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Comparison of three flood runoff models in the Shonai River basin, Japan

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Abstract Distributed parameter runoff models are recently developed and expected to be used in practice. They can take into account spatial distribution of rainfall, land surface conditions and their changes, which affect the runoff from river basins. This paper introduces a grid-cell based distributed rainfall-runoff model that was developed by the authors in 1997. The model uses hydraulics-based overland flow theory and geographic information such as digital elevation models (DEM), land cover/use based on either the National Land Information developed by Geological Survey Institute (GSI) or remote sensing imageries.

The objective of this paper is to compare this distributed runoff model with two models conventionally used in Japan: the storage function model and the slope-channel system kinematic wave model. The models are assessed in terms of runoff prediction accuracy in the Shonai River (Shonai-gawa) basin at Shidami (532 km^2).

This paper discusses some problems to improve the precision of the distributed runoff model and to put it to practical use, by comparing the three models on the basis of the indices for the model parameter sensitivity, such as the difference in peak time, peak discharge and hydrograph shape between observed and simulated hydrographs. The slope-channel system kinematic wave model can reproduce the observed hydrographs well with the optimum model parameters, which are almost the same as the conventionally recommended values. Although the grid-cell based distributed model also can reproduce the observed hydrographs well, it has a tendency to give earlier peak than the observed one. Further investigation is necessary to improve this tendency by adjusting the roughness coefficient of channel much affecting the peak time. In the storage function model, the optimum parameters depend on flood events. Variation in optimum parameters is greater than the other runoff models.

Key word grid-cell based distributed model; storage function model; kinematic wave model; GIS; DEM

INTRODUCTION

Distributed parameter runoff models are recently developed and expected to be used in practice. They can take into account spatial distribution of rainfall, land surface conditions and their changes, which affect the runoff from river basins. The authors developed a grid-cell based distributed rainfall-runoff model in 1997. The model which is physically-based uses geographic information such as digital elevation models (DEM), land cover/use based on either the National Land Information developed by Geological Survey Institute (GSI) or remote sensing imageries. However, the accuracy and practicality of the distributed runoff model has not been sufficiently confirmed.

This paper compares the conventional lamped model with the distributed runoff model, and discusses some problems to improve the precision of the distributed runoff model and to put it to practical use. The following three runoff models are compared in this paper.

- storage function model
- slope-channel system kinematic wave model
- grid-cell based distributed runoff model

TEST SITE AND DATA

The Shonai River basin is about 1,010 km^2. Its lower basin is almost urbanized area, while 70% of its upper basin is forest area, 15% is urbanized area and 15% is other land use area. It is expected to expand the urbanized area in the both of upper and lower basin. Figure 1 shows the location of the precipitation stations (raingauges) and the discharge sites (gauging stations) in the Shonai River basin. Discharge is observed at Shidami, Tajimi, Toki and Mizunami. The test basin in this study is about 532 km^2 at Shidami upper site in the Shonai River basin. There are ten precipitation stations in the test basin. The runoff models are applied to seven flood events (see Table 1). These flood events have relative large ones from 1990 to 1995. Most of the events are the annual maximum peak discharge.

Effective rainfall is estimated with the rainfall-retention curves (Figure 2), which were obtained for urban, paddy and bare land at Uji, Kyoto, Japan, and for forest at the Takatoki River, Shiga, Japan (Chikamori *et al.*, 1998). The base flow - direct flow separation is based on the following concept. The base flow increases from the time which the hydrograph begins to increase, and it decreases after the peak time (Figure 3). The land use area rates of each sub basin, each slope and each cell are determined using the Digital National Land Information (KS-202-1; 100-m grid land use data). These land use rates are used to determine the amount of the effective rainfalls and the model parameters. For example, if the forest area and the urbanized area are 70% and 30% respectively, and the equivalent roughness coefficient of forest class and urban class are 0.5 and 0.25 respectively, the equivalent roughness coefficient at the cell is 0.5 x 70% + 0.25 x 30% = 0.425.

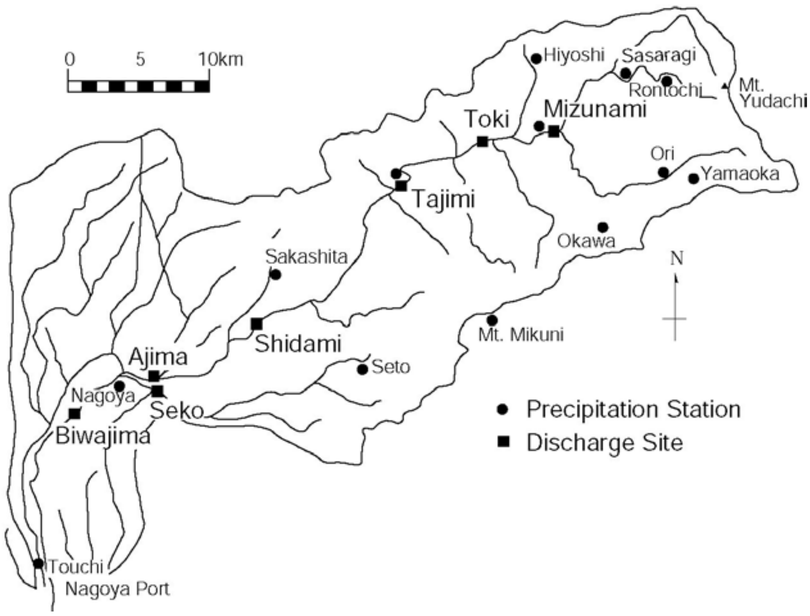


Figure 1. Test basin.

Table 1. Flood event list.

No	Date	Biwajima	Tajimi
Flood 0	17/9/1990	annual maximum	annual maximum
Flood 1	18/9/1991	annual maximum	annual maximum
Flood 2	9/9/1993	annual maximum	
Flood 3	14/9/1993		annual maximum
Flood 4	16/9/1994		
Flood 5	29/9/1994	annual maximum	annual maximum
Flood 6	2/7/1995	annual maximum	annual maximum

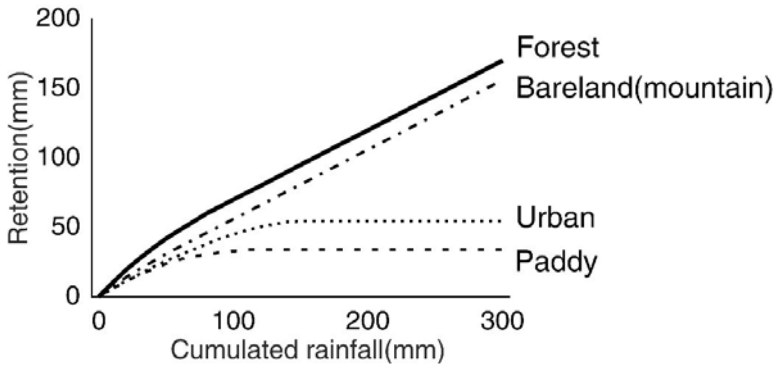


Figure 2. Rainfall-retention curves of each land use class.

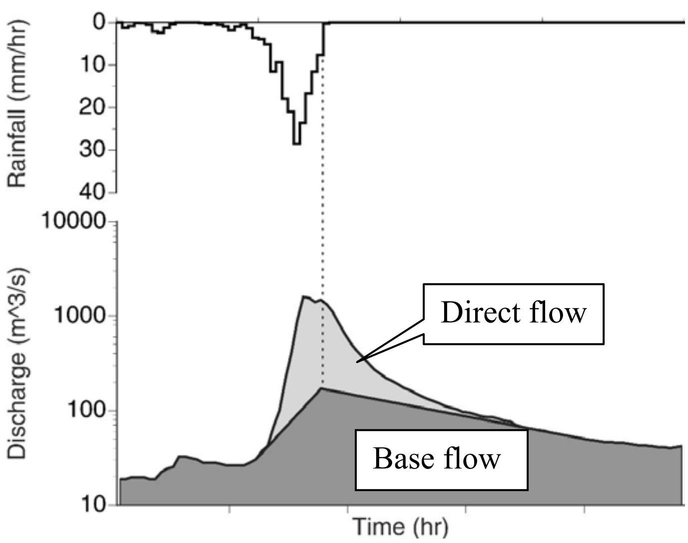


Figure 3. Illustration of base flow and direct flow separation.

EVALUATION OF EACH MODEL

Three runoff models are applied to the seven past flood events and simulate the hydrographs which are compared with the observed hydrographs. The model parameters are optimized by evaluating the conformity of the observed and simulated hydrographs. The following five indices are used to evaluate the models in terms of the accuracy of simulated hydrograph.

- **COR:** Correlation coefficient between observed and simulated hydrographs during the runoff event
- **MIRE:** Mean relative error between observed and simulated hydrographs during the runoff event

- **R.RMSE:** Relative root mean square error between observed and simulated hydrographs during the runoff event
- **TE:** Peak time error
- **RPE:** Relative peak discharge error

Storage function model. In the storage function runoff model, the storage-discharge relation is given as follows.

$$S = Kq^{P}$$

$$\frac{\partial S}{\partial t} = r_e(t-T) - q$$

where S is volume of storage, q is direct discharge, K and P are model parameters, r_e is effective rainfall, t is time and T is the so-called delay time.

The practical rainfall-runoff model for flood prediction in the Shonai River basin has been constructed by the Shonai River Work Office, Ministry of Land, Infrastructure and Transport (MLIT), Japan. The model divides the whole basin into twenty sub-basins and six stream sections. The storage function model estimates the discharge volume in each sub-basin and each stream section. The model parameters K and P have been calibrated by the Office using historical hydrological data. The authors simulated the hydrographs using the storage function model with the fixed value of P and the 0.1 to 1.0 times of K in the study area. Figure 4 is the variations of the evaluation indices for Flood 1. Figure 4 shows that if we use 0.2 x K as the value of K, we may minimize the error between observed and simulated hydrographs (see COR, MRE, R.RMSE in Figure 4).

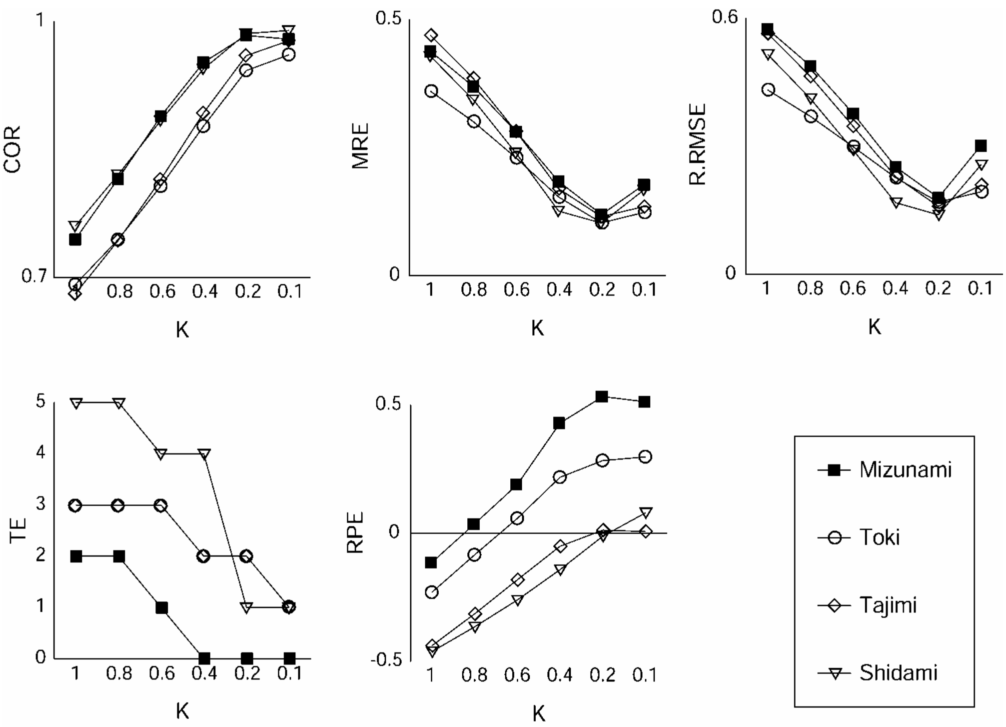
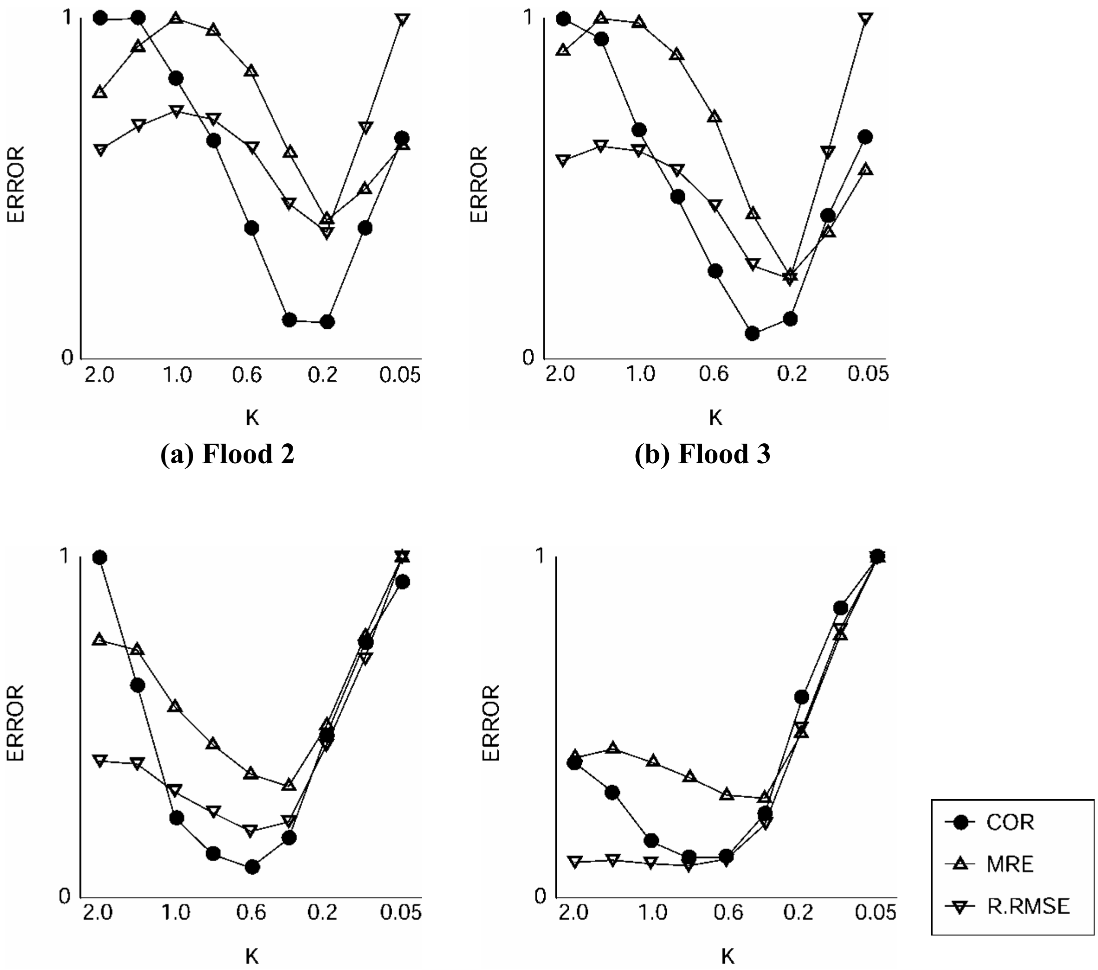


Figure 4. Variations of the evaluation indices of the storage function model for Flood 1. The horizontal axis shows a magnification of K value.



(a) Flood 2 (b) Flood 3

(c) Flood 4 (d) Flood 5

Figure 5. Variations of the three evaluation indices of the storage function model.

The authors also simulated the hydrographs with the storage function model, using the 0.05, 0.1, 0.2, 0.4, 0.6, 0.8, 1.0, 1.5 and 2.0 times of *K* in the study area. Figure 5 shows the variations of COR, MRE and R.RMSE at Shidami. Figure 5 shows that the optimum magnification factors of *K* are about 0.2 for Flood 2, about 0.2 to 0.4 for Flood 3, about 0.4 to 0.6 for Flood 4 and about 0.4 to 0.6 for Flood 5 respectively. The optimum parameters of the storage function model change much depending on the flood events.

Although we used effective rainfall produced with the rainfall-retention curve, effective rainfall often used in practical work by the MLIT is based on a combination of the runoff ratio and the saturated rainfall, in the Shonai River basin. Figure 6 represents how the determination of the effective rainfall

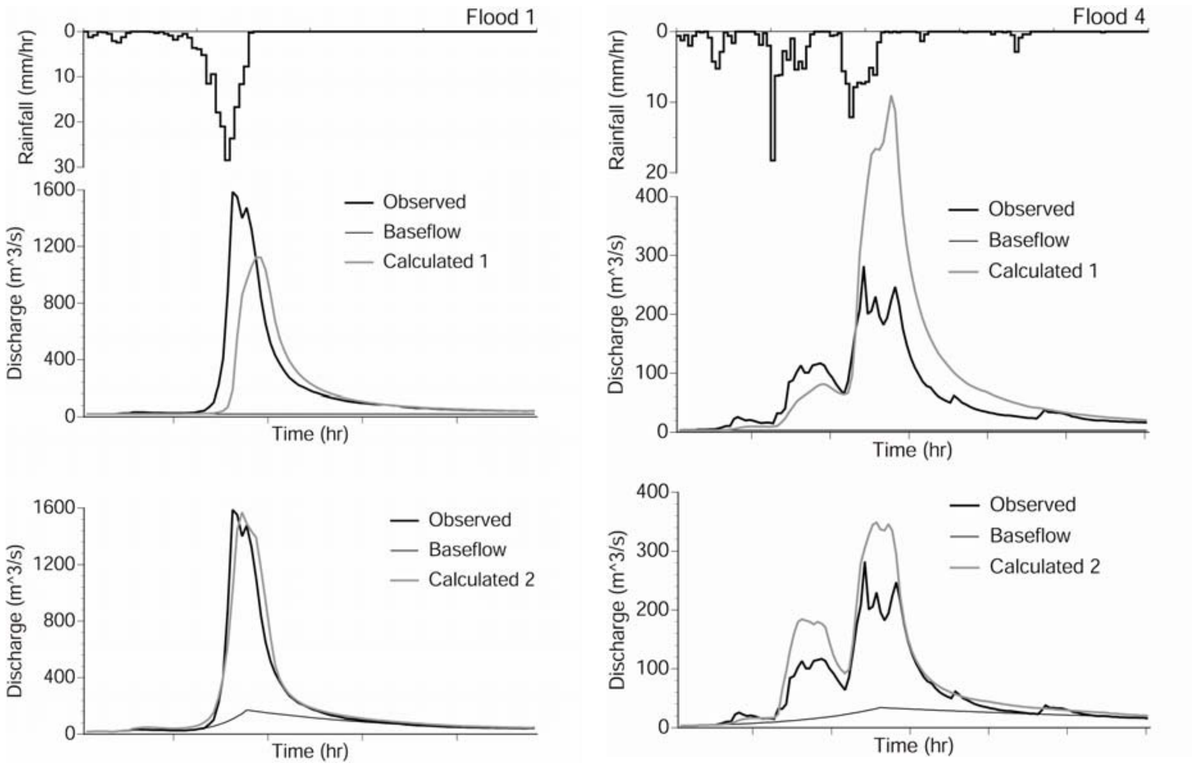


Figure 6. Application of the storage function model to Flood 1 and Flood 4. The upper panels are rainfall rate, the middle panels are hydrographs obtained by using the effective rainfall conventionally used, and the lower panels are using the modified effective rainfall (produced with the rainfall-retention curve).

affects the simulated hydrographs. The upper panels are rainfall rate, the middle panels are the simulated hydrograph with the effective rainfall using the runoff ratio and the saturated rainfall, and the lower panels with the rainfall-retention curve. The traditional model underestimates the peak volume for the short-term rainfall concentration events (such as Floods 0, 1, 2, 3, and 5), and overestimates the peak volume for the long-term rainfall continued events (such as Floods 4 and 6). Figure 6 shows that the storage function model needs to optimize the model parameters by the flood events because the peak volume depends on the events.

Slope-channel system kinematic wave model. The slope-channel system model considers a sub-basin as the river channel section and the rectangular slopes at its both sides, in which the kinematic wave model is applied to simulate overland flow. This runoff model requires the topographical properties of the land surface, such as slope angle, slope length and river length. These topographical properties are automatically calculated by tracing the drainage path based on DEM. The drainage path is produced from a 50-m DEM. This paper investigates the sensitivity of the equivalent roughness, which represents land use class of each slope. The land use is classified into six categories in this study area. The authors only checked about the model parameters of urban, river and forest, which affect the simulated hydrograph most. The fixed values of each land use class are 1.0, 0.05, 0.3, 1.5 and 0.025

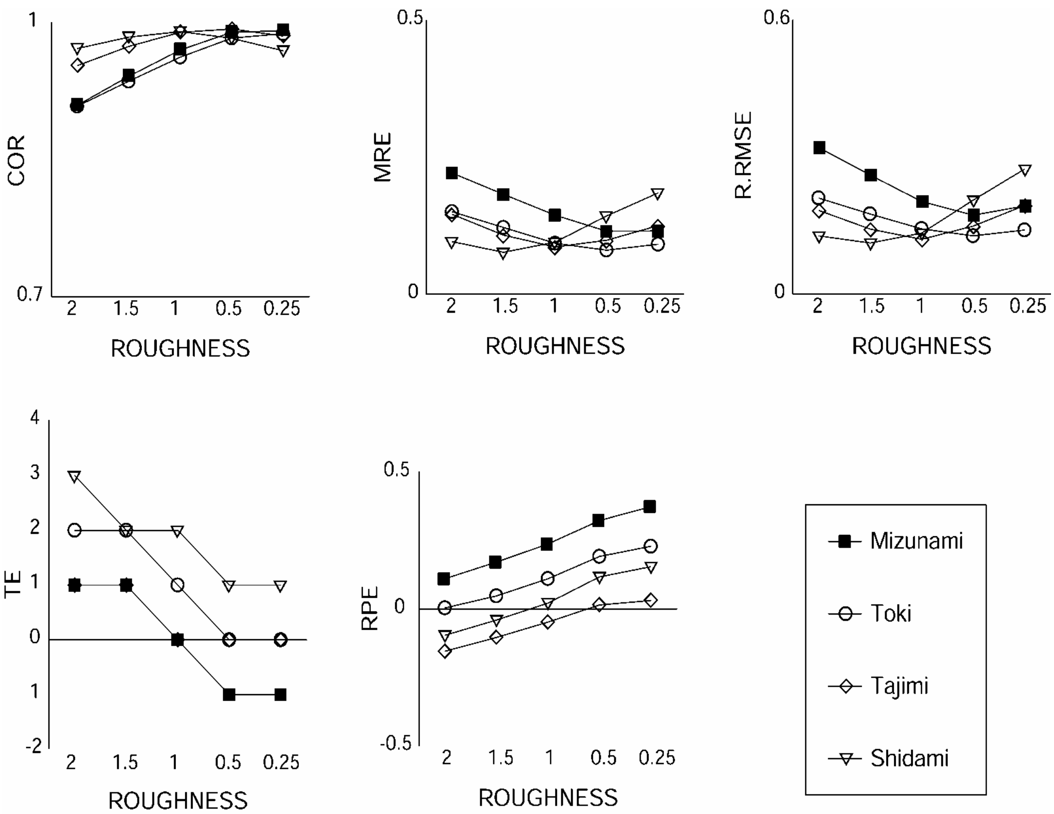


Figure 7. Variations of the evaluation indices of the slope channel system kinematic wave model for Flood 1. The horizontal axis shows different equivalent roughness coefficients for forest class, while other parameters are fixed.

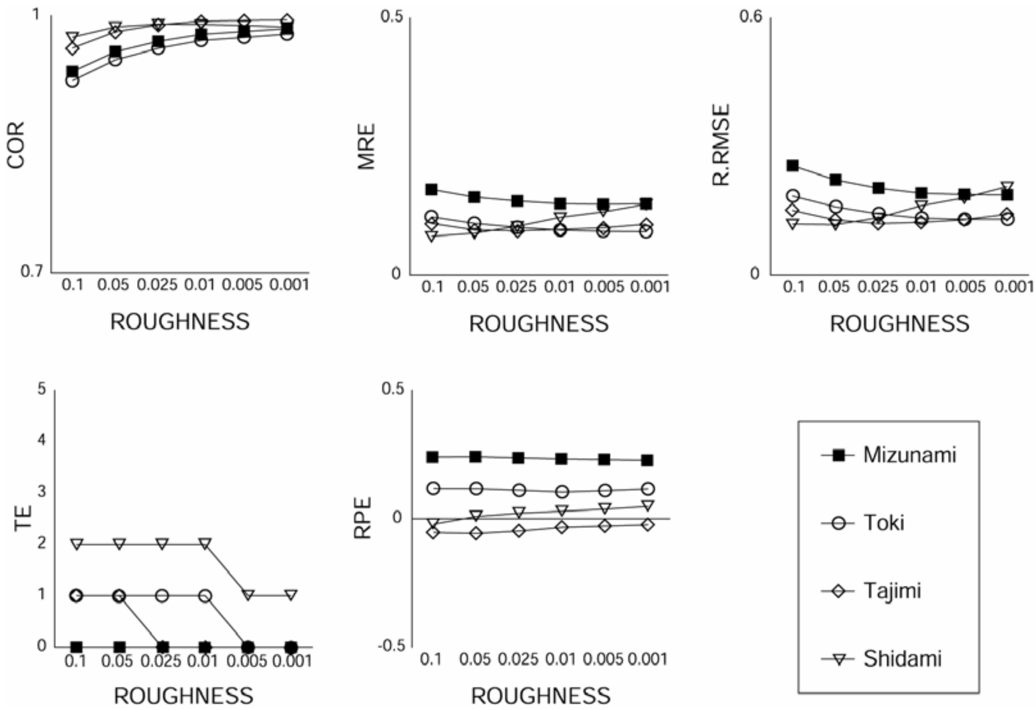


Figure 8. Variations of the evaluation indices of the slope channel system kinematic wave model for Flood 1. The horizontal axis shows different equivalent roughness coefficients for river class, while other parameters are fixed.

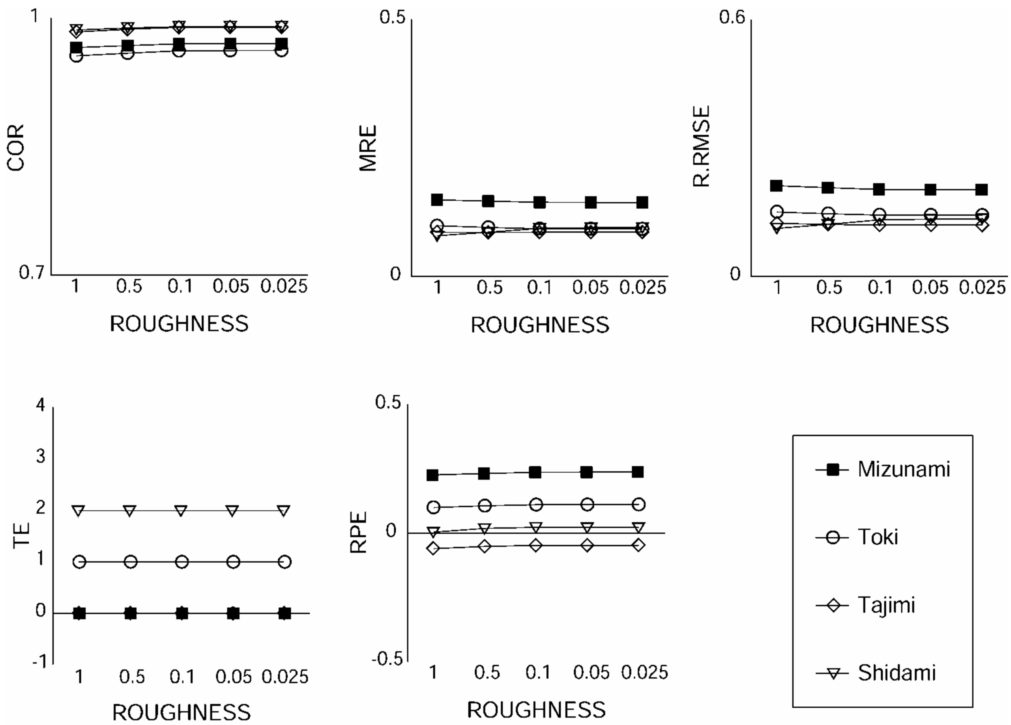


Figure 9. Variations of the evaluation indices of the slope channel system kinematic wave model for Flood 1. The horizontal axis shows different equivalent roughness coefficients for urban class, while other parameters are fixed.

for 'forest', 'urban', 'grass', 'paddy field' and 'river' respectively. These values are conventionally used in Japan (River Bureau, Ministry of Construction, 1998).

Figure 7 shows the variations of the evaluation indices when the equivalent roughness coefficient of forest class varies 0.25 to 2.0 for Flood 1. The variations of the evaluation indices in Figure 7 such as COR, MRE, R.RMSE and RPE show that the accuracy of the simulated hydrograph at Shidami gets worse when the equivalent roughness coefficient of forest class is smaller than 1.0. Figure 8 shows the variations of the evaluation indices if the equivalent roughness coefficient of river class is 0.001 to 0.1 for the Flood 1. Figure 9 shows the variations of the evaluation indices if the equivalent roughness coefficient of urban class is 0.025 to 1.0 for the Flood 1. The variations of the roughness coefficient of river and urban classes almost never affect the values of the evaluation indices.

Grid-cell based distributed runoff model. The grid-cell based distributed runoff model which was developed by the authors in 1997. This model has the following features (Kojima *et al.*, 1998).

1) A *d*-m square area on a node point of a *d*-m DEM is considered as a sub-basin, which is called a cell. The whole of river basin consists of many square cells.
2) A DEM produces drainage paths. A drainage path connects upper cell with lower cell. A discharge from upper cell to lower cell flows to only one direction of eight neighborhood cells.
3) In each cell, the total amount of outflows from upper cells is the inflow to the cell, and the outflow from the cell is calculated using the kinematic wave model with the inflow and the rainfall over the cell.

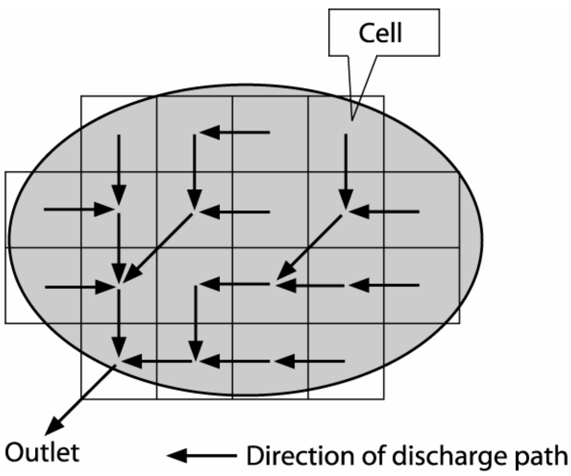


Figure 10. Illustration of a grid-cell based distribution runoff model.

Figure 10 shows the concept of a grid-cell based distribution runoff model. The equivalent roughness of each cell is determined based on the land use class of the cell. The cell with river is considered as the 'river' class. Figure 11 shows the variations of the evaluation indices if the equivalent roughness coefficient of 'forest' is 0.25 to 2.0 for Flood 1. Figure 12 shows the variations of the evaluation indices when the equivalent roughness coefficient of 'river' class is 0.001 to 0.1 for Flood 1. Figure 13 shows the variations of the evaluation indices when the equivalent roughness coefficient of 'urban' class is 0.025 to 1.0 for Flood 1.

When the roughness coefficients of 'river' and 'urban' class get small, the peak discharge errors almost never change, but MRE and R.RMSE get worse a little at the Shidami site. COR, MRE and R.RMSE get worse at the Shidami site when the roughness coefficient of 'forest' class is smaller than 1.5. The variations of the model parameters of the grid-cell based distributed runoff model hardly ever affect the accuracy of the simulated hydrographs as does the slope-channel kinematic wave model.

COMPARISON WITH THE EACH RUNOFF MODELS

For Flood 1, any runoff models can simulate good hydrographs at the lowest site Shidami. The storage function model (Smodel in the figures) overestimates the discharge volume at the upper site such as Mizunami and Toki, such as Figure 14.

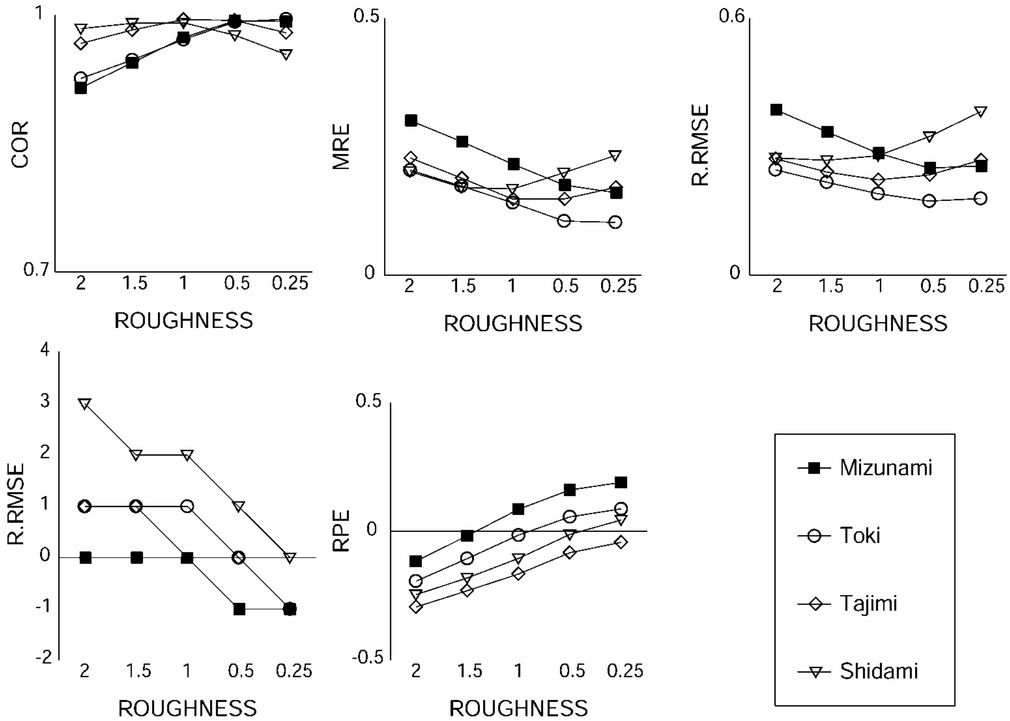


Figure 11. Variations of the evaluation indices of the grid-cell based distributed runoff model for Flood 1. The horizontal axis shows different equivalent roughness coefficients for forest class, and other parameters are fixed.

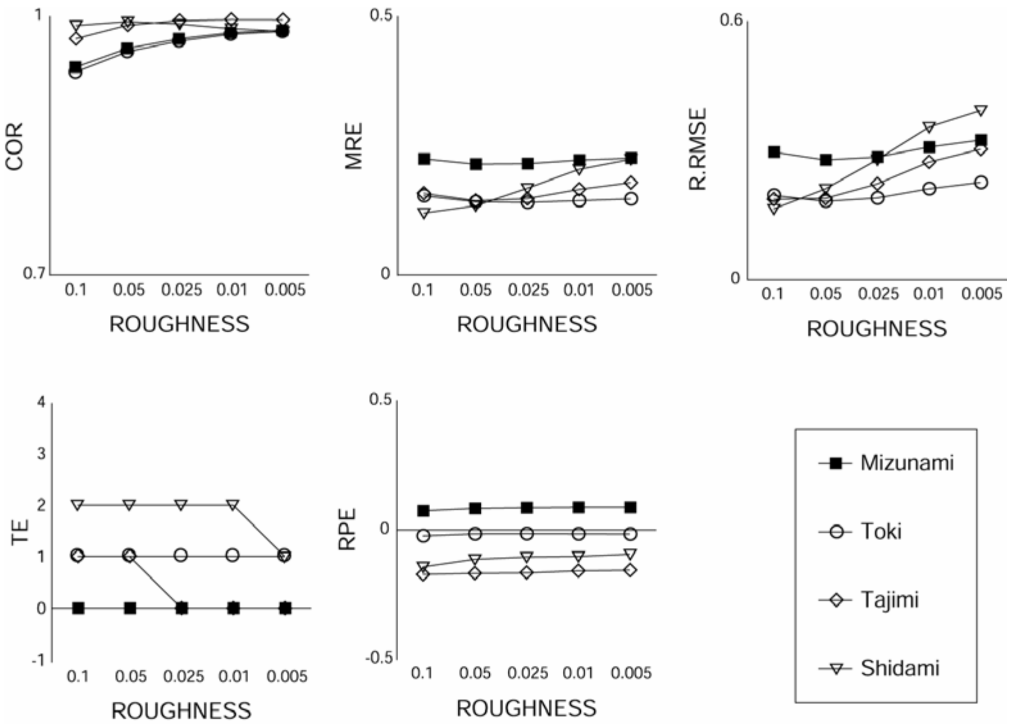


Figure 12. Variations of the evaluation indices of the grid-cell based distributed runoff model for Flood 1. The horizontal axis shows different equivalent roughness coefficients for river class, and other parameters are fixed.

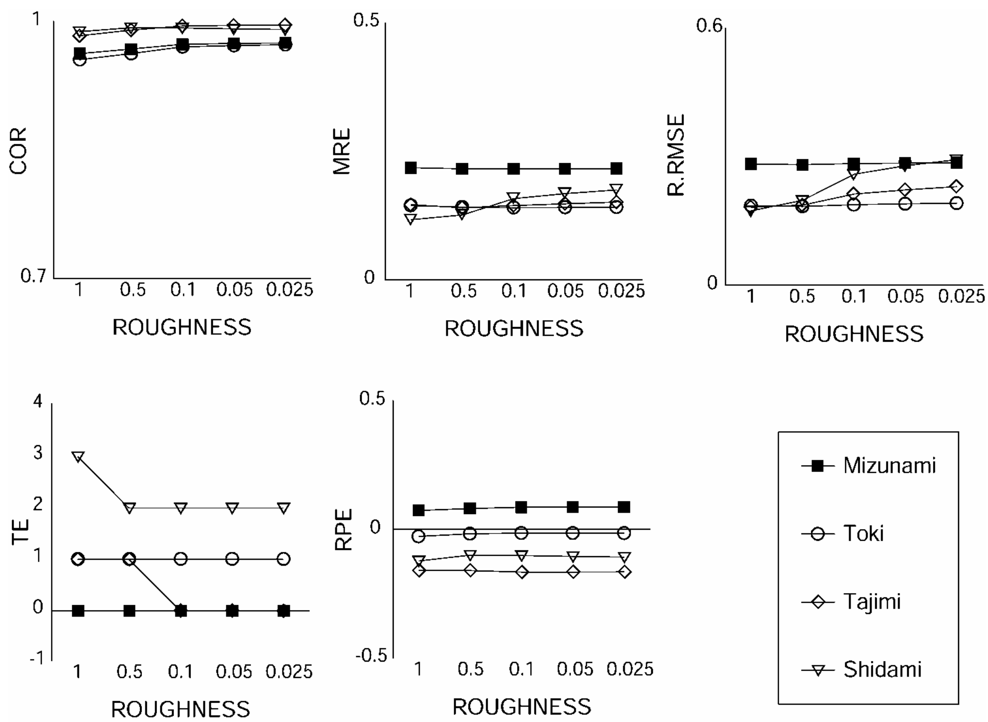
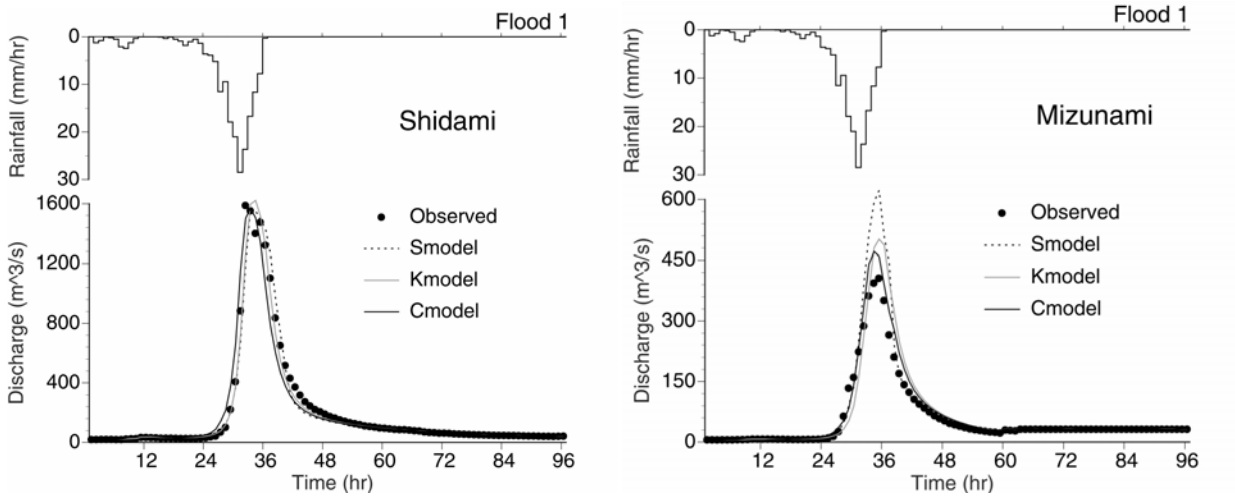


Figure 13. Variations of the evaluation indices of the grid-cell based distributed runoff model for Flood 1. The horizontal axis shows different equivalent roughness coefficients for urban class, and other parameters are fixed.

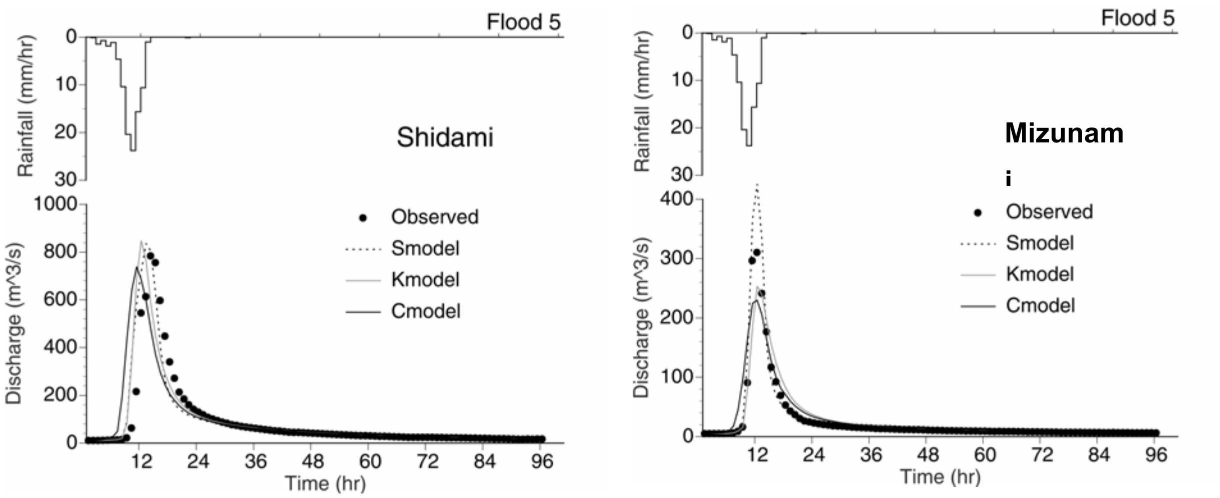


(a) Shidami **(b) Mizunami**

Figure 14 Comparison of the simulated and the observed hydrographs for Flood 1.

Figure 15 shows the hydrographs for Flood 5. The grid-cell based runoff model (Cmodel) simulates the hydrographs with early peak time, and it underestimates the peak discharge volume. Although the storage function model reproduces the observed hydrographs well at Shidami, it overestimates the

peak discharge volume at the other observation sites. The slope-channel kinematic wave model (Kmodel) can reproduce the observed hydrographs well.



(a) Shidami **(b) Mizunami**

Figure 15 Comparison of the simulated and the observed hydrographs for Flood 5.

CONCLUSIONS

The authors compared three runoff models, and investigated the model parameter sensitivities. The following findings were acquired:

1) In the storage function model, further investigation is necessary for the model parameters and the determination of the effective rainfall to improves the accuracy of the simulation. The optimum model parameters depend on the flood events.
2) The slope-channel system kinematic wave model can reproduce the original hydrographs well. The optimum model parameters which do not depend on the flood events are almost the same as the conventionally recommended values.
3) Although the grid-cell based distributed runoff model also can reproduce the original hydrographs well, it has a tendency to give earlier peak than the observed one. Further investigation is necessary to improve this tendency by adjusting the roughness coefficient of river class much affecting the peak time.
4) The slope-channel kinematic wave model is better runoff model than the other two models because it can reproduce the shape of the original hydrographs well.

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