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Effect of Difference in Vegetation Type on Runoff Simulation Results in Arid Land

Osamu YOKOHAGI[1], Toshinori KOJIMA*[1), 2)], Hideki SUGANUMA[1] and Tadaomi SAITO[3]

Abstract: We have established a research site for afforestation near Leonora (annual rainfall 200 mm evapotranspiration 2,400-2,600 mm y^{-1}) in Western Australia. In arid land, the most serious problem is water shortage for afforestation, because of the rainfall deficiency and fluctuation. In addition, because of high rainfall intensity, large amount of runoff water flows out without being used by plants. To understand water behavior for selecting appropriate afforestation sites, we developed an original numerical runoff model to simulate water behavior. This model consists of three simulation processes which are penetration, evaporation and runoff as water behavior. This model has two fitting parameters. One is penetration rate adjustment factor (*PR*) and the other is equivalent roughness coefficient (*N*). This model simulation was conducted using one minute cumulative data calculated from rainfall measurement data obtained on 24th March 2003. In this study we also carried out cylinder intake rate tests at bare ground (vegetation cover: less than 1%) and grass fields (vegetation cover: 1-10%) to estimate the effect of vegetation type. We made experimental equations according to three types of infiltration formula (Kostiakov, Philip and Horton), and then incorporated them into the penetration process model, which notably affected runoff simulation results.

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. Hence large scale afforestation of arid land, which was not used for crop cultivation, has been proposed and demonstrated in Western Australia (Yamada *et al*., 2003; Kojima *et al*., 2006). 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 a water-harvesting system. Also the afforestation area should be selected to use runoff water efficiently (Kojima *et al*., 2010). In the present series of studies, we aim to develop an original runoff model for arid land afforestation, and select areas suitable for large scale afforestation by numerical calculation about water behavior. This study focused on the effect of differences in three types of infiltration formula (Kostiakov, Philip and Horton) made from different types of cylinder intake rate tests at bare ground (vegetation cover: less than 1%) and grass fields (vegetation cover: 1-10%).

2. Materials and Methods

2.1. Research area

We have established a research site (6×4.8 km^2) which includes an enclosed basin (inside of the dot-line) near Sturt Meadows Station (STM), Leonora, Western Australia as shown in **Figure 1** (UTM coordinate system zone 51: Upper left 301990, 6823670; Lower right 307980, 6818880). 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 y^{-1} [A)], which is classified into arid land (Kojima *et al*., 2006).

Furthermore, a hardpan layer with extremely low permeability is located between about several tens of centimeters deep and a few tens of 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). A water level gauge was installed at the 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 used rainfall data recorded on 24th March 2003. Rainfall data recorded

* Corresponding Author: kojima@st.seikei.ac.jp
3-3-1, Kichijoji-Kitamachi, Musashino, Tokyo, 180-8633, Japan
(Received, September 14th, 2013; Accepted, February 10th, 2014)
1) Department of Materials and Life Science, Seikei University, Japan
2) Centre for Ecosystem Management, School of Natural Sciences, Edith Cowan University, Australia
3) Department of Biological and Environmental Sciences, Tottori University, Japan

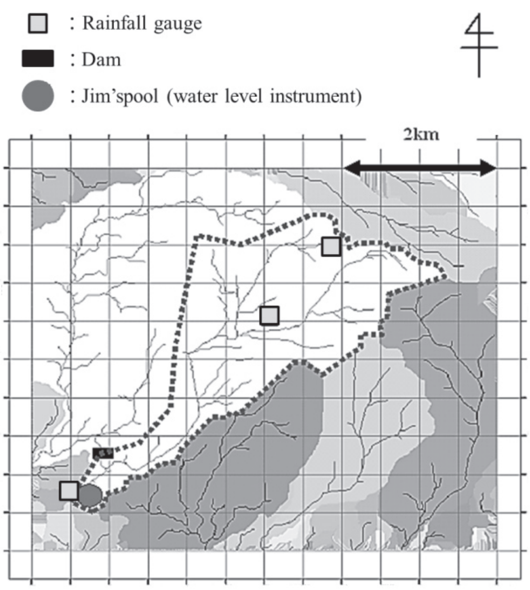

Fig. 1. Flow Area and Locations of Instruments.

by three rainfall gauges were very similar on that day, so these data were considered to indicate a uniform rainfall event throughout the target area.

2.3. Concept of original runoff model

The present runoff model has been developed to predict water behavior in arid areas by inputting only Digital Elevation Model (DEM) data and rainfall data. DEM with 10 m grid spacing (10 m mesh) was purchased from Kevron Aerial Survey Pty. Ltd. and used as the elevation data in this model. 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 the 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 values between 0.05 and 0.4 (Kojima *et al*., 2010) considering the actual dry condition. Time difference method with an interval (time step) for approximating real-time progress was used in the model. As water movement expression, the penetration, evaporation and runoff after rainfall were calculated in all meshes. Previous studies revealed that calculation results were affected by time step, and 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 soil infiltration experimental results by the cylinder intake rate method of two points in bare ground (1. faster 2. slower) and one point in the grass field (3.). We also used three types of infiltration

Table 1. Infiltration formula.

	Kostiakov	Philip	Horton
	$I=kt^{m}$	$I=St^{0.5}+At$	$f_t=f_c+(f_0-f_c)e^{-Kt}$
1	$I=3.03t^{0.82}$	$I=2.82t^{0.5}+0.92t$	$f_t=1.20+(1.363)e^{-0.0541t}$
2	$I=1.37t^{0.72}$	$I=1.28t^{0.5}+0.27t$	$f_t=1.13+(0.722)e^{-0.0657t}$
3	$I=4.92t^{0.78}$	$I=4.80t^{0.5}+1.38t$	$f_t=1.88+(2.480)e^{-0.0579t}$

I : Permeability [mm], k : Coefficients [mm/minm], t : Time [min], m : Coefficients [-], S : Water absorbency [mm/min0.5], A : Final infiltration rate [mm/min], f_t : Permeation rate at time t [mm/min], f_0 : Initial permeation rate [mm/min], f_c : Saturated permeation coefficient [mm/min], K : Coefficients [min^{-1}], t : Time [min] 1: faster penetration bare ground 2: slower penetration bare ground 3: grass field.

formula for simulation (**Table 1**) for their analysis. In our model, we modify infiltration formula in Table 1 giving time variation of permeation I or penetration rate f_t into f_θ, penetration rate as a function of volumetric water content of soil θ. Also penetration rate adjustment factor (*PR*), which was one of the fitting parameters in this model, was employed for correcting differences between experiment and actual penetration rate as shown in Eq. (1) (Kojima *et al*., 2010).

$$F_\theta = f_\theta / PR \quad (1)$$

where F_θ is corrected permeation rate [mm/min]; f_θ is permeation rate at water content of soil θ [mm/min]; *PR* is penetration rate adjustment factor [-].

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 annual average pan evaporation rate as shown in Eq. (2). Evaporation rate from soil was divided into two drying steps from the result of the 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. (3). And also, decreasing evaporation rate E_{S2}, which is slower evaporation rate with decreasing water content of soil, was estimated from the evaporation experiment from soil as shown in Eq. (4) (Kojima *et al*., 2010).

$$E_L=7.67\times10^{-8} \quad (2)$$

$$E_{S2}=E_L \quad (3)$$

$$E_{S2}=E_L\times54.0\times(\theta\text{-}0.05)^{2.677} \quad (4)$$

where E_L is water surface evaporation rate [m/s]; E_{S1} is constant evaporation rate [m/s]; E_{S2} is 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. (5)). Manning's equation is the equation for a river with uniform flow, and it could not express water movement at a catchment pond. Thus, in this model, error trap was introduced in the runoff calculation. In order to avoid the 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 cannot be reversed after one time step of runoff calculation (Kojima *et al.*, 2010).

$$v = \frac{1}{N} R^{2/3} I^{1/2} \qquad (5)$$

where v is velocity [m/s]; N is equivalent roughness coefficient [$sm^{-1/3}$]; I is water surface inclination [m/m]; R is hydraulic radius [m].

2.7. Fitting parameters

This model includes two fitting parameters. The fitting parameters are penetration rate adjustment factor (*PR*) and equivalent roughness coefficient (N). Both of parameters also include the averaging effect inside a wide mesh.

2.8. Evaluation methods

In this study, we calculated simulation model changing fitting parameter N with increment of 0.001, and fitting parameter *PR* with increment of 0.1. The differences between calculation results and the observed data were evaluated by RMSE (Root Mean Square Error) values, and we decided that optimized combination of N and *PR* had the smallest RMSE value.

3. Results and Discussion

3.1. Numerical results using penetration equation for bare ground

Calculation results using Kostiakov's equation and point 1 data are shown in **Figure 2**. From the graph, water level raised around 120 minutes after rain started, which was caused by rainwater that fell near the catchment pond. Although, after 240 minutes, surface runoff water far from upstream reached the catchment pond and water level raised again. In the prediction of surface runoff near the catchment pond, there were few effects of differences in the fitting parameters.

However, in the prediction of surface runoff water from far area, changed fitting parameters affect calculation results. We applied the same evaluation for the various combinations of *PR* and N (N: 0.010-0.020, *PR*: 15-25).

Figure 3 shows comparison of RMSE values and various fitting parameter pairs (N, *PR*) of Kostiakov equation (point 1).

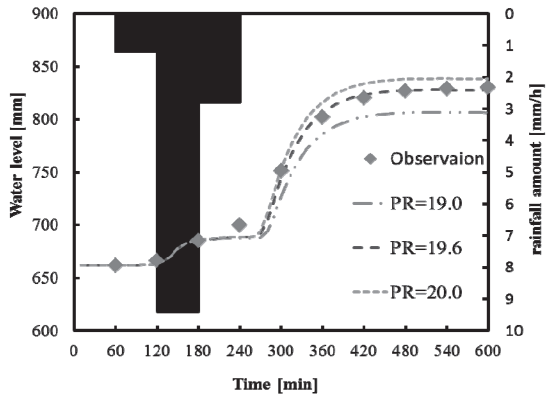

Fig. 2. Comparison of calculation results and observation data (Kostiakov equation of point 1 and N=0.015 $sm^{-1/3}$).

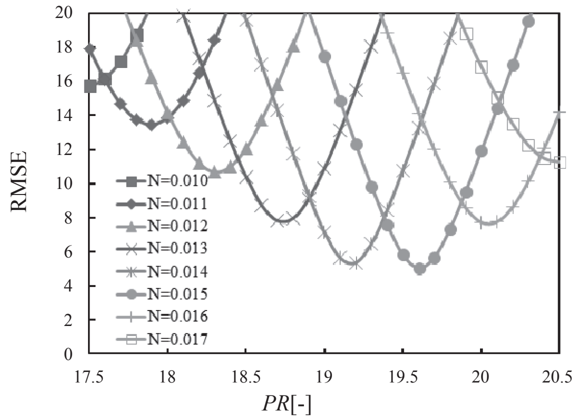

Fig. 3. Comparison of RMSE values and various fitting parameter pairs (N, *PR*) of Kostiakov equation (point 1).

Table 2. Best fit parameter pairs of numerical results 1: faster penetration bare ground 2: slower penetration bare ground 3: grass field.

	Kostiakov			Philip			Horton		
	N	*PR*	RMSE	*N*	*PR*	RMSE	*N*	*PR*	RMSE
1	0.015	19.6	5.04	0.014	18.2	4.96	0.015	20.6	4.78
2	0.014	4.9	5.05	0.014	4.5	6.22	0.014	7.3	4.68
3	0.014	30.5	4.85	0.014	31.5	5.07	0.015	35.4	4.89

Best fit parameter pairs were found to be N=0.015 and *PR*=19.6, which is given in **Table 2**.

The best fit results for using Philip and Horton equations are also shown in Table 2.

Furthermore the evaluations using the penetration data at point 2 are also conducted as for point one and their results are shown in Table 2.

3.2. Numerical results using penetration equation for grass fields

As well as bare ground, we conducted the numerical calculation using infiltration formula by grass fields. Calculation results of Kostiakov's equation of point 3 are

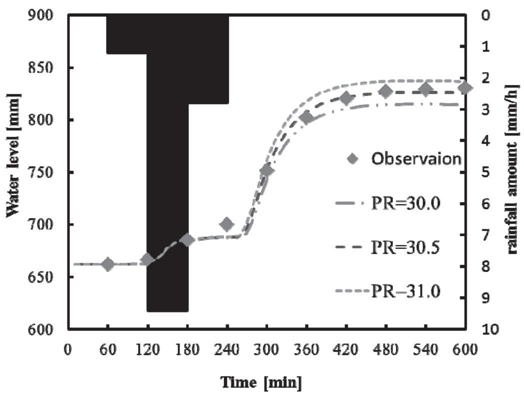

Fig. 4. Comparison of calculation results and observation data (Kostiakov equation of point 3 and N=0.014 sm$^{-1/3}$).

shown in **Figure 4**, including the best fit one.

3.3. Discussion of best fit parameter pairs

Comparing the calculation results of bare ground, fitting parameter of N is almost the same of 0.014~0.015 for all nine cases. But, these results are different from Manning's roughness coefficient, n of 0.025~0.06 for smoothest and roughest natural streams. (Ven Te Chow, 1959). We consider that differences between fitting parameter N and Manning's roughness coefficient n are caused by used mesh size in this model, because inside the each rectangular mesh is flat and water flow is expanded to the entire mesh. However, actual terrain is rough and water flow is not wide compared to mesh size. Further, there is a large difference in the best fit values of the fitting parameter of PR. When using the penetration equation for faster penetration rate point, PR is about 20, while for slower penetration rate point, PR is a one digit value. Using the grass field data, PR is over 30. We found that the penetration rate is different due to differences of soil properties.

4. Conclusion

In this study, we used three types of infiltration formula made from 3 points of cylinder intake rate tests at bare ground and grass fields. Calculation results for best fit using infiltration formula and bare ground intake rate test data gave almost constant fitting parameters N. On the other hand, in the case of fitting parameters PR gave far different values of PR among infiltration formula made from point 1 (penetration rate is relatively fast) and point 2 (penetration rate is relatively slow). Regardless of the type of formula, simulation results of using the infiltration formula and data point 2 (penetration rate is relatively slow), the values of fitting parameter PR are in the range of 4-8. This result is close to the report that infiltration rates measured by cylinder intake rate test were five to six times higher than that observed under natural rainfall (Rao *et al*., 1998). The present results are convincing because the area surrounding Jim's Pool is almost bare ground, though several times differences were observed among the obtained values of best fit. PR between points 1 and 2 are unconvincing. Also, simulation results of using infiltration formula made from point 3 (grass fields) gave fitting parameter PR in the range of 30-35. In order to apply our model to a wide area, it is necessary to change the penetration equation with appropriate soil properties.

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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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