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Runoff Model Development and Validation for Afforestation in Arid Land of Western Australia

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Abstract: As a countermeasure against global warming, large scale afforestation of arid land has been done by fixing atmospheric CO_2 into plants. In arid land, however most of the rainwater is lost by runoff and evaporation. Effective use of rainwater is required for afforestation. Thus, we made an original runoff model to evaluate water distribution in a research area. In this study, we report determination of parameters in the original runoff model with Digital Elevation Model (DEM) to estimate water movement for the selection of afforestation place. From the comparison of actual and numerical results, the two sensitive parameters were decided and the characteristics of runoff water movement were elucidated hydrologically. Moreover, validation on expansion of mesh size for application of this model in large scale area was done. However, numerical results with large size mesh hadn't been approximated to small size mesh, because of roughness information of large size mesh. It was our assignment of future investigation.

Keywords: Afforestation, DEM, Mesh size, Runoff, Simulation

1. Introduction

For the mitigation of global warming issue, a large scale afforestation of arid land has been promoted to fix atmospheric carbon on land which is not effectively used. Arid land area is huge in the world but the most important problem is lack of water for afforestation because of the small amount of rainfall and occurrence of runoff on soil surface. Most of runoff water is evaporated without using for plants, therefore, it is necessary to use runoff water effectively for arid land afforestation. The authors have demonstrated the improve the land condition for afforestation by introducing artificial technologies (Yamada *et al*., 2003).

The purpose of this study is to estimate the distribution of runoff water by using the original runoff model for selection of the best afforestation places. In this report, two sensitive parameters in the original runoff model were decided to estimate water movement for the selection of afforestation place. Moreover, expansion of mesh size by using our model was validated to calculate in large scale area.

2. Materials and Methods

2.1. Research area

We have set a research place (4×5km) near Sturt meadows station, Leonora, Western Australia (**Fig. 1**). In this area, most rainwater flows into a catchment called Jim's pool. Average annual rainfall is about 200 mm. And, hardpan layer with extremely low permeability locates from several tens of centimeters and a few meters in depth. Therefore, water is hard to penetrate into the ground, and then plants' growth is inhibited.

2.2. Observed data

Rainfall data was obtained from rainfall gauges at Top, Middle, Bottom, and water level was obtained from water level instrument in a catchment area called Jim's pool.

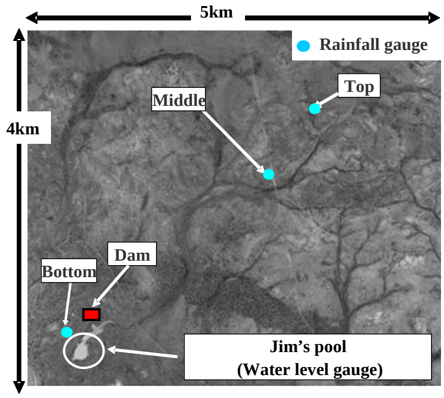

Fig.1. Research area and set instruments.

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The model validation was performed by comparison between obtained data and numerical results of water level in the main catchment area.

Table 1. Input data used in runoff model.

Altitude	DEM [Digital Elevation Model] 10, 20, 50, 100m mesh
Time stpe	0.25, 0.5, 1, 2, 5 s
Soil depth	Uniformity 0.15m
Soil water content range	0.05 – 0.4

2.3. Concept of original runoff model

Input data in original runoff model was showed **Table 1**. Soil depth and Soil water content range were estimated from actual data. A suitable value of time step was validated with each mesh. And, effect of mesh size expansion was validated with some size meshes.

This model consists of three main steps after rainfall (penetration, evaporation and runoff).

2.3.1. Penetration

Penetration rate equation was estimated by analyzing cylinder intake rate method with Horton's equation (Horton, 1939), and also used penetration adjustment (PR) which was one of fitting parameters in this model for difference between experiment and actual penetration rate.

$$f_t = f_c + (f_0 - f_c) \times e^{-k_f t} \qquad f_T = f_t / PR$$

f_t: Adjusted penetration rate at t [m/s], f_0 : Initial penetration rate [m/s], f_c: Penetration rate approaching minimum value [m/s], k_f : Constant value [1/s], t : Time [s], f_T: Penetration rate at t [m/s], PR : Penetration adjustment [-]

Moreover, estimated equation of the relation between f_T and soil water content at t (Θ_t) was made from the relation between f_T and Cumulative penetration volume at t (V_t) on the experiment. Θ_t [-] = Cumulative penetration volume per unit area (V_t) [m^3]/ Soil volume per unit area (V_s)[m^3]

2.3.2. Evaporation

Evaporation was divided into evaporation from liquid and from soil.

From liquid : Annually average pan evaporation rate ($E_L = 7.67\times10^{-8}$ m/s)

From soil : Evaporation from soil was divided by two drying steps from a result of evaporation experiment from soil.

a. Constant ratio drying step: Constant ratio drying rate (E_{S1} [m/s]) equation was considered almost evaporation from soil surface. Thus, E_S was supposed E_L.

b. Decreasing drying step: Decreasing drying rate (E_{S2} [m/s]) equation was estimated with E_L from the relation between E_{S2} and soil water content (Θ) [-] on evaporation experiment from soil.

a. $E_{S1} = E_L$ **b.** $E_{S2} = E_L \times 53.0 \times (\theta - 0.05)^{2.67}$

2.3.3. Runoff

Runoff calculation from objective mesh toward 4 direction meshes was used Manning's equation (Chow, 1959) including one of fitting parameters, i.e. roughness coefficient (n).

$$v = \frac{1}{n} R^{2/3} I^{1/2}$$

v: Ave. velocity [m/s], n : Roughness coefficient [$m^{-1/3}$ s]
I: Slope of water surface [-], R : Effective water depth [m]

Manning's equation is the equation for river of uniform flow, and it couldn't be expressed water movement at like pond. Thus, this model was used error trap in runoff calculation.

Generally, the flow of water is occurred to become the horizontal. Thus, water level difference before 1time step of runoff calculation can't be reversed after 1time step of runoff calculation.

So, to become the horizontal, the limit value of runoff toward dawn flow meshes calculated from Manning's equation was set by the average water level of objective and down flow meshes before every time step of runoff calculation.

3. Results and Discussion

3.1. Time step

It was considered that runoff calculation results were influenced by change of time step. Therefore, determination of the suitable time step was required for validation of fitting parameters and mesh size. The first, its validation was performed between 5 patterns (time step = 0.25, 0.5, 1, 2, 5 s) by using 20 m mesh

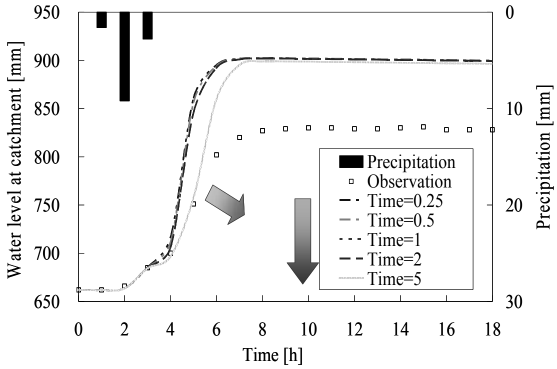

Fig. 2. Validation of Time step with 20m mesh

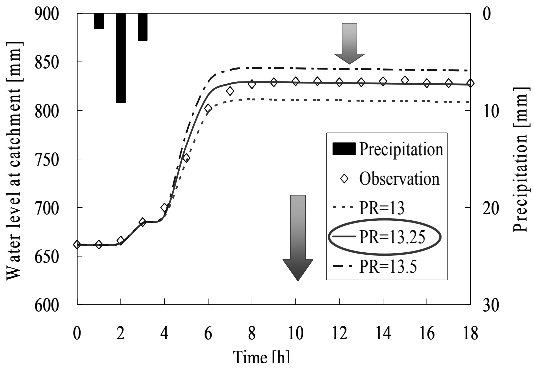

Fig. 3. Determination of PR to n = 0.012 with 20m mesh

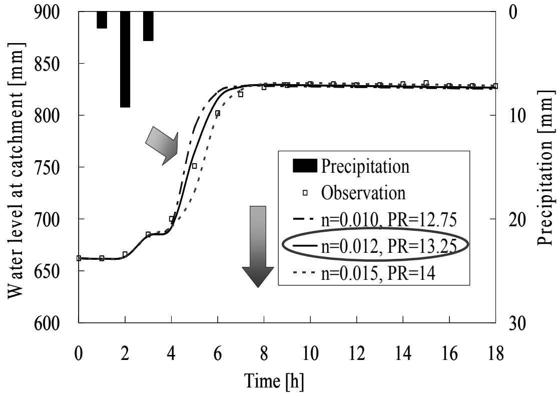

Fig. 4. Determination of a suitable couple of n and PR with 20m mesh.

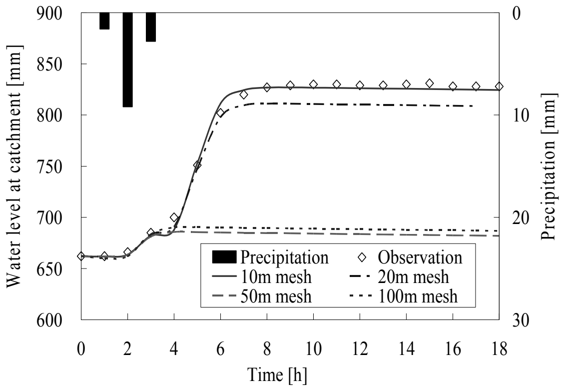

Fig. 5. Validation of mesh size expansion from change of runoff water flowing into catchment.

and same parameters (n = 0.015, PR = 14, Total rainfall 13.6 mm) (**Fig. 2**).

As a result, increase of time step influenced rainwater flowing into catchment i.e. water movement in this model. However, there were little differences between the results of less than 2 s. So, a suitable time step with 20 m mesh was decided to 2 s or less. And, the results with 10 m mesh by same method were showed their differences were little with time step to 0.5 s or less.

So, the calculation with 10 m mesh was performed with 0.5 s and with 20 m or more size mesh was performed with 1 s.

3.2. Fitting parameters determination

Two sensitive fitting parameters (n, PR) in this model were related to runoff water flowing into the catchment. Both n and PR influence to quickness of rising water level and water level after runoff water flowed. However, main effect of “n” was the former, and main effect of “PR” was the latter.

Parameter fitting was performed from comparison between numerical results and actual data on water level at catchment. The first, each “PR” was decided on final water level to each “n” selected (ex. **Fig. 3**). The next, a suitable couple of parameter was decided on quickness of rising water level from some couples of “n” and “PR” (ex. **Fig. 4**).

In arid land, there are little rainfall events, and most of them have regional rainfall patterns. Therefore, a suitable couple of parameter in this model was estimated by nearly uniform rainfall in the research place (Used rainfall pattern: total rainfall 13.6 mm (± 0.2 mm between rainfall gauges in research area)).

As a result, a suitable fitting parameters couple of 10 m mesh (the most advanced mesh) was decided

(n = 0.012, PR = 13)

3.3. Validation of mesh size expansion

This study was aimed to selection of the afforestation in large scale area (more than 100 km square). Time step had been decided by analysis of the simulation results, and mesh size should be investigated.

The basis of comparison data was the most advanced data calculated with 10 m mesh with it's suitable parameters (Time step = 0.5 s, n = 0.012, PR = 13). The runoff calculation of large size mesh (20, 50, 100 m) was performed with same parameters without time step = 1 s.

The calculated water level at Jim's pool estimated by various mesh size is shown in **Figure 5** and water balance after 18 hours after rainfall in flow area is shown in **Figure 6**.

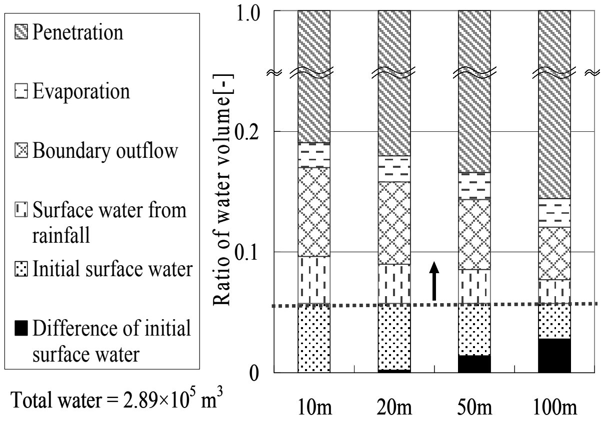

Fig. 6. Water volume ratio in flow area of other size mesh (18 hours after rainfall).

They were indicated mesh size expansion influence both of water movement and water balance. Especially, in the results of large size meshes, surface water and boundary outflow water from flow area decreased, and most of other rainwater became penetration water.

As a result, it was considered the calculation with large size mesh couldn't express rainwater gathered and flowed because of roughness information. Therefore, in the simulation results with larger mesh, surface water tends to spread horizontally and penetrate into the soil on large area by comparison with those simulated with small mesh (or actual condition).

4. Conclusions

An original runoff model was developed and validated by using the observed data. The best combination of the parameters with 10 m mesh was decided (Time step = 0.5 s, n = 0.012, PR = 13) in our model. And, as the result of mesh size expansion validation in our model, it was considered the calculation with large size mesh couldn't express rainwater gathered and flowed because of roughness information. Therefore, application of our model to large size mesh calculation was required the countermeasures for its assignment.

Acknowledgements

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