RESEARCH ARTICLE
ScienceAsia 34 (2008): **215–222**
doi: 10.2306/scienceasia1513-1874.2008.34.215

Climatological Z-R relationship for radar rainfall estimation in the upper Ping river basin

Punpim Puttaraksa Mapiam , Nutchanart Sriwongsitanon*

Department of Water Resources Engineering, Faculty of Engineering, Kasetsart University, Bangkok 10900, Thailand.

* Corresponding author, E-mail: fengnns@ku.ac.th

Received 6 Jun 2007
Accepted 2 Jun 2008

ABSTRACT: Weather radar can potentially provide high-resolution spatial and temporal rainfall estimates bringing more accuracy to flood estimations as well as having some other applications in areas with insufficient rainfall stations like Thailand. Weather radar cannot be used to measure the rainfall depth directly; so an empirical relationship between the reflectivity (*Z*) and rainfall rate (*R*), called the *Z-R* relationship ($Z = AR^b$), is generally used to assess the rainfall depth using radar. In this study, an optimization approach was used to find a suitable climatological *Z-R* relationship for the upper Ping river basin, Northern Thailand. The reflectivity data between June and October in 2003 and 2004 at the Omkoi radar station located in Chiangmai Province, together with the daily rainfall depths at fifty rainfall stations located in and around the basin during the same periods were used. A climatological *Z-R* relationship in the form Z = 74R 1.6 shows acceptable statistical indicators, making it suitable for radar rainfall prediction for the upper Ping river basin.

KEYWORDS: climatological *Z-R* relationship, radar rainfall estimation, Omkoi radar station, upper Ping river basin

INTRODUCTION

Conventional practice in flow runoff and flood estimations is to use rainfall observations at selected stations within a catchment and its surroundings as the input data. The distribution of rainfall usually varies significantly in both space and time[1]; therefore, the area number of rainfall stations in the catchment can have a significant impact on the accuracy of flood estimations[2–4]. This problem occurs in Thailand where the number of rainfall stations is limited, few gauges are automated, and gauges are not distributed evenly.

Weather radar can potentially provide spatial and temporal rainfall data as input to hydrologic models with the aim of increasing the accuracy of flood estimations. The basic principles of radar meteorology for rainfall estimation are well known[5–8].

Weather radar has been used in hydrology for over 50 years and is now becoming increasingly used as an alternative tool to improve rainfall measurement[9]. Weather radar measures the power of electromagnetic waves backscattered by raindrops in the atmosphere (P_r) according to

$$P_r = \frac{C|K|^2 Z}{r^2} \quad , \tag{1}$$

where C is a radar constant depending upon wavelength, transmitted power, antenna gain, beam width, pulse length, and sum of all losses; r is radar range, $|K|^2$ is a dielectric factor depending on the physical properties of the target; and Z is radar reflectivity factor. The radar reflectivity factor can be calculated using the above equation from the known backscattering power and the other variables. For radar rainfall estimation, an empirical power relationship between the reflectivity and rainfall rate ($Z = AR^b$) called the *Z-R* relationship is generally used to assess the radar rainfall rate.

Although there are many *Z-R* relationships[5], they cannot be directly applied to different areas. This is because the parameters *A* and *b* in the *Z-R* relationship usually change from one area to another and depend upon the variations of raindrop size distribution in both space and time. Consequently, there is no universal relationship that can be applied to all rainfall fields[7]. The *Z-R* relationship determination can be determined by two approaches; raindrop size distribution (DSD) and optimization[10]. For the first approach (DSD), *Z* and *R* are calculated directly by using raindrop size distribution data recorded by a disdrometer. For the second approach (optimization), the relationship is determined using reflectivity data measured by radar and true rainfall recorded at rain gauges. A suitable relationship is then obtained by minimizing the errors between estimated radar and gauged rainfall.

In this study, the upper Ping river basin located in Northern Thailand, an area that has been facing serious flooding problems during the last decade, is selected as the study area for radar rainfall estimation.

An appropriate climatological *Z-R* relationship using an ensemble of several events at Omkoi radar station and the corresponding rain gauge data were investigated. The relationship is then applied for radar rainfall estimation in the study area. Since the DSD data has not been measured in Thailand, the optimization approach was used to determine a suitable *Z-R* relationship for this study.

DATA COLLECTION

Radar reflectivity data

The upper Ping river basin is located in Northern Thailand within Chiangmai and Lumphun Provinces. Two departments in this basin, the Thai Meteorological Department (TMD) and the Bureau of Royal Rainmaking and Agricultural Aviation (BRRAA) collect reflectivity data at Amphor Muang Chiangmai and Amphor Omkoi, respectively. The reflectivity data collected by the BRRAA was chosen for an investigation of the *Z-R* relationship for the following reasons.

Firstly, the BRRAA uses the S-band Doppler radar, whereas the C-band radar is used by the TMD. These different kinds of radar transmit radiation at different wavelengths, which is highly related to beam attenuation error. The shorter wavelengths are more attenuated in power by the vibration of particles in the atmosphere and better absorbed by water than the longer wavelength[11]. Attenuation is therefore a severe problem for the X-band radar, which has quite a short wavelength (2.8 cm). It can also be a problem for the C-band radar with a wave length of 5.5 cm. However, attenuation is not a problem for the S-band radar, which has a longer wave length of 10.7 cm[12,13].

Secondly, the BRRAA has collected the reflectivity data as volume scans, which are derived at 6 min interval using radar beam with different elevation angles (0.6°, 1.4°, and 2.2°). The reflectivity measuring instruments with a maximum range of 240 km provided by the BRRAA are in the form of pseudoCAPPI. This pseudoCAPPI reflectivity is the data obtained from the 2.5-km CAPPI (Constant Altitude Plan Position Indicator) and PPI (Plan Position Indicator) products.

At a constant altitude of 2.5 km, the data collected within a radar range of approximately 135 km is considered as the CAPPI data, and the data beyond the range of 135 km is produced from the lowest PPI (0.6°). On the other hand, the TMD has collected hourly PPI which is extracted from the raw reflectivity data from the beam at the elevation angle of 0.75°.

To avoid the bright band effect, the pseudoCAPPI reflectivity data belonging to the BRRAA lying within the radar range that causes the height of the upper beam to be below the freezing level was chosen for the analysis. Silverman and Sukarnjanaset[14] determined that the freezing levels in Chiangmai, Thailand are 4.9–5.5 km.

The maximum radar range (calculated using the equation proposed by Doviak and Zrnic[7]) that gives the height of the upper beam below the freezing level of 4.9 km is about 160 km. The reflectivity and rain gauge data that lie within a range of 160 km from the radar were therefore used for the analysis. It was concluded that this 2.5 km pseudoCAPPI reflectivity data is free from the bright band effect.

Lastly, the data collected by the BRRAA has higher temporal resolution (5–6 min) than the data collected by the TMD (every hour).

The S-band Doppler radar at Omkoi station transmits the radiation with a wave length of 10.7 cm, and produces a beam width of 1.2° and a 240 km maximum range. The pseudoCAPPI reflectivity instrument with the spatial resolution of 1 km^2 between June and October in 2003 and 2004 were used to collect data for an investigation of the *Z-R* relationship in the upper Ping river basin because of its accuracy and the suitability of the rainfall data within the same periods as the reflectivity data.

Gauge rainfall data

Most of the rainfall stations in and around the upper Ping river basin are (non-automated) stations providing daily rainfall data. Consequently, the climatological *Z-R* relationship was determined based on a daily data basis. There are 50 gauge rainfall stations located in the basin and nearby area, but only 42 stations are within 160 km of the radar. The available data within the period between June and October in 2003 and 2004 collected at these 42 stations were therefore used for the calibration of the *Z-R* relationship. The locations of daily rainfall stations operated by the Royal Irrigation Department (RID) and the Thai Meteorological Department (TMD) within the Omkoi radar radius are shown in Fig. 1.

METHODS

Radar reflectivity measurement errors

Weather radar measures signals that are backscattered by targets that include not only the raindrops, but also any objects in the atmosphere leading to some errors in reflectivity measurement.

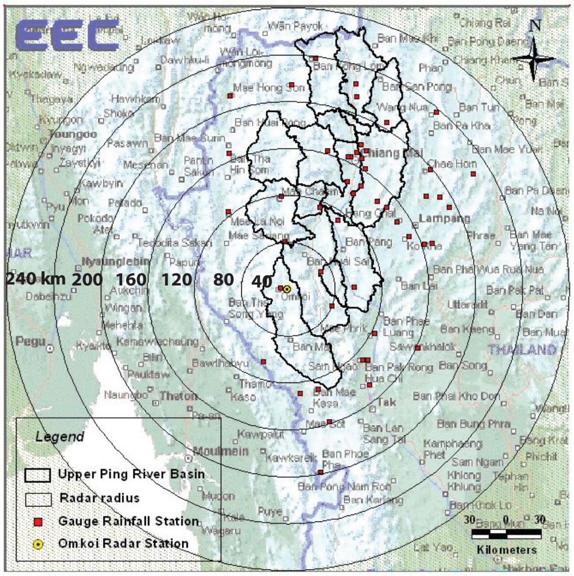

Fig 1. Locations of daily rainfall stations within the Omkoi radar radius.

During the *Z-R* relationship calibration process, the following errors have to be removed to improve the accuracy of the reflectivity values.

1) *Height sampling errors caused by the bright band that result in a range dependent bias*[15–20].

The radar antennas transmit the signals at several elevation angles. The Earth's curvature and the refraction of the radar beam through the atmosphere cause the height of the beam to increase in a non-linear fashion with range[7]. Bright band contamination occurs where the radar beam intersects the melting layer. During the melting process in this layer, snowflakes and hail become coated with a film of water leading to the appearance of giant raindrops. The reflectivity in the bright band is generally 5–10 dB stronger than in the rain below or the snow directly above[17,21–24]. The pseudoCAPPI reflectivity data at the altitudes below the freezing levels is therefore selected for further analysis to avoid the bright band effect that could cause radar rainfall overestimation.

2) *Ground clutter*

Ground clutter is non-precipitation radar echo occurring where the main or side lobes of radar beam encounter other targets such as mountains, ground, buildings, and trees. The backscattered radar signals from those objects result in strong persistent radar reflectivity leading to an overestimation of the radar rainfall.

Gabella and Perona[25] have suggested that the ground clutter effect can be significantly reduced by increasing the elevation angle of the radar beam. However, ground clutter correction using this strategy may cause increases in height sampling error[26]. This study applies an easier alternative using a topography map of known ground clutter locations and discarding radar measurement in these areas[25–26].

3) *Radar beam attenuation*[11]

Attenuation of radar power (electromagnetic wave) transmitted into the atmosphere can be caused by atmospheric gases in the clear atmosphere and by precipitation. Water vapour and oxygen are the major atmospheric gases that need to be considered as absorbers[5]. The basic principle of the attenuation by these gases was explained by Vleck[27–28].

Attenuation caused by rain may vary strongly according to rainfall rate[26]. As mentioned in the sub-section "Radar reflectivity data", the sensitivity of the radar beam attenuation due to atmospheric gases and precipitation is higher at shorter wavelength. Since the reflectivity data used in this study is categorized as the S-band radar with the longer wavelength compared to the X-band and C-band radars the beam attenuation effect is not significant for this kind of radar and it was therefore not considered in this study.

As mentioned earlier regarding the properties of reflectivity values collected by the Omkoi radar, some of the errors comprising beam attenuation and bright band are not included. Moreover, the errors from ground clutter and beam blocking were already removed by using the correction strategy recommended by Gabella and Perona[25] and Chumchean[26] as mentioned above in the sub section on "Ground Clutter".

To avoid the effect of noise and hail, the reflectivity values that ware less than 15 dBZ and greater than 53 dBZ[29] were eliminated from the analysis[30–33]. Once these errors are removed, the reflectivity values can be used for further analysis.

Radar rainfall accumulation

For a conventional practice in radar rainfall estimation, a power empirical relationship between the measured radar reflectivity and rainfall rate as illustrated in the equation (2) is used to convert the reflectivity into the rainfall intensity.

$$Z = AR^b \tag{2}$$

where A and b are the relationship parameters, Z is the reflectivity data in mm^6/m^3, and R is the rainfall rate in mm/h.

Since most of the rainfall stations in the upper

Ping river basin are non-automatic, the daily rainfall data were used to calibrate the climatological *Z-R* relationship in this study. As the gauge rainfall data are in mm per day and the reflectivity data are in mm^6/m^3 per 6 minute interval, the measured instantaneous reflectivity needs to be converted as the radar rainfall rate in mm/h using original *Z-R* relationship (details in the next item). However, the units of the radar rainfall rate and gauge rainfall need to be expressed as mm per day for calibrating the *Z-R* relationship. Radar rainfall rates are therefore converted into daily radar rainfall in mm unit using a radar rainfall accumulation algorithm, which is developed in this study and based on the method proposed by Fabry *et al*[15]. In this method, the rainfall field is assumed to remain stationary in space and intensity during the sampling interval. The radar rainfall accumulation is therefore computed by multiplying the radar rainfall rates (mm/h) by the reflectivity data interval and thereafter adding radar rainfall data for each interval to become the daily radar rainfall in mm.

Climatological Z-R relationship calibration

As there was no calibrated *Z-R* relationship available for the Omkoi radar, the BRRAA has been using the relationship of $Z=200R^{1.6}$ proposed by Marshall and Palmer[34] to convert the reflectivity data recorded from the Omkoi radar into radar rainfall. In this study, the most suitable climatological *Z-R* relationship of Omkoi radar for daily radar rainfall estimation in the upper Ping river basin was therefore calibrated using several events of the measured instantaneous reflectivity and daily rain gauge rainfall data during June and October in 2003 and 2004. Since rain gauge rainfall data in the upper Ping river basin are in the daily basis, the calibration techniques based on daily basis proposed by Seed *et al*[35] and Fields *et al*[38] were applied to attain the suitable *Z-R* relationship. Using this technique, the instantaneous reflectivity values are initially converted into radar rain rates using the standard *Z-R* relationship ($Z=200R^{1.6}$) and then accumulated into daily radar rainfall. The most suitable relationship will be calibrated by minimising the errors between the accumulated daily radar and rain gauge rainfall. The calibrated results obtained by Seed *et al*[35] and Fields *et al*[38] showed that the multiplicative term A based on daily basis by using the data from Sydney, Melbourne, Darwin, and Brisbane, Australia are within the ranges of 50 to 280. Details of the methodology in *Z-R* calibration used in this study can be summarized as follows.

1) Parameters *A* and *b* in the *Z-R* relationship were initially specified as 200 and 1.6, respectively, which are suitable for the stratiform rainfall[34], to be used to convert instantaneous reflectivity data into initial radar rain rates.

2) The instantaneous radar reflectivity data during 2003 and 2004 of all radar pixels that contain the rainfall stations were converted into rain rates using the initial *Z-R* relationship ($Z=200R^{1.6}$). The estimated radar rain rate for each time interval at a particular rainfall station was then accumulated into daily radar rainfall in mm using the radar rainfall accumulation algorithm as mentioned earlier.

3) Mean gauge rainfall and mean radar rainfall of each day were estimated using the equations (3) and (4), respectively:

$$\overline{G}_j = \frac{1}{N}\sum_{i=1}^{N} g_{ij} \tag{3}$$

$\overline{G}_j$ is the mean gauge rainfall on day *j*; g_{ij} is gauge rainfall at station i and on day j; and *N* is the total rain gauge numbers.

$$\overline{R}_j = \frac{1}{N}\sum_{i=1}^{N} r_{ij} \tag{4}$$

$\overline{R}_j$ is the mean radar rainfall on day j, and r_{ij} is radar rainfall accumulation computed using the relationship $Z=200R^{1.6}$, for day *j* at the radar pixels that contain the *N* rainfall gauges.

4) Estimated mean radar rainfall and mean gauge rainfall were compared using four statistical measures recommended by Seed *et al*.[35] as explained below.

Mean error,

$$ME = \frac{1}{n}\sum_{i=1}^{N}(\overline{R}_i - \overline{G}_i) \tag{5}$$

mean absolute error,

$$MAE = \frac{1}{n}\sum_{i=1}^{N}\left|\overline{R}_i - \overline{G}_i\right| , \tag{6}$$

root mean-square error,

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{N}(\overline{R}_i - \overline{G}_i)^2} , \tag{7}$$

bias,

$$B = \frac{\sum_{i=1}^{n}\overline{G}_i}{\sum_{i=1}^{n}\overline{R}_i} \tag{8}$$

where *n* is the number of mean daily rainfall records.

Several *Z-R* relationships would be specified by repeating the calculation of steps 1 to 4. Whichever relationship gives the minimum of the four statistical measures will be chosen as the most suitable relationship for the study.

Many researchers suggested that parameter b does not need to be varied as much as the parameter A[35–37]. Chumchean[26] found the suitable values of A and b to be within the ranges of 31–500 and 1.1–1.9, respectively. To reduce complications in the minimization process, the algorithm proposed by Fields *et al*[38] was applied to estimate the appropriate parameter that would give the minimum errors. The exponent b was fixed as 1.6 and only the multiplicative term A was adjusted to minimize the errors. The new parameter A can be determined from the following equation.

$$A_1 = \frac{A_0}{m^b} \tag{9}$$

where A_1 is the new multiplicative term A in Z-R relationship; A_0 is the initial parameter A, m is the gradient of the regression line between the predicted radar rainfall and the observed gauge rainfall obtained from an original Z-R relationship, and b is the exponent in the Z-R relationship.

RESULTS

The reflectivity and gauge rainfall data between June and October in 2003 and 2004 were analysed by the steps as explained in the previous section. The results of the mean radar rainfall and mean gauge rainfall using the standard relationship of Z=200$R^{1.6}$ are compared in Fig. 2. The statistical measures comparing these two sets of data are also calculated and summarized in Table 1. It can be noted that the estimated radar rainfall is generally lower than the gauge rainfall. Parameter A in the Z-R relationship needs to be adjusted using the Equation (9) with the m value equal to 1.868, which is the slope gained from the relationship in Fig. 2. The adjusted A value is 74, and then the new Z-R relationship; Z = 74$R^{1.6}$, was used to recalculate each step (1 to 4) as explained above. The results show that the modified Z-R relationship can improve the accuracy of the mean daily radar rainfall compared to the application of Z=200$R^{1.6}$. Significant reductions of the statistical measures resulting from the calibrated relationship are shown in Table 1. Fig. 3 shows that the scatter plot of the mean radar rainfall attained from the adjusted relationship (Z = 74$R^{1.6}$) and mean gauge rainfall (Fig. 3) are closer compared to the scatter plot produced using the previous relationship (Z = 200$R^{1.6}$). Radar rainfall estimated using the adjusted relationship (Z = 74$R^{1.6}$) and gauge rainfall

Table 1. Comparisons of the statistical measures gained from the different Z-R relationships

Statistical Measures	Z= 200$R^{1.6}$	Z= 74$R^{1.6}$
mean error (mm)	-3.47	-1.23
mean absolute error (mm)	3.51	2.30
root mean-square error (mm)	4.65	3.14
bias (mm)	2.33	1.25

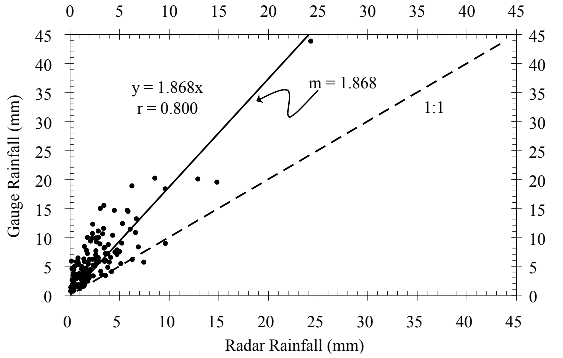

Fig. 2 Scatter plot of mean radar rainfall and mean gauge rainfall based on the relationship Z = 200$R^{1.6}$.

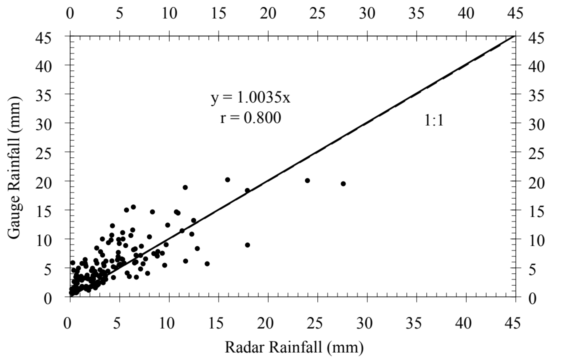

Fig. 3 Scatter plot of mean radar rainfall and mean gauge rainfall based on the relationship Z = 74$R^{1.6}$.

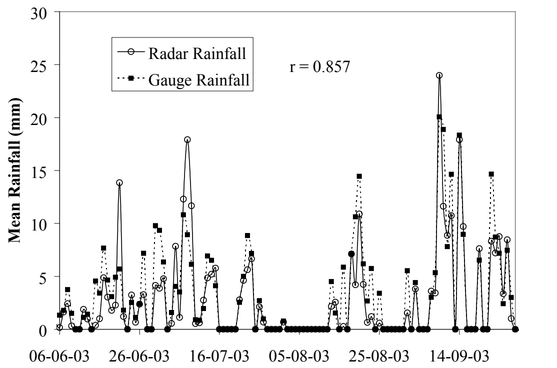

Fig. 4 Time series plot of mean gauge rainfall and radar rainfall in 2003 using the relationship Z = 74$R^{1.6}$.

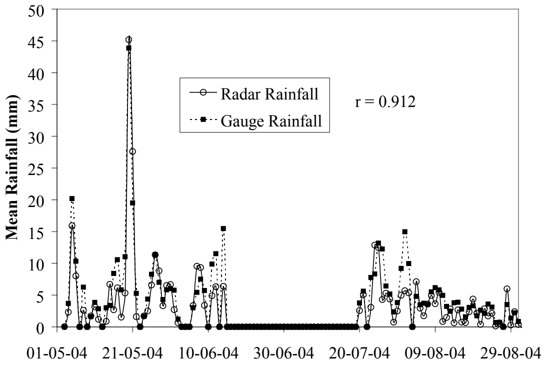

Fig 5. Time series plot of mean gauge rainfall and radar rainfall in 2004 using the relationship $Z = 74R^{1.6}$.

for the daily basis in 2003 and 2004 were plotted as shown in Figs. 4 and 5, respectively. The figures show that estimated radar rainfall is not significantly lower than the gauge rainfall. An agreement between estimated radar and gauge rainfall was examined using correlation coefficient (r). The results show that the overall correlation coefficients between the estimated radar and calculated rain gauge rainfall for the data sets in 2003 and 2004 are 0.857 and 0.912, respectively (Fig. 4 and 5), which are acceptable. The calibrated *Z-R* relationship ($Z = 74R^{1.6}$) is therefore appropriate to be used for an estimation of daily radar rainfall in the upper Ping river basin.

DISCUSSION

Since most of rainfall stations located in and around the upper Ping river basin are non-automatic stations, the climatological *Z-R* relationship was therefore determined by uses of daily gauge rainfall at 42 stations and the reflectivity data at the Omkoi radar station. During the calibration procedure, parameter *A* was adjusted to minimize four statistical measures (mean error, mean absolute error, root mean-square error, and bias), whereas the parameter *b* was set as a constant of 1.6. The results showed that the climatological *Z-R* relationship gave more accurate results using $A=74$ than $A=200$. The climatological *Z-R* relationship of $Z = 74R^{1.6}$ is therefore the appropriate equation for radar rainfall assessment in the upper Ping river basin. Within the calibration period (between June and October in 2003 and 2004), this relationship produced the minimum mean error, mean absolute error, root mean-square error, and bias of approximately -1.23, 2.30, 3.14, and 1.25 mm, respectively. Daily radar rainfall in 2003 and 2004 were then computed using this relationship and were compared to the daily gauge rainfall in the form of time series plot as shown in the Figs. 4 and 5. Even the estimated radar rainfall tended to be a bit lower than the gauge rainfall. The overall results are acceptable with the correlation coefficient between the estimated radar and gauge rainfall of around 0.857 and 0.912, respectively.

This study aimed was investigate the suitable *Z-R* relationship for daily radar rainfall estimation in the upper Ping river basin to reduce some radar rainfall errors caused by *Z-R* conversion. The proposed climatological relationship ($Z = 74R^{1.6}$) represents the average relationship for Omkoi radar station and can also be used as an initial relationship to convert measured reflectivity into daily radar rainfall. However, the parameters *A* in the *Z-R* relationship usually change in both space and time. The applications of the proposed relationship to estimate daily rainfall at different storm events especially in real time environment possibly have a number of uncertainties. To improve the accuracy of radar rainfall, the estimated radar rainfall calculated by the proposed *Z-R* relationship should be adjusted by applying a mean-field bias correction technique[5,32,39–42]. An adjustment factor which is the ratio between accumulated rain gauge rainfall and accumulated radar rainfall will be assessed. Thereafter, the adjusted radar rainfall will be finally calculated by multiplying the adjustment factor to the radar rainfall estimated by the proposed *Z-R* relationship. There are many mean field bias techniques, and each technique can be used to correct the errors caused by temporal and/or spatial variability. The most suitable technique will be chosen and further applied to improve the accuracy of the estimated radar rainfall. Radar rainfall estimates can then be used as the input data for the selected rainfall-runoff model for flood estimation in the upper Ping river basin.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the Thailand Research Fund through the Royal Golden Jubilee Ph.D. program (Grant No. PHD/0118/2547) and Kasetsart University Research and Development Institute for financially supporting this research. We wish to thank Dr. Ashish Sharma (Associate Professor at School of Civil and Environmental Engineering, The University of New South Wales, Sydney, Australia) and Dr. Siriluk Chumchean (Lecturer at Department of Civil Engineering, Mahanakhon University of Technology, Bangkok, Thailand) for many helpful suggestions. We also appreciate the Bureau of Royal Rainmaking and Agricultural Aviation (BRRAA), the Royal Irrigation Department (RID), Thai Meteorological Department (TMD) for providing the radar data and hydrological data used in this study. Finally the authors wish to thank Dr. Michael Waters for correcting the manuscript.

REFERENCES

1. Seed A, Austin GL (1990) Sampling errors for rain gauge derived mean-areal daily and monthly rainfall. *J. Hydrol.* **118**, 163–73.
2. Wilson CB, Valdes JB, Rodriguez-Iturbe I (1979) On the influence of the spatial distribution of rainfall on storm runoff. *Water Resour. Res.* **15**, 321–8.
3. Bevan KJ, Hornberger GM (1982) Assessing the effect of spatial pattern of precipitation in modelling stream flow hydrograph. *Water Resour. Bull.* **18**, 823–9.
4. Hamlin MJ (1983) The significance of rainfall in the study of hydrological processes at basin scale. *J. Hydrol.* **65**, 73–94.
5. Battan LJ (1973) Radar observation of the atmosphere, University of Chicago Press, Chicago.
6. Rinehart RE (1991) Radar for Meteorologist, University of North Dakota Press, Grand Forks, North Dakota, U.S.A.
7. Doviak RJ, Zrnic DS (1992) Doppler radar and weather observations, Acadamic Press Inc., Orlando, Florida, U.S.A.
8. Collier CG (1996) Applications of Weather Radar System. In: A guide to uses of radar in meteorology and hydrology, John Wiley and Sons, New York.
9. Uijlenhoet R (2001) Raindrop size distributions and radar reflectivity-rain rate relationships for radar hydrology. *Hydrol. Earth System. Sci.* **5**, 615–27.
10. Krajewski WF, Smith JA (2002) Radar hydrology: rainfall estimation. *Adv. Water Resour.* **25**, 1387–94.
11. Hildebrand PH (1978) Iterative correction for attenuation of 5 cm radar in rain. *J. Appl. Meteorol.* **17**, 508–14.
12. Hitschfeld W, Bordan J (1954) Errors inherent in the radar measurement of rainfall at attenuating wavelengths. *J. Appl. Meteorol.* **11**,58–67.
13. Delrieu G, Andrieu H, Creutin JD (2000) Quantification of path-integrated attenuation for X- and C-band weather radar systems operating in Mediterranean heavy rainfall. *J. Appl. Meteorol.* **39**, 840–50.
14. Silverman BA, Sukarnjanaset W (2000) Results of the Thailand warm-cloud hygroscopic particle seeding experiment. *J. Appl. Meteorol.* **39**, 1160–75.
15. Fabry F, Bellon A, Duncan MR, Austin GL (1994) High resolution rainfall measurements by radar for very small basins: the sampling problem re-examined. *J. Hydrol.* **116**, 415–28.
16. Kitchen M, Brown R, Davies AG (1994) Real-time correction of weather radar for the effects of bright band, range and orographic growth in widespread precipitation. *Q.J.R. Meteorol. Soc.* **120**, 1231–54.
17. Andrieu H, Creutin JD (1995) Identification of vertical profiles of radar reflectivity for hydrological applications using an inverse method. Part I: Formulation. *J. Appl. Meteorol.* **34**, 225–39.
18. Fabry F, Zawadzki I (1995) Long-term radar observations of the melting layer of precipitation and their interpretation. *J. Atmos. Sci.* **52**, 838–61.
19. Vignal B, Andrieu H (1999) Identification of vertical profiles of reflectivity from volume scan radar. *J. Appl. Meteorol.* **38**, 1214–28.
20. Vignal B, Krajewski WF (2001) Large-sample evaluation of two methods to correct range-dependent error for WSR-88D rainfall estimates. *J. Hydrometeorol.* **2**, 490–504.
21. Stewart RE, Marwitz JD, Pace JC (1984) Characteristics through the melting layer of stratiform clouds. *J. Atmos. Sci.* **41**, 3227–37.
22. Klaassen W (1988) Radar observations and simulations of the melting layer of precipitation. *J. Atmos. Sci.* **45**, 3741–53.
23. Fabry F, Austin GL, Tees D (1992) The accuracy of rainfall estimates by radar as a function of range. *Q.J.R. Meteorol. Soc.* **118**, 435–53.
24. Williams CR, Ecklund WL (1995) Classification of precipitation clouds in the tropics using 915-MHz wind profiles. *J. Appl. Meteorol.* **12**, 996–1012.
25. Gabella M, Perona G (1998) Simulation of the orographic influence on weather radar using geometric-optics approach. *J. Atmos. Oceanic. Technol.* **15**, 1485–94.
26. Chumchean S (2004) Improved Estimation of Radar Rainfall for Use in Hydrological Modelling. Ph.D. thesis, University of New South Wales,

Sydney, Australia.
27. Van Vleck JH (1947) The absorbtion of microwaves by uncondensed water vapor. *Phys. Rev.* **71**, 425–33.
28. Van Vleck JH (1947) Absorption of microwaves by oxygen. *Phys. Rev.* **71**, 413–24.
29. Fulton RA, Breidenbach JP, Seo D-J, Miller DA, O' Brannon T (1998) The WSD-88D rainfall algorithm. *Wea. Forecast.* **13**, 377–95.
30. Chumchean S, Sharma A, Seed A (2003) Radar rainfall error variance and its impact on radar rainfall calibration. *J. Phys. Chem. Earth* **28**, 27–39.
31. Chumchean S, Seed A, Sharma A (2004) Application of scaling in radar reflectivity for correcting range dependent bias in climatological radar rainfall estimates. *J. Atmos. Oceanic Technol.* **21**, 1545–55.
32. Chumchean S, Seed A, Sharma A (2006) Correcting of real-time radar rainfall bias using a Kalman filtering approach. *J. Hydrol.* **317**, 123–37.
33. Chumchean S, Sharma A, Seed A (2006) An Integrated Approach to Error Correction for Real-Time Radar-Rainfall Estimation. *J. Atmos. Oceanic Technol.* **23**, 67–79.
34. Marshall JS, Palmer WM (1948) The distribution of raindrops with size. *J. Meteorol.* **5**, 165–6.
35. Seed AW, Sirivardena L, Sun X, Jordan P, Elliott J (2002) On the calibration of Australian weather radars, Cooperative Research Centre for Catchment Hydrology, Technical Report 02/7, p 40, Melbourne, Australia.
36. Seed AW, Nicol J, Austin GL, Stow CD, Bradley SG (1996) The impact of radar and raingauge sampling errors when calibrating a weather radar. *Meteorol. Appl.* **3**, 43–52.
37. Steiner M, Smith J, Burges SJ, Alonso CV, Darden RW (1999) Effect of bias adjustment and raingauge data quality control on radar rainfall estimation. *Water Resour. Res.* **35**, 2487–503.
38. Fields G, Seed A, Yu B, Malone T (2004) Calibration of weather radar in South East Queensland. Sixth international symposium on hydrological applications of weather radar, Melbourne, Australia
39. Wilson JW (1970) Integration of radar and raingauge data for improved rainfall measurement. *J. Appl. Meteorol.* **9**, 489–97.
40. Brandes EA (1975) Optimising rainfall estimates with the aid of radar. *J. Appl. Meteorol.* **14**, 1339–45.
41. Collinge VK (1991) Weather radar calibration in real time: Prospects for improvement. In: Hydrology Applications of Weather Radar (Cluckie ID, Collier CG, Eds.), pp 25–42, Ellis Horwood, Chinchester. U.K.
42. Seo D-J, Breidenbach JP (2002) Real time correction of spatially nonuniform bias in radar rainfall data using raingauge measurements. *J. Hydrometeorol.* **3**, 93–111.