Effects of land-use change on groundwater recharge model parameters

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Abstract Land development usually induces large changes in flood peak and infiltration properties, thus affecting the entire hydrological environment of the area. In order to evaluate such negative effects caused by land-use change, it is necessary to estimate the changes in surface runoff and groundwater recharge rate. The effects of land-use changes on the parameter values of a groundwater recharge model were studied and are presented. The response of groundwater level was examined at several observation wells for two different unconfined aquifers consisting of weathered granite. The spatially calibrated parameters of the groundwater recharge model were classified in order to evaluate the effects of land-use change. It was shown that the parameter values most affected by land-use change were the surface runoff coefficient, F_∞, followed by the shape parameter, $(r)_{1/2}$. The field capacity parameter, R_0, was also greatly affected. By defining the land-use change for these three parameters the hydrological change can be predicted.

Key words regional-scale hydrological processes; groundwater recharge model; land-use change; weathered granite; parameter adjustment; quasi-three-dimensional groundwater flow

Effets d'un changement d'occupation du sol sur les paramètres d'un modèle de recharge de nappe

Résumé Le développement du territoire induit généralement d'importants changements dans les pics de crue et dans les propriétés d'infiltration, ce qui a des impacts dans l'ensemble de l'environnement hydrologique. Afin d'évaluer de tels effets négatifs causés par des changements d'occupation du sol, il est nécessaire d'estimer les changements en termes d'écoulements de surface et de recharge hydrogéologique. Les effets des changements d'occupation du sol sur les valeurs des paramètres d'un modèle de recharge de nappe souterraine ont été étudiés et sont présentés. La réponse du niveau piézométrique a été étudiée pour plusieurs puits d'observation, pour deux aquifères non confinés en granite altéré. Les paramètres calés spatialement du modèle de recharge ont été classés afin d'évaluer les effets du changement d'occupation du sol. Il apparaît que les paramètres les plus affectés par le changement d'occupation du sol sont le coefficient de ruissellement de surface, F_∞, puis le paramètre de forme, $(r)_{1/2}$. La paramètre capacité au champ, R_0, est également très affecté. Le changement hydrologique peut être prévu en définissant le changement d'occupation du sol pour ces trois paramètres.

Mots clefs processus hydrologiques à l'échelle régionale; modèle de recharge de nappe souterraine; changement d'occupation du sol; granite altéré; ajustement de paramètre; modèle d'écoulement de nappe en quasi-trois dimensions

INTRODUCTION

Urbanization and land-use change significantly increase the surface water flow to rivers and its travel time becomes shorter. Consequently, groundwater recharge to shallow unconfined aquifers decreases by the same amount. Often the hydrological impact of land development is evaluated as a local effect with minor or no regional impact. As the urbanization process extends over increasingly larger areas, it comes to a point when the sustainable use of river and subsurface water resources and the ecological environment cannot be guaranteed at the regional level. Accordingly, both surface and subsurface water processes need to be evaluated at a regional scale in terms of land-use change (Virtual Water Forum, 2003; International Network of Basin Organizations, 2003).

The hydrological system integrates several processes, such as rainfall, evapotranspiration, surface runoff, unsaturated flow, and saturated subsurface water movement. Despite decades of

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research effort into individual processes, their integrated application to practical problems has been limited (e.g. Klemeš, 1983; Van Laanen & Demuth, 2002). This may be due to rather complicated procedures proposed to the practitioner, such as estimation of the groundwater recharge rate to shallow groundwater. Groundwater recharge may be described by unsaturated flow through surface humic soil, weathered clay and fractured rock. In spite of well defined unsaturated flow theory (e.g. Beven, 1987), such a system can hardly be quantified without sufficient hydro-geological information and without the aid of numerical simulation using a fine grid mesh. Even if these requirements are satisfied, the evapotranspiration is still not easily estimated, although there are many formulae for calculating potential evapotranspiration (e.g. Penman, 1948; Kristensen & Jensen, 1975; Monteith, 1981; Alkaeed *et al.*, 2006). As a result, unreliable recharge and evaporation rates are often used in the solution of practical problems involving groundwater flow. Consequently, the prediction of hydrological impact by urbanization on the regional water environment is not easy, unless simplification of various processes is performed by limiting both dimensionality and calculation capacity. Although numerical models for rainfall infiltration and evapotranspiration from the unsaturated zone exist, and are useful to understand the physical processes for groundwater recharge, such detailed description is less applicable in the practical reality. In many cases it is necessary to replace these detailed models with more simple and practically useful recharge models when water management for larger regions is required.

To meet the above requirements, the authors presented a groundwater recharge model for an unconfined aquifer (Tsutsumi *et al.*, 2004). The proposed model was capable of separating rainwater into surface runoff and groundwater infiltration at the ground surface in a realistic way. Using the model, actual evapotranspiration based on the potential evapotranspiration and the direct surface water discharge to rivers were also estimated. Besides, the recharge model was coupled with a quasi three-dimensional unconfined groundwater flow model to produce the effects on groundwater levels. The major advantage of the proposed recharge model approach is that model parameters can be evaluated using records of precipitation and groundwater table change without a direct numerical simulation of unconfined groundwater flow.

Most models describing regional-scale subsurface hydrological processes mainly target the representation of current surface and subsurface water movement. Very little information on how to adjust the parameters after land-use change at the same location is normally given. This may arise from the fact that the parameters in most models are not systematically examined to compare the situation before and after land-use change. If a schematic procedure can be introduced for adjusting model parameters also after land-use change, better watershed management could be implemented that also would be useful for other applications.

In the present paper, the parameters in the proposed groundwater recharge model were examined using river discharge and groundwater data taken from an area in Ohnojyo City, Japan, both before and after land-use changes. This allowed an assessment of the relationship between model parameter values and land-use change. The paper starts with a presentation of the experimental area and a summary of the proposed methodology. After this, model parameter values are analysed for the conditions before and after change. The paper closes with a discussion of the practical results of the study.

TOPOGRAPHICAL AND GEOLOGICAL CHARACTERISTICS OF THE EXPERIMENTAL AREA

Two areas were studied in the present analysis, as shown in Fig. 1. The first area is located in western Fukuoka City, Japan, where the new Kyushu University campus (Ito campus) is under construction. At the construction site, deforestation and levelling of land surfaces are currently occurring. Residential areas with relatively wide garden spaces are located at the foot of a hill (Kyushu University, 2006). The elevation of the ground surface ranges from 0.3 m at the lowest point to about 100 m a.m.s.l. at the top of the hill. The lowland area is an alluvial plain used for agriculture, such as greenhouse cultivation and paddy fields. In the alluvial plain, a shallow

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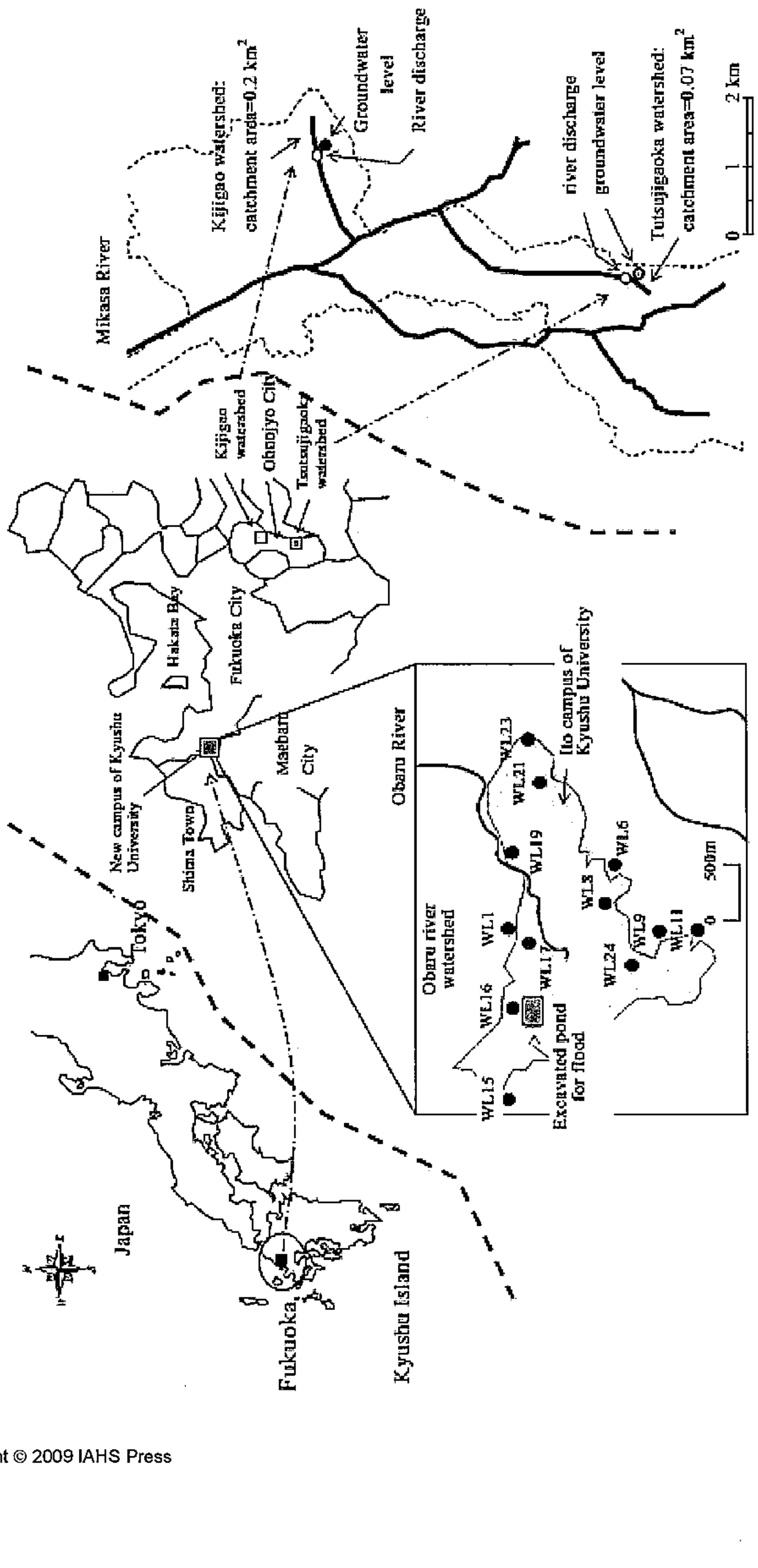

Fig. 1 Study areas: Kijigao, Tsutsujigaoka in Ohnojyo City and new Kyushu University campus, Fukuoka, Japan.

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unconfined aquifer which is partly intruded by saltwater is formed. The thickness of the unconfined aquifer under the lowland is approx. 50 m on average. The hilly areas, where groundwater recharge occurs, consist mainly of weathered Cretaceous Itoshima granodiorite at 5–10 m, non-weathered rock below 40–50 m, and partly developed cracks between 10 and 40 m depth. The area of Ito campus is approximately 2.75 km^2 (Tsutsumi *et al.*, 2004).

The second area is located in Ohnojyo City, a satellite city south of Fukuoka. The ground elevation of Ohnojyo City ranges from approx. 20 to 450 m a.m.s.l. The lowland is covered by approximately 20-m thick deposited soil. The Mikasa River flows into Hakata Bay in the north. The area of Ohnojyo City is approx. 27 km^2. Two watersheds in Ohnojyo City with different land-use were selected for the study: Kijigao watershed (0.2 km^2) has a natural forest without development, while Tsutsujigaoka watershed (0.07 km^2) is a densely populated residential area. Both Kijigao and Tsutsujigaoka watersheds are situated on a Sawara granite which was formed after the Cretaceous Itoshima granodiorite. The thickness of the weathered Sawara granite ranges from 15 to 35 m which is similar to that of the Ito campus of Kyushu University.

PRINCIPLES OF APPLIED GROUNDWATER RECHARGE MODEL

Review of the proposed model

The proposed groundwater recharge model was explained in detail in a previous paper (Tsutsumi *et al.*, 2004); only a brief summary is given herein. The fundamental physical processes which take place at the ground surface and near-surface unsaturated infiltration were represented conceptually by the simplified recharge model, emphasizing practical applicability. The reader can refer to the various characteristics of the model in Tsutsumi *et al.* (2004). Below the parameter setting for different land uses is emphasized. Figure 2 illustrates the groundwater recharge model that functions so as to separate the rainwater reaching the ground surface into a direct surface runoff component and a groundwater infiltration component.

In forest areas, rainwater is intercepted by the canopy. The amount of rainwater interception is denoted by $r_{\text{int}}(t)$, which is assumed to evaporate after rainfall has ended (Kondo *et al.*, 1992). In humid temperate areas this assumption may not be true. However, in areas where high potential evapotranspiration is expected, such as the experimental watersheds, this is a relevant assumption. The rainwater $r(t)$ that reaches ground surface is then calculated by:

$$r(t) = r_{\text{total}}(t) - r_{\text{int}}(t) \qquad (1)$$

where $r_{\text{total}}(t)$ is the total rainfall intensity and t denotes time. In areas without canopy $r_{\text{int}}(t)$ is obviously zero and:

$$r(t) = r_{\text{total}}(t) \qquad (2)$$

As can be seen from Fig. 2, $F(r)\cdot r(t)$ is the rate of surface runoff that goes directly to the river, while $[1 - F(r)]\cdot r(t)$ represents the infiltration rate. The dependency of the surface runoff coefficient $F(r)$ on the rainfall intensity at the ground surface is shown schematically in Fig. 2.

Both intermediate runoff and groundwater discharge to rivers are calculated through a quasi three-dimensional groundwater flow model coupled with the present groundwater recharge model. Needless to say, $F(r)\cdot r(t)$ at every grid mesh of discretized area for groundwater numerical simulation goes directly to the river as surface runoff. A delayed arrival time of flood peak to a measurement point can be calculated by the time–area method (Alkaeed *et al.*, 2006).

The groundwater recharge model uses the parameter R_0, which denotes the vertical height of water in the conceptual tank model. This quantity corresponds to the field capacity which characterizes the maximum water holding capacity resisting the gravitational force. In practice, this quantity can be estimated by observing a significant rise of the shallow groundwater table after a specific rainfall event. The water tank shown in Fig. 2 stores the infiltrated rainwater and allows vertical infiltration when the water depth $h_w(t)$ exceeds R_0. The rate of infiltration to the unconfined groundwater $q_w(t)$ is then calculated by:

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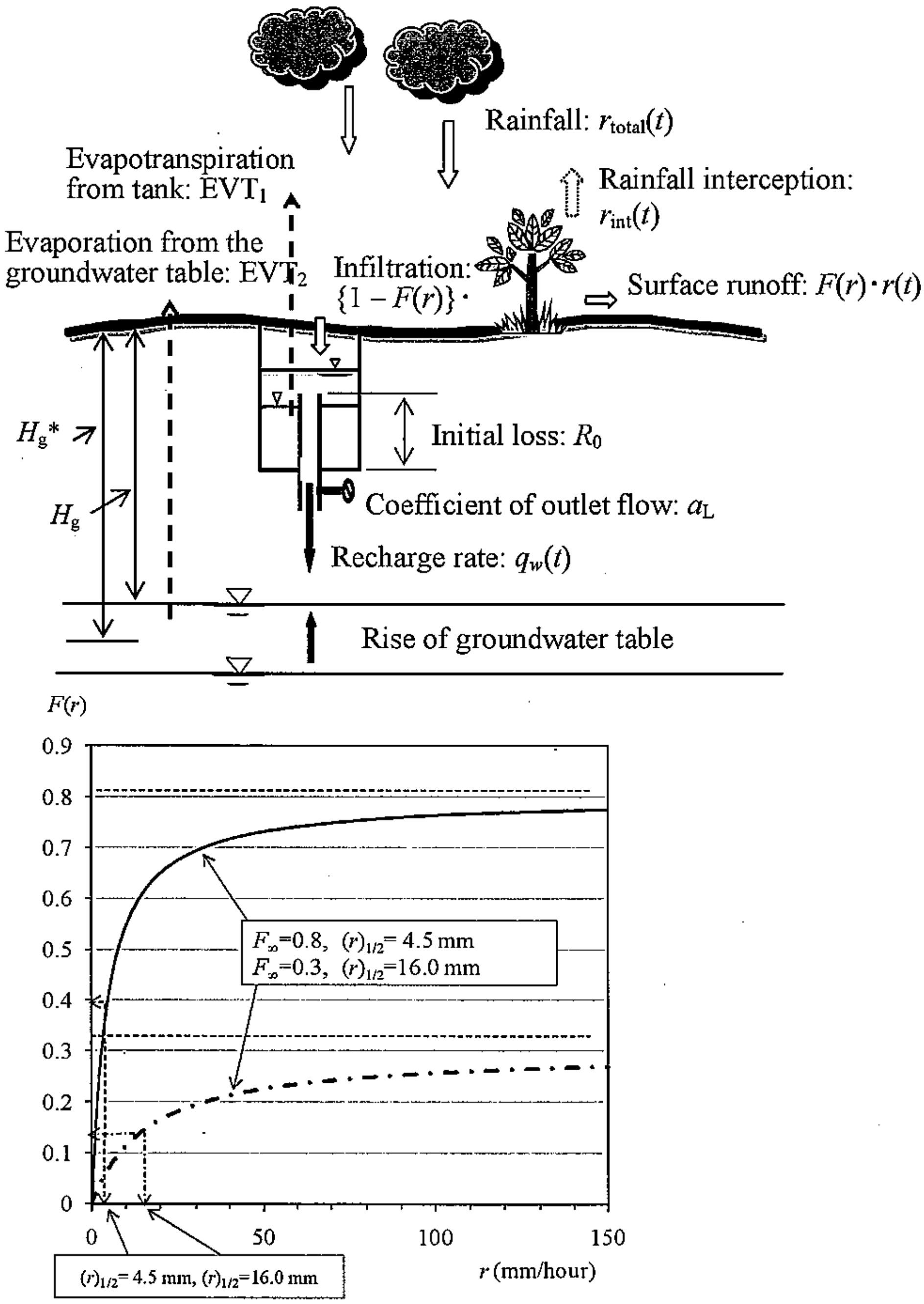

Fig. 2 Groundwater recharge model to unconfined groundwater and surface runoff coefficient.

$$q_w(t) = a_L\left[h_w(t) - R_0\right]\cdot Y\left[h_w(t) - R_0\right] \qquad (3)$$

where $Y[h_w(t) - R_0]$ is a step function which is equal to 1 for $h_w(t) > R_0$ and 0 for $h_w(t) < R_0$. The outlet coefficient a_L (unit h^{-1}) controls the rate of infiltration to the groundwater table. The change in the stored water depth is given by:

$$\frac{dh_w(t)}{dt} = \left[1 - F(r)\right]\cdot r(t) - q_w(t) - EVT_1(t) \qquad (4)$$

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where $h_w(t)$ and $\mathrm{EVT}_1(t)$ denote the water depth and evapotranspiration from the storage tank, respectively. The value of $\mathrm{EVT}_1(t)$ is set equal to the potential evapotranspiration until the storage becomes empty. Any formulae for estimating potential evapotranspiration are applicable depending on the local climatic conditions (Alkaeed *et al.*, 2006). When the storage tank is empty and the vertical distance to the groundwater table from ground surface (H_g) is smaller than H_g^*, additional evapotranspiration $\mathrm{EVT}_2(t)$ will occur. The maximum groundwater depth (H_g^*) that allows water uptake by plants, is called the extinction depth (see e.g. Anderson *et al.*, 1992). Since $\mathrm{EVT}_2(t)$ is dependent on H_g which varies with groundwater level, the groundwater flow equation needs to be solved simultaneously. Therefore, $\mathrm{EVT}_2(t)$ is included in the following:

$$n_e \frac{\partial h_f}{\partial t} = -\frac{\partial\{(h_f - b)u_f\}}{\partial x} - \frac{\partial\{(h_f - b)v_f\}}{\partial y} - \sum_m Q_m(x,y,t)\delta(x - x_m)\delta(y - y_m) + q_w(x,y,t) - \mathrm{EVT}_2(x,y,t) \tag{5}$$

where $h_f(x,y,t)$ and $b(x,y)$ are fresh groundwater elevation and impermeable base elevation taken from the reference level, respectively. The Darcy velocity components are denoted by u_f and v_f in the x and y horizontal direction, 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 effective porosity n_e can be related to the rise in the unconfined groundwater level immediately after rainfall events and before significant horizontal groundwater flow occurs:

$$\frac{\partial h_{f\mathrm{obs}}(i,t)}{\partial t} = \frac{q_w(t)}{n_e} \tag{6}$$

where $h_{f\mathrm{obs}}(i,t)$ denotes observed groundwater level at location i. The surface runoff coefficient in the present model is assumed to vary as a function of the rainfall intensity as:

$$F_i(r) = \frac{r(t)}{r(t) + (r)_{1/2}} \cdot F_{i\infty} \tag{7}$$

where $(r)_{1/2}$ is the value of $r(t)$ when $F_i(r)$ is equal to $F_{i\infty}/2$. If typical $F_{i\infty}$ values are adopted, such as exemplified in Table 1, then $(r)_{1/2}$ is the only undetermined parameter in equation (7). It should be noted that $(r)_{1/2}$ can be identified using observations of either river discharge or the rise in groundwater level when it rains. If both observations are available, a more reliable estimate of $(r)_{1/2}$ can be obtained and validated from the surface and subsurface hydrological viewpoint.

The remaining parameters to be determined in Fig. 2 are R_0, n_e and a_L. Both R_0 and n_e can be estimated by carefully observing the maximum values of total precipitation from several rainfall events where no significant rise of the groundwater table occurs. In other words, R_0 corresponds to the maximum water depth in the pore storage where retention forces acting on the pore water and soil surface can resist the gravitational force.

MODEL APPLICATION TO ITO CAMPUS CATCHMENT

Figure 3 shows the relationship between the total amount of precipitation from several rainfall events and recorded rise of groundwater table at Ito campus of Kyushu University. It can be seen that in WL-16, R_0 is 9 mm, since no significant rise of groundwater table is observed below this value. The following procedure was used: for every rainfall event, the amount of total direct surface runoff, $\Sigma_t F(r)\cdot r(t)$, was first calculated and then the amount of the groundwater infiltration, $\Sigma_t[1 - F(r)]\cdot r(t)$, was obtained. The response of the groundwater level ΔH was then plotted. The maximum rainfall of $\Sigma_t r(t)$, which does not influence the groundwater table, was assumed to correspond to R_0. The evapotranspiration was not considered during the parameter evaluation period of rainfall. The effective porosity n_e was then calculated as:

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Table 1 Guidelines of surface runoff coefficient by the Ministry of Education, Culture, Sports, Science and Technology, Japan.

Type of ground surface		Coefficient of surface runoff
Road	Permeable pavement	0.70–0.90
	Pavement	0.30–0.40
	Gravel road	0.30–0.70
Shoulder or top of slope	Fine soil	0.40–0.65
	Coarse soil	0.10–0.30
	Hard rock	0.70–0.85
	Soft rock	0.50–0.75
Grass plot of sand	Incline 0–2%	0.05–0.10
	2–7%	0.10–0.15
	Above 7%	0.15–0.20
Grass plot of clay	Incline 0–2%	0.13–0.17
	2–7%	0.18–0.22
	Above 7%	0.25–0.35
Roof		1.00
Unused bare land		0.20–0.40
Athletic field		0.40–0.80
Park with vegetation		0.10–0.25
Mountain with a gentle slope		0.30
Mountain with a steep slope		0.50
A paddy field or water		0.70–0.80
Farmland		0.10–0.30

$$n_e = \frac{\sum_t r(t) - R_0}{\Delta H} \tag{8}$$

The parameter a_L was obtained by numerically integrating equation (6) so that the criterion by equation (9) could be minimized with respect to a_L. As mentioned earlier, $(r)_{1/2}$ can also be determined by using direct surface runoff rate:

$$J = \sqrt{\sum_{t=1}^{N} \frac{[h_{f\mathrm{obs}}(i,t) - h_{f\mathrm{cal}}(i,t)]^2}{N}} \tag{9}$$

where J is the criterion to be minimized with respect to $(r)_{1/2}$ and a_L. The terms $h_{f\mathrm{obs}}(i,t)$ and $h_{f\mathrm{cal}}(i,t)$ represent the observed groundwater level and that calculated by equations (3), (4), (6) and (7), respectively, and N is the number of time steps for selected rainfall events. It should be noted that $(r)_{1/2}$ can also be obtained as the direct surface runoff component as explained earlier. The parameters used in the groundwater recharge model can be determined from groundwater level observations in wells prior to coupling with the numerical simulation. Then the recharge model is linked to the groundwater numerical simulation model considering the land-use conditions.

Figure 3 shows the schemes for evaluating: (a) R_0, (b) n_e, (c) the estimation of both a_L and $(r)_{1/2}$ based on the least-squares criterion (equation (9)), and (d) the confirmation of both the observed and calculated rise of the groundwater table. Figure 3(d) also shows the estimated recharge rate q_w(t) at WL16.

In summary, there are five unknown parameters in this model: F_∞, a_L, R_0, n_e and $(r)_{1/2}$. The major advantages of the present model are: F_∞ can be conveniently taken from typical manuals used in rainwater drainage design; R_0 and n_e are directly estimated by examining the rise of groundwater level and amount of precipitation from several rainfall events; and, finally, a_L and $(r)_{1/2}$ can be evaluated by the following least-squares estimate using observed groundwater level change together with corresponding rainfall data. Figure 4 illustrates an application of the present model schematically.

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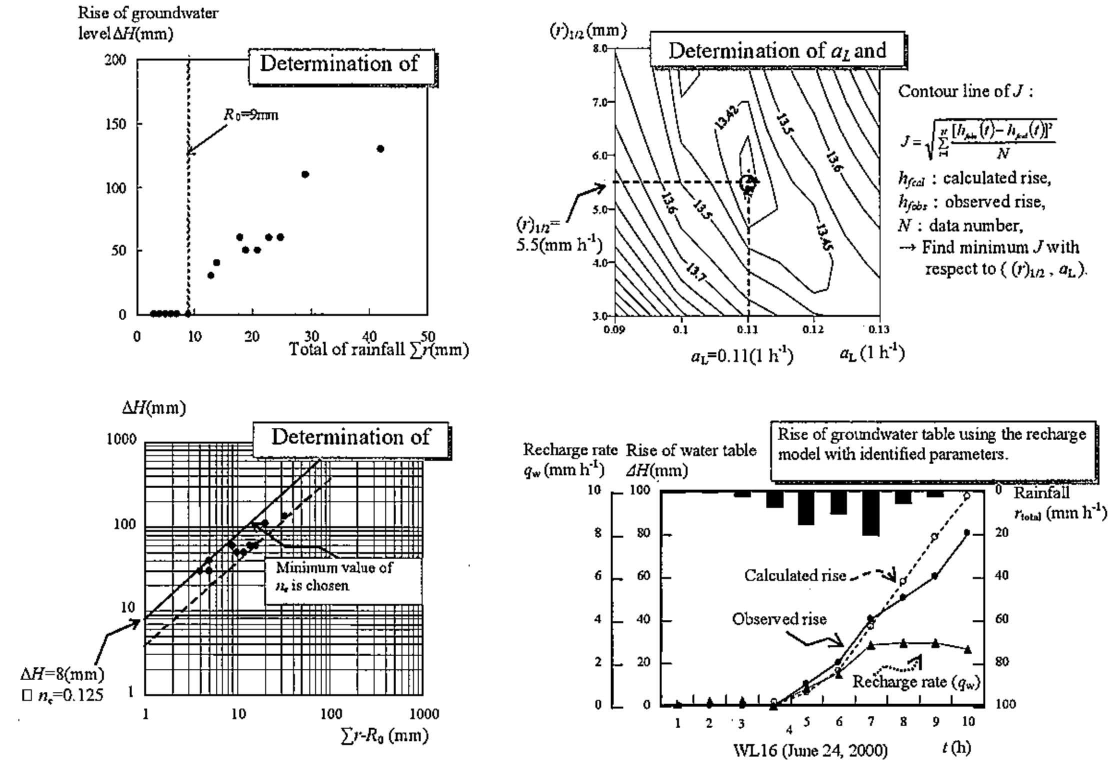

Fig. 3 Determination of R0 from rainfall and rise of the groundwater table at WL16.

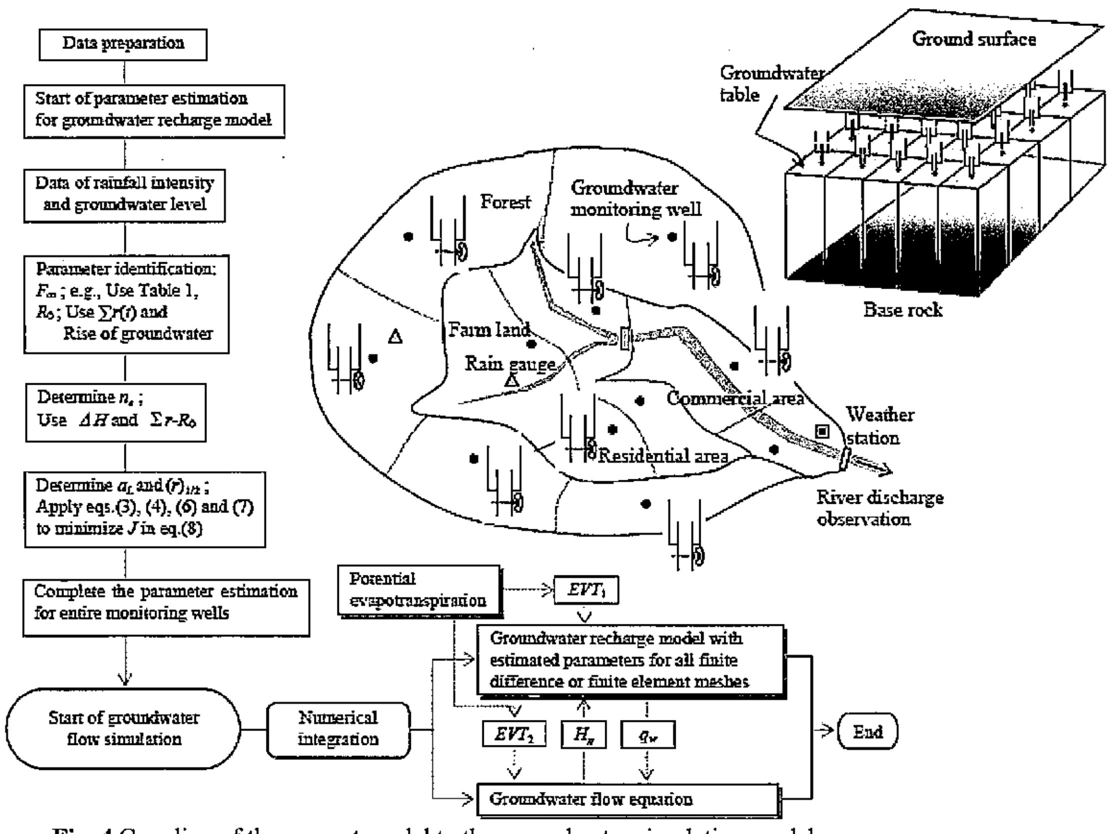

Fig. 4 Coupling of the present model to the groundwater simulation model.

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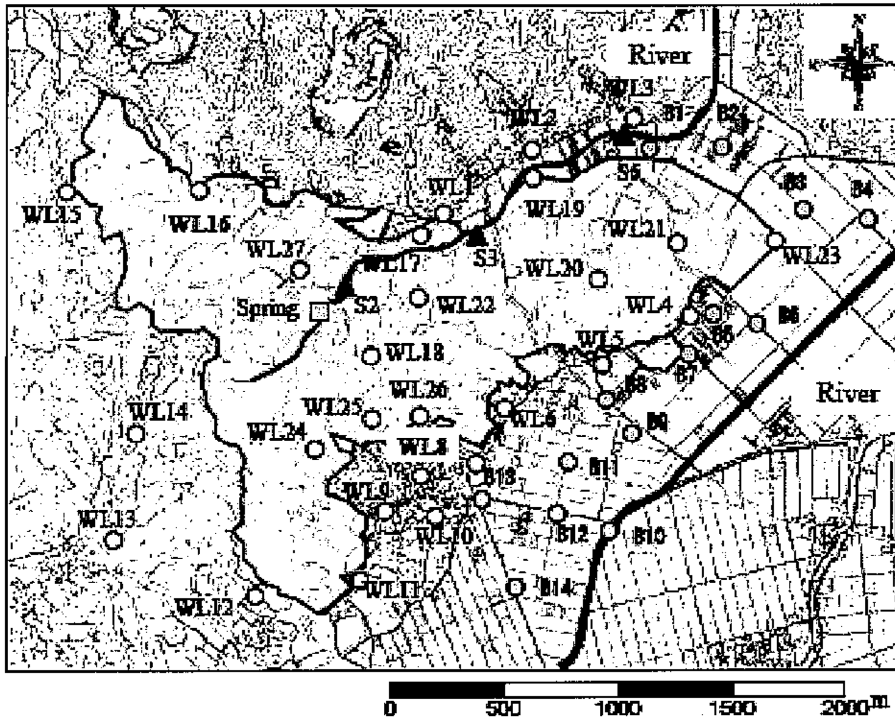

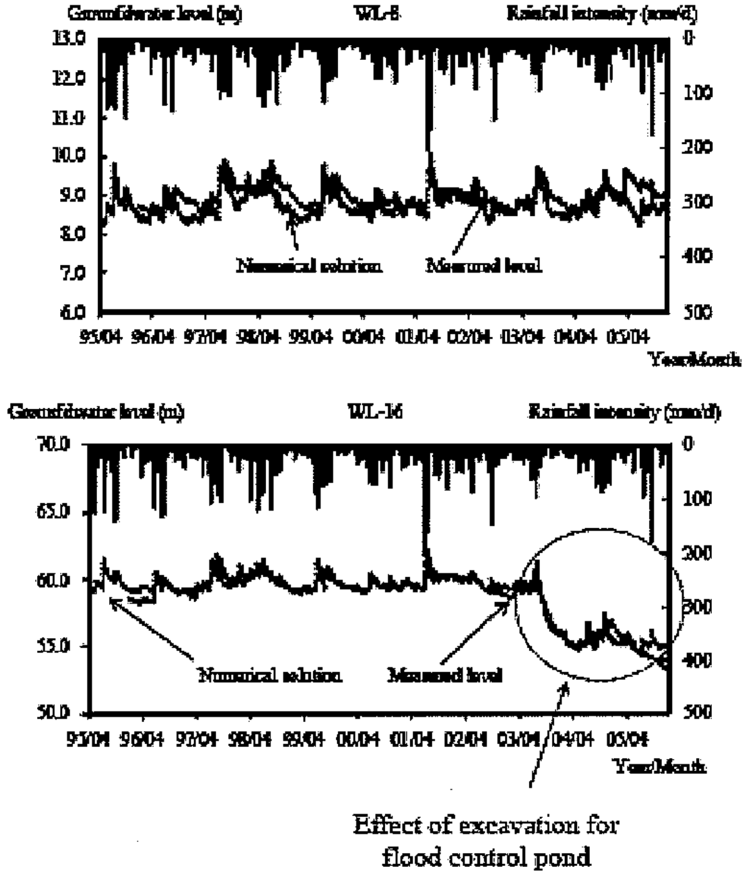

Mark	Purpose
○	Groundwater level
◉	Electric conductivity (*EC*)
▲	River discharge

Fig. 5 Variation of groundwater level at WL8 and WL16.

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To validate the proposed groundwater recharge model, the variation in groundwater level at several wells was simulated numerically using equation (5) for 10 observation years, as shown in Fig. 5. The variation in groundwater level in these wells, located in both high- and low-elevation residential areas, agrees reasonably well with the model (Fig. 5).

APPLICATION TO KIJIGAO AND TSUTSUJIGAOKA WATERSHEDS

Estimation of $(r)_{1/2}$ from direct surface runoff component

As mentioned in the previous section, the parameters F_∞ and $(r)_{1/2}$ used in the proposed model can be easily evaluated because this procedure is basically independent from the groundwater simulation. This means that, for the initial stage immediately after a rainfall event, the response of unconfined groundwater level induced by rainfall can be described by the present groundwater recharge model. The other advantage of the present model is that the parameters F_∞ and $(r)_{1/2}$ in the recharge model can also be estimated using the direct surface runoff component of river discharge.

Figure 6 shows the specific river discharge and groundwater level in Kijigao and Tsutsujigaoka, Ohnojyo City. It is clearly seen that there are distinct differences in the specific river discharge and groundwater level response between the two watersheds, although hydrogeological and topographical conditions do not differ significantly, only the land use.

The Tsutsujigaoka watershed is an urbanized residential area. The river discharge in this area was measured and the direct surface runoff was found to be dominant, since most of the area is covered by houses and paved roads which limit rainwater infiltration. The parameters F_∞ and $(r)_{1/2}$ are more sensitive to the direct surface runoff as compared to rise in the unconfined groundwater level. Hence, $(r)_{1/2}$ was first evaluated assuming that F_∞ was 0.8 (from Table 1, as for a dense residential area). Once $(r)_{1/2}$ is identified, the direct surface runoff rate is calculated as:

$$Q_{\text{dir}}(t) = [F(r)] \cdot r(t) \cdot A_T \qquad (10)$$

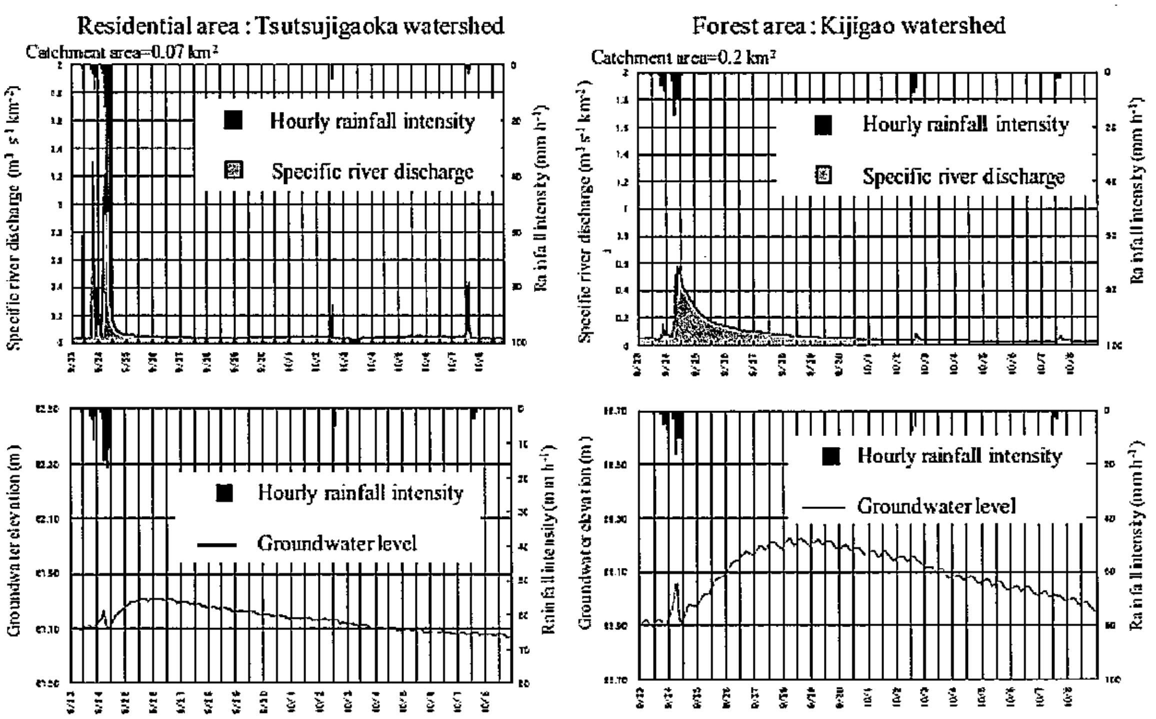

Fig. 6 Responses of river discharge and groundwater level at sites of different land use (23 September–8 October 2000).

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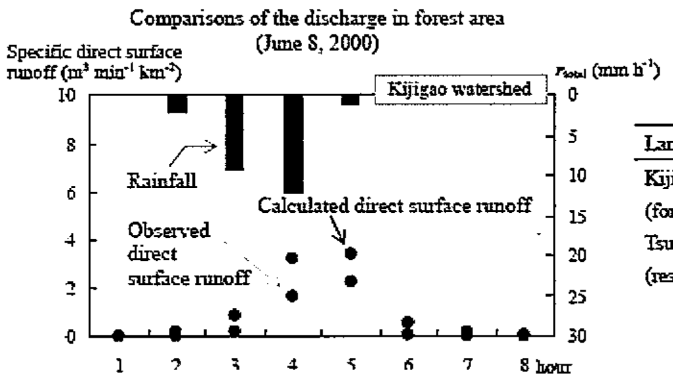

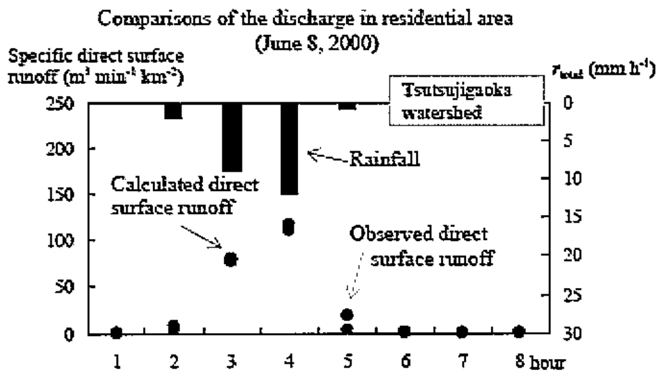

Parameters of the groundwater recharge model in Ohnojyo city

Land use type	n_e [-]	a_L [s^{-1}]	R_0 [mm]	$(r)_{i,c}$ [mm]	F_x [-]
Kijigao (forest area)	0.34	0.15	32.9	16.0	0.3
Tsutsujigaoka (residential area)	0.26	0.17	13.6	4.5	0.8

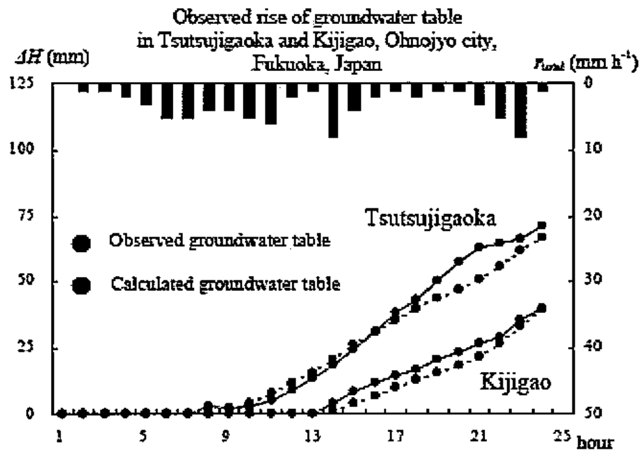

Fig. 7 Separated direct surface runoff and parameter tuning for the groundwater recharge model in forest and developed areas.

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where A_T is the ground surface area of the watershed. The parameters R_0, n_e and a_L were evaluated using the groundwater infiltration rate, which is equal to $[1 - F(r)]\cdot r(t)$ and the time series of the rise of the groundwater table. Similarly, the parameters of the groundwater recharge model in the Kijigao watershed were estimated taking into account the rainwater interception by trees. Assuming that the interception rate is 20% of rainfall intensity, as previously discussed, 80% of rainfall was used as throughfall. Detailed explanation of separating the hydrograph into the direct and remaining components was given in the previous paper by Tsutsumi *et al.* (2004).

The response of direct surface runoff was analysed for the two watersheds. This was done since the arrival time of peak direct surface discharge was anticipated to be longer in Kijigao watershed due to the relatively large water collecting area (0.2 km^2) as compared to Tsutsujikaoga watershed (0.07 km^2). One hour delay was observed for Kijigao, while no significant delay was found for Tsutsujigaoka. The time–area method (WMO, 1974) was adopted for the Kijigao watershed. Since the major river reach to the discharge measurement point in Kijigao is four times longer than that of Tsutsujigaoka, the river reach was divided into four equal sections having 15 min flow time each. Four surface runoff rates from the divided river reach were then superposed. Since hourly rainfall intensity was only available in the study area, 15-min rainfall intensity was generated by dividing the hourly rainfall intensity into four equal parts.

Figure 7 shows the results for the direct surface runoff component, for 8 June 2000, in both Kijigao and Tsutsujigaoka watersheds. Although the calculated result for Kijigao seems to be slightly greater than the graphically separated component, the hydrograph calculated by the present method agrees reasonably well with the graphically separated component.

CHARACTERISTICS OF PARAMETERS USED IN THE GROUNDWATER RECHARGE MODEL

The important question, whether the proposed recharge model is applicable to the different basins by changing the model parameters, was examined next. Table 2 shows the estimated parameter values of the recharge model applied for both Ito campus and Ohnojyo City, together with the current land-use type.

It should be noted that the Tsutsujigaoka watershed is covered by dense residential areas compared to the more sparse residential area near the Ito campus of Kyushu University in Fukuoka City. Therefore, the Tsutsujigaoka watershed is classified as a Type II residential area. In Kijigao watershed, where the forest areas are preserved, the depth to groundwater table is about 9 m, so deeper than at the Ito campus, where the groundwater table is usually 1–5 m from the ground surface. Corresponding to the depth of groundwater level, the Kijigao watershed is classified as Type II forest, in order to distinguish it from the Ito campus before construction.

Average values for parameters of different land uses are shown in Fig. 8(a). As understood from the principles of the groundwater recharge model, the direct surface runoff rate becomes larger as F_∞ increases for the same rainfall intensity. The value of F_∞ at Tsutsujigaoka was set equal to 0.80. This value is much larger than those for other land-use types, corresponding to 0.2 or 0.3 in Table 2. This difference is related to the ground surface conditions. However, there is less significant difference in $(r)_{1/2}$ for the Type I and Type II residential areas. This could be explained by the fact that F_∞ is more dominant in controlling rainwater separation at the ground surface. Although $(r)_{1/2}$ values for both Type I and Type II residential areas are similar, $(r)_{1/2}$ values in Type I and Type II forest areas are significantly different. This is due to the fact that the weathering levels of the cretaceous Itoshima granodiorite and Sawara granite are different. In fact, for the Type I forest of the former Ito campus region, $(r)_{1/2}$ is smaller than that of the Type II forest at Kijigao. Also, it is known that the weathered depth of Sawara granite found particularly in Ohnojyo City is generally deeper than the Cretaceous Itoshima granodiorite at the Ito campus.

Figure 8(b) depicts the relationship between H_g and R_0. It seems that this is well described by a linear relationship. This could be explained by the fact that more pore space above the

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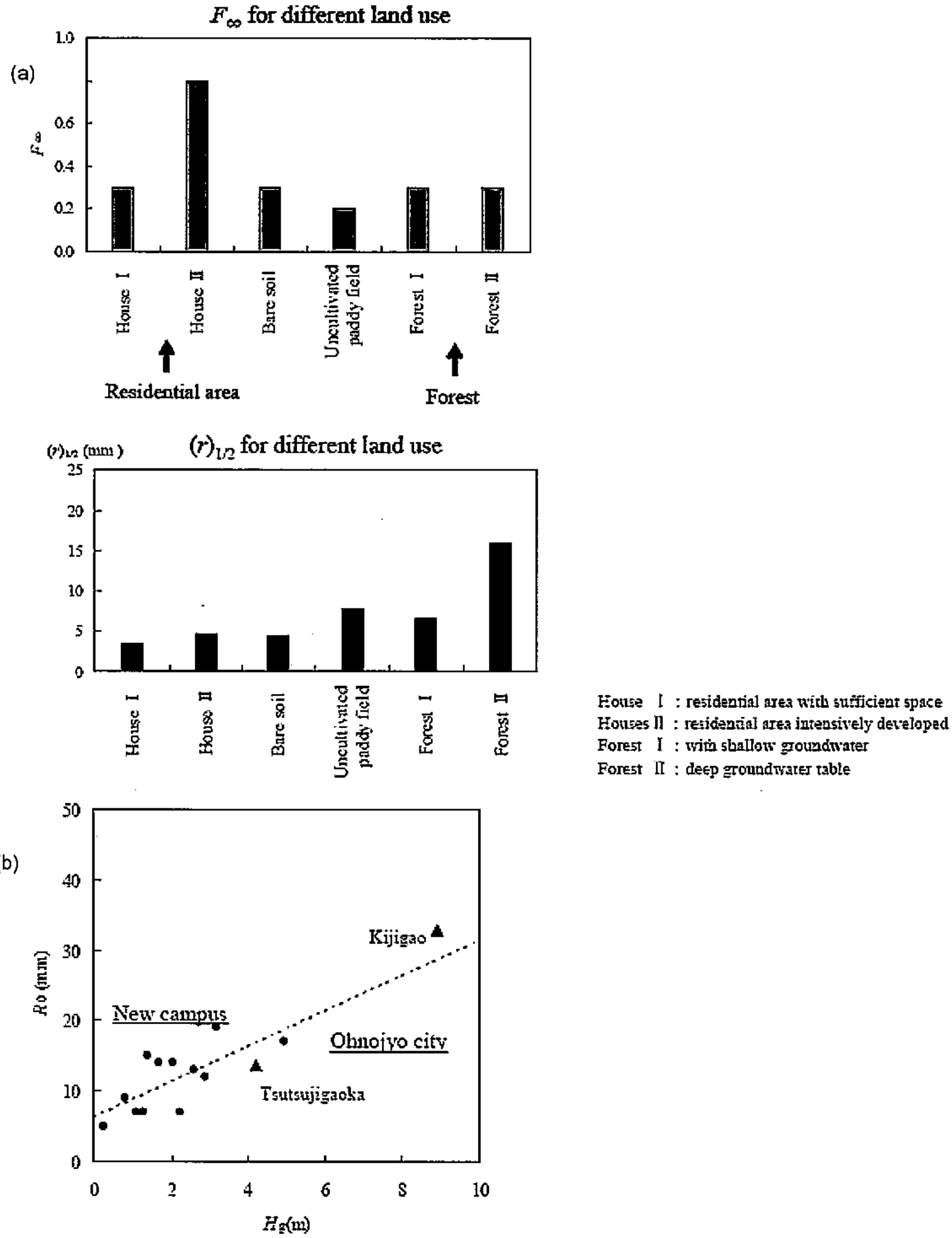

Fig. 8 (a) Classification of F_∞ and $(r)_{1/2}$ for different land uses. (b) Relationship between R_0 and H_g.

groundwater table needs to be filled with rainwater before the groundwater table starts to rise. Consequently, R_0 becomes large where the groundwater level is deep. If a relationship according to Fig. 8(b) is applicable, R_0 may be estimated based on observed groundwater depth. However, it should be noted that the groundwater depth changes seasonally depending on both the rainfall and groundwater exploitation.

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Table 2 Estimated parameters of the groundwater recharge model.

Location	Well no. Watershed	H_g (m)	n_e (-)	a_L (1 h^{-1})	R_0 (mm)	$(r)_{1/2}$ (mm)		F_∞	Land use
New campus of Kyushu Univ.	WL1	2.24	0.075	0.22	7.0	3.8	Average	0.3	Residential area Type I
	WL6	2.59	0.140	0.09	13.0	2.5	3.4		
	WL8	1.70	0.200	0.17	14.0	1.6			
	WL9	3.20	0.225	0.30	19.0	4.5			
	WL11	2.89	0.280	0.20	12.0	4.7			
	WL15	1.39	0.129	0.44	15.0	5.3	Average	0.3	Bare soil land
	WL16	0.81	0.125	0.11	9.0	5.5	4.4		
	WL21	1.28	0.080	0.43	7.0	2.5			
	WL17	2.06	0.090	0.51	14.0	8.5	Average	0.2	Unused paddy field
	WL19	1.11	0.175	0.39	7.0	9.0	7.7		
	WL23	0.27	0.175	0.19	5.0	5.7			
	WL24	4.96	0.225	0.13	17.0	6.6	6.6	0.3	Forest area Type I
Ohnojyo City	Kijigao	8.89	0.34	0.15	32.9	16.0	16.0	0.3	Forest Type II
	Tsutsujigaoka	4.22	0.26	0.17	13.6	4.5	4.5	0.8	Residential area Type II

PROCEDURES FOR CHANGING THE PARAMETERS FOR LAND-USE CHANGE

To predict land-use effects on hydrological processes it is common that only the surface runoff coefficient is modified. However, there are many other factors which need to be considered when land use is changed: the change in elevation, the effect of compaction or removal of soft surface soil, etc. This means that other parameters also need to be examined if they are likely to affect the hydrological processes near the ground surface.

It is worthwhile examining whether the present hydrological response to rainfall in the Tsutsujigaoka watershed, a dense residential area, can be represented by changing the parameters of the groundwater recharge model when the land use is altered in Kijigao watershed, a natural forest. Several scenarios were checked for the rainfall event of 8 June 2000: (a) to increase F_∞, (b) to decrease R_0 to describe the ground clearing, and (c) to decrease $(r)_{1/2}$ assuming that the ground surface is made less permeable by land development. It should be noted that the outlet coefficient a_L was not changed, as it was assumed that infiltration of rainwater through the unsaturated zone above the groundwater table is not significantly affected by land-use change.

Application of larger F_∞ in Kijigao

Figure 9(a) shows the predicted rise in the groundwater level in Kijigao watershed when F_∞ is changed to 0.8 from 0.3, based on the values in Table 1 (assuming that the trees in Kijigao watershed are cut down to develop a residential area similar to Tsutsujigaoka). For comparison, the current groundwater level in Tsutsujigaoka is also depicted. It should be noted that the simulated groundwater level rises higher than the present groundwater level of Tsutsujigaoka, in spite of a larger F_∞ value being used. This result can be explained by the fact that more rainwater can reach the ground surface and, consequently, infiltration will increase compared to the original land use. Thus, cutting trees down does not necessarily lower the groundwater level, even if the surface runoff coefficient increases.

Application of smaller R_0 in addition to larger F_∞

The groundwater level in Tsutsujigaoka is at about 4 m depth and at about 9 m depth in Kijigao. Therefore, R_0 was decreased as compared to the original value based on the relationship in Fig. 8, where R_0 is related to the groundwater depth. Two cases were tested: R_0 was set to 1/2 and 1/3 of the original value in Kijigao. It is seen that the case when R_0 was set to 1/2 of the original value is a better choice as compared to R_0 at 1/3 of the original value.

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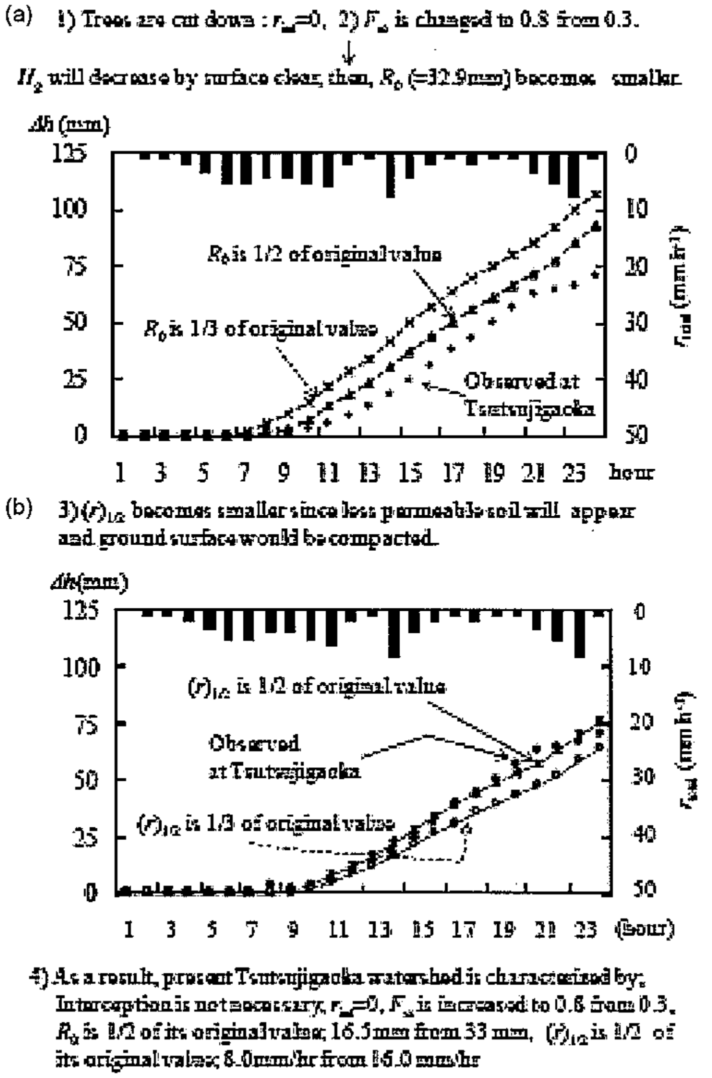

Fig. 9 Parameter adjustment for land-use change from forest to residential area: (a) effect of cutting trees and land clearance; and (b) effect of compaction or less permeable soil exposition.

Application of smaller $(r)_{1/2}$

A smaller $(r)_{1/2}$ value was also applied in addition to changing of F_∞ and R_0. In Fig. 9(b), two cases are presented, with $(r)_{1/2}$ equal to 1/2 and 1/3 of the original values, respectively. When 50% of the value of $(r)_{1/2}$ in Kijigao was assigned to Tsutsujigaoka, the rise of the groundwater level showed changes similar to those in the Tsutsujigaoka watershed. From this result, it is anticipated that another land surface condition, besides F_∞ and R_0, would be necessary. This fact implies that less permeable ground surface should be exposed by either levelling or compacting the surface soil.

CONCLUSIONS

In order to predict the effect of land-use changes on regional-scale hydrological processes, the parameters of the proposed groundwater recharge model were examined. The following results were obtained:

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1. A linear relationship was shown between the vertical distance to the groundwater table H_g and the initial loss denoted by R_0. This relationship demonstrates that when H_g increases, more pore space needs to be filled with rainwater to induce infiltration.
2. When the land surface is levelled, decreasing H_g, the value of R_0 also needs to be decreased. The relationship in the present paper can be used to approximate R_0.
3. Deforestation reduces rainfall interception and increases rainfall amount that reaches the ground surface.
4. When $(r)_{1/2}$ decreases due to compaction work, or the exposure of less permeable soil or less weathered rock at the ground surface, the direct surface runoff rate increases.
5. If the Kijigao watershed in Ohnojyo City, which is a natural forest at present, were deforested in the same way as the Tsutsujigaoka residential area, both R_0 and $(r)_{1/2}$ should be set to half of their original values in addition to changing F_∞ to 0.8.

In conclusion, the relationship presented in Fig. 8(a) and (b) can be used as parameters for the proposed groundwater recharge model. Further verification is necessary in order to confirm that this procedure is applicable for different unconfined aquifers consisting of granite in this region.

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REFERENCES

Alkaeed, O., Florese, C., Jinno, K. & Tsutsumi, A. (2006) Comparison of several reference evapotranspiration methods for Itoshima Peninsula Area, Fukuoka, Japan. *Memoirs of the Faculty of Engineering*, Kyushu University **66**(1), 1–14. http://kenkyo.eng.kyushu-u.ac.jp/memoirs-eng/bulletin.php.

Alkaeed, O., Tsutsumi, A., Jinno, K. & Hiroshiro, Y. (2007) Application of a groundwater recharge model for estimating surface runoff components in Sakurai River watershed, Fukuoka, Japan (Session; B1.b Surface hydrology parameter estimation) (32nd Congress of the International Association of Hydraulic Engineering & Research, 1–6 July 2007, Venice, Italy). CD-Rom, paper no. 546, http://www.iahr.net/site/index.html.

Anderson, M. P. & Woessner, W. W. (1992) *Applied Groundwater Modeling Simulation of Flow and Advective Transport.* Academic Press, San Diego, California, USA.

Beven, K. (1987) Towards a new paradigm in hydrology. In: *Water for the Future: Hydrology in Perspective* (Proc. Rome Symp., April 1987), 393–403. IAHS Publ. 164. IAHS Press, Wallingford, UK http://iahs.info/redbooks/164.htm.

International Network of Basin Organizations (2003) http://www.inbo-news.org/ [last accessed: 13 February 2009].

Klemeš, V. (1983) Conceptualization and scale in hydrology. *J. Hydrol.* **65**, 1–23.

Kondo, J., Nakazono, S., Watanabe, T. & Kuwagata, T. (1992) Hydrological climate in Japan. 3. Evapotranspiration from forest. *J. Japan Soc. Hydrol. Water Resour.* 5(4), 8–18 (in Japanese).

Kristensen, K. J. & Jensen, S. E. (1975) A model for estimating actual evapotranspiration from potential evapotranspiration. *Nordic Hydrol.* **6**, 70–88.

Kyushu University (2006) http://suisin.jimu.kyushu-u.ac.jp/en/index.html [last accessed: 13 February 2009].

Monteith, J. L. (1981) Evaporation and surface temperature. *Quart. J. Roy. Met. Soc.* **107**, 1–27.

Penman, H. L. (1948) Natural evaporation from open water, bare soil, and grass. *Proc. Roc. Soc.* Ser. A **193**, 120–145.

Tsutsumi, A., Jinno, K. & Berndtsson, R. (2004) Surface and subsurface water balance estimation by the groundwater recharge model and a 3-D two-phase flow model. *Hydrol. Sci. J.* **49**(2), 205–226.

Van Lanen, H. A. J. & Demuth, S. (2002) (eds) *FRIEND 2002—Regional Hydrology: Bridging the Gap between Research and Practice* (Proc. Fourth FRIEND Conf., Cape Town, March 2002). IAHS Publ. 274. IAHS Press, Wallingford, UK.

Virtual Water Forum (2003) *Final Report.* Third World Water Forum in Kyoto, Japan.

WMO (World Meteorological Organization) (1974) *Guide to Hydrological Practices* (third edn). WMO-TD no.168, 5.55–5.64. WMO, Geneva, Switzerland.

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