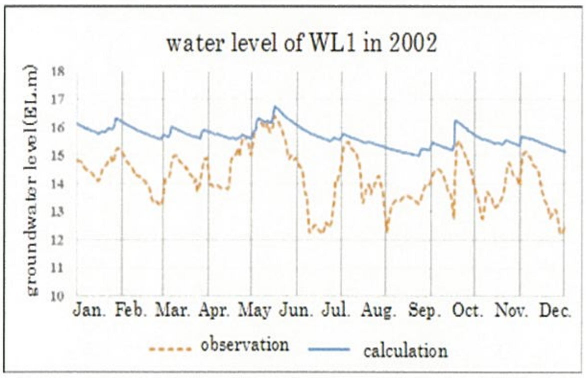

Fig.7 Observation and calculation groundwater level at WL1

Fig.7shows the observation value of groundwater level at WL1 point in2002 and calculated value considered exist of pre-improved channel and recharge. Though calculation value exceeded observation value through a period, the variation pattern of groundwater could be reproduced except the period from June to August. A well of WL1 is used as a personal well, and influence of pump discharge rate of flow wasn't easy to grasp quantitatively, but the observation value and the variation pattern of the calculation result and observation value is almost identical.

Table1 shows the calculation flow rate at S6 point. “Before improvement” is the results by TSUTSUMI-JINNO model. The calculation flow rate is about 450,000m^3 higher than that of observation. On the other hand, in this study, the calculation flow rate and the observation value shows good correlation at S6 because exist of pre-improved channel and recharge are considered. The cause of great difference between the calculation flow rate and the observation value is regarded as exist of pre-improved channel and recharge aren’t considered.

CONCLUSION

The cause of great difference between the calculation flow rate and the observation value in only S6 point is regarded as exist of pre-improved channel and recharge aren’t considered. In this study, the calculation flow rate and the observation value is almost identical that those phenomena are considered. It is important for understanding present hydrological cycle to produce natural condition quantitatively by mirroring hydraulicgical condition of the study area with the model.

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