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Estimation of Surface Runoff and Groundwater Infiltration Components by the Groundwater Recharge Model (Itoshima Area, Japan)

by

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Abstract

This paper presents the estimation of the parameters F_∞ and $(r)_{1/2}$ used in the groundwater recharge model by separating the surface runoff component for isolated rainfall event. The time-area distribution method was used. Several types of land use were considered. The watershed of the upstream of Sakurai River at Suematsu Bridge in Itoshima Peninsula which includes the western part of the new campus (Ito campus) area of Kyushu University in southern Japan, was selected as a site study to test the model approach. Since more than 80% of study area is covered with forest, the proposed model considers rainfall interception by forest canopy. The runoff parameters F_∞ and $(r)_{1/2}$ were identified in this study using records of river discharge at the outlet point of the watershed. The results indicate that the separation approach satisfactorily predicted runoff parameters for different land use, and also showed that simulated runoff results agree well with observed results.

Keywords: Groundwater recharge model, Land use, Rainfall event, Rainfall interception, Surface runoff

1. Introduction

Land development often results in adverse environmental impact for surface and subsurface water systems. For areas close to the coast, land use changes may also result in seawater intrusion into coastal aquifers. Due to this, it is important to evaluate potential adverse effects in advance of any land development. Rapid urbanization leading to changed ground surface conditions often means that the time available for planners to include hydrological conservation strategies is not sufficient. Alteration of land use, especially the introduction of impermeable areas, induces a rapid and increased surface runoff and less recharge to shallow groundwater. These adverse effects are

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typically found in rapidly growing metropolitan areas where infrastructure development is lagging behind the pace of urbanization [1), 2)].

In order to adequately manage the local hydrological cycle due to land use changes, the above key hydrological processes need to be effectively foreseen with a level of confidence.

Therefore, understanding the flow of water including surface runoff and groundwater flow through watersheds is essential for accurate analyses of many environmental problems, since surface runoff and groundwater flow are considered as central components of most aspects of water resources and water management [3)].

The efficient utilization of surface and ground water as agricultural irrigation, drinking water and wineries is an important issue in Itoshima Peninsula, the western region of Fukuoka City, Japan, where a new campus of the Kyushu University (Ito Campus) is under construction [4)]. The construction of a new university campus and urbanization in the neighbouring area is anticipated to reduce the groundwater flow toward the residential areas. Therefore, hydrological components such as surface runoff discharge, groundwater recharge to the shallow groundwater, groundwater spring to the ground surface, groundwater level and movement of both freshwater and saltwater need to be analyzed [2)].

In the present study, a simple but efficient approach to estimate surface runoff and groundwater infiltration components by the separation of rainwater reached to the ground surface from groundwater recharge model is proposed. The result is confirmed by comparing the values of runoff and infiltration parameters F_∞ and $(r)_{1/2}$ with those of previous study which has been carried out in Ito campus area by (Tsutsumi. A., et al., 2004).

2. Methodology

2.1 Groundwater recharge model for shallow unconfined groundwater [2)]

The fundamental concept of the proposed groundwater recharge model is only briefly presented in the present paper in order to explain the parameters used in the model. Details of the principles and properties of the model are shown in the paper by authors (Tsutsumi. A et al., 2004).

Figure 1 illustrates the conceptual groundwater recharge model that functions so as to separate the rainwater reaching ground surface into a direct surface runoff component and groundwater infiltration rates.

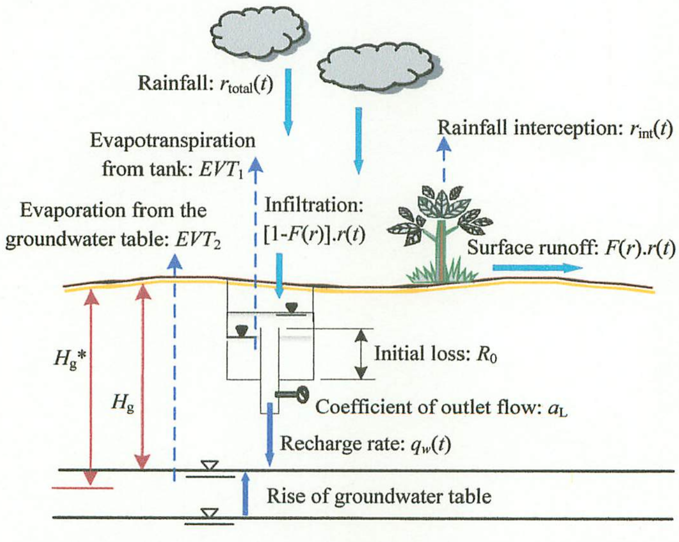

Fig. 1 Groundwater recharge model for unconfined groundwater.

The amount of rainfall interception by forest canopy is denoted by $r_{\mathrm{int}}(t)$ which is evaporated after rainfall has ended. The rainfall that reaches the ground surface $r(t)$ is calculated by

$$r(t) = r_{total}(t) - r_{\mathrm{int}}(t) \tag{1}$$

where $r_{\mathrm{total}}(t)$ is the total rainfall intensity and t denotes time. For areas without trees $r_{int}(t)$ is obviously zero and

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

The rainfall that reaches the ground surface is then separated into two components: the surface runoff that goes directly to the river, whose rate is given as $F(r)\cdot r(t)$ and the infiltration, with rate $[1 - F(r)]\cdot r(t)$, as shown in **Fig. 1.** $F(r)$ denotes the surface runoff coefficient as a function of rainfall intensity. $F(r)$ in the present model is assumed to change as a function of the rainfall intensity as

$$F_i(r) = \frac{r(t)}{r(t)+(r)_{1/2}} \cdot F_{i\infty} \tag{3}$$

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, then only $(r)_{1/2}$ is an undetermined parameter in the equation. The parameter $F_{i\infty}$ depends only on the ground surface condition. For example, $F_{i\infty}$ may be close to 0.3 for forest areas and close to 0.8 for asphalt areas (see e.g. Ven Te Chow, 1964 [5], for typical values). It should be noted that $(r)_{1/2}$ can be identified using observations of either river discharge or the rise in groundwater level. If both observations are available, more reliable estimate of $(r)_{1/2}$ can be obtained and validated from the surface and subsurface hydrological point of view.

The advantage of equation (3) is that practitioners can apply typical local $F_{i\infty}$ values that best describe the ground surface conditions. It is also empirically known that surface runoff coefficient changes with increase in the rainfall intensity. The dependency may be described by the Monod type function. The other parameters such as H_g, H_g^*, R_0, a_L and $q_w(t)$ which are used for describing the evapotranspiration and groundwater recharge rate are also explained in the previous paper (Tsutsumi. A., et al., 2004).

Kondo et al. (1992) [6] presented potential evapotranspiration for a forest covered by trees of 15 m height and a leaf area index (LAI) equal to 6 in summer and 3 in winter. In their study, data from 66 regional meteorological stations in Japan were used for determining interception. The heat balance-bulk method was applied to calculate transpiration and direct evaporation of intercepted rainfall.

Figure 2 shows the monthly precipitation and estimated monthly rainfall interception by Kondo et al. (1992) in Fukuoka and for 12 months, hence, the direct evapotranspiration from the forest canopy can be calculated.

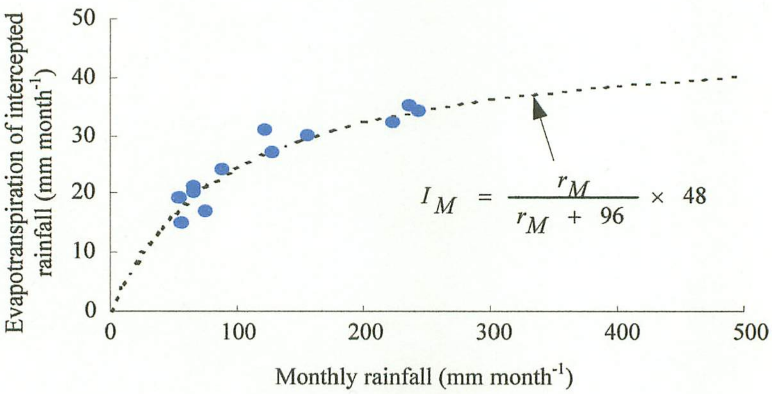

Fig. 2 Evaporation of intercepted rainfall, Dots represent the original data by Kondo et al., 1992. The regression curve was made by the authors.

Equation (4) describes the broken line in **Fig. 2** and was used to calculate direct evapotranspiration for an arbitrary monthly precipitation:

$$\frac{I_M}{r_M} = \frac{48}{r_M + 96} \tag{4}$$

where r_M denotes monthly rainfall and I_M monthly interception.

The mean annual interception from 1986 to 1990, given by Kondo et al. in Fukuoka, was 305 mm year^{-1} for a mean annual precipitation of 1519 mm year^{-1} and this ratio approximately accounts for 20% of the annual precipitation.

Ogawa et al. (2001) [7] reported that the rainfall interception in Fukuoka was 126.7 mm, transpiration was 101.8 mm and the through fall was 267.0 mm during the periods 15 July- 15 September, 11–26 November and 1–14 December 1999, in Fukuoka. For the same periods, the total rainfall was 495.5 mm. The ratio of interception for this period was 25.6%.

Fukushima & Suzuki (1987) [8] also reported that the observed rainfall interception accounted for 20% of the precipitation from 1971 to 1981, based on water balance calculations. It therefore appears reasonable to use the suggested empirical relationship for estimating interception by forest canopy at the study area.

2.2 Isochrone method (Time-area distribution method) [9]

The isochrone method is an expression of one of the fundamental concepts of runoff from a basin. The runoff from different portions of a basin arrives at a point in the stream at different times. The first water to appear in a stream rise comes from the area near the catchment outlet. Later, water comes from larger areas in the central portion of the basin and, finally, water comes from remote portions of the catchment area. Thus, the basin may be divided into zones from which the water arrives sequentially at the measurement point. The lines dividing these zones are called isochrones as shown in **Fig. 3**. The distribution of the isochronal area (the time-area distribution) is considered as being constant for a given basin for all flood hydrographs.

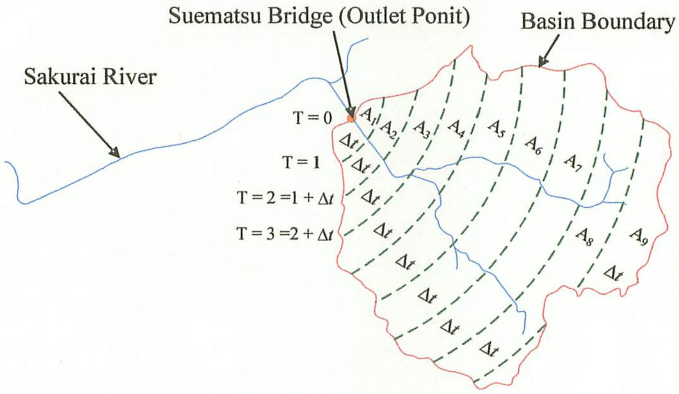

Fig. 3 Basin map with isochrone.

In order to compute this distribution it is necessary to compute or assume an average travel time as explain later. The isochrones are drawn according to the average travel time. The area of each zone is then determined and the values are plotted against the corresponding time lag.

2.3 Site description

The site which has been selected for this study is the watershed of a tributary of Sakurai River at Suematsu Bridge, located in Itoshima Peninsula, the western region of Fukuoka City, northern part of Kyushu Island, Japan.

The area of Itoshima in **Fig. 4** was divided into grid elevation points in which every mesh size is set by 50x50 m. The highest elevation of the ground surface is approximately 260 m. a. s. l.

The climate in the area is characterized as having high humidity, and heavy precipitation. The lowland area is used for agriculture such as greenhouse farming and paddy fields.

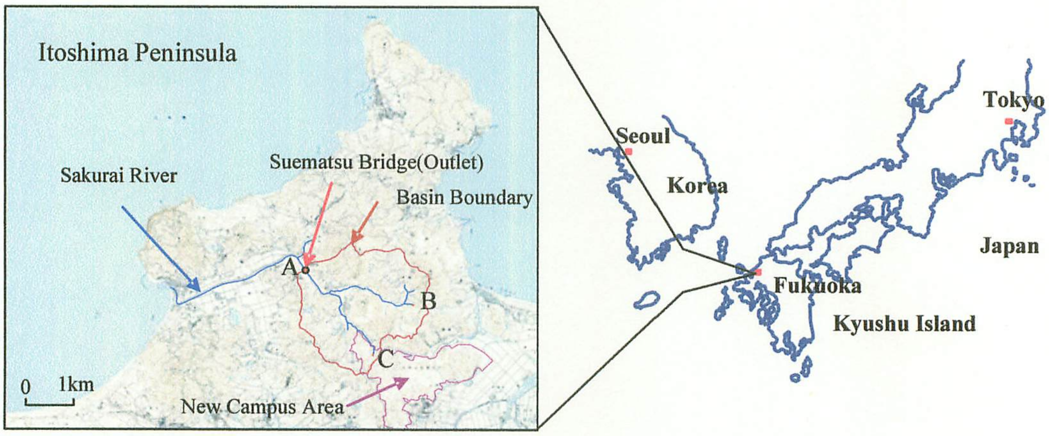

Fig. 4 Location of Suematsu Bridge watershed.

2.4 Land use description

The watershed is mostly vegetation consisted of forest and agriculture with total area 5.84 km^2. Forest constitutes 81% of the watershed. The remaining land use is paddy fields 8%, residential area 5%, water bodies and others are about 6% as listed in **Table 1**.

Table 1 Land use distribution at Suematsu watershed.

No.	Land use type	Area (km^2)	*Area (%)*
1	Forest	4.75	*81*
2	Paddy field	0.47	*8*
3	Residential area	0.29	*5*
4	Water bodies and Others	0.33	*6*
5	*Total Area*	*5.84*	*100*

The watershed lies between 13 to 260 meters above mean sea level with the high points generally located on the north and low points on the west. **Figure 4** shows Sakurai River with its tributaries within the watershed and the location of the outlet point A.

A sensor has been put at A Suematsu outlet point to observe the water depth of the river every 10 minutes. The hourly precipitation data in the present study was obtained from the Maebaru Automated Meteorological Data Acquisition System (AMeDAS) station which is located in Maebaru City, and the 10 minutes rainfall data was recently available at new Kyushu University Campus.

3. Result and Discussion

3.1 Identification of travel time

The travel time between the remote point in **Fig. 4** and the outlet was calculated based on equation (5) which is approved by Japanese Ministry of Agriculture;

$$T = 1.67 * 10^{-3} (l / \sqrt{s})^{0.7} \quad (5)$$

where T: is the travel time in hour between the remote point and the outlet point (hr). l: is the actual length between the remote point and the outlet point (m). s: is the average gradient between the remote point and the outlet point.

Table 2 shows the result of travel time between B point and outlet point A of the watershed in **Fig. 4**.

Table 2 Result of travel time in the watershed area between B and A.

Outlet	Tributary	l (m)	$\sqrt{s}$	T (hr)
A	B-A	2642	0.159	1.5

Depending on the result of **Table 2** and according to the time-area method, the watershed area can be divided into 9 equal travel time or 9 isochrones every 10 minutes as listed in **Table 3** and shown in **Fig. 5**.

Table 3 Area of each zone in the catchment corresponding to its travel time.

	A1	A2	A3	A4	A5	A6	A7	A8	A9
T_I[min]	10	20	30	40	50	60	70	80	90
Area [km^2]	0.29	0.45	0.37	0.68	0.71	0.94	0.84	0.95	0.61

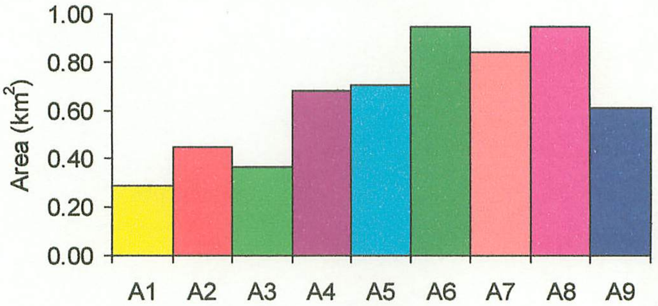

Fig. 5 Area of each zone of the catchment [km^2].

3.2 Relationship between water depth and discharge of the river

Flow observation was made at the outlet point of the watershed, point A in **Fig. 4** for the river water depth. The river water depth has been recorded every 10 minutes as shown in **Fig. 6** for the time period started since 12:00 o'clock of 7th of March 2005.

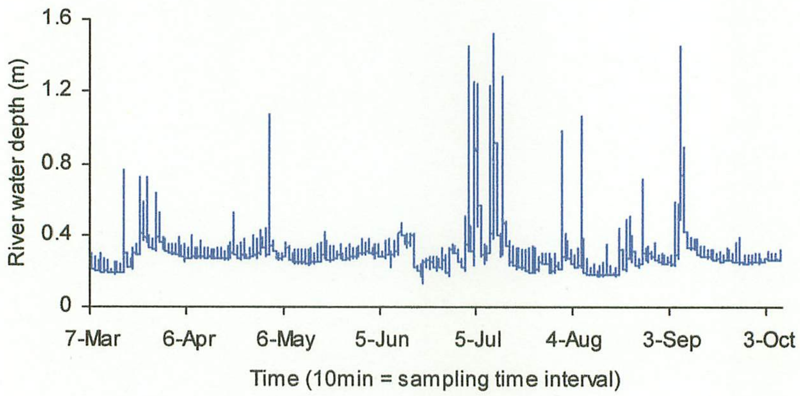

Fig. 6 Observed river water depth every 10 minutes.

The relationship between the river water depth and the discharge of the river is shown in **Fig. 7**.

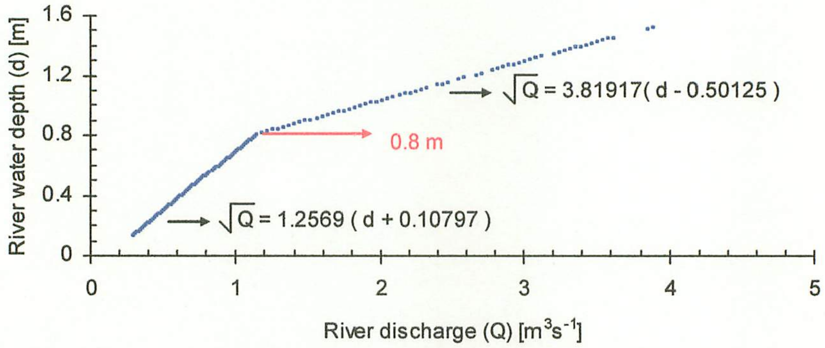

Fig. 7 Relationship between the river water depth and discharge.

The transformed result of observed river discharge is shown in **Fig. 8**.

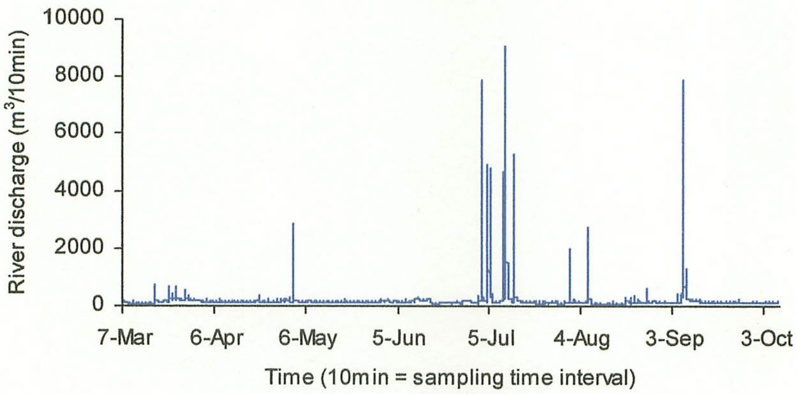

Fig. 8 Transformed result of observed river discharge.

3.3 Result discussion

In order to clarify basic hydrological processes in the study area, rainfall–runoff properties, specifically the direct surface runoff component was analyzed. This component can be utilized to verify the present groundwater recharge model by comparing the direct surface runoff component and the rainwater infiltration rate, if the record of groundwater level is available. The parameters F_∞ and $(r)_{1/2}$ used in the proposed model in **Fig. 1** can easily be evaluated because this procedure is basically independent from the groundwater simulation. It should be also remembered that these parameters can be determined by using the record of groundwater rise for the initial stage immediately after rainfall event, since the short term response of groundwater level induced by rainfall may be described by the groundwater recharge model.

The river discharge at the outlet point A in the present study area as shown in **Fig. 4** was measured every 10 minutes and used in the model approach, together with observed rainfall from the nearby meteorological station, the direct surface runoff was found to be dominant,

Figure 9 shows the 10 minutes rainfall and corresponding river discharge for the period study, from 15/March/2005 to 7/October/2005. The discharge is characterized by large flows in June–July-August, corresponding to the rainy season.

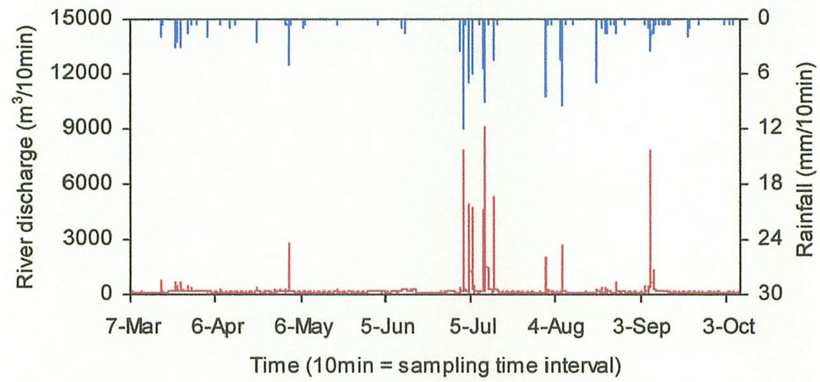

Fig. 9 River discharge and rainfall at point A in **Fig. 4** from March to October 2005.

Two single rainfall events were analyzed in the present paper in order to validate the proposed model to separate rainwater into surface runoff discharge and groundwater infiltration rate at ground surface.

One of them occurred on 17th of March 2005 that is out of rainy season is shown in **Fig. 10**.

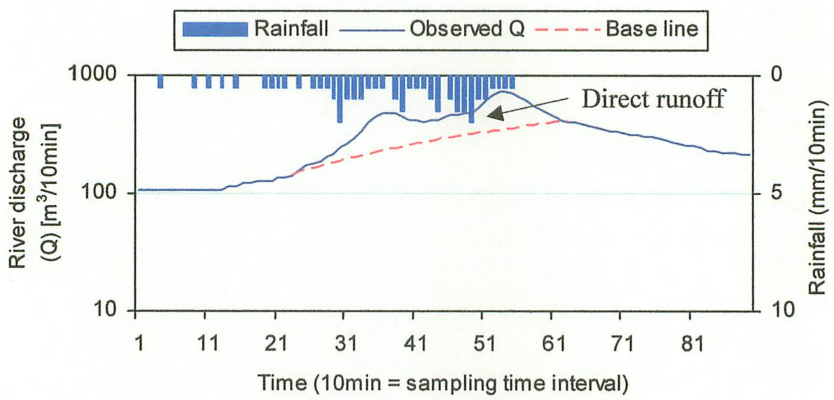

Fig. 10 Rainfall event occurred on 17th of March 2005.

The calculated result of direct surface runoff component is compared with the observed runoff as shown in **Fig. 11**.

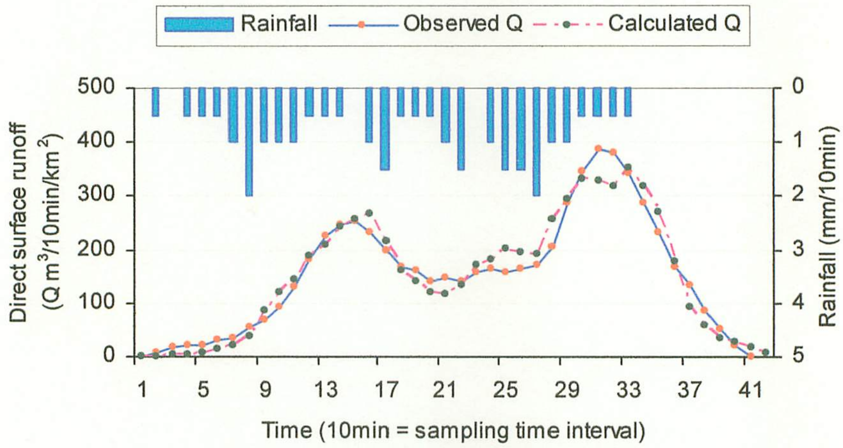

Fig. 11 Result of separated direct surface runoff occurred on 17th of March 2005.

The calculated values of F_∞ and $(r)_{1/2}$ for different land use are shown in **Fig. 12**.

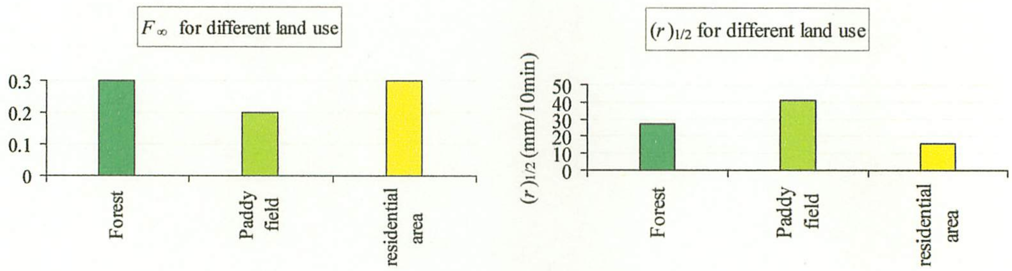

Fig. 12 Values of F_∞ and$(r)_{1/2}$ for different land use.

Analyses were also carried out to the rainfall event which occurred on 31st of July 2005 is in rainy season as shown in **Fig. 13**.

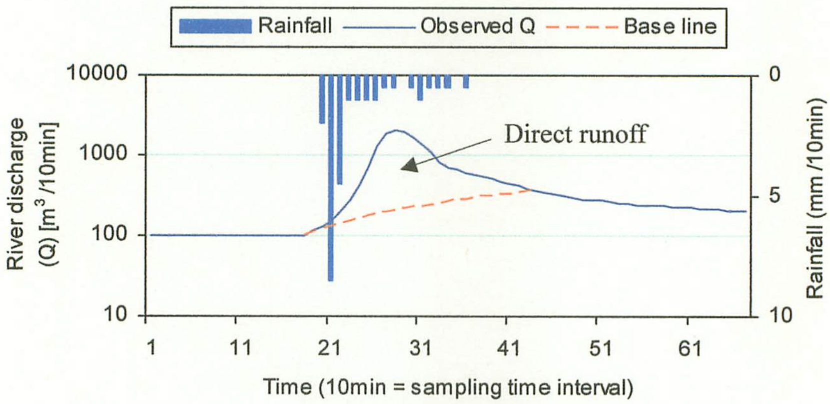

Fig. 13 Rainfall event occurred on31st of July 2005.

The calculated results of separated direct surface runoff of this rainfall event and the average values of the parameters F_∞ and $(r)_{1/2}$ are shown in **Fig. 14** and **Fig. 15** respectively.

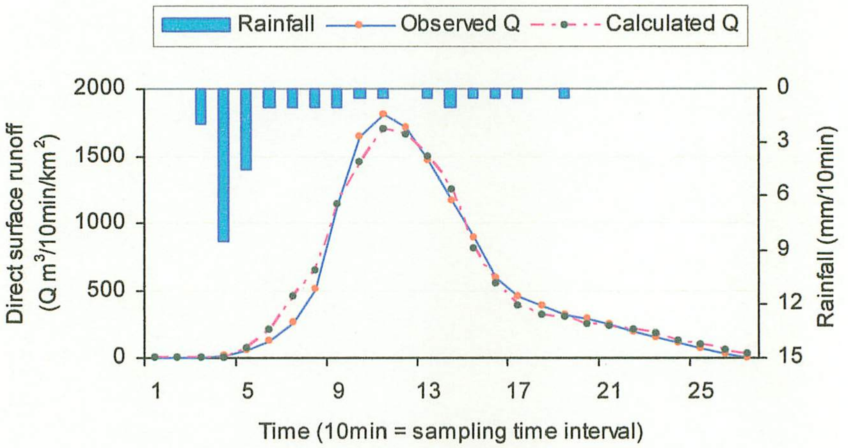

Fig. 14. Result of separated direct surface runoff of rainfall event occurred on 31st of July 2005.

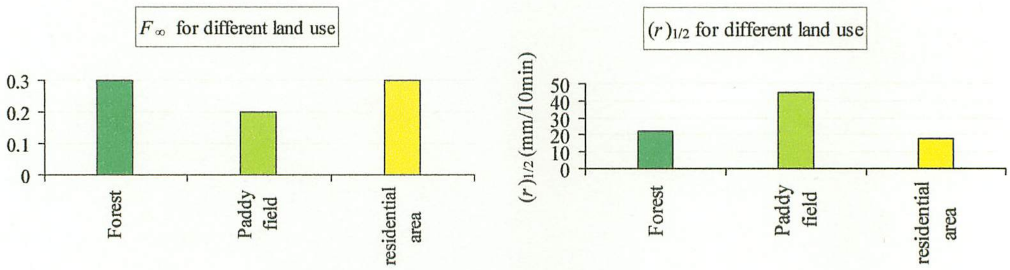

Fig. 15 Values of F_∞ and $(r)_{1/2}$ for different land use.

The two important parameters F_∞ and $(r)_{1/2}$ used in equation (1) which is needed for surface runoff coefficient F(r) for location i of different ground surface conditions. These parameters can be easily evaluated since this procedure is basically independent on the groundwater simulation. It means that for the initial stage immediately after rainfall event, the short term response of groundwater level induced by rainfall is described by the groundwater recharge model. Therefore, the parameters F_∞ and $(r)_{1/2}$ can be separately determined by using the direct surface runoff rate if the river discharge measurement is available, and R_0, n_e, $(r)_{1/2}$ and a_L can be estimated if shallow groundwater variation is recorded with short time interval.

Tsutsumi. A., et al., (2004), have estimated the direct surface runoff in new Kyushu University Campus area using standard graphical base-flow separation. According to their study, the surface runoff component accounts for a maximum of about 10% of the total rainfall after the intercepted rainfall was removed.

In the present study the direct surface runoff component corresponding to the distribution of several land use types was estimated to be 154 mm year^{-1} which accounts10.2% of total rainfall. This can be compared to the 10% estimated by the graphical base flow separation method.

The simulated results of rainfall interception, direct surface runoff, and rainfall infiltration, with their percentage of total rainfall for several land use types are listed in **Table 4**.

Table 4 Average of interception, runoff, and infiltration for 2005. 1500 mm/year was the amount of precipitation in 2005. Unit; mm/year.

Land use type	Interception (%)	Runoff (%)	Infiltration (%)
Forest	275 (18%)	181 (12%)	1054 (70%)
Paddy field	-	147 (10%)	1363 (90%)
Residential area	-	291 (19%)	1219 (81%)

The calculated values of F_∞ and $(r)_{1/2}$ with typical values of F_∞ for different ground surface conditions, and the result of Tsutsumi. A., et al., 2004, are shown in **Table 5**. Tsutsumi et al., 2004, have calculated F_∞ and $(r)_{1/2}$ by groundwater recharge model using the records of the rise in groundwater table in the initial stage before significant horizontal flow takes place. While, in the present study, F_∞ and $(r)_{1/2}$ were identified using the record of river discharge when direct surface runoff components were observed. Interestingly, the identified F_∞ and $(r)_{1/2}$ by using the surface runoff component of the river discharge in the present paper are very close to those obtained by using the rise of groundwater level. The fact means that F_∞ and $(r)_{1/2}$ can be evaluated by the record of either river discharge or groundwater level after rainfall. If both records are usable, cross check of accuracy for surface and groundwater level can be made. Further, it can be said that an application of the present recharge model for regional scale water flow analyses automatically integrates both surface and subsurface hydrological processes.

Table 5 Estimated and typical values of F_∞ and $(r)_{1/2}$.

Land use type	Estimated F_∞	Typical F_∞	Estimated $(r)_{1/2}$ mm/10min	Tsutsumi. et. al $(r)_{1/2}$ mm/10min
Forest	0.3	0.3	22~27	39.6
Paddy field	0.2	0.2	41-45	46.2
Residential area	0.3	0.3	16-18	20.2

4. Conclusion

A groundwater recharge model and time-area distribution method were applied for determination the parameters used in the groundwater recharge model and subsequently the surface runoff components at Sakurai river, Suematsu bridge watershed in Itoshima Peninsula, Japan, for 2005.

Two separated hydrographs for 2 different rainfall events, and 4 land use types with different slopes, were analyzed.

The proposed model was shown to be able to separate rainwater into surface runoff and groundwater infiltration rate at ground surface in a realistic way.

The average direct surface runoff obtained by the proposed model was approximately 10% of total rainfall, similar to the result estimated by the graphical base flow separation method.

It was verified that F_∞ and $(r)_{1/2}$ can be identified using the record of either river discharge when direct surface runoff component is observed or the rise in the groundwater table at the initial stage before significant horizontal flow takes place. It was suggested that more reliable estimate of F_∞ and $(r)_{1/2}$ can be obtained from the surface and subsurface point of view if both records are available.

It should be emphasized that an application of the present groundwater recharge model for regional scale water flow is applicable for the simultaneous study of both surface and subsurface hydrological processes.

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