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Development of distributed red soil runoff model using radar data

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Abstract Okinawa region (the south part of Japan) has been suffering from problems caused by red soil runoff. This region is often attacked by heavy rainfall, which causes overland flow and soil erosion. The soil particles of this region are very fine and will not sink once they are involved in water flow. The muddy water pollutes the shores and coasts, and causes heavy damage to ecosystems of the sea, farming and tourism. The final goal of this research is to develop a distributed red soil runoff model combined with the rainfall data observed by the bistatic radar, which the Communications Research Laboratory (CRL) is now installing at Okinawa main island. In this paper, we developed a distributed red soil runoff model based on a kinematic wave flow model and a digital topographic model, as a preliminary step to the research. The model was applied to Taiho River basin (24 km^2), which is located at the north part of Okinawa main island. The application did not show favourable results. The model should be improved so that it takes into account the change of land cover, which has considerable influence on soil erosion processes.

Key words distributed model; Japan; Okinawa region; red soil; runoff; slope erosion

INTRODUCTION

Okinawa region (the south part of Japan) has been suffering from problems caused by severe red soil runoff (Yoshinaga *et al.*, 1996). This soil is distributed over Okinawa region and is red-yellow. It is quite erosive because it consists of very fine particles and has medium permeability (Noborikawa & Terasawa, 1982; Onaga & Yoshinaga, 1988). When the soil is eroded and involved in water flow, the soil particles will not sink and will stay in the water for a long time. Since the courses of rivers in Okinawa region are generally short and steep, the muddy water containing red soil particles easily reaches the shores and coasts, and it causes heavy damage to ecosystems of the sea, farming and tourism.

In order to mitigate the red soil runoff, it is essential that the volume of the soil runoff be predicted and the effects of countermeasures be evaluated by using a physically-based model. The final goal of this research is to develop a distributed red soil runoff model combined with rainfall data observed by the radar which Communications Research Laboratory (CRL) is now installing at Okinawa Island. This radar will be able to observe spatial distribution of rainfall with high resolution as well as the size distribution of rain drops, which has considerable influence on the soil detachment. In this paper, we developed a distributed red soil runoff model based on a rainfall–runoff model developed by the authors (Shiiba *et al.*, 1998, 1999; Ichikawa *et al.*, 2001), as a preliminary step to the research.

METHODOLOGY

The volume of the red soil runoff has strong relation to the rainfall–runoff processes. Therefore, in order to precisely evaluate the volume of the soil runoff, a rainfall–runoff model which can physically describe the rainfall–runoff processes is needed. As mentioned above, we have been developing a physically based rainfall–runoff model. This model represents a hill slope as a set of small rectangular planes (slope units), and routes water flow by applying a kinematic wave model to each slope unit (Shiiba *et al.*, 1999; Ichikawa *et al.*, 2001). In this study, we develop a red soil runoff model based on this rainfall–runoff model. However, we have not yet applied it to Okinawa region and do not know whether it can reproduce rainfall–runoff phenomena of the Okinawa region. We then examine the ability of this model before developing a red soil runoff model.

EXAMINATION OF THE APPLICABILITY OF THE RAINFALL–RUNOFF MODEL

Outline of the rainfall–runoff model

The rainfall–runoff model used in this study represents a hill slope as a set of slope units, and routes water flow by using a kinematic wave model considering the field capacity of the soil layer. This model assumes that a part of the water which infiltrates into a soil layer is captured by the capillary force and lateral water flow occurs when water content exceeds the field capacity. The kinematic wave equations considering field capacity (Shiiba *et al.*, 1998) are as follows:

$$h = \begin{cases} h_f + h_c\left\{1 - \left(d - h_f/d\right)^N\right\}^{1/N} & (0 \le h_f < d) \\ h_f + h_c & (h_f \ge d) \end{cases} \tag{1}$$

$$q = \begin{cases} ah_f & (0 \le h_f < d) \\ \alpha(h_f - d)^m + ah_f & (h_f \ge d) \end{cases} \tag{2}$$

where q is discharge per unit width, h is water content, h_f is free water content, $a(= k\sin\theta/\gamma_e)$ is water flow velocity in a soil layer, k: permeability, γ_e: effective porosity

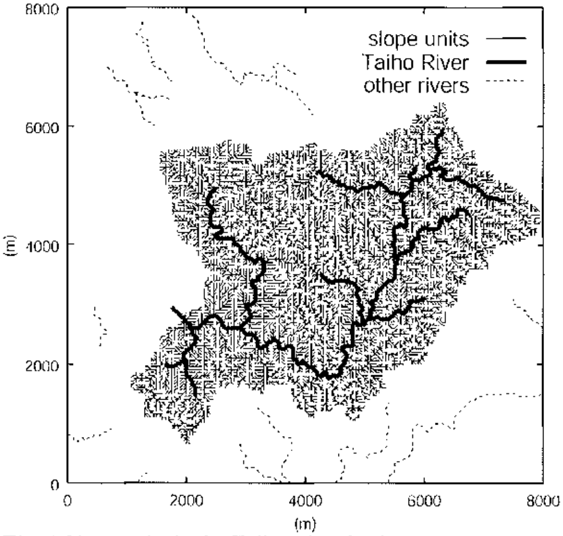

Fig. 1 Slope units in the Taiho River basin.

of a soil layer, $d(=\gamma_e D)$ is depth of effective pore contained in a soil layer, D: depth of a soil layer, $\alpha = \sqrt{\sin\theta}/n$, θ is slope gradient, n is Manning's roughness coefficient, m is a constant, N is a constant, $h_c = \gamma_c D$, and γ_c is the field capacity of a soil layer. This kinematic wave model is applied to each slope unit and is solved by using a finite difference scheme.

Application of the rainfall–runoff model

The rainfall–runoff model was applied to Taiho River basin (24 km^2) which is located in the northern part of Okinawa main island. Figure 1 shows the slope units in the basin. They were generated from a grid based DEM whose grid spacing was 50 m. The period of application was from 16 to 18 August 1997. First, we conducted a runoff simulation with the parameter values which we have usually used in the application to Honshu Island (the main island of Japan). The parameter values were given as: $n = 0.3$ (m$^{-1/3}$ s^{-1}), $m = 1.667$ [-], $k = 0.015$ [m s^{-1}], $\gamma = 0.4$ [-], $\gamma_c = 0.1$ [-], $D = 1.0$ [m], and $N = 6.0$ [-].

Figure 2 shows the simulation result with the above values. The solid line, dotted line and dot-dash line are the calculated discharge, observed discharge and observed rainfall intensity, respectively. We can see a considerable difference between the calculated and observed discharge around the time of peak. The observed discharge responds to the temporal variation of the rainfall quickly, while the response of the calculated one is relatively slow. This simulation means that the parameter values used in the application to Honshu Island are not available in the application to the Okinawa region.

Then we revised the values of k $(0.015 \rightarrow 3.9 \times 10^{-5})$, γ $(0.4 \rightarrow 0.5)$, γ_c $(0.1 \rightarrow 0.4)$ and D $(1.0 \rightarrow 0.35)$ on the basis of the information collected from a field survey and the documents (Noborikawa & Terasawa, 1982; Onaga & Yoshinaga, 1988). Figure 3

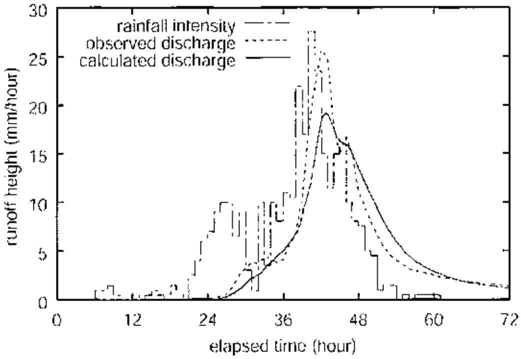

Fig. 2 Rainfall–runoff simulation with the parameter values used in the application to Honshu Island. The period of simulation is 16–18 August 1997.

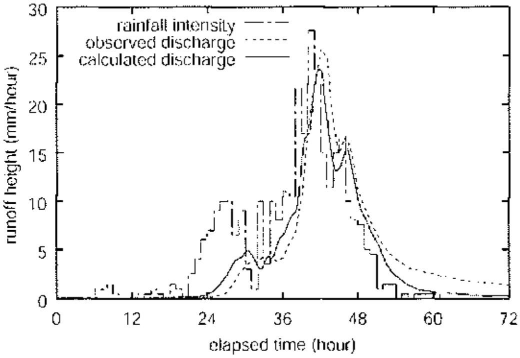

Fig. 3 Rainfall–runoff simulation with the revised parameter values (16–18 August 1997).

shows the simulation result with the revised values. Although there are differences between the calculated and observed discharge around the rising and recession parts of the hydrographs, the degree of agreement of the hydrographs was generally improved. Figure 4 shows the simulation result of another period (1–2 October 1997) with the revised parameter values. This simulation also shows a reasonable result. These

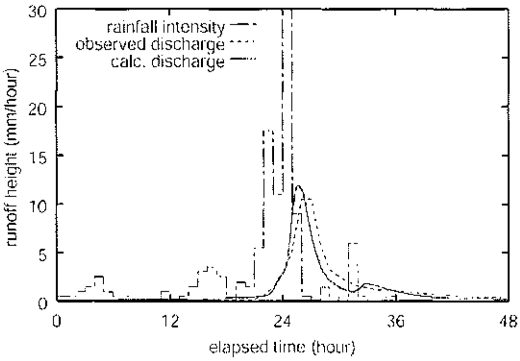

Fig. 4 Rainfall–runoff simulation with the revised parameter values (1–2 October 1997).

simulations mean that the rainfall–runoff model has sufficient applicability to Okinawa region if the parameter values are properly determined. In the next section, we develop a red soil runoff model based on this rainfall–runoff model.

DEVELOPMENT OF RED SOIL RUNOFF MODEL

The weight of eroded fine particles per unit area and unit time, m_f, is given by the following equation (Ashida *et al.*, 1980):

$$m_f = \rho_s E(1-\gamma)p_f \tag{3}$$

where ρ_s is density of the soil (kg m^{-3}), E is erosion rate (m s^{-1}), γ is porosity of the soil [-], and p_f is percentage of fine particles in the soil by weight. ρ_s, γ and p_f are the physical properties which are known by using soil tests. In order to evaluate E, we employ a relationship between the erosion rate and the friction velocity which was obtained by Ashida & Tanaka (1974).

Ashida & Tanaka (1974) conducted an experiment of clay erosion and examined a relationship between E/u_* (erosion rate/friction velocity) and τ/τ_c (tractive force/critical tractive force). From the experiment, they found that the erosion rate increased considerably with increasing tractive force when τ/τ_c was nearly equal to 1, while E/u_* was almost constant when τ/τ_c exceeded 5, and that the constant value ranged between 10^{-4} and 10^{-5}. In the field test of bare ground erosion, Ashida *et al.* (1980) also detected that the relationship E/u_* became constant when the tractive force increased considerably. The constant value was observed to be 10^{-3}–10^{-4}. In this study, we assume that the tractive force becomes sufficiently large when the surface flow occurs, and evaluate the erosion rate as the product of the friction velocity and a constant value. This constant value is determined by calibration in this study, although it should be obtained from an experiment or a field test.

From the above discussion, we give the basic equations of the red soil runoff model as:

$$\frac{\partial(CA)}{\partial t} + \frac{\partial(CQ)}{\partial x} = R_E \tag{4}$$

$$R_E = \rho_s E(1-\gamma)p_f S \tag{5}$$

$$E = cu_* \tag{6}$$

where C is concentration of suspended soil, A, Q and S are cross-sectional area, discharge and wetted perimeter of surface flow, respectively, R_E is rate of soil entrainment, and c is a constant.

The discharge and cross-sectional area of surface flow can be calculated by using the rainfall–runoff model. Also, S in equation (5) and u_* in equation (6) can be calculated from the water depth of surface flow. These three equations are applied to each slope unit, and C is calculated by using a finite difference scheme. This model assumes that the erosion of the red soil due to surface flow occurs on the slope units of bare ground including the cultivated land.

APPLICATION OF THE RED SOIL RUNOFF MODEL

The red soil runoff model was applied to Taiho River basin. The same parameter values of the rainfall–runoff model as the application of the rainfall–runoff model were used. The soil density, ρ_s, and the percentage of fine particles, p_f, which are the parameters of the red soil runoff model, were determined as 2750 (kg m^{-3}) and 1.0 [-], respectively. Although the constant, c, in equation (6) should be determined from an experiment or a field test, we have not yet conducted either of them. Then we used the following three values as c: (a) 10^{-7}, (b) 5.0×10^{-8}, and (c) 10^{-8}, in the application of the model. The periods of applications were 16–18 August 1997 and 1–2 October 1997.

Figures 5 and 6 show the simulation results of 16–18 August 1997 and 1–2 October 1997, respectively. The marks (×) in both figures show the observed soil flux and the three lines in the figures are the calculated soil flux hydrographs. Figure 5 shows that the calculated hydrograph of case (B) ($c = 5.0 \times 10^{-8}$) agrees well with the observation. However, Fig. 6 shows that none of the calculated hydrographs agree with the observation. The observed soil flux at the time of peak shown in Fig. 5 is smaller than the one shown in Fig. 6, though the total rainfall amount of the former event (August) is larger than that of the latter event (October) as shown in Figs 3 and 4 (the peak rainfall intensities are almost same). This finding means that the volume of

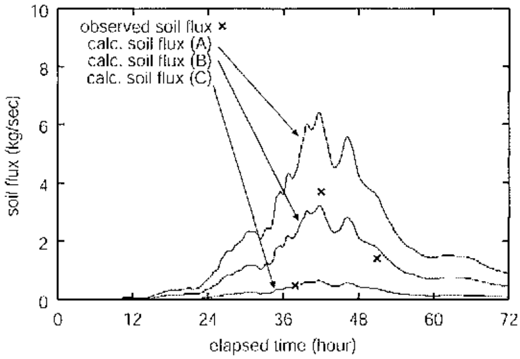

Fig. 5 Red soil runoff simulation (16–18 August 1997).

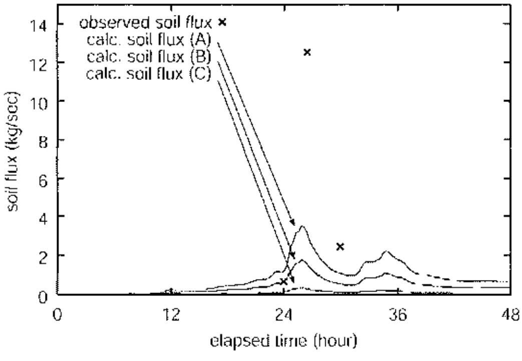

Fig. 6 Red soil runoff simulation (1–2 October 1997).

soil erosion does not always correspond with the magnitude of rainfall event in this basin. The soil erosion processes are considerably affected by the state of land cover, especially in the cultivated land. However, the soil runoff model developed in this study does not take the change of land cover into consideration. The soil runoff model should be improved in this phase.

CONCLUSIONS

In this study, we developed a red soil runoff model for Okinawa region on the basis of the physically-based rainfall–runoff model. We first examined the applicability of the rainfall–runoff model to Okinawa region. The model showed favourable applicability when the parameter values were properly determined according to the soil properties of Okinawa region. Then we developed a red soil runoff model by combining the rainfall–runoff model with the relationship between the erosion rate and the friction velocity, and applied this model to Taiho River basin. Since we have not yet conducted an experiment or a field test to determine the ratio of the erosion rate to the friction velocity, we used the three values as the ratio in the application. We applied the model to two events, and could not find the ratio which was available for both events. The model should be improved so that it takes into account of the change of land cover, which has considerable influence on the soil erosion processes, as well as the soil detachment due to rain drops, whose size distribution will be detected by the radar.

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REFERENCES

Ashida, K., Egashira, S. & Kanayashiki, T. (1980) On the yield of wash load by slope erosion. (Proc. 24th Japanese Conference on Hydraulics), 135–141. JSCE (in Japanese).

Ashida, K. & Tanaka, K. (1974) Erosion and sediment transport mechanism on the sandy bed with some clay content (in Japanese with English abstract). *Ann. Disaster. Prev. Res. Inst.* Kyoto University **17**(B), 571–584.

Ichikawa, Y., Murakami, M., Tachikawa, Y. & Shiiba, M. (2001) Development of a basin runoff simulation system based on a new digital topographic model (in Japanese with English abstract). *J. Hydraul., Coastal Environ. Engng JSCE* **691**, 43–52.

Noborikawa, S. & Terasawa, S. (1982) Physical properties of the great soil groups of Okinawa island (in Japanese with English abstract). *Soil Phys. Cond. Plant Growth* **46**, 2–11.

Onaga, K. & Yoshinaga, A. (1988) Physical properties of major Okinawan upland soils (in Japanese with English abstract). *Soil Phys. Cond. Plant Growth* **58**, 17–29.

Shiiba, M., Ichikawa, Y., Sakakibara, T. & Tachikawa, Y. (1999) A new numerical representation form of basin topography (in Japanese with English abstract). *J. Hydraul., Coastal Environ. Engng JSCE* **642**, 1–9.

Shiiba, M., Tachikawa, Y., Ichikawa, Y., Hori, T. & Tanaka, K. (1998) Development of slope runoff models which consider field capacity and pipe flows (in Japanese with English abstract). *Ann. Disaster Prev. Res. Inst.* Kyoto University **41**(B-2), 229–235.

Yoshinaga, A., Onaga, K. & Sakai, L. (1996) Preventive measures for red clay outflow on farmland in Okinawa and prevention treaty of outflow of red clay (in Japanese). *Water Sci.* **228**, 1–13.