ABE
Agricultural and Biological Engineering
https://ph04.tci-thaijo.org/index.php/abe/index
Published by the Faculty of Engineering, Khon Kaen University, Thailand

Analysis of Z-R relationship equations varying by rain cluster for rainfall estimation using Sattahip radar

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doi: 10.14456/abe.2025.20

Received 19 August 2025
Revised 17 September 2025
Accepted 29 September 2025

Abstract

Weather radar measures the reflectivity of radar waves when they interact with raindrops. This radar reflectivity varies according to the size and distribution pattern of the raindrops. When using radar reflectivity data to estimate rainfall, this data is converted to rainfall intensity (R, (mm/h)) using the Z-R relationship equation ($Z=aR^b$). This study collected data from 510 rainfall events between February 2, 2018, and August 31, 2020, comprising hourly rainfall from 110 automatic rain gauges and radar reflectivity within a 240 km radius of the Sattahip radar. The data was analyzed to determine the most appropriate rainfall estimation using various Z-R relationship equations: Z-R relationships that vary according to rain clusters based on radar reflectivity, Z-R relationships that vary according to rain clusters based on rainfall intensity measured by automatic rain gauges, climatological Z-R equation, $Z=300R^{1.4}$, and $Z=200R^{1.6}$. Each of these rainfall estimations was then compared to the rainfall intensity from automatic rain gauges to find the statistical values of RMSE (Root Mean Squared Error), MSE (Mean Squared Error), and MAE (Mean Absolute Error). The results indicated that the rainfall estimation method using Z-R relationships that vary according to rain clusters based on rainfall intensity provided the most accurate rainfall estimation for the Sattahip radar. This was determined by examining the statistical values of RMSE, MSE, and MAE, which were closest to zero for both calibration and verification rainfall events, when compared to rainfall estimation methods using Z-R relationships that vary according to rain clusters based on radar reflectivity, climatological Z-R equation, $Z=300R^{1.4}$, and $Z=200R^{1.6}$ respectively.

Keywords: Weather radar, Radar reflectivity, Raindrops, Sattahip radar

1. Introduction

Thailand often faces flooding problems, especially in the eastern, western and central regions, which are areas receiving water flowing from the high mountains in the north, including drought problems that occur. This is due to the problem of lack of proper and systematic water resource management. Water resource management requires information showing the amount and distribution of rainfall both in terms of space and time. Therefore, if we can correctly assess the amount of rainfall in the area, it will help to make water management planning in the area more efficient. However, from past studies, it was found that natural phenomena related to rain have a very complex process. Therefore, rain measurement using a rain gauge station with a specific resolution [1] covering an area of 200 cm^2 results in a lack of accurate spatial rainfall data for use in water management in the area. Therefore, remote sensing technology using weather radar has begun to be used to measure rainfall, which can measure rainfall with high spatial and temporal resolution. Therefore, if the spatial rainfall data measured by weather radar is used to assess rainfall together with rainfall data from automatic telemetry rain gauge stations on the ground, it will help increase the accuracy of the spatial rainfall assessment measured by radar to be more accurate. However, since weather radar does not directly measure rain, but sends out electromagnetic waves to measure rain after the waves hit the raindrops, the waves will reflect back to the receiver (Radar receiver) and be converted into the radar reflectivity (Radar reflectivity, Z (mm^6/m^3)), which varies depending on the size and distribution characteristics of raindrop particles within a volume of the atmosphere that is surveyed. When the radar reflectivity data is used to assess the amount of rain, the data will be converted into rain intensity data (R (mm/h)) using the Z-R relationship equation ($Z=aR^b$). From such a complicated process, there are errors in the rain assessment process by radar, which include the error in measuring the radar reflectivity value and the error due to using the Z-R relationship equation to convert the radar reflectivity value into rain intensity. Therefore, using only the average Z-R relationship equation to assess the Sattahip radar rain still has some errors, which is consistent with the study [2-5] that stated that using the average Z-R relationship equation has a limitation that it cannot represent the true relationship equation of different rains. The error is caused by the different distribution of raindrop particles and rain types in each period, resulting in different values of the Z-R relationship equation. In order to reduce the error, this study applied the following methods: [6] considered separating rain group types according to the radar reflectivity and analyzed the average Z-R relationship equation of rain groups in each radar reflectivity range; [7] considered separating rain group types from the rain intensity measured from the ground rainfall measurement station and analyzed the average Z-R relationship equation of rain groups in each rain intensity range, respectively. To study the Z-R relationship equation that changes according to the rain group type according to the radar reflectivity, the Z-R relationship equation that changes according to the rain group type according to the rain intensity measured from the ground automatic telemetry station to be used in estimating the radar rain to be the most accurate within the measurement radius of 240 km of the Sattahip radar station.

2. Materials and methods

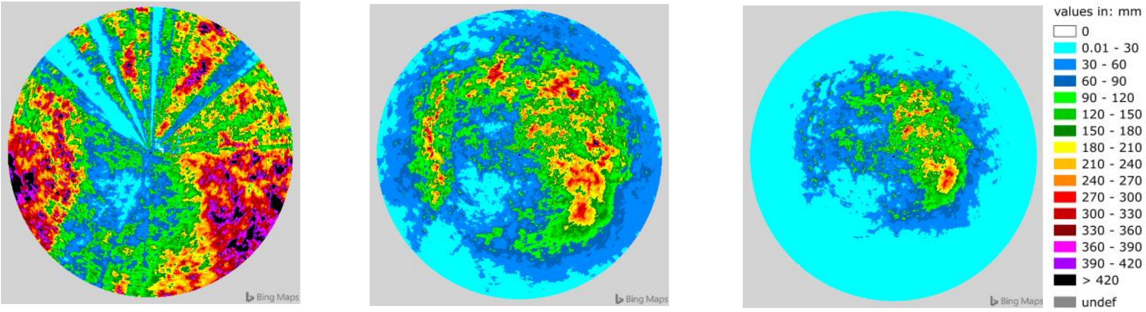
2.1 Data used in the study

This study collected rainfall events occurring within a 240 km measurement radius of the Sattahip Royal Rainmaking Radar Station, an S-band Doppler radar, located in Sattahip District, Chonburi Province. Coordinates: latitude 12° 38’ 56” N, longitude 100° 57’ 46” E, at an altitude of 174 m above mean sea level, as shown in Figure 1. The data of radar reflectivity measurements that measure rain are stored in Volume files format, recorded in Coordinated Universal Time (UTC), with measurements every 6 min from a total of 14 measured elevation angles: 0.5°, 1.5°, 2.4°, 3.4°, 4.3°, 5.2°, 6.2°, 7.5°, 8.7°, 10.0°, 12.0°, 14.0°, 16.7°, and 19.5°, respectively, during February 2, 2018 to August 31, 2020. Radar Reflectivity (Z) data are stored. In the form of Volume files and rain data from the ground-based automatic telemetry station of the Water Resources Information Institute (WRI), each rain event used in the study must have rain measurement data from radar and rain data from the ground-based automatic telemetry station that are consistent. Both of these data must pass quality checks and data error correction before being used in the study as follows:

Figure 1 Image of the Sattahip Doppler radar station, S-band type

This study checked the data quality and adjusted the error of the Sattahip radar wave reflectivity data, which was affected by the problem of the radar beam hitting the permanent reflecting target (Ground clutter) such as mountains, buildings or other structures on the ground that are not rain clouds, resulting in the error of the measured radar wave reflectivity data. In adjusting the error value due to the Ground clutter problem for this study, a Ground Clutter Map was created. The radar wave reflectivity value in the Ground Clutter position was adjusted by calculating from the Reflectivity value of the adjacent pixels by the method Interpolation [8-9], In the part of the effect due to the problem of radar beam hitting the permanent reflecting target, resulting in the radar reflectivity value measured in the area behind the obstacle is lower than normal. This study has adjusted by taking the data of the radar reflectivity from the monthly accumulated rainfall measurements to consider the location of the beam blockage. The radar reflectivity value of the pixels in the beam blockage position has been adjusted by calculating from the radar reflectivity value of the neighboring pixels by the interpolation method [8-9], while the effect due to the radar energy being absorbed (Attenuation) when traveling through the gas in the atmosphere, water vapor, oxygen and rainfall [10-11], the radar energy is absorbed and has a reduced value. The sensitivity of the radar signal to the reduction of energy depends on the wavelength of the radar that is transmitted. The power reduction is a problem for X-band and C-band radars, which have wavelengths of 2.5 and 5.5 cm, respectively, but not for S-band radars with wavelengths of 10.7 cm [12]. Therefore, for the S-band radar, the Sattahip radar is not affected by the attenuation problem. In order to avoid radar reflectivity that does not result from rain clouds, only radar reflectivity data greater than 15 dBZ were used. In addition, to avoid radar reflectivity that results from hail, a reflectivity greater than 53 dBZ was considered to be 53 dBZ [13]. The Sattahip radar reflectivity data, after adjusting for errors from 14 measurement angles, were used to select the appropriate measurement angle for the radar. Sattahip from the measurement angle that provides the rain measurement value covering the area under the measurement radius of the Sattahip radar, together with being able to measure the amount of rain that is closest to the amount of rain measured from the automatic telemetry station on the ground, and having the least error value after adjusting the radar reflectivity data due to the problems of Ground Clutter and Beam Blockage remaining. The results of the examination of the appropriate measurement angle of the Sattahip radar show examples of 3 measurement angles that measure closest to the ground, shown in Figure 2. It was found that the measurement angle 1, which is 0.5°, which is the lowest measurement angle, still has a problem due to a lot of Beam Blockage. When considering the measurement angle 2, which is 1.5°, it can be seen that the problem due to Beam Blockage has decreased and the rain can still be measured covering the area under the measurement radius of the radar station. While considering the 3rd measurement angle, which is

2.4°, the rain clouds covered less area under the measurement radius of the radar station compared to the measurement angle 2. For the reasons mentioned above, when considering the quality of the radar wave reflectivity data, after adjustment, the error values caused by Ground Clutter and Beam Blockage must be reduced to a minimum. The rain clouds must cover the area under the measurement radius of the Sattahip radar station as much as possible compared to other measurement angles. Therefore, the radar wave reflectivity data from the 2nd measurement angle is the most suitable measurement angle for the Sattahip radar.



(a) Elevation angle 0.5° (b) Elevation angle 1.5° (c) Elevation angle 2.4°

Figure 2 Examples of monthly cumulative rainfall measured by the Sattahip radar from 3 elevation angles of the July 2020 rain event

This study examined the quality of hourly rainfall data from automatic ground telemeter stations that passed the Double Mass Curve method and had an R-squared value greater than 0.90. Details of the inspection of rainfall data quality using the Double Mass Curve method will consider plotting the hourly cumulative rainfall data of the desired station with the average hourly cumulative rainfall value of neighboring stations. If the data of the desired station are consistent with the neighboring station, the slope of the Double Mass Curve will not change significantly or the slope will increase steadily. While the analysis of the R-squared value of the station that wants to inspect the quality of rainfall data will consider the hourly cumulative rainfall data of the desired station with the average hourly cumulative rainfall value of neighboring stations. If the rainfall data of the desired station is consistent with the neighboring station from the Double Mass Curve method and has an R-squared value greater than 0.90, the desired station will be considered to pass the quality inspection criteria. The results of the quality control of hourly rainfall data from the ground-based telemetry stations collected data from February 2, 2018 to August 31, 2020, totaling 110 stations, were examined for data quality. It was found that 108 ground-based telemetry stations passed the data quality control and 2 stations did not. In order to make the rainfall assessment using weather radar data more accurate, this study will use rainfall data from the ground-based telemetry stations that passed the data quality control criteria and are not located in the blind area of the Sattahip radar (area within a 10 km radius from the radar station). This is because in the blind area, the radar will measure less rain than the actual. The ground-based telemetry stations that passed the quality control and did not pass the quality control are shown in Figure 3.

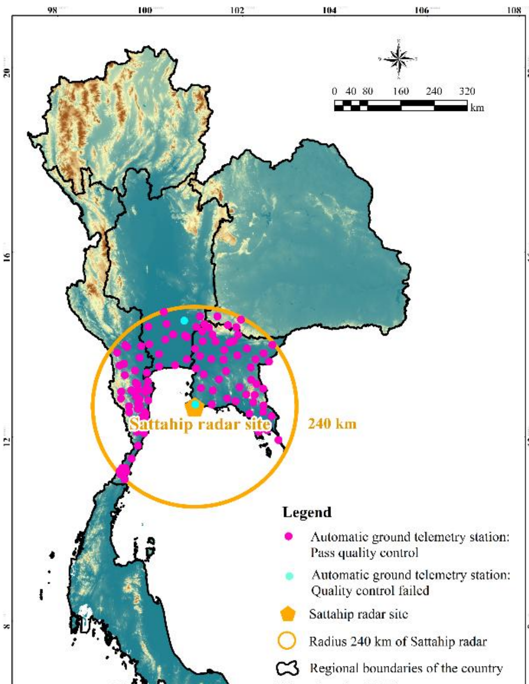


Figure 3 Location of automatic ground telemetry stations located in the area within the 240 km measurement radius of the Sattahip radar that passed and did not pass the rainfall data quality check

2.2 Analysis of Z-R relationship equation

The data of 510 rainfall events during February 2, 2018 to August 31, 2020 were analyzed to find the Z-R relationship equation using the Regression method. The principle of the Regression method is to select a pair of relationships between the radar reflectivity and the rainfall intensity values from the automatic ground telemetry station at the same location and time to be used in the analysis of the Z-R relationship equation. In this study, the radar reflectivity data with a value greater than 15 dBZ will be selected. In order to avoid the problem of the impact of the radar signal from hail, in the case where the radar reflectivity value is greater than 53 dBZ, it will be considered equal to 53 dBZ [13]. The rainfall value from the automatic ground telemetry station that is greater than 0.2 mm/h is considered and the method of randomly selecting the automatic ground telemetry station to obtain the Z-R pair for each rainfall event on each day is chosen. The random sampling was divided into 2 groups as follows: Group 1 data will randomly select 80% of the automatic ground telemetry stations from all the automatic ground telemetry stations in each rain event of each day. The result is the Z-R data pair used in the analysis to find the Z-R relationship equation ($Z=aR^b$). Group 2 data, the Z-R relationship equation analyzed in Group 1 data was tested for reliability by using the Z-R data pairs of the remaining automatic ground telemetry stations from Group 1 data, 20% from all the automatic ground telemetry stations in each rain event of each day. From the previous research [14-16] used Disdrometer to measure Drop Size Distribution (DSD) and when the DSD data was known, it was used to analyze the Z-R relationship equation [17-18] and found that the appropriate value of parameter b to represent the Z-R equation was b=1.6. Similarly, from the study [19] it was found that the value of parameter b did not affect the change of the square root of the mean square error (RMSE) between rain from radar and rain from automatic ground telemetry stations much. From the review of the previous research above, it can be concluded that the radar reflectivity and rain intensity are related to the distribution characteristics of raindrops in each rain group. Therefore, in this study, the Z-R relationship equation was analyzed by considering the constant b parameter value equal to 1.6 [17-18] and the analysis was conducted to find the value of parameter a that varies according to the distribution characteristics of raindrops in each rain group. by analyzing the value of parameter a that makes the value (Mean Square Error, MSE) between the rain intensity values from the radar and the rain intensity from the automatic ground telemetry station have the least value from the rain event data used in the calibration of data group 1. In the study, the case study for analyzing the Z-R relationship equation will be divided into 3 cases.

Case 1: Analyze the climatological Z-R relationship equation

Case 2: Analyze the climatological Z-R relationship equation in each rain group divided by the value of the radar reflectivity [6] as follows:
Rain group 1 15 dBZ <= Reflectivity < 30 dBZ
Rain group 2 30 dBZ <= Reflectivity < 38 dBZ
Rain group 3 38 dBZ <= Reflectivity < 44 dBZ
Rain group 4 44 dBZ <= Reflectivity <= 53 dBZ

Case 3: Analyze the climatological Z-R relationship equation in each rain group divided by the rain intensity value measured from the automatic ground telemetry station by dividing the rain intensity range according to the study [7] as follows:
Rain group 1 Rain intensity < 10 mm/hr
Rain group 2 10 mm/hr <= Rain intensity <= 30 mm/hr
Rain group 3 3 Rain intensity > 30 mm./hr

The Z-R relationship equations in all 3 cases analyzed from the rain event data used for calibration of data group 1 and added 2 more commonly used equations, namely, Case 4 using the Woodley and Herndon equation [20], $Z=300R^{1.4}$ and Case 5 using the Marshall and Palmer equation [2], $Z=200R^{1.6}$ will be analyzed to find the appropriate Z-R relationship equation for the Sattahip radar by considering the RMSE (Root Mean Squared Error), MSE (Mean Squared Error), MAE (Mean Absolute Error) statistics as shown in Equations 1-3 between the amount of rain from the Sattahip radar estimated from the Z-R relationship equations in all 5 cases compared to the amount of rain from the ground automatic telemetry station must have the lowest value of both the rain event data used for calibration of data group 1 and the rain event data used for reliability verification. (Verification) of data group 2

$$RMSE = \sqrt{\frac{1}{N \times N_t}\sum_{t=1}^{N_t}\sum_{i=1}^{N}\left(R_{i,t} - G_{i,t}\right)^2} \quad (1)$$

$$MSE = \frac{1}{N \times N_t}\sum_{t=1}^{N_t}\sum_{i=1}^{N}\left(R_{i,t} - G_{i,t}\right)^2 \quad (2)$$

$$MAE = \frac{1}{N \times N_t}\sum_{t=1}^{N_t}\sum_{i=1}^{N}\left|R_{i,t} - G_{i,t}\right| \quad (3)$$

where
$R_{i,t}$ is the rainfall calculated from the relationship equation (Z-R) at the automatic telemetering station i at time t (mm/h)
$G_{i,t}$ is the rainfall from the automatic ground telemetering station i at time t (mm/h)
N is the total number of automatic telemetering stations used
N_t is the rainfall period (h)

3. Results and discussion

The study analyzed the Z-R relationship equation by considering the constant b parameter value of 1.6 and analyzed a parameter value that varies according to the distribution characteristics of raindrop particles in each rain group. The analysis found a parameter value that resulted in the lowest (Mean Square Error, MSE) between the rain intensity values from the radar and the rain intensity values from the automatic ground telemetry station from the rain event data used in the calibration of the data group 1. The results of the analysis found a parameter value of the proposed Z-R relationship equation in all 3 cases and added 2 more commonly used equations: Case 4 used the Woodley and Herndon equation, $Z=300R^{1.4}$ and Case 5 used the Marshall and Palmer equation, $Z=200R^{1.6}$, shown in Table 1.

Table 1 Analysis of a parameter value of the Z-R relationship equation in all 5 cases

Case	Rain group	a	b
Case 1: Analyze the climatological Z-R relationship equation	Total rain group	175	1.6
Case 2: Analyze the average Z-R relationship equation in each rain group divided by the value of the radar reflectivity	Rain group 1 15 dBZ <= Reflectivity < 30 dBZ	121	1.6
	Rain group 2 30 dBZ <= Reflectivity < 38 dBZ	175	1.6
	Rain group 3 38 dBZ <= Reflectivity < 34 dBZ	174	1.6
	Rain group 4 44 dBZ <= Reflectivity < 53 dBZ	220	1.6
Case 3: Analyze the climatological Z-R relationship equation in each rain group divided by the rain intensity value measured from the automatic ground telemetry station	Rain group 1 Rain intensity < 10 mm/hr	465	1.6
	Rain group 2 10 mm/hr <= Rain intensity <= 30 mm/hr	94	1.6
	Rain group 3 Rain intensity > 30 mm./hr	67	1.6
Case 4: The climatological Z-R relationship equation is from Woodley and Herndon	Total rain group	300	1.4
Case 5: The climatological Z-R relationship equation is from Marshall and Palmer	Total rain group	200	1.6

When considering the RMSE, MSE and MAE statistics between the rainfall amount from the Sattahip radar estimated by the Z-R relationship equation in all 5 cases compared to the rainfall amount from the automatic ground telemetry station of the rainfall event data, group 1 data used for calibration to find the Z-R relationship equation and the rainfall event data, group 2 data used for verification, are shown in Figures 4-6, respectively. The RMSE results in Figure 4 show that the rainfall estimate using the average Z-R relationship equation in each rainfall group divided by the rainfall intensity measured from the automatic ground telemetry station in Case 3 has the lowest RMSE value for the rainfall event data used for calibration of group 1 data with a value of 3.53 (mm/h) and the rainfall event data used for verification of the confidence of group 2 data with a value of 3.44 (mm/h) compared to the rainfall estimate using the remaining 4 Z-R relationship equations.

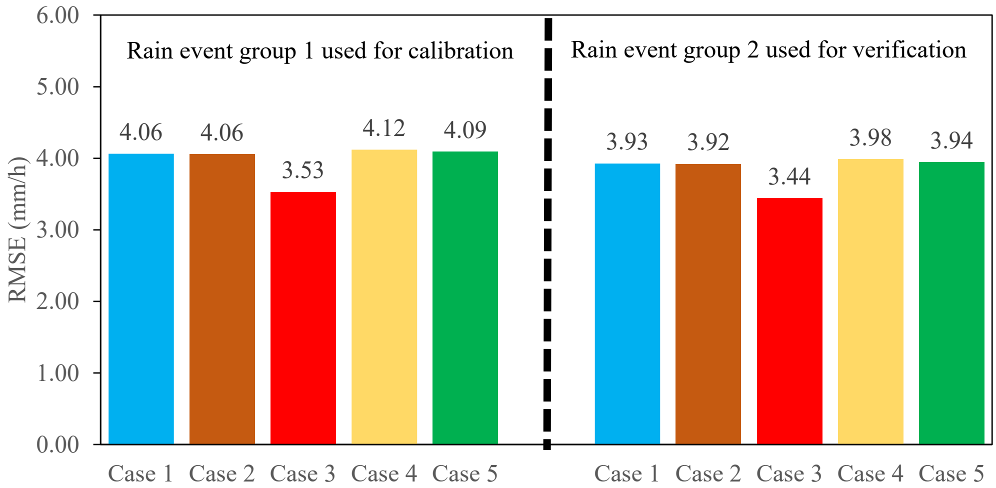


Figure 4 RMSE values between rainfall from the Sattahip radar and rainfall estimates using the Z-R equation used in this study in 5 cases

The MSE results in Figure 5 show that the rainfall estimates using the average Z-R equation in each rain group divided by the rainfall intensity values measured from the automatic ground telemetry station in Case 3 have the lowest MSE values for the rainfall data used for calibration of the first group of data with a value of 12.45 (mm/h) and the rainfall data used for the verification of the confidence of the second group of data with a value of 11.83 (mm/h) compared to the rainfall estimates using the remaining 4 Z-R equations.

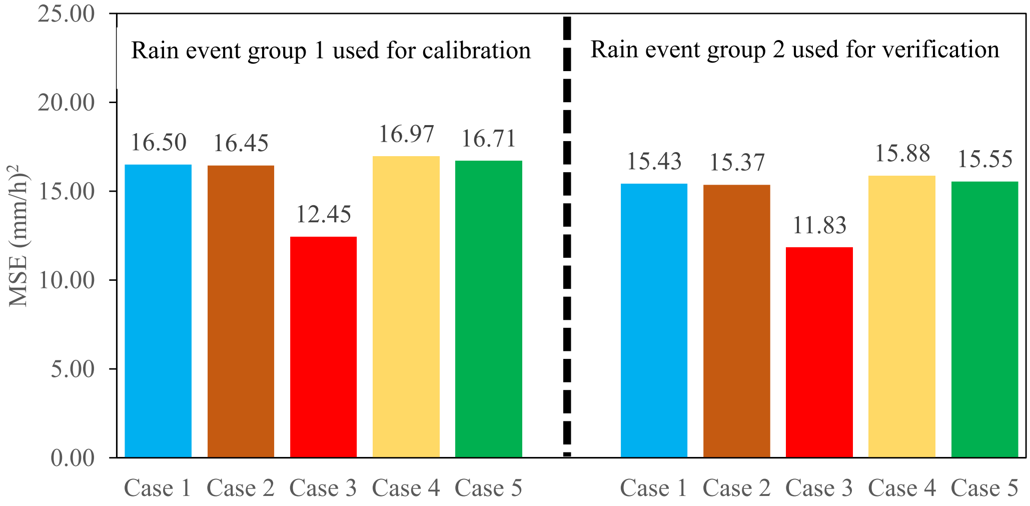


Figure 5 MSE values between rainfall from the Sattahip radar and rainfall estimates using the Z-R equation used in this study

The MAE results in Figure 6 show that the rainfall estimates using the average Z-R equation in each rainfall group divided by the rainfall intensity values measured from the automatic ground telemetry station in Case 3 have the lowest MAE values for the rainfall event data used for calibration of the first group of data with a value of 1.75 (mm/h) and the rainfall event data used for reliability verification of the second group of data with a value of 1.74 (mm/h) when compared to the rainfall estimates using the remaining four Z-R equations.

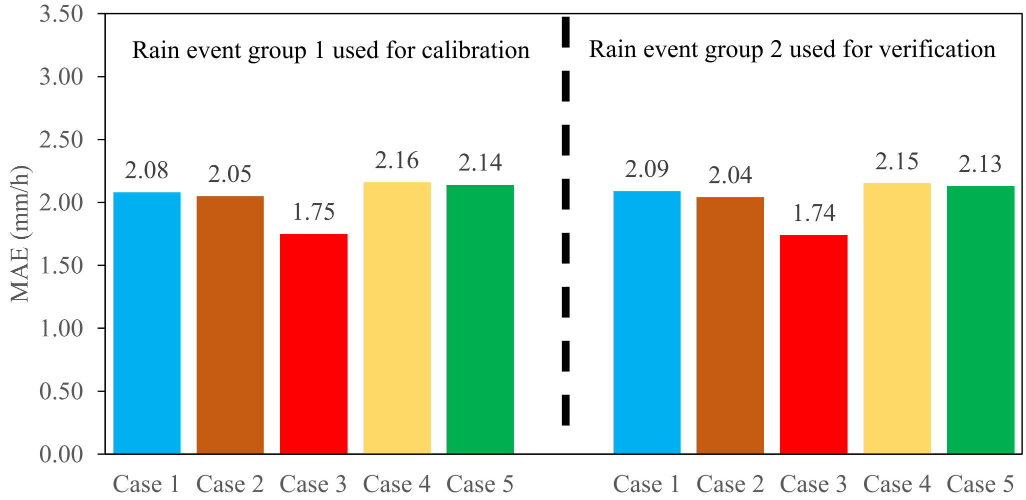


Figure 6 MAE between rainfall from Sattahip radar and rainfall estimated from Z-R relationship equations used in this study in 5 cases

The results of the study in Figures 4-6 show that the rainfall assessment using the average Z-R relationship equation in each rain group divided by the rainfall intensity measured from the automatic ground telemetry station in Case 3 is the most appropriate Z-R relationship equation for the Sattahip radar rainfall assessment with the lowest RMSE, MSE, and MAE values between the Sattahip radar rainfall estimated from the equation compared to the rainfall from the automatic ground telemetry station for both the rainfall event data used for calibration and the rainfall event data used for reliability verification when compared to the rainfall assessment using the remaining 4 Z-R relationship equations. Meanwhile, the rainfall assessment using the average Z-R relationship equation in each rain group divided by the radar reflectivity value in Case 2, the rainfall assessment using the average Z-R relationship equation in Case 1, the rainfall assessment using the Marshall and Palmer equation in Case 5, and the rainfall assessment using the Woodley and Herndon equation in Case 4 gave the following accurate rainfall assessments, respectively. The results of this study are consistent with the study [6-7] in estimating radar rain using only average Z-R relationship equation in case 1, case 5 and case 4, there are still some errors. This error is caused by the different distribution of raindrop particles in each rain group, resulting in different values of Z-R relationship equation in each rain group. Therefore, using the appropriate Z-R relationship equation in each rain group in case 2 and case 3 can increase the accuracy of Sattahip radar rain estimation more than the current Woodley and Herndon equation.

Recommendation for the study was found that the Z–R relationships derived for the Sattahip radar in all five cases are suitable only for rainfall estimation using the Sattahip radar. For other radar stations in Thailand, it is recommended to analyze and determine new Z–R relationships appropriate for each radar, since raindrop size distribution varies across regions and time periods. This variation causes the parameters *a* and *b* in the Z–R equation ($Z = aR^b$) to differ among radars.

4. Conclusions

1) The Z-R relationship equation has different values in each rain group. Therefore, using the appropriate Z-R relationship equation in each rain group in Case 2 and Case 3 that is suggested can increase the accuracy of the Sattahip radar rain assessment more than the current Woodley and Herndon equation.

2) Sattahip radar rain assessment using the average Z-R relationship equation in each rain group divided by the rain intensity values measured from the automatic ground telemetry station in Case 3 is the most appropriate Z-R relationship equation for use in the Sattahip radar rain assessment with the highest RMSE, MSE and MAE values between the Sattahip radar rain amounts assessed by the equation. Compared with the amount of rain from the ground-based automatic telemetry station, there was a minimum value of the rain event data used for calibration and the rain event data used for reliability verification.

3) Assessment of Sattahip radar rain using the average Z-R relationship equation in each rain group divided by the rain intensity value measured from the ground-based automatic telemetry station, in Case 3, when considering the RMSE value, it can help increase the accuracy of rain assessment by 16.75%, 15.86%, when considering the MSE value, it can help increase the accuracy of rain assessment by 36.29%, 34.23%, when considering the MAE value, it can help increase the accuracy of rain assessment by 23.43%, 23.56% compared to the rain assessment using the Woodley and Herndon equation currently used for the rain event used for calibration and the rain event used for reliability verification, respectively.

5. Acknowledgements

This study would like to thank the Royal Rainmaking and Agricultural Aviation Department for providing the Sattahip radar reflectivity data stored in CAPPI and UF files, and the Water Resources Information Institute (Public Organization) for providing the hourly rainfall data from the automatic ground telemetry station and providing various facilities during the study.

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