

IMPROVING FLOOD SIMULATION IN URBAN RIVER BASIN USING X-BAND POLARIMETRIC RADAR AND DISTRIBUTED HYDROLOGICAL MODEL

Ratih Indri Hapsari¹, Satoru OISHI², Kengo SUNADA³, Tetsuya SANO⁴

¹Student member of JSCE, PhD student, Dept. of Civil Eng., Univ. of Yamanashi (Kofu, Yamanashi 400-8511, Japan)

²Member of JSCE, Dr. of Eng., Prof., Dept. of Civil Eng., Univ. of Yamanashi (Kofu, Yamanashi 400-8511, Japan)

³Fellow of JSCE, Dr. of Eng., Prof., Dept. of Civil Eng., Univ. of Yamanashi (Kofu, Yamanashi 400-8511, Japan)

⁴Dr. of Sci., Assistant Prof., Dept. of Civil Eng., Univ. of Yamanashi (Kofu, Yamanashi 400-8511, Japan)

The advantages of X-band polarimetric radar over the conventional radar in estimating rainfall and simulating flood in urban river basin using distributed hydrological model were investigated. Classical radar-rainfall algorithm $R(Z_H)$ and composite polarimetric radar-rainfall algorithm $R(Z_H) R(K_{DP})$ which have been corrected from rain attenuation were used to estimate the rainfall intensity and simulate storm event. Performance of the hydrological model using high spatial resolution rainfall estimated from X-band was compared to that of using lower resolution. The comparison demonstrated the advantages of X-band observation over the observation with lower spatial resolution for detecting a heavy rainfall in small area that led to runoff underestimation. Integrating polarimetric algorithm to the model allowed for more accurate rainfall estimates and gave an improved model performance. The effects of systematic and random error in radar-rainfall data to hydrological model performance were subsequently examined.

Key Words: *X-Band polarimetric radar, distributed hydrological model, urban river basin, radar-rainfall algorithm, sensitivity analysis*

1. INTRODUCTION

Urban rivers respond rapidly to intense rainfall events. Due to decreasing of retarding function, time to reach the peak discharge become shorter and peak discharge increase, hence there will be a greater risk of flooding. Flash floods in urban areas have severe adverse impacts on community. However, it can be avoided by recognizing the potential of danger and by taking preventive action. Detecting the extreme rainfall events and recognizing basin hydrologic response are important for reducing the vulnerability.

Considering the small size of catchment of urban river basins, providing severe rainfall information at small scales is essential. Furthermore, flash flood events are generally characterized by high space-time variability. Recent studies have confirmed the significance of the rainfall spatial structure in flood runoff generation^{1,2)}. Weather radars offer an enhanced severe rainfall estimation as they have a capability to achieve fine spatial and temporal resolution. Distributed hydrological model better represent spatial variability of gridded space-time radar-rainfall observations, thus it is expected to produce an improved rainfall-runoff modeling³⁾.

X-band radar observation, whereby 0.5 km

resolution can be achieved, provides more detail rainfall information than conventional radars⁴⁾. Recent studies revealed that more accurate rainfall rate can be obtained from polarimetric radars^{5,6)}, since polarimetric radar-rainfall algorithms are less sensitive to drop size distribution (DSD) variation⁶⁾.

Some advanced research pertaining to integration of radar information into distributed the hydrological model has been developed by some researchers^{7,8,9)}. However, most of them have been performed for radars at S-band and C-band wavelength. Therefore, there is a necessity to conduct a study pertaining to X-band radar application. Previous studies regarding the polarimetric parameter radar measurements for rainfall estimates mostly discussed on its accuracy over the surface observation^{6,10)}. Furthermore, the comparison of conventional radar with X-band polarimetric radar application for simulating flood due to short-term heavy rainfall has not been adequately assessed. It is also found that there is a lack of this study within urban river basin context.

In this paper, the application of X-band polarimetric radar for rainfall-runoff modeling by using distributed hydrological model in urban river basin is introduced. The objective of this study is to investigate the advantages of using polarimetric

parameter K_{DP} over the conventional parameter Z_H to estimate rainfall and simulate flash flood due to short-term heavy rainfall. A comparison of flood modeling using 0.5 km spatial resolution of rainfall input obtained from X-band radar with those using lower resolution was also conducted. The effect of error in radar-rainfall data to hydrological model performance was also examined.

2. X-BAND POLARIMETRIC RADAR OBSERVATIONS

In April 2009, University of Yamanashi, Japan launched an X-band polarimetric Doppler radar (hereafter called UY Radar) in Kofu area (35.6792°N, 138.5725°E), as shown in **Fig. 1**. In contrast to conventional radars, which measure horizontal reflectivity Z_H , polarimetric radars measure from both horizontal and vertical polarizations. The fundamental polarimetric parameters for estimating rainfall intensity R are differential reflectivity (Z_{DR}) and specific differential phase (K_{DP}). K_{DP} is derived from differential propagation phase (ϕ_{DP}). Some previous researches have introduced $R(Z_H)$, $R(Z_{DR})$, $R(K_{DP})$ algorithms or their combinations^{(6),(11),(12)}. These algorithms should be adapted by considering local conditions, such as climatic regime, topography, and rain system type.

X-band radars have some advantages, but their reflectivity is greatly affected by rain attenuation⁽¹³⁾. As K_{DP} is less affected by attenuation⁽¹⁰⁾, it can be used to overcome this problem. Moreover, in mountainous terrain, K_{DP} has great potential since blocking of the radar beam will not affect the K_{DP} as it does the

Z_{DR} ⁽¹⁰⁾. However, in comparison to Z_H , K_{DP} at low rainfall rate is relatively noisy. Therefore, in practice, classification and combination of the algorithm is likely to be recommended.

A composite method proposed by Park *et al.*⁽¹²⁾ derived from observation of X-band polarimetric radar in Tsukuba, Japan, which is representative of mid-latitude regime, was adapted and modified in this study. The radar-rainfall algorithms using the classical estimator for stratiform and convective precipitation system types are as shown below:

$$R(Z_H) = 7.07 \times 10^{-3} Z_H^{0.819} \text{ for } Z_H \leq 30 \text{ dBZ} \quad (1a)$$

$$R(Z_H) = 7.40 \times 10^{-2} Z_H^{0.566} \text{ for } Z_H > 30 \text{ dBZ} \quad (1b)$$

where, R is in mm/h and Z_H is in mm^6m^{-3} . The composite algorithms are expressed as follows:

$$R(Z_H) = 7.07 \times 10^{-3} Z_H^{0.819} \text{ for } Z_H \leq 30 \text{ dBZ or } K_{DP} \leq 0.3^\circ\text{km}^{-1} \quad (2a)$$

$$R(K_{DP}) = 19.63 K_{DP}^{0.823} \text{ otherwise} \quad (2b)$$

where, K_{DP} is in $^\circ\text{km}^{-1}$. Eq. (1b) and Eq. (2b) correspond to convective rainfall. For the validation, one rain-gauge was set up near the radar. Observations of several rainfall occurrences in Kofu City using UY Radar have shown that this algorithm can estimate the rainfall intensity reasonably.

Some preparation processes were undertaken before applying radar-rainfall estimator. Rain attenuation of Z_H was corrected by using modified self-consistent method for X-band wavelength application⁽¹³⁾.

$$10 \log_{10}[Z'_H(r)] = 10 \log_{10}[Z_H(r)] - 2 \int_0^r A_H(s) ds \quad (3)$$

$$A_H(r) = \frac{[Z'_H(r)]^b}{I(r_1, r_0) + (10^{0.1ba\Delta\phi_{DP}-1})I(r, r_0)} \quad (4)$$

where, Z'_H is attenuated Z_H (mm^6m^{-3}), r is range, A_H is specific attenuation (dBkm^{-1}), α and b are coefficients, and ϕ_{DP} is differential propagation phase ($^\circ$). The coefficients were determined in accordance with optimal values for X-band⁽¹²⁾.

The Z_H and K_{DP} data were obtained from constant altitude plan position indicator (CAPPI) scans every 6 minutes at 750 m elevation. The horizontal resolution was 0.5 km x 0.5 km. As shown in **Fig. 1**, it is apparent that there are some missing parts of UY radar observation in the north of radar location due to a surface obstacle. Thiessen method was used to extrapolate rainfall data within this area.

3. METHODOLOGY

This study was conducted in urban river basin of Kofu City, Yamanashi Prefecture, Japan, which has

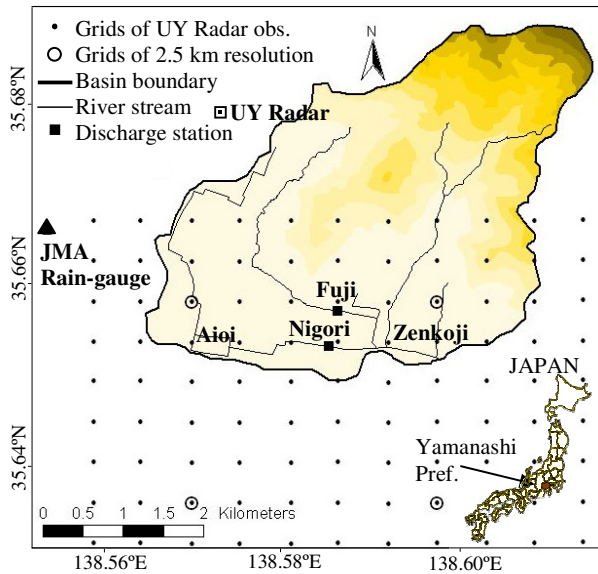


Fig. 1 Nigorikawa River Basin in Kofu urban area, flood vulnerable areas (Aioi and Zenkoji), UY Radar, rain-gauge, grid points of radar observation in 0.5 km and 2.5 km resolution, and location of discharge observation.

catchment area of 12.3 km², as depicted in **Fig. 1**. Nigorikawa River passes through the center of Kofu City and this river is vulnerable to flood hazard. Aioi and Zenkoji are a highly urbanized area and have been observed to have the highest inundation occurrence. The solid dots in **Fig. 1** are UY Radar observation grids with resolution of 0.5 km. Ten-minute rainfall intensity data from the closest rain-gauge observation provided by JMA are available. Two staff-gauges were installed at two points, Nigori and Fuji discharge stations, in order to obtain observed runoff data. Surveys of channel geometry and flow velocity as well as gauge calibration were carried out to obtain a correct rating curve. These observations have provided 10-minutes runoff data series needed for model calibration and validation since June 2009 continuously.

The distributed physically-based hydrological model used in the present study was BTOPMC developed at the University of Yamanashi¹⁴⁾. Block-wise use of TOPMODEL for runoff generation and Muskingum-Cunge method for routing are the core module. For representing spatial variability, a basin is composed of grid cells and each cell is considered as a block. Essentially, the BTOPMC model was developed for simulation for large basins. A latter modification of BTOPMC had an objective to amplify its application for event-based simulation by introducing the canopy interception and TCA based infiltration model¹⁵⁾. The evapotranspiration can be neglected for flood event simulation¹⁵⁾.

Japan terrain map of 10 m resolution was used to generate the DEM of the area. A further investigation has shown that 60 m spatial resolution is the proper sizes for maintaining numerical stability of simulation. Field surveys have been carried out to ascertain land use data as well as ground river stream. Considering the drainage system complexity within the small basin in urban area, it is necessary to assure that the generated river stream was in close match with the ground stream. The DEM was corrected according to the natural flow paths. When the rain-gauge data are applied for distributed hydrological models, a conversion into spatially-distributed is required. The distributed hydrological model supported the grid formatted radar data, thus the transformation is no longer needed.

Several storm events from June to August 2009 were selected. The model parameters were tuned using rain-gauge and observed runoff data from June to July, and validated during simulations in August. Three indices have been computed to quantify model performance, Nash-Sutcliffe Efficiency (NSE), Root Mean Square Error (RMSE), and Peak RMSE (PRMSE). The hydrological model can simulate flood hydrograph reasonably (**Fig. 2**).

Rainfall intensity data were retrieved from CAPPI map by using both R(Z_H) and R(K_{DP}) algorithm and aggregated to hourly rainfall sums subsequently. The low resolution of rainfall spatial distribution referred to those observed by C-band radar. The data retrieved from R(Z_H) R(K_{DP}), were transformed to 2.5 km resolution as observed by C-band radar by making spatial averaging. Non-solid dots in **Fig. 1** are the grids of 2.5 km resolution. Hydrological simulations were performed employing these three different data sources as well as using point rainfall data from rain-gauge. The model was applied to simulate and evaluate the recent heavy storm event on Aug 2, 2009. Water level at Nigori point observed by staff-gauge was 2.0 m at 20:00 JST, whereas the channel depth is 2.7 m. As observed by JMA rain-gauge the maximum rainfall intensity was 36 mm/h at 19:50 JST and hourly maximum rainfall intensity was 13 mm/h at 20:00 JST.

Kato and Maki⁴⁾ compared X-band radar and radar AMeDAS versus surface rain-gauge data (**Fig. 3**). It can be inferred that though X-band radar and rain-gauge data were in good agreement, the uncertainties still exist. The characteristic of the error in X-band radar in estimating rainfall has not been adequately recognized, as previous studies mainly conducted at C-band or S-band wavelength. In this study, effect of error in radar-rainfall data to hydrological model was assessed by the Eq. 5 shown below. Systematic error of rainfall data can be formulated by¹⁶⁾:

$$Pj' = (1 + k)Pj \quad (5)$$

where, Pj is original rainfall at time j , Pj' is perturbed rainfall, and k is coefficient for testing of

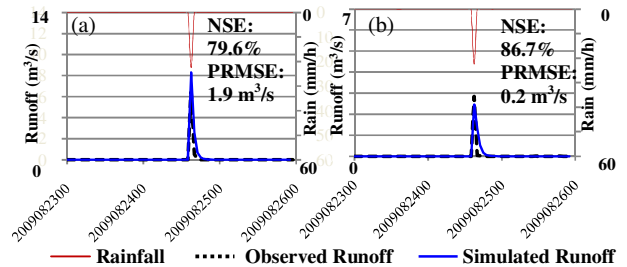


Fig. 2 Result of hydrological model validation in, (a) Nigori outlet, (b) Fuji outlet.

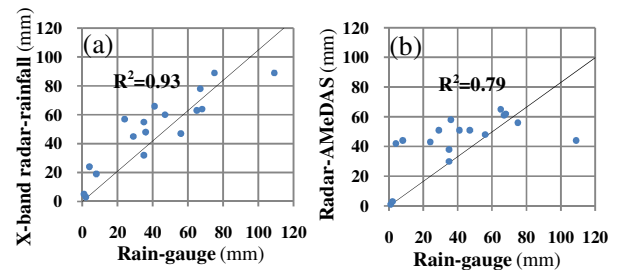


Fig. 3 Surface rain-gauge data versus, (a) X-band radar-rainfall, (b) Radar-AMeDAS⁴⁾.

several systematic under/over estimation. Random error model is random noise and it is defined by¹⁶⁾:

$$Pj' = Pj \exp\left(\sigma\eta_j - \frac{\sigma^2}{2}\right) \quad (6)$$

where, σ is random error intensity, which could vary from 0 to 1 and η_j is Gaussian error. Gaussian error is assumed as a set of random numbers in normal distribution with mean equals zero and standard deviation equals to one. The rainfall input was corrupted by applying these errors on rainfall data.

4. RESULTS AND DISCUSSION

The analysis of Z_H and K_{DP} within the radar range indicated that rainfall system recorded during selected storm event was categorized as convective type, moved from southwest to northeast. The spatial distribution of rainfall over the Kofu urban river basin at 19:48 and 20:00 JST is presented in **Fig. 4**, comparing the rainfall intensity from $R(Z_H)$ $R(K_{DP})$ with $R(Z_H)$ and lower resolution rainfall estimates.

A strong rainfall region initially could not be diagnosed from Z_H due to attenuation caused by strong rainfall between observed area and radar. At 35.55°N 138.54°E 19:00 JST, UY Radar detected a weak Z_H of 32.7 dBZ or equal to rainfall of 5.3 mm/h. However, K_{DP} can detect this attenuated rainfall. After correction process, the corrected Z_H became 45.5 dBZ or equal to rainfall of 27.8 mm/h (**Fig. 5**).

The rainfall intensity derived from UY Radar measurement using $R(Z_H)$ $R(K_{DP})$ algorithm at 19:48 JST and 20:00 JST are shown in **Fig. 4** (a). Maximum rainfall intensity was 54.8 mm/h at 19:54 JST, while JMA rain-gauge observed 36 mm/h at 19:50 JST. The strong rainfall started crossing the basin at 19:48 JST and heading to northeast direction at 20:12 JST. The available rain-gauge was not adequate to provide such comprehensive information.

$R(Z_H)$ detected maximum rainfall intensity of 34.4 mm/h at 19:54 JST. From **Fig. 4** (b) it can be seen that $R(Z_H)$ algorithm could not recognize the rainfall region where the rainfall intensity was larger than 40 mm/h. However, for the case of weak rainfall, there was an insignificant difference between $R(Z_H)$ and $R(Z_H)$ $R(K_{DP})$. Furthermore, convective rain was not detected in the target area. This underestimation possibly attributable to the sensitiveness of $R(Z_H)$ to DSD variation⁶⁾, as one of major source error in $R(Z_H)$. Furthermore, beam blockage problem may contribute to the error¹⁰⁾, as UY Radar is located in the mountainous area.

Fig. 4 (a) and **Fig. 4** (c) clearly demonstrates the advantage of X-band radar against observation in 2.5 km resolution in representing rainfall spatial variability throughout the basin. Even though

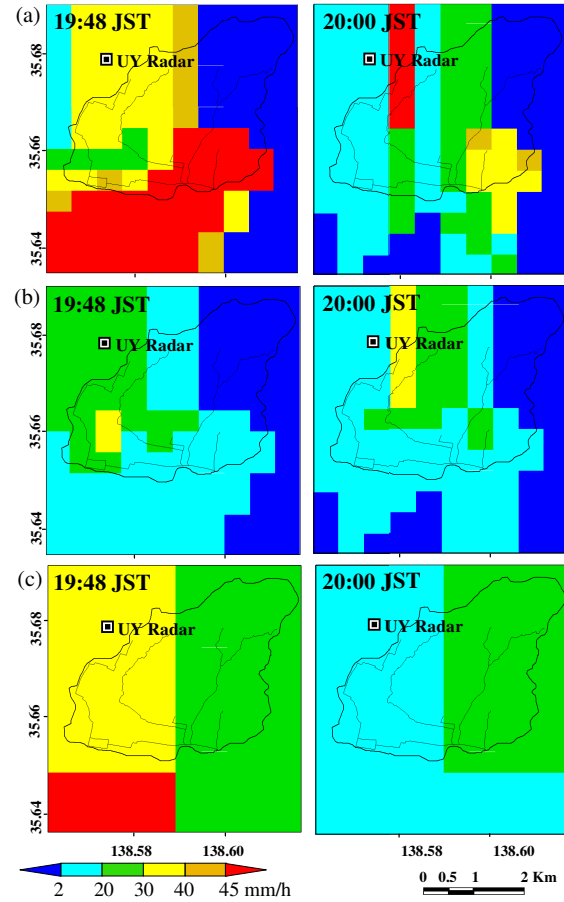


Fig. 4 Rainfall spatial distribution of storm events of Aug 2, 2009 at 19:48 and 20:00 JST using (a) X-band $R(Z_H)$ $R(K_{DP})$, (b) X-band $R(Z_H)$, (c) $R(Z_H)$ $R(K_{DP})$ in 2.5 km resolution.

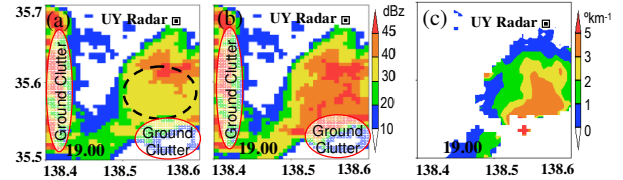


Fig. 5 (a) Z_H before correction, high Z_H at area within dotted line was not detected, (b) Z_H after correction, (c) K_{DP}

Fig. 4 (c) is capable of estimating strong rain rate, some part of the local rain indicated by red grids in **Fig. 4** (a) was poorly captured. Nevertheless, it should be noted that the inadequacy of this estimates to identify detailed rainfall structure is dependent on the rainfall event characteristics.

The enhanced rainfall information from UY Radar allows for more accurate rainfall estimates than the conventional one in terms of quantitative rainfall estimates as well as the spatial pattern. In terms of rainfall temporal evolution, however, they all monitored a similar motion. More detail rainfall structure was adequately assessed, such as a local heavy rainfall in 35.67°N 138.58°E at 20:00 JST (red grids in **Fig. 4** (a)) with an intensity of 48.3

mm/h, which was previously unavailable.

The BTOPMC considered the catchment as a collection of many hill slopes with each being considered as one unit of water balance. According to DEM resolution, the catchment composed of 60 m x 60 m grid cells. Considering the urban river basin with various topographic features and complex drainage system, there can be many hill slopes exist in each cell. The fine resolution (0.5 km) of heterogeneous rainfall data was disaggregated at each hill, resulting in more detailed representation of the hydrologic process. In urban catchment, effects of spatial rainfall on stream flow will be greater than for rural areas and these effects would increase with decreasing catchment scale²⁾.

The result of simulations of Aug 2, 2009 storm event is shown in **Fig. 6** and **Table 1**. Compared with the other three simulations, integrating X-band polarimetric parameter to distributed hydrological model can better simulate flood event (**Fig. 6** (a)). There was a good agreement between the observed and simulated hydrograph. It was also shown by high model performance indicators, for example, the NSE was 89.8%. For the case of simulating with rain-gauge data as an input (**Fig. 6** (b)), storm event was poorly simulated. The high PRMSE indicates that peak flood discharge magnitude, which is critically important in a flood estimation context, could not be simulated accurately. The available rain-gauge obviously could not characterize the rainfall over the target basin which is significant in hydrological modeling.

The hydrological simulation using $R(Z_H)$ showed a lower performance than those using $R(Z_H) R(K_{DP})$ (**Fig. 6** (c)). The NSE of the model using $R(Z_H)$ was 86.8%, whereas $R(Z_H) R(K_{DP})$ gave 89.8%. Basically, $R(K_{DP})$ promises more reliable rain rate estimates, particularly for heavy rain. In $R(Z_H)$ algorithm there was an underestimation of strong rain in some area as can be seen in **Fig. 4** (b). However, the strong rainfall echo which was underestimated by $R(Z_H)$ did not move northwestward in which upstream of Nigori sub-basin is mainly located. This situation noticeably contributed to the slight difference of model performance between $R(Z_H)$ and $R(Z_H) R(K_{DP})$.

There was a deterioration in the model performance, which has been simulated by applying low spatial resolution rainfall data (**Fig. 6** (d)). Compared with those using rain-gauge data, the simulation showed a better performance, indicated by the NSE improvement from 34.2% to 75.7% at Nigori. However, compared with those using X-band data it was still insufficient to simulate the peak flow. The peak simulated runoff of 7.1 m³/s could not reach the observed runoff 14.0 m³/s. This

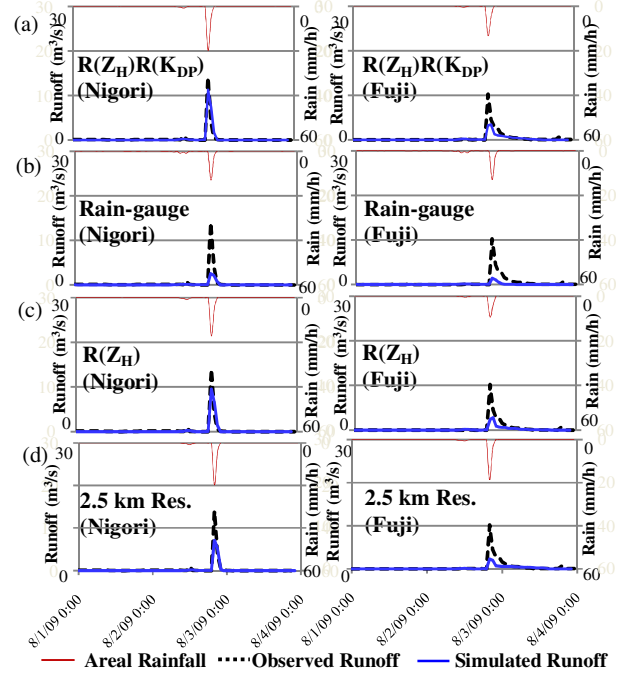


Fig. 6 Areal rainfall, observed and simulated hydrograph of storm events of Aug 2, 2009 at Nigori and Fuji outlet by using, (a) X-band $R(Z_H) R(K_{DP})$, (b) surface rain-gauge, (c) X-band $R(Z_H)$, (d) $R(Z_H) R(K_{DP})$ in 2.5km resolution.

Table 1 Summary of model performance

Indices	Outlet	X-band $R(Z_H) R(K_{DP})$	Rain- gauge	X-band $R(Z_H)$	2.5 km resolution $R(Z_H) R(K_{DP})$
NSE (%)	Nigori	89.8	34.2	86.8	75.7
RMSE (m ³ /s)	Nigori	4.6	11.6	5.2	7.0
PRMSE (m ³ /s)	Nigori	1.1	4.1	1.7	2.5
NSE (%)	Fuji	58.2	21.2	45.2	20.4
RMSE (m ³ /s)	Fuji	7.5	10.3	8.6	9.0
PRMSE (m ³ /s)	Fuji	2.5	3.1	2.8	2.9

problem was attributable to the inadequate representation of rain spatial variability. Some part of local rain was poorly captured, lead to runoff underestimation.

In terms of discharge variation over the time it was found that there was a good agreement between the simulated and the observed hydrograph for all simulations. According to **Table 1**, it can be noticed that the model could not satisfactorily simulate rainfall-runoff at Fuji sub-basin. As shown in **Fig. 1** there is an absence of radar data in the north part in which the upstream of the Fuji sub-basin is mainly situated. It is reasonable to conclude that the extrapolation method for filling in this missing data may have less accuracy. This problem should be taken into account in the future utilization of UY Radar for weather monitoring.

Hydrological model sensitivity to error of rainfall rate in terms of peak RMSE is presented on the plot of **Fig. 7**. It gave a clear indication a higher

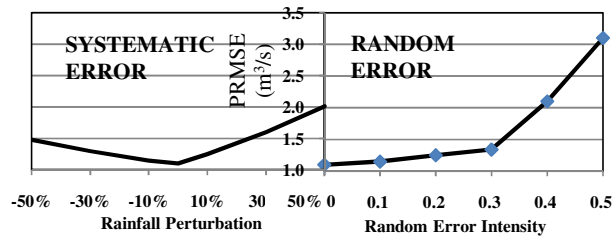


Fig. 7 PRMSEs variation due to systematic and random error.

sensitivity of model performance with respect to the overestimation than to the underestimation of rainfall data due to systematic error. The physical character of the basin which is mostly impervious surface might account for this sensitiveness. Perturbed radar-rainfall data with random error intensity exceeding 0.3 significantly influenced the model performance. In case of small error intensity, the effects of the random errors might be damped out by the storage components of the model. Radar random error can be reduced by providing a number of samples and making a spatial or temporal averaging¹¹⁾.

5. CONCLUSIONS

With the objective of further investigating the advantages of using X-band polarimetric radar over the conventional radar in estimating rainfall and simulating flood in urban area, a comparison of composite polarimetric algorithm $R(Z_H)$ $R(K_{DP})$ using X-band radar against rain-gauge data, classical algorithm $R(Z_H)$, and rainfall estimates in lower resolution were performed. Applying $R(Z_H)$ $R(K_{DP})$ using X-band radar, a detailed rainfall distribution and an accurate rainfall intensity could be estimated. Distributed hydrological model with this advanced rainfall estimation was able to simulate and evaluate storm event in urban river basin. Simulation of selected storm event revealed that the model performance was significantly improved, indicated by NSEs of 34.2%, 75.7%, 86.8%, and 89.8% for simulation using rainfall input from rain-gauge, 2.5 km resolution of rainfall distribution, $R(Z_H)$, and $R(Z_H)$ $R(K_{DP})$ respectively. Hydrological model was more sensitive to the overestimation than to the underestimation of radar-rainfall input due to systematic error. Perturbed radar-rainfall data with random error intensity exceeding 0.3 significantly influenced the model performance. Engineering approach with feedback from rain-gauge is needed to achieve more accurate estimation. A further research is necessary to investigate the error structure of radar-rainfall estimation as observed by UY Radar. Providing a likely short-term prediction of rainfall conditions is expected to be useful in the urban flood disaster prevention system.

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