

Effect of precipitation spatial distribution on the hydrological response in the upper Tone River of Japan

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Abstract Besides the land surface heterogeneity, spatial distributions of precipitation are another key factor for hydrological simulations. With the development of weather radar techniques it is possible to incorporate radar measurements with distributed models for investigating hydrological applicability, especially for flood forecasting. A grid-based distributed hydrological model was used to evaluate the effect of spatial distributions of precipitation on the hydrological response in the Aimata catchment of the upper Tone River basin in Japan. The precipitation data in 2001, obtained by gauge and radar measurements, were used as input data to the hydrological model. As a result of the two input data sources, the long-term hydrological responses and simulation of flood event are compared and discussed.

Key words distributed hydrological model; hydrological response; radar precipitation; Tone River

INTRODUCTION

With the progress in atmospheric sciences, hydrology can greatly update the modelling approach and then upgrade the simulation accuracy. Apart from conventional raingauge measurements, operational weather radars and numerical weather prediction models offer new opportunities in hydrology to improve flood forecasting and the prediction of water resources. For practical applications of water resource management and flood forecasting, lumped models are commonly employed. Current lumped models use averages for meteorological inputs and watershed characteristics and such are prone to calibration and extrapolation difficulties in the ungauged or poorly gauged basins. The spatial pattern of precipitation input cannot be translated into the simulated hydrograph by the lumped models. However, distributed models incorporate the temporal and spatial variability of watershed and meteorological inputs and allow better representations of the hydrological processes compared with other model types (Yang *et al.*, 2002). Developments of the distributed hydrological models have emphasized capturing the local unique contributions due to different land cover, soil property and topography, and the sensitivity analysis of surface spatial heterogeneity (Yang *et al.*, 2001a). At the same time, many studies have addressed the hydrological model response to precipitation inputs of various spatial and temporal resolutions (Finnerty *et al.*, 1997; Cranmer *et al.*, 2001). These studies have mainly focused on calculation of area mean precipitation and evaluation of the lumped models. Recently, a few studies evaluated the performance of several distributed hydrological models by utilizing spatial distribution of precipitation (Cranmer *et al.*, 2001; Taschner *et al.*, 2001; Anderson *et al.*, 2002). Incorporation of

distributed inputs of precipitation was expected to improve the simulation of hydrographs, but some research showed no significant improvement. It is still necessary to examine the performance of different distributed models incorporating different data sources of spatial distributed precipitation.

Now the operational weather radars cover most of the land area of Japan and radar interpreted precipitation is available. Several research projects have been initiated for studying the applicability of radar precipitation data for flood forecasting and water resources management. The main objective of this study was to identify the effect on hydrological responses of the spatial distribution of precipitation and to examine the applicability of radar precipitation data for flood forecasting. For this purpose, a grid-based distributed model has been applied to the upper Tone River of Japan. The precipitation data of 2001, obtained by gauge measurement and radar measurement, were used as the input data. The results corresponding to the two input data sources are compared for long-term hydrological responses and flood events.

METHODOLOGY

Study area

The Tone River is located in northeast Tokyo, Japan. The upper Tone River basin is a high mountainous region. The long-term mean annual precipitation in this region is near 2000 mm. This region suffers heavy snowfall, commonly during the winter (December–February) and typhoons, sometimes in late summer (August and September). The snowmelt runoff is the major water resource used to supply Tokyo, and typhoons also cause high flood risks to Tokyo. Therefore, the upper Tone River has been selected as one of the study areas in the research project of radar precipitation application. As the first step of this research programme, the Aimata catchment, a headwater area of the upper Tone River, was studied. The study area is the same drainage area of the Aimata Dam, by which a reservoir with total storage of 25 million $\times 10^6 \text{ m}^3$ has been formed. The Aimata catchment has a drainage area of 110.8 km², of mainly high mountains covered by forests. The elevation varies from about 400 m to 2000 m, and the depth of topsoil is very shallow.

The geographical information used in this research includes topography, land cover, soil and geology maps. The digital data were obtained from the Japanese Geographical Survey Institute. The topography is simulated by a grid-based DEM (digital elevation model) of 50-m resolution with the available finest data. The digital land cover map is available in 100-m resolution, and has been grouped into four categories including forest (85%), bare soil covered by sparse grass (14%), built-up land (<1%) and water body (<1%). The soil map is available in 1000-m resolution, and it is re-sampled into three types. Combining with the geology map the topsoil depth has been estimated to be from 0.8 to 5 m, and around 1 m in most areas. The vertical distribution of saturated soil hydraulic conductivity is assumed to decrease exponentially from K_0 near the soil surface to K_g of groundwater in a depth of 5 m (the maximum depth of topsoil). The value of K_0 is estimated from the soil data, and the hydraulic conductivity (K_g) of groundwater in unconfined aquifer is a calibrated

Table 1 Soil parameters used in the hydrological model.

Soil type		High permeable soil	Black soil	Forest soil
Coverage (%)		34	14	52
Saturated hydraulic conductivity (mm h ⁻¹)	Near surface	50	15	25
	Groundwater	1.0	1.0	1.0
Volumetric moisture content of topsoil	Saturated	0.51	0.51	0.51
	Residual	0.17	0.17	0.17
Parameter in Van Genuchten's expression (1980) of soil water retention curve and hydraulic conductivity *	α	0.01695	0.01695	0.01695
	n	1.4132	1.4132	1.4132

*The unit for matric pressure is cm water.

parameter according to the baseflow. Table 1 shows the soil-water parameters used in the hydrological simulations.

Precipitation

Conventional meteorological measurement Conventional meteorological measurements are available from the Automated Meteorological Data Acquisition System (AMeDAS) by the Meteorological Agency. The AMeDAS data include precipitation, temperature, wind speed and sunshine hours, and are available in hourly temporal resolution. By checking the data availability for the Aimata catchment, there is no AMeDAS gauge located inside of this catchment. The nearest AMeDAS gauge (around 10 km from the catchment centre) was selected and the potential evaporation was calculated using the Priestley-Taylor method (Brutsaert, 1982). Because there is only one gauge measurement that can be used for the hydrological simulation in the Aimata catchment, no interpolation has been used to distribute the point data. The values of rainfall and potential evaporation are specified uniformly (as the same as the point value) in the discrete catchment at the 100-m grid size.

Radar measured rainfall The radar interpreted rainfall is provided in 5-min temporal resolution and 1-km spatial resolution for 2001 by the Foundation of Rivers & Basin Integrated Communications (FRICS) of Japan. These rainfall data have been corrected according to the surface gauge measurements. A simple disaggregation is performed, duplicating each grid value to a 100-m grid. The hourly precipitation data are created by aggregating the 5-min rainfall.

Comparison between the gauge and radar measurements Because the accuracies of snowfall measurement by both radar and gauge are poor, only the no-snow season (i.e. from June to November) was examined in this study. Firstly, the daily catchment mean rainfall was compared between the gauge and radar measurements. The total amount of the gauge measured rainfall from 1 June to 30 November 2001 was 1248 mm, which is considered as uniform over the catchment. The rainfall measured by radar shows high spatial variability ranging from 1228 to 2639 mm, and has catchment mean value of 1655 mm in the same time period.

Distributed hydrological model

The grid-based distributed hydrological model used in this study was modified from the geomorphology-based hydrological model (GBHM) (Yang *et al.*, 2002). As mentioned above, the finest DEM is available in 50-m spatial resolution. For accurate simulation of the topography, the hydrological model should also use the same resolution. Unfortunately, grid-based distributed hydrological models usually cannot run at the high spatial resolution for practical applications due to heavy computation and limited land surface information. Considering the capacity of the present commonly used PCs Windows system, this model uses a grid size of 100 m as the same resolution as the land cover map. Since the grid-based DEM represents the topography of a grid by a single slope and average elevation, aggregating DEM from 50-m resolution to 100-m will decrease the gradient and increase the length of the hillslopes. A sub-grid parameterization scheme is necessary when the coarse grid size is used.

Sub-grid parameterization Distinguishing characteristics of the methodology on the sub-grid parameterization is representing sub-grid variability in topography by the geomorphological properties. In the geomorphology-based hydrological model (GBHM) developed by Yang *et al.* (2002), the geomorphological property of river-hillslope formation was used to represent catchment topography. In a similar way, it is assumed that a grid comprises a set of hillslopes located along the rivers. Within a grid, the hillslopes located in a grid are viewed as geometrically similar. The same hillslope model in the GBHM was used, which is a rectangular inclined plane. Length of hillslope is calculated from the 50-m DEM. Slope angle is taken by the mean slope of all sub-grids in the 100-m DEM. The impermeable bedrock slope is assumed to be parallel to the surface. Land cover and soil type are uniform in each grid.

Hillslope hydrological model A physically-based model is used to simulate hillslope hydrological response, in which the vertical plane is divided into several layers, including canopy, soil surface, unsaturated zone and groundwater aquifer (Yang *et al.*, 2002). Canopy interception depends on the LAI (leaf area index) and differs over time. The actual interception is determined according to the rainfall intensity and deficit of canopy storage (Yang *et al.*, 1998). The actual evapotranspiration is estimated from the potential evaporation considering individual component from canopy water storage, root zone, and soil surface. The Richards equation is employed to describe soil water movement in the unsaturated zone. The surface runoff is the infiltration and saturation excesses, which flow through the hillslope into the river and is modelled by the kinematic wave method. The subsurface flow is generated by gravity movement of soil moisture above the field capacity along the hillslope. The groundwater aquifer is treated as individual storage corresponding to each grid. The exchange between saturated zone and the river is considered as steady flow and calculated by Darcy's law (Yang *et al.*, 1998).

The runoff output from one grid is the sum of hillslope responses (both surface and subsurface runoff) within the same grid. The state variable, soil moisture content, of a grid is the average soil moisture of hillslopes. The vertical flux, actual evapotranspiration, of a grid is the total evapotranspiration simulated from the hillslopes.

River network routing In order to simulate flow routing in the river networks, it is necessary to number the river segments (links) and define the flow sequences. Here the Pfafstetter basin numbering scheme (Yang *et al.*, 2000, 2001b) has been applied. It allows a catchment to be divided into a number of small sub-catchments systematically. The size of the final sub-catchments depends on the simulation requirement and the DEM resolution. In the present application to the Aimata catchment, a total of 81 sub-catchments have been derived in an average area of 1.4 km². Within a derived minimum sub-basin, the river networks are simplified using the main stream. The flow sequences of the river networks are defined by the codes of the divided sub-catchments. River routing is modelled by the kinematic wave approach. The lateral inflow to a flow interval is the runoff generated from the grids at the same flow distance in the same sub-catchment. Once the water is routing in the river network it is still keeping a dynamic connection with the groundwater, the exchanges between river and groundwater has been described in the hillslope hydrological model.

Model application

Since the precipitation input from both radar and gauge measurements are available hourly, the hydrological simulations have been carried out at an hourly time step. Inflow of the Aimata reservoir is available in hourly temporal resolution from the Ministry of Land, Infrastructure and Transportation (MLIT), and is used for evaluating the model performance. Due to poor accuracy of snowfall measurement, this hydrological simulation focuses on the no-snow season (i.e. from June to November). After the snowmelt season most areas of the catchment are very wet, therefore initial conditions over the study area are specified with soil moisture at field capacity in the root zone and saturated soil moisture in the deeper layers, and full groundwater. The groundwater hydraulic conductivity is calibrated by checking the base discharges in a long-term (June–November) simulation. The calibrated value of the groundwater hydraulic conductivity is shown in Table 1.

RESULTS AND DISCUSSION

Rainfall input effect to the hydrological responses

Hydrological simulations are performed employing different rainfall data obtained by gauge and radar measurements. Figure 1 compares the daily hydrographs simulated using the two data sets. The simulation overestimates peaks for both gauge and radar data. Results given by gauge rainfall give higher simulation of the large peaks, and the radar data mainly overestimate the small peaks. In general it is difficult to evaluate which data source is better from the long-term simulation of daily hydrographs. From the water balance in Table 2, it is known that the gauge rainfall produces slight underestimation of total runoff, but the radar precipitation produces near 40% overestimates of total runoff. It can be concluded that the gauge gives better measurement of total rainfall in the long-term than the radar does.

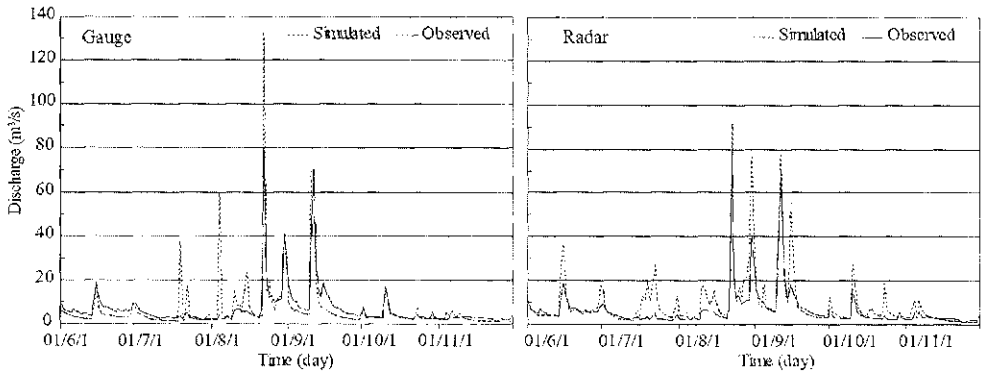


Fig. 1 Comparison of daily hydrographs simulated using different precipitation data.

Table 2 Comparison of long-term hydrological simulations by different data sources (simulated period: 1 June–30 November).

Data source	Precipitation (mm)	Simulated component (mm):		Observed runoff (mm)	Total runoff error (%)
		Evapotranspiration	Runoff		
Gauge data	1248	414	900	941	-4.4
Radar data	1655	431	1289	941	+37.0

For evaluating the effect of rainfall input on the simulation of flood, the hourly hydrograph obtained by the same simulation as the above is examined for a flood event with the highest peak (21–23 August). Figure 2 shows the comparison of the simulated and observed hydrographs for a 72-h period centred to the peak, and the characteristics are summarized in Table 3. The radar rainfall gives much better simulation of this flood event than the gauge rainfall. The difference of total rainfall amounts between gauge and radar measurements is only about 20%. The maximum rainfall intensities

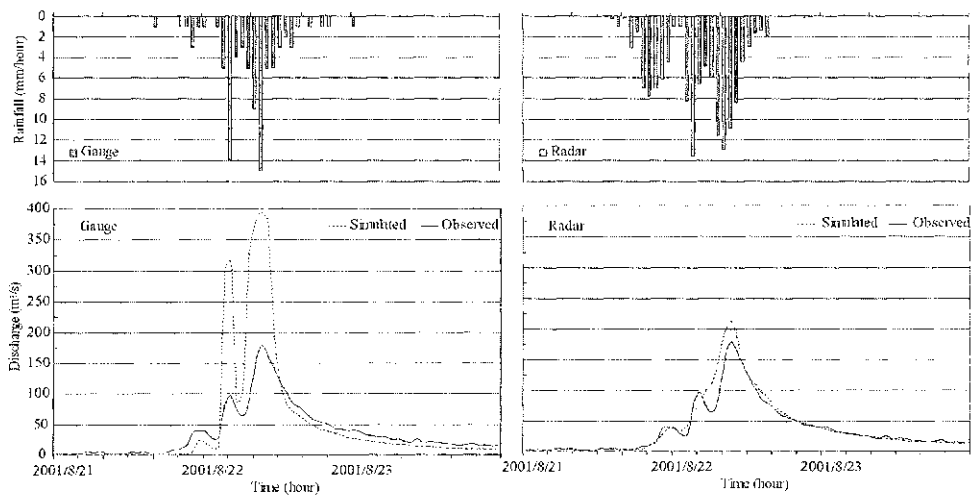


Fig. 2 Comparison of simulation of flood event using different precipitation data.

Table 3 Comparison of flood event (21–23 August) by different data sources.

Data source	Precipitation (mm)	Deviation to the measured hydrograph			Efficiency ϵ
		Peak flow (%)	Peak time (hr)	Peak volume (%)	
Gauge data	159	+220	± 0.0	+137	-1.6
Radar data	136	+1.2	± 0.0	+1.1	0.9

* The efficiency criterion $\epsilon = 1 - \frac{\sum_{i=1}^{T-1} (Q_i - \bar{Q}_i)^2}{\sum_{i=1}^{T-1} (Q_{oi} - \bar{Q}_{oi})^2}$ (where Q_i and Q_{oi} are hourly discharges)

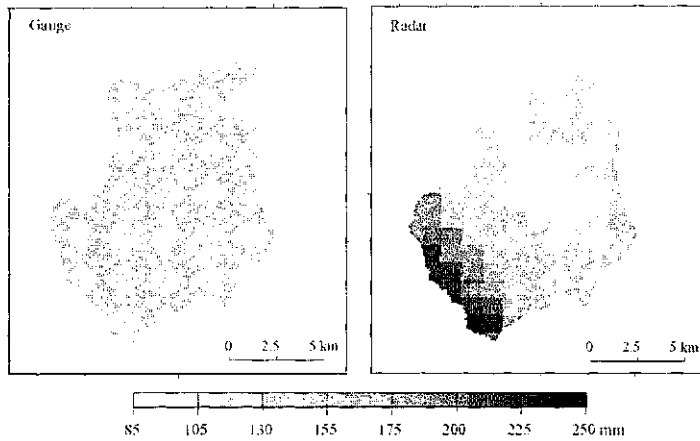


Fig. 3 Spatial distribution of rainfall during the flood event (21–23 August).

from both the gauge and radar are not much different too, but the peak flow simulated by the gauge rainfall is about two times higher than the peak flow simulated by the radar rainfall. This difference is caused mainly by the spatial distribution of rainfall shown in Fig. 3.

Flood sensitivity to the spatial distribution of rainfall

The difference of flood hydrographs between the gauge and radar simulations has shown the importance of rainfall spatial distribution. A simple sensitivity test has been carried out in the study. To account for possible movements of heavy rainfall in space, 2-km adjacency shifts of the rainfall field to four directions are performed and the sensitivities of flood responses are examined. Figure 4 shows the consequent results to the four shifted rainfall fields. When the rainfall field shifts 2 km towards the east and north from the original field, the peak flow occurs about one hour earlier and become near 50% higher than the original case. However, the peak flows slow down slightly and become a little smaller when the rainfall field shifts to western and southern directions. The results again enforce our understanding of the importance of spatial distribution of precipitation in hydrological simulations, especially for flood forecasts.

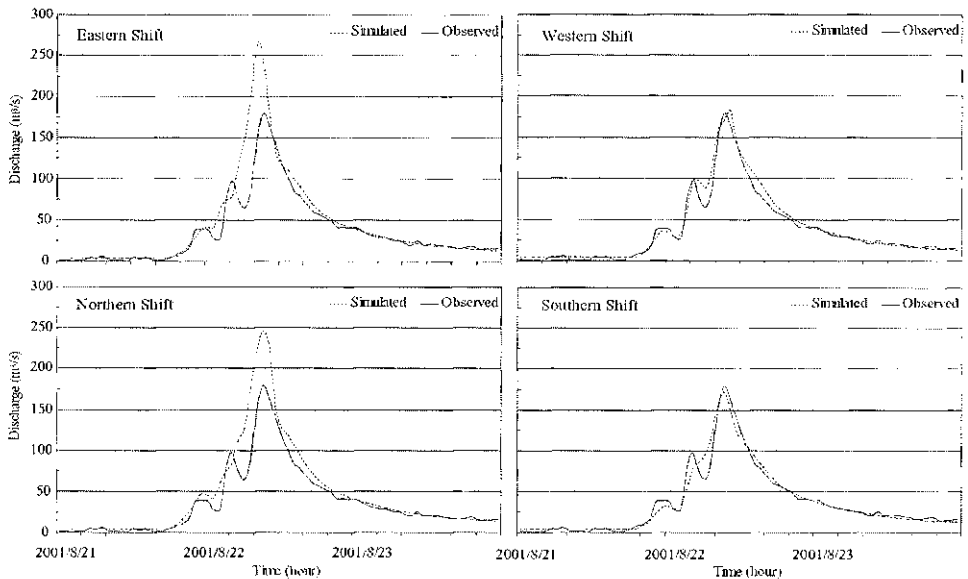


Fig. 4 Flood sensitivity to the spatial distribution of rainfall (2 km shift from the original data).

CONCLUSIONS

A grid-based distributed model has been applied to investigate the effect of rainfall spatial distribution to catchment hydrological responses. Results have shown that the spatial pattern of rainfall can cause significant changes to the catchment hydrological response at high temporal resolution, and this is especially important for flood simulation. A comparison between the gauge and radar measurements of precipitation indicates that the gauge offers a better measurement of long term (no snowfall season) total amount than the radar. However, the radar could measure the spatial pattern of precipitation, which is a key factor for flood simulation. It has been shown that the distributed hydrological model has the capability of incorporating the spatial distribution of precipitation into hydrological simulation. The radar rainfall measurement and distributed model have potentially important applications to flood forecasting in applied hydrology.

Acknowledgements The authors would like to thank the Reservoir Management Office of the Upper Tone River, MILT, for providing the river discharge data, and the Foundation of Rivers & Basin Integrated Communications (FRICS) of Japan for providing the radar precipitation data.

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