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Investigation of Rainfall Spatial Variation Scale to be Considered in Runoff Simulation Using Distributed Model and Radar Data

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ABSTRACT: A rainfall spatial variation scale to be considered in a runoff simulation will be investigated using mesh-type rainfall data and a distributed runoff model. At first, a runoff simulation is conducted by using a mesh-type rainfall data as it is, and the result is regarded as a standard result. As the next step, the rainfall data is averaged in some area and a runoff simulation is conducted by using this averaged rainfall data. If we have little difference between the standard result and the result obtained by using the averaged data, we do not have to explicitly consider the rainfall spatial variability in the area where the data is averaged, and we can use the average rainfall data as an input of the runoff simulation. Conversely, if the difference is large, we have to consider the rainfall variability in the averaging area when conducting a runoff simulation. These numerical experiments indicate that it is important to find out a scale of rainfall spatial variability which affects the results of runoff simulations and the scale changes with the size of drainage area.

1 Introduction

Which extent is the scale of rainfall spatial variation to be considered in a runoff simulation? For example, which extent is the spatial resolution of radar rainfall data which might be necessary to reproduce the discharge hydrograph for a basin of 1000 km^2? How many meters should we choose as the interval of the rain gauge in order to reproduce the discharge hydrograph in a small experimental basin? We do not have any clear answers to these questions. Also, we have developed a method to derive a lumped relationship between storage volume and outflow discharge of basin slope systems (Ichikawa et al., 1999; 2000; in submitting). This method is based on the assumption that the rainfall intensity is spatially constant. It then means that this method should be applied to an extent in which the rainfall intensity can be regarded as constant and that we have to know how the extent is.

In this study, the rainfall spatial variation scale to be considered in a runoff simulation will be investigated using a radar rainfall data and a distributed runoff model.

2 Methodology

The methodology of the investigation is as follows. At first, a runoff simulation is conducted by using a mesh-type rainfall data as it is, and the result is assumed to be a standard result. As the next step, the rainfall data is averaged in some area and a runoff simulation is conducted by using this averaged rainfall data. If we have little difference between the standard result and the result obtained by using the averaged data, we do not have to explicitly consider the rainfall spatial variation in the area where the data is averaged, and we can use the average rainfall data as an input of the runoff model. Conversely, if the difference is large, we have to consider the rainfall variation in the averaging area when conducting a runoff simulation.

As a preliminary analysis, numerical experiments will be conducted using mesh-type rainfall data generated by a random field generation computer program. Because this program can control statistical characteristics of generated rainfall data, we can investigate a relationship between the characteristics and results of runoff simulations. After this analysis, a similar analysis will be conducted using observed radar rainfall data.

The distributed runoff model used in this study represents a hill slope system as a set of small rectangular planes (Shiiba et al., 1999), which are called slope units, and routes water flow from upstream slope units to downstream slope units by applying kinematic wave model considering field capacity of soil layer to each slope unit (Ichikawa et al., in printing). The input data of this runoff model is a mesh-type rainfall data. When the model calculates the water flow of a slope unit, it uses a rainfall intensity of the mesh which overlaps with the slope unit.

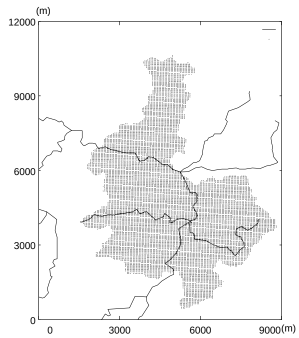

Figure 1. Study area

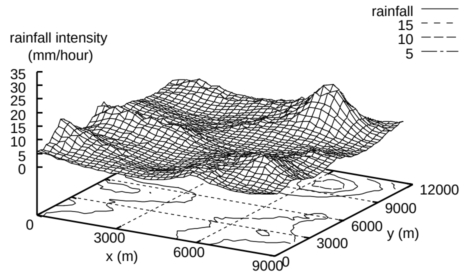

Figure 2. Example of generated rainfall field ($\mu = 5.0$, $\delta = 0.5$, $\alpha = 1500.0$)

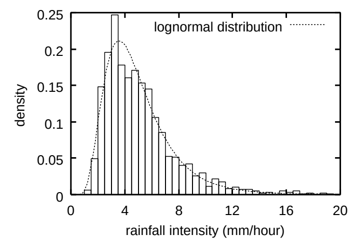

Figure 3. Histogram of rainfall intensity

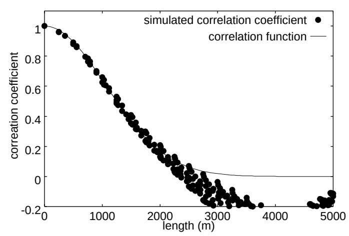

Figure 4. Spatial correlation of generated rainfall field

Table 1. Parameter values for rainfall field generation

case	μ (mm/hour)	δ	α(m)
1	5.0	1.0	500.0
2	5.0	1.0	1500.0
3	5.0	0.5	500.0
4	5.0	0.5	1500.0
5	10.0	1.0	500.0
6	10.0	1.0	1500.0
7	10.0	0.5	500.0
8	10.0	0.5	1500.0

3 Analysis using generated rainfall data

In this section, numerical experiments will be conducted in order to investigate a relationship among rainfall averaging scale, characteristics of rainfall field (average rainfall intensity, coefficient of variation, correlation length) and runoff simulation error.

3.1 Generating mesh-type rainfall data

Figure 1 shows a study area of this analysis (33 km^2). The mesh-type rainfall data will be generated over the rectangular area (9000 m $\times$ 12000 m) which covers the study area. The rainfall data are generated using a random field generation program coded by Tachikawa and Shiiba (2000). The size of each mesh is 250 m $\times$ 250 m. It means 36 $\times$ 48 mesh data will be generated over the rectangular area. Each generated data has log normal distribution and also has spatial correlation expressed by Gauss function.

There are three parameters to generate random mesh-type rainfall data, which are spatial average rainfall intensity, μ [mm/hour], coefficient of variation of rainfall intensity, δ, and correlation length, α [m]. α is the length where the spatial correlation coefficient is $1/e$ and can be regarded as a representative scale of spatial variation of rainfall field. Figure 2 shows the generated rainfall data using $\mu = 5.0$, $\delta = 0.5$, and $\alpha = 1500.0$. Figure 3 and Figure 4 show the histogram of rainfall intensity and the spatial correlation coefficient of the generated data, respectively.

The rainfall data are generated using the parameter values shown in Table 1. For each case, five data are generated in order to eliminate a chance factor. The data generated in this process are referred to as the data of level 1.

3.2 Averaging rainfall field

The rainfall data of level 1 are spatially averaged over: 750m $\times$ 750m (referred to as level 2), 1500m $\times$ 1500m (level 3), 3000m $\times$ 3000m (level 4) and 9000m $\times$ 12000m (level 5).

3.3 Runoff simulation

Runoff simulations are conducted using the rainfall field data generated in 3.1 and 3.2 . First of all, runoff simulations are conducted using the level 1 rainfall field data for each case shown in Table 1. For each

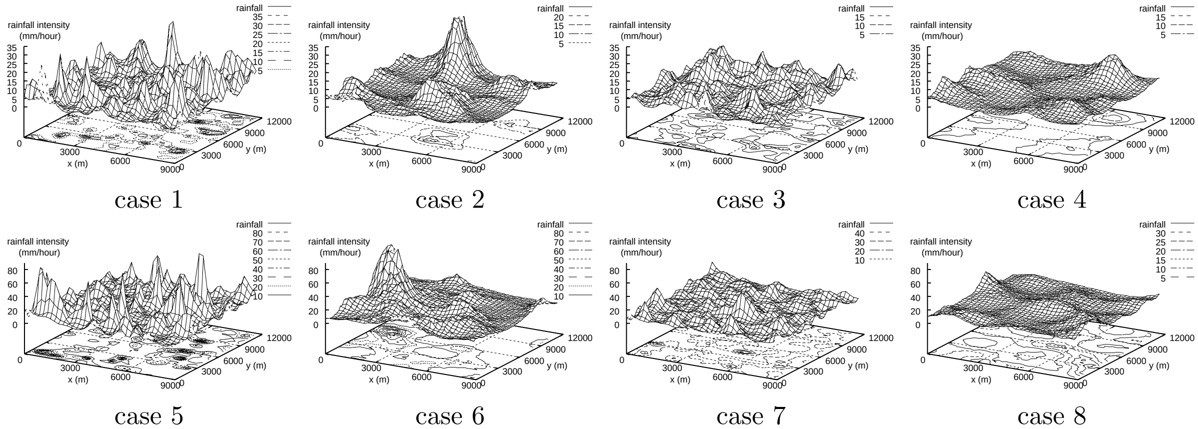

Figure 5. Generated rainfall fields

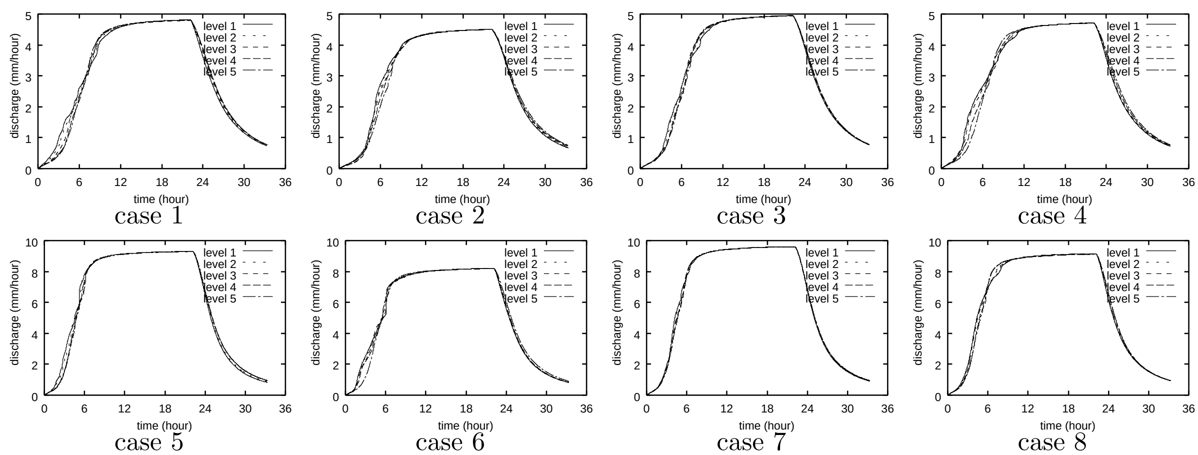

Figure 6. Runoff simulation results

case, there are five rainfall field data, then it means that the runoff simulations are conducted five times. The results of these simulations are considered as the standard results for evaluating the simulation error due to rainfall averaging. Next, runoff simulations are conducted using the level 2 rainfall field data in the same way as the simulations using the level 1 data. Runoff simulations using the rest of the rainfall data (level 3, 4 and 5) are also conducted. The rainfall inputs are given for 80000 seconds at constant intensity.

3.4 Evaluating runoff simulation error

Runoff simulation error ϵ_r is evaluated by comparing the simulation results of level 2 - 5 with the results of level 1, which is considered as the standard result. ϵ_r is written as:

$$\epsilon_r = \frac{1}{5}\sum_{i=1}^{5}\left\{\sqrt{\frac{\sum_{j=1}^{N^i}(Q_{1,j}^i - Q_{k,j}^i)^2}{N^i}}/R_m^i\right\} \tag{1}$$

where i shows a rainfall data and a simulation result for each case, j shows calculation time, R_m^i is the average rainfall intensity of ith rainfall data, N^i is the number of calculation steps of the ith simulation result, $Q_{k,j}^i$ is runoff height at time j of the ith simulation result obtained by using level k data.

3.5 Simulation results and discussion

Figure 5 shows the rainfall field data of level 1 of each case and Figure 6 shows the runoff simulation results of each case.

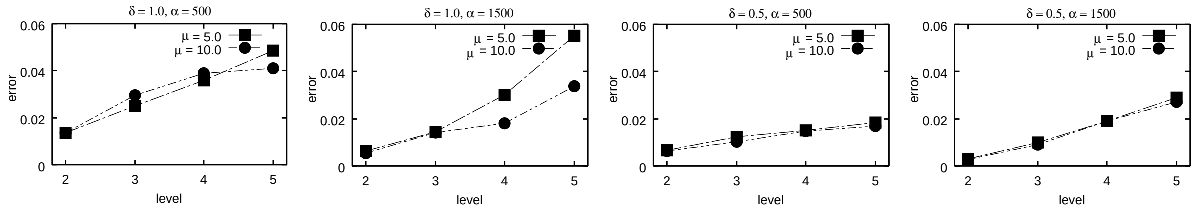

Figure 7. Comparisons of ϵ_r between $\mu = 5.0$ and 10.0

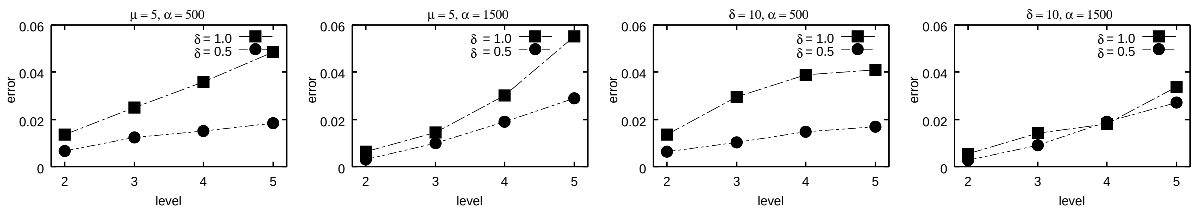

Figure 8. Comparisons of ϵ_r between $\delta = 1.0$ and 0.5

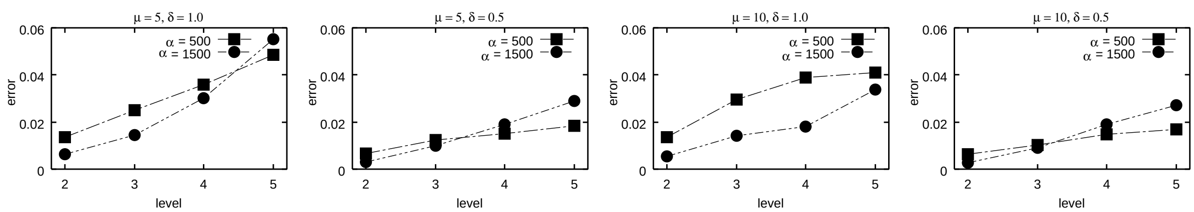

Figure 9. Comparisons of ϵ_r between $\alpha = 500$ and 1500

Figure 7 shows comparisons of ϵ_r between the case of $\mu = 5.0$ and 10.0. The vertical axis of the graphs is the calculation error (ϵ_r) and the horizontal axis is the level of rainfall averaging. For all of the cases, the calculation errors become greater as the rainfall averaging area is extended. Also, there are no large differences of ϵ_r between the cases being compared. Because ϵ_r is an index standardized by dividing by the rainfall intensity, the differences between the calculation results (differences of runoff height) are in proportion to the rainfall intensity.

Figure 8 shows comparisons of ϵ_r between the case of $\delta = 0.5$ and 1.0. From this figure, it can be said that the calculation errors for the case of $\delta = 1.0$ are greater than the case of $\delta = 0.5$.

Figure 9 shows comparisons of ϵ_r between the case of $\alpha = 500$ and 1000. In the case of $\alpha = 500$, the calculation errors due to spatial averaging of rainfall appear constantly in the process of extending the averaging area, because the spatial variation scale of rainfall field is relatively small compared to the size of the study area. In the case of $\alpha = 1500$, the calculation errors are relatively small when the size of averaging area is 750 m (level 2). However they increase much when the size of the averaging area exceeds the spatial correlation length (1500 m). This fact implies that the essential scale of rainfall spatial variation is 1500 m for this case and that it is important to find out a scale of rainfall spatial variability which affects the results of runoff simulations.

4 Analysis using observed radar rainfall data

In this section, numerical experiments using observed radar rainfall data will be conducted in the same way as the previous section. A runoff simulation is conducted by using an observed rainfall radar data as it is, and the result is assumed to be a standard result. Then the observed radar data is spatially averaged and runoff simulations are conducted by using the averaged radar data. By comparing these simulation results, a relationship among spatial averaging scale, size of drainage area and calculation error is discussed.

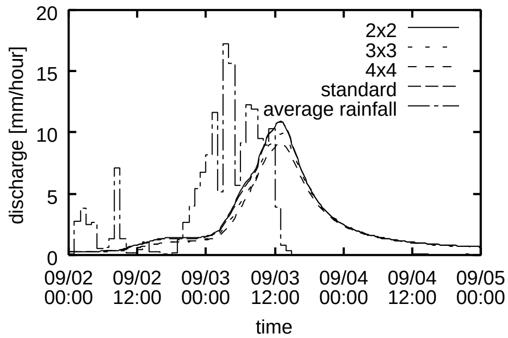

Figure 10. Drainage area of 74.5 km^2

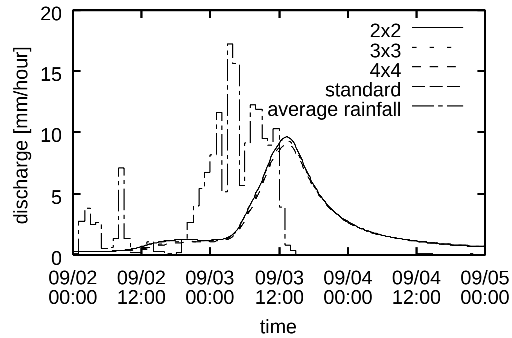

Figure 11. Drainage area of 278.4 km^2

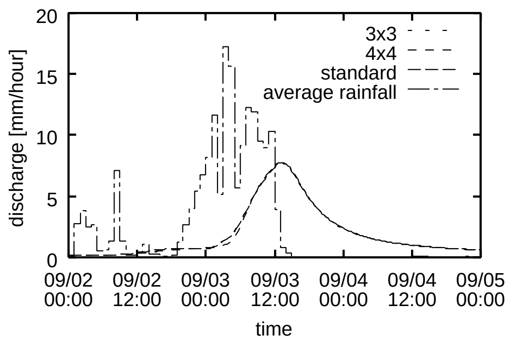

Figure 12. Drainage area of 582.0 km^2

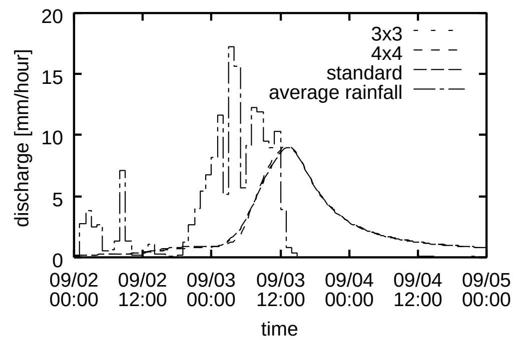

Figure 13. Drainage area of 710.2 km^2

4.1 Study basin and radar data

The study basin is Katsura River basin (710.2 km^2). Runoff simulations for this basin are conducted using the rainfall data observed at Miyama radar site from September 2 to 5, 1989. The radar reflectivity (Z) was converted to rainfall intensity (R) by Z-R relationship ($Z = BR^{\beta}$; $B = 80$, $\beta = 1.7$). Furthermore, the rainfall intensity was calibrated with rain gauge. The spatial resolution of the radar data is 3 km.

4.2 Results and discussions

The simulation results are shown in Figure 10 - 13. The lines labeled as “standard” in the figures show the standard results, that is, the simulation results obtained by using the observed radar data as it is. The lines labeled as “2×2”, “3×3” and “4×4” show the simulation results using the radar data averaged over (A) 2 × 2 radar meshes (6 km × 6 km), (B) 3 × 3 radar meshes (9 km × 9 km) and (C) 4 × 4 radar meshes (12 km × 12 km), respectively.

From these results, the runoff calculation error due to spatial averaging of the rainfall data, ϵ, is evaluated as:

$$\epsilon = \{\int_{t_s}^{t_e} |Q(t) - Q_s(t)|dt\}/\{\int_{t_s}^{t_e} Q_s(t)dt\} \qquad (2)$$

where t_s is integration starting time, t_e is integration ending time, $Q_s(t)$ is calculated discharge using the observed radar data, and $Q(t)$ is calculated discharge using the averaged radar data.

Figure 14 shows the relation between ϵ and the drainage area. The curved lines in this figure are the envelope curves of the calculation errors ((A): broken line, (B): dotted line, (C): solid line). The envelope curves are given by $\epsilon = \exp(ax^c + b)$ where x is drainage area (km^2), a, b and c are constants. In Figure 14 the straight line is also drawn to denote $\epsilon = 0.05$. The drainage areas where this line intersects with the envelope curves are (A): 52 km^2, (B): 202 km^2 and (C): 465 km^2. For case (A), in which the radar data is averaged over 6 km × 6 km, the minimum size of drainage area at which the error of runoff simulation can be regarded as relatively small is about 50 km^2. In other words, the radar resolution of 6 km is required in order to precisely simulate outflow discharge from about 50 km^2 drainage area. Similarly, from case (B) and (C), it can be said that the radar resolutions of 9 km and 12 km are required in order to obtain precise discharge at the outlets of drainage areas of 200 km^2 and 450 km^2, respectively. These experiments indicate the importance to find out a scale of rainfall spatial variability which affects the

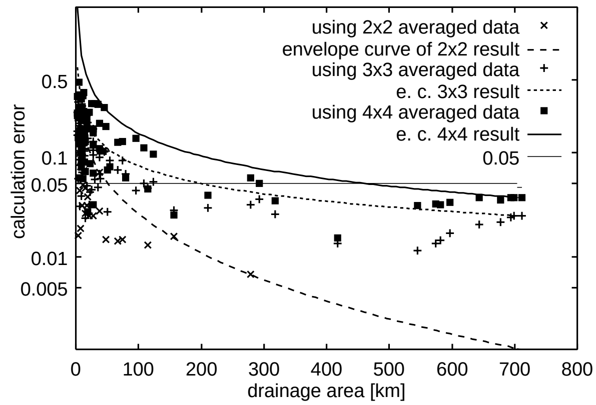

Figure 14. calculation error and drainage area

accuracy of runoff simulations, which is already pointed out in the previous section. Furthermore, they imply that the scale changes with the size of drainage area.

These analyses, however, do not have universal applications because they are based on one rainfall event of one river basin, and implicitly assume that the spatial variability of rainfall field is sufficiently captured by the radar system used in this study. Further investigations based on various rainfall events and river basins will be required.

5 Conclusion

This study investigated a rainfall spatial variation scale to be considered in a runoff simulation by using mesh-type rainfall data and a distributed runoff model. As a preliminary analysis, numerical experiments were conducted using generated rainfall data in order to investigate a relationship among rainfall averaging scale, characteristics of rainfall field and runoff simulation error. This analysis showed that (1) the runoff simulation error is in proportion to the rainfall intensity, (2) the error becomes greater as the coefficient of variation of rainfall increases, and (3) it is important to find out a scale of rainfall spatial variability which affects the results of runoff simulations. Next, numerical experiments using observed radar rainfall data were conducted in the same way as the preliminary analysis. These experiments indicated the importance to find out a scale of rainfall spatial variability which affects the accuracy of runoff simulations, which was already pointed out in the previous analysis. Furthermore, they implied that the scale changes with the size of drainage area.

References

Ichikawa, Y., Tachikawa, Y. and Shiiba, M. (1999). “Lumping slope runoff model using digital elevation model and steady state assumption” *Proc. 2nd Intl. Conf. on Water Resour. and Environ. Res.*, Vol. 1, pp. 113–118.

Ichikawa, Y., Ogura, T., Tachikawa, Y., Shiiba, M. and Takara K. (2000). “Lumping general kinematic wave equation of slope runoff system” *Annual Journal of Hydraulic Engineering*, JSCE, Vol. 44, pp. 145–150 (in Japanese with English summary).

Ichikawa, Y., Murakami, M. Tachikawa, Y. and Shiiba, M. “Development of a basin runoff simulation system based on a new digital topographic model” *Journal of Hydraulic, Coastal and Environmental Engineering*, JSCE, in printing (in Japanese with English summary).

Ichikawa, Y., Murata, Y. and Shiiba, M. “Lumping of kinematic wave equation considering field capacity” *J. Japan Soc. Hydrol. & Water Resour.*, in submitting (in Japanese with English summary).

Shiiba, M., Ichikawa, Y., Sakakibara, T. and Tachikawa, Y. (1999). “A new numerical representation form of basin topography” *Journal of Hydraulic, Coastal and Environmental Engineering*, JSCE, No. 621 / II-47, pp. 1–9 (in Japanese with English summary).

Tachikawa, Y. and Shiiba, M. (2000). “Gaussian and log normal random field generation based on the square root decomposition of a covariance matrix” *Journal of Hydraulic, Coastal and Environmental Engineering*, JSCE, No. 656/II-52, pp. 39–46 (in Japanese with English summary).