沙漠研究 **22**-1, 307 -310 (2012)
Journal of Arid Land Studies

"ICAL 1 / DT X"
－Refereed Paper－

Effect of Difference in Rainfall Patterns and Intensities on Runoff Simulation Results in Arid Land

Osamu YOKOHAGI[1), Hironori TABUCHI[1), Hideki SUGANUMA[1),
Katsuhiko KUROSAWA[1) and Toshinori KOJIMA*[1)2)

Abstract: Currently, a sustainable carbon fixation system with large scale afforestation in arid land has been established for the mitigation of global warming. We have set a research site near Leonora (rainfall 200 mm: evapotranspiration 2,400-2,600 mm) in Western Australia. In arid land, the most important problem is water shortage for afforestation, because of the small amount of rainfall. In addition, large amount of runoff water flows out without being used by plants in this area. In this study, we developed an original runoff model for understanding water behavior to select appropriate afforestation sites. This model consists of three simulation processes which are penetration, evaporation and runoff as water behavior. This model has two fitting parameters. One is corrective coefficient of penetration (*PR*) and the other is equivalent roughness coefficient (*N*). To estimate these two parameters, a closed hydrographic basin (6 × 5 km^2) including a water collecting pond and its DEM (Digital Elevation Model) data with spatial resolution of 10 meters were used. Rainfall gauges with rainfall amount resolution and time resolution as 0.2 mm and 0.5 s, respectively, were set near the main creek flowing into the pond, and water level indicator was set in the pond. This model simulation was conducted using one hour cumulative data or one minute cumulative data calculated from these rainfall measurement data obtained on 24th March 2003. We also evaluated effects of various patterns of rainfall intensities on calculated results of runoff water behavior using other rain data.

Key Words: Afforestation, Arid land, Carbon fixation, Hydrologic simulation, Runoff model

1. Introduction

For the mitigation of global warming, we have to establish a sustainable carbon fixation system, thus large scale afforestation of arid land which was not used for crop cultivation, has been proposed and tested in Western Australia. The biggest problem for establishment of afforestation is the lack of available water because of the rainfall shortage and the large amount of runoff water loss by evaporation. To avoid such disadvantages, our afforestation system has adopted the water-harvesting system. Also the afforestation area should be selected to use runoff water efficiently (Yamada *et al*., 2003).

In the present series of studies, we aimed to develop an original runoff model for arid land afforestation, and select large scale afforestation by numerical calculation about water behavior. This study focused on the effect of difference in rainfall patterns and intensities of input rainfall data on original runoff model. We compare different patterns of rainfall data input (1 minute cumulative input and 1 hour cumulative input). Also we used not only ideal rainfall data with almost same rainfall at the three rainfall gauges but also other rainfall data comparing results of numerical calculation.

2. Materials and Methods

2.1. Research area

We have set a research place (6 × 5 km^2) which includes an enclosed basin (inside dot-line) near Sturt Meadows station (STM), Leonora, Western Australia as shown in **Figure 1**. In this area, most runoff flows into a catchment pond called Jim's pool. Average annual rainfall of STM is about 200 mm and evapotranspiration is about 2,400-2,600 mm[A), which is classified into arid land (Kojima *et al*., 2006). Furthermore, hardpan layer with extremely low permeability locates between about several tens centimeters deep and a few tens meters deep.

2.2. Observed data

Rainfall gauges (resolution: 0.2 mm, measurement unit: 0.5 s) were installed at three points along the main creek to catchment pond (shown by the squares in Fig. 1). Water level gauge installed at catchment pond (shown by the circle in Fig. 1) and water level data were obtained for every hour (Hamano *et al*., 2010). In this study, we adopted a rainfall data recorded on 24th March 2003. Those data recorded with the three rainfall gauges were very similar, and it was considered as a uniform rainfall event throughout the target area. We used the data as

* Corresponding Author: kojima@st.seikei.ac.jp
3-3-1, Kichijoji-kitamachi, Musashino, Tokyo, 180-8633, Japan
1) Department of Materials and Life Science, Faculty of Science and Technologies, Seikei University, Japan
2) Centre for Ecosystem Management, School of Natural Sciences, Edith Cowan University, Australia

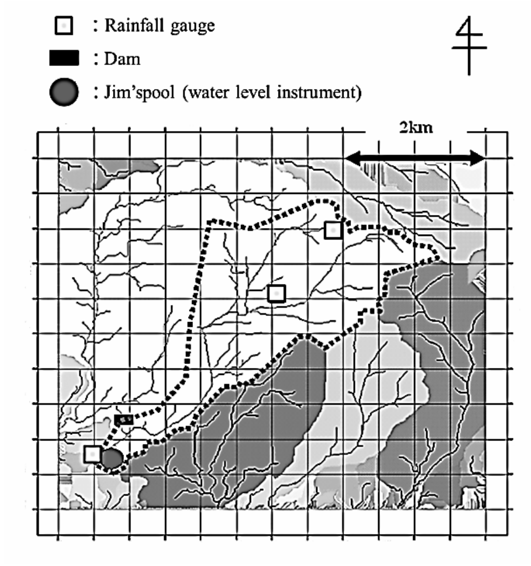

Fig. 1. Research area and locations of instruments.

an ideal rainfall event for the present model development and validation.

2.3. Concept of original runoff model

The present runoff model has been developed to predict water behavior in arid area by inputting only Digital Elevation Model (DEM) data and rainfall data. However, this model needs some measured parameters such as soil depth and initial volumetric water content of soil θ [-] as local environmental conditions. In this study, we adopted 0.15 m for soil depth as the measured averaged data and 0.05 for the initial volumetric water content of soil, the lowest value of the range of possible value between 0.05 and 0.4 (Kojima *et al.*, 2010), because of the actual dry condition.

Time difference method with an interval (time step) for approximating real-time progress was employed to the model. As the water movement expression, penetration, evaporation and runoff after rainfall were calculated in all meshes. DEM with 10m grid spacing (10 m mesh) was purchased from Kevron Aerial Survey Pty. Ltd. and employed as the elevation data in this model. Previous studies revealed that calculation results were affected by time step. The optimal time step depends on the mesh size (Kojima *et al.*, 2010). In this study, optimal time step was set as 0.5 s for 10 m mesh.

2.4. Penetration

Penetration rate was estimated by analyzing the results of cylinder intake rate method with Horton's equation (Eq. (1)) (Horton, 1939). In our model, we modify Eq. (1) giving time variation of penetration rate to give Eq. (2) by giving penetration rate as a function of volumetric water content of soil θ, which is calculated by Eq. (3)

Also penetration rate adjustment factor (*PR*) which was one of the fitting parameters in this model was employed for correcting difference between experiment and actual penetration rate as shown in Eq. (4) (Kojima *et al.*, 2010).

$$f_t = f_c + (f_0 - f_c)\times\exp(-K_f t) = 2.00\times10^{-5} + 3.06\times10^{-5}\times\exp(-3.42\times10^{-3}\times t) \qquad (1)$$

$$f_\theta = -1.530\times10^{-3}\times\theta^3 + 1.487\times10^{-3}\times\theta^2 - 4.782\times10^{-4}\times\theta + 7.115\times10^{-5} \qquad (2)$$

$$\theta = W/0.15 \qquad (3)$$

$$F_\theta = f_\theta / PR \qquad (4)$$

f_t : Permeation rate at time, t [m/s], f_0 : Initial permeation rate [m/s], f_c : Saturated hydraulic conductivity [m/s], K_f : Constant value [s^{-1}], t : Time [s], f_θ : Permeation rate at volumetric water content of soil, θ [m/s], θ : Volumetric water content of soil [-], W : penetrated water depth [m], F_θ : Corrected permeation rate [m/s], *PR* : Correction factor for f_θ [-]

2.5. Evaporation

Evaporation rate was evaluated as the sum of that from surface water and that from soil. Water surface evaporation rate was given as annually average pan evaporation rate as shown in Eq. (5). Evaporation rate from soil was divided into two drying steps from the result of evaporation experiment from soil. Constant evaporation rate E_{S1} was considered to be almost same as evaporation rate from surface water. Thus, E_{S1} was supposed to be equal to E_L as shown in Eq. (6). And also, decreasing evaporation rate E_{S2}, which is slower evaporation rate with decreasing water content of soil, was estimated from evaporation experiment from soil as shown in Eq. (7) (Kojima *et al.*, 2010).

$$E_L = 7.67\times10^{-8} \qquad (5)$$

$$E_{S1} = E_L \qquad (6)$$

$$E_{S2} = E_L \times 54.0 \times (\theta - 0.05)^{2.677} \qquad (7)$$

E_L : Water surface evaporation rate [m/s], E_{S1} : Constant evaporation rate [m/s], E_{S2} : Decreasing evaporation rate [m/s]

2.6. Runoff

Runoff from the target mesh to the adjacent meshes (four directions) was calculated by using Manning's equation (Ven Te Chow, 1959). Manning's equation includes roughness coefficient, n representing stream resistance, while in the present model, equivalent roughness coefficient N was introduced as one of the fitting parameters (Eq. (8)). Manning's equation is the equation for a river with uniform flow, and it couldn't express water movement at a catchment pond. Thus, in this model, error trap was introduced in the runoff calculation. In order to avoid phenomenon of water level oscillation, the flow of water is stopped when levels become horizontally flat. Thus, water level difference before one time step of runoff calculation can't be reversed after one time step of runoff calculation (Kojima *et al.*, 2010).

$$v = \frac{1}{N} R^{2/3} I^{1/2} \quad (8)$$

v : Velocity [m/s], N : Equivalent roughness coefficient [sm$^{-1/3}$]
I : Water surface inclination [m/m], R : Hydraulic radius [m]

2.7. Fitting parameters

This model includes two fitting parameters. The fitting parameters are correction factor for f_t (PR) to correct the difference between experimental penetration rate and actual penetration rate and equivalent roughness coefficient (N) that represents stream resistance of soil surface. Both of the parameters also include the averaging effect inside a wide mesh. In the previous study, sensitivity study of N and PR was conducted (Kojima *et al.*, 2010).

2.8. Rainfall input

The previous study used 1 hour cumulated rainfall data converted from observed rainfall data (Kojima *et al.*, 2010). However, instantaneous intensity of rainfall is often much larger than the time averaged one. Thus in the present study, one minute cumulated rainfall input was used and the calculation results of water behavior was compared with that of 1 hour cumulated rainfall input to evaluate the effect the time resolution for rainfall.

2.9. Other rainfall data

In the previous study the runoff model was applied only to the rainfall data on 24th March 2003. In the present study, we also conducted the calculation for the rainfall data on 1st June 2004 and decided fitting parameters. One hour cumulative rainfall data of the latter were shown in **Table 1**.

3. Results and Discussion

3.1. Effect of difference in rainfall patterns

Difference in overall cumulative rainfall data between one hour cumulative and one minute cumulative rainfall input data is shown in **Figure 2**. Difference in rainfall intensity is also shown in **Table 2**. From Table 2, one minute cumulative rainfall input gives more instantaneously strong rainfall intensity than one hour cumulative rainfall input. The numerical results of time variation of the water level of the catchment pond for the different rainfall patterns are shown in **Figure 3**, with the parameters of N = 0.011 s m$^{-1/3}$, PR = 24.5 which gives the best fit for one hour cumulative input. The numerical results for one minute cumulative input give seriously higher value of water level than the observed one and numerical results from one hour cumulative input. The present results indicate strong effects of instantaneous rainfall intensity on the runoff phenomena. Consequently we decided

Table 1. One hour cumulative rainfall data.

Time[h]	Rainfall[mm]	
	2003/3/24	2004/6/1
0-1	0	0
1-2	1.6	1.8
2-3	9.2	8.4
3-4	2.8	0.8
4-5	0	0
5-6	0	0.4
6-7	0	0
7-8	0	0
8-9	0	0
9-10	0	0

Table 2. Maximum rainfall intensities for two rainfall input patterns.

	Max Rainfallintensity [mm/s]
1 hour cumulative	0.00256
1 min cumulative	0.00667

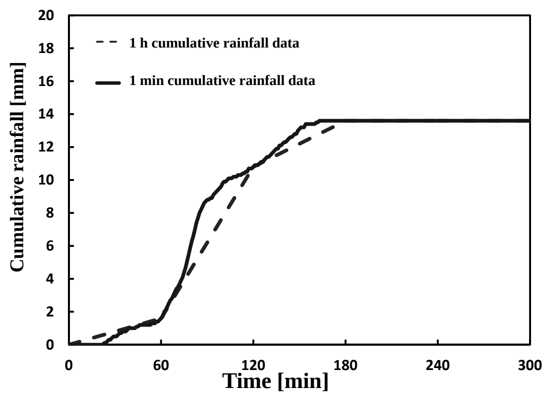

Fig. 2. Overall cumulative rainfall data using one hour cumulative and one minute cumulative rainfall data.

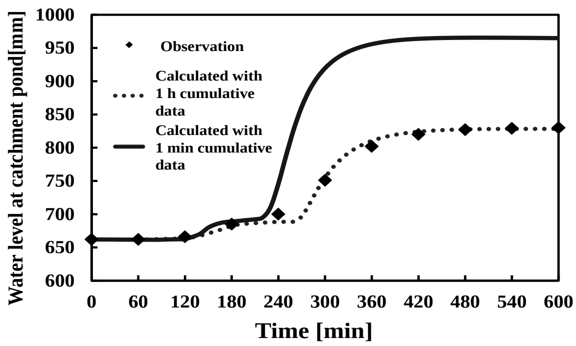

Fig. 3. Observed time variation of water level of catchment pond on 24th March 2003 and numerical results with two different rainfall input patterns (N = 0.011 s m$^{-1/3}$, PR = 24.5).

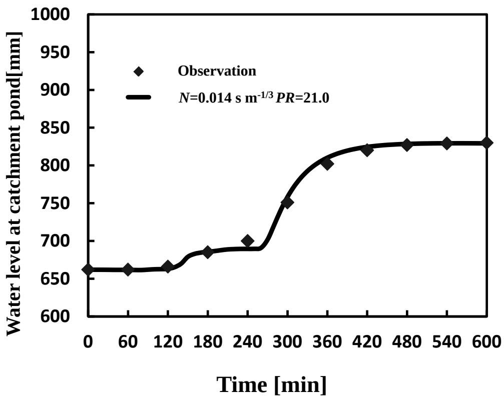

Fig. 4. Observed time variation of water level of catchment pond on 24th March 2003 and numerical results with one minute rainfall input data (N = 0.014 $s\ m^{-1/3}$ and PR = 21.0).

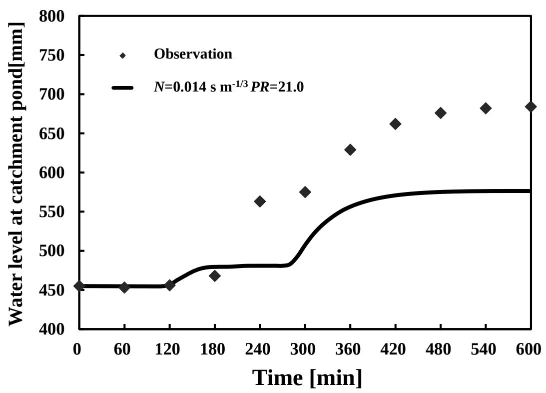

Fig. 5. Water level at Catchment Pond on 1st June 2004.

to use one minute cumulative rainfall input, i.e., closer to the actual rainfall pattern, for further numerical analysis.

3.2. Fitting parameters for one minute cumulative input

We conducted the numerical calculation using original runoff model with one minute cumulative rainfall data. Calculation results are shown in **Figure 4**. The observed water level was well reproduced with one minute cumulative rainfall and with fitting parameters of N = 0.014 s $m^{-1/3}$ and PR = 21.0. It was demonstrated that the observed data were well reproduced with a little bit different fitting parameters.

3.3. Calculation of other rainfall data

We conducted the numerical calculation using the original runoff model with one minute cumulative rainfall data on 1st June 2004 using the same fitting parameters of Figure 4. Calculation results are shown in **Figure 5**. Calculation results did not well fit the observation data. As shown in the previous section, small difference among the rainfall gages data may affect the calculation result of water level of catchment pond, however small modification may improve the matching between numerical and observed results.

4. Conclusion

Our original model was modified to use one minute cumulative rainfall input, and as a result it can express more detail response to instantaneously strong rainfall intensity than one hour cumulative rainfall input. We decided fitting parameters as N=0.014 s $m^{-1/3}$, PR=21.0 for the data on 24th March 2003, whose values did not differ so much. Though the calculated results for other rainfall data on 1st June 2004 did not fit observation data, it is expected that small modification of the fitting parameters will give better fit of numerical results to the observation.

Acknowledgement

This work was conducted under the support of the Mitsui & Co., Ltd. Environment Fund, Grant-in-Aid for Scientific Research (22254002) of Japan Society for the Promotion of Science and the Global Environment Research Fund of The Ministry of Environment of Japan (GHG-SSCP project).

Note

A) Bureau of Meteorology, Australia (http://www.bom.gov.au/jsp/ncc/climate_averages/evapotranspiration/index.jsp?maptype=6&period=an#maps)

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