The Radar-Rainfall Relationship for Northern Region of Peninsular Malaysia

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***Abstract*—Rain gauge and weather radar is a tool to measure rainfall depth. But, weather radar cannot measure the rainfall depth directly as oppose to rain gauge. Therefore, an empirical relationship between reflectivity (*Z*) and rainfall rate (*R*), called the *Z-R* relationship ($Z=AR^b$), is commonly used to assess the rainfall depth using radar. Using the optimization technique, new relationship for northern of Peninsular Malaysia was developed. Using the daily rainfall data, calibration process has been performed by varying the value of *A* and fixed the exponential *b* to 1.6. The calibration process done, new climatological *Z-R* relationship, $Z=40R^{1.6}$ indicates the closeness between radar rainfall and gauge rainfall. To justify the new relationship, validation process has been performed using the calibrated equation which shows the value of Mean Error, Absolute Mean Error, Root Mean Square Error and Bias within the acceptable statistical indicators with the values of 2.65, 3.29, 3.81, and 0.85 respectively**

***Index Terms*—*Z-R* relationship, radar rainfall estimation, Alor Star Radar, optimization.**

I. Introduction

For thousands of years man has been trying to predict the weather so that he can adjust his nearby future in the best possible manner. Most of us are depending on weather forecasting for better lifestyle. Furthermore, the weather forecast is one of the most important things to consider before making a decision such as planning a holiday, festival or gathering.

As an engineer, part of engineering structure also operated based on weather forecasting especially if we looking from the economical aspect. For example, dam engineer must know amount of water pouring into a reservoir might cause a dam to overflow.

Rainfall and flood forecasting is a challenge to engineer for fulfilling the need of community. Various techniques and engineering application were used to forecast rainfall and flood, one of them is using radar. Application of radar-rainfall forecasting is not new to engineering world, but in Malaysia application of radar-rainfall is still at the early stage especially in hydrological modelling work [1].

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In a relationship between measured radar reflectivity and rainfall rate, the power empirical equation as illustrated below is commonly used to convert the reflectivity into the rainfall intensity

$$Z = AR^b \quad (1)$$

where *A* and *b* are the relationship parameters, *Z* is the reflectivity data in mm^6/mm^3, and *R* is the rainfall rate in mm/hr. As the radar reflectivity, Z (mm^6/mm^3) commonly varies across many orders of magnitude, therefore Z used in this study is the reflectivity expressed in term of dBz as shown below:

$$Z\,(dBz) = 10 \times \log_{10} Z \left(\frac{mm^6}{mm^3}\right) \quad (2)$$

Marshall and Palmer (1947) [2] has developed an equation $Z=200R^{1.6}$ and was used since then until today. This equation was used as initial equation before the new equation developed according to the location since the parameter *A* and *b* in the relationship is usually different according to the location and also depends on the variation of the raindrop size distribution in both space and time. The use of Marshall-Palmer equation for the *Z-R* relationship is no longer appropriate for rainfall estimation and the most suitable *Z-R* relationship for particular location shall be developed [3]. Therefore, the new relationship for Peninsular Malaysia and for northern region specifically will be extended.

The main objective for study is to develop new *Z-R* relationship and determine the new parameters *A* and *b* in *Z-R* relationship for Alor Star Radar.

II. Data Collection

A. Radar Reflectivity Data

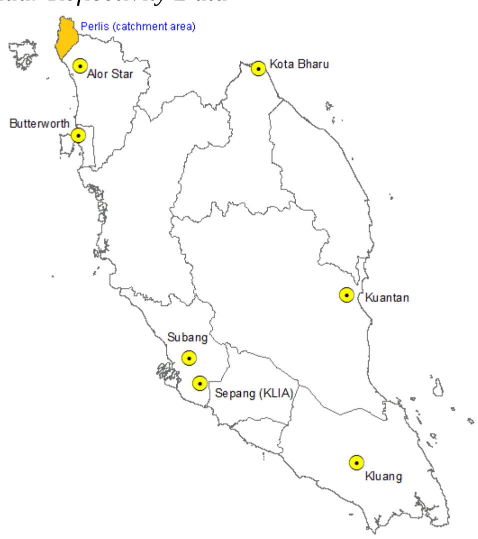

Fig. 1. Location of seven radars in Peninsular Malaysia [4].

In Malaysia, Malaysian Meteorological Department (MMD) under Ministry of Science, Technology and Innovation are responsible to collect reflectivity data. MMD operates two integrated radar networks, one in Peninsular Malaysia and the other in Sabah/Sarawak. The Peninsular Malaysia network consists of seven radars while four radars in Sabah and Sarawak. Fig. 1 shows seven locations of radar in Peninsular Malaysia.

MMD has collected the reflectivity data in two different types which is Composite Plan Position Indicator, CompPPI (make from 2 to 4 PPI scan), and Volumetric data (contain 15 PPI scans at 0.5, 1.2, 1.9, 2.7, 3.5, 4.7, 6.0, 7.5, 9.2, 11.0, 13.0, 16.0, 20.0, 25.0 and 32.0 degree elevation).

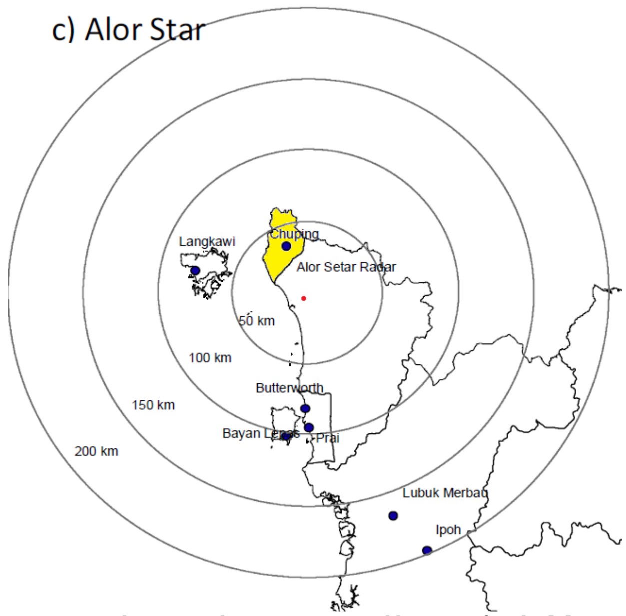

Fig. 2. Alor Star Radar scans ranges and location of Perlis [4].

In this study, reflectivity data collected from Alor Star Radar was chosen for an investigation of the Z-R relationship since the study area is in Perlis and close to the radar location.

Alor Star Radar is the nearest radar station to Perlis and the scan range cover for the whole Perlis is less than 100km as shown in Fig. 2.

In this study, the reflectivity data used is CompPPI data which are derived at 10 minutes interval using radar beam with three different angles (0.5°, 0.8°, and 1.1°). Station number for Alor Star Radar is 267 and located at 6.183°N, 100.408°E, with 4 meter altitude and using S-band radar. S-band radar has longer wave length compare with C-band or X-band radar, which means attenuation, is not a problem for the S-band radar. S-band radar has a maximum horizontal coverage of 480km [5]. So that, it is very practical to use in this study because of the length of the radar fit with the catchment area.

Reflectivity data produced by MMD is in ASCII format and it contains the reflectivity values measured in decibels (dBZ). The value of rain rates was computed by using the Marshall Palmer relationship ($Z=200R^{1.6}$). Data were captured every 2km by 1° range bin and there is no data for the first 4 km. The 1°× 2 km resolution data collected every 10 minutes using the 16 level encoding systems to compress the data decoded for this study.

B. Rain Gauge Data

Rain gauge data is provided by Department of Irrigation and Drainage Malaysia (DID). Rainfall data were derived according to time interval of radar which is in 10 minutes interval. Data retrieved using Time Dependant Data (TIDEDA®). The available data from 2006 to 2007 collected at 14 stations were used for the calibration of the *Z-R* relationship. Fourteen active rainfall stations in Perlis are shown in Table I below and location for all the rainfall station is illustrated in Fig. 3.

TABLE I: RAINFALL STATION (RF STATION) FOR *Z-R* CALIBRATION (SOURCE: DID, 2010)

No	RF Station	Location	Latitude	Longitude
1	6301001	Kg Behor Lateh	06 23 40	100 11 01
2	6401002	Padang Katong	06 26 45	100 11 15
3	6402006	Guar Nangka	06 28 30	100 17 00
4	6402007	Arau	06 25 50	100 16 15
5	6402008	Ngolang	06 28 30	100 14 50
6	6403001	Ulu Pauh	06 27 30	100 21 10
7	6501005	Abi Kg Bahru	06 30 20	100 10 55
8	6502010	Bukit Temiang	06 32 20	100 13 55
9	6503001	Ladang Perlis Selatan	06 32 10	100 20 15
10	6601001	Wang Kelian	06 40 16	100 11 13
11	6602002	Kaki Bukit	06 38 40	100 12 45
12	6602003	Tasoh	06 37 06	100 14 01
13	6602005	Lubok Sireh	06 38 59	100 13 27
14	6603002	Padang Besar di titi keretapi	06 39 25	100 18 35

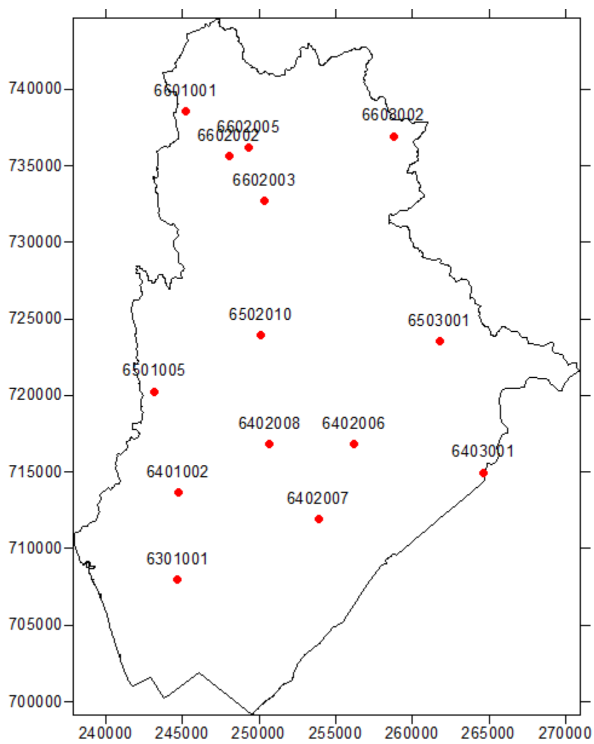

Fig. 3. Hydrological station in Perlis.

III. METHODOLOGY

To determine the best value of parameters A and b, calibration and validation process were done. According to [6], *Z-R* relationship is normally derived using several methods such as raindrop size distribution (DSD) [2] or optimization (regression techniques) method. Since the Disdrometer (a device that measures the size distribution of raindrops) in Malaysia was not available, the optimization method is then applied in this study to derive the most accurate *Z-R* relationship for Alor Star Radar by determining the best correlation and minimizing the errors between radar reflectivity and rain gauge observations.

A. Climatological Z-R Relationship Calibration

Daily data were used and technique proposed by [4], [6] and [7] were applied to determine the suitable *Z-R* relationship.

This technique used the standard *Z-R* relationship (Marshall-Palmer equation, Z=200$R^{1.6}$) to convert the reflectivity data recorded by Alor Star Radar into the rainfall rate and then accumulated into daily rainfall.

Accumulation of daily rainfall data in unit mm was done using the radar rainfall accumulation procedure proposed by [8]. This method assumes the precipitation field remain stationary in space and intensity during the sampling interval [8]. To get the accumulation daily data, the rainfall accumulation is computed by multiplying the rainfall rates (mm/hr) with the sampling interval (here 10 minutes) and after that, adding radar rainfall data for each interval to become the daily radar rainfall in mm.

In this study, rainfall station operated by DID were used to calibrate the most suitable climatological *Z-R* relationship of Alor Star Radar. This calibration process used twenty events of the measured instantaneous reflectivity and daily rain gauge rainfall data during 2006 and 2007.

Method applied in this calibration process can be summarized as follows.

1) Parameter A and b were fixed at 200 and 1.6 respectively. Z=200$R^{1.6}$ were used to convert reflectivity
2) Estimated radar rain rate was then accumulated into daily radar rainfall in millimetre (mm). Same goes to gauge rainfall.
3) Mean gauge rainfall and mean radar rainfall of each day were estimated using Equation 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; r_{ij} is radar rainfall accumulation computed using the Z=200$R^{1.6}$, for day j at the pixels that contain the N rain gauges.

4) Four statistical measures recommended by [8] were using to compared estimated mean radar rainfall and mean gauge rainfall as stated below

Mean error (ME),

$$ME = \frac{1}{n}\sum_{i=1}^{n}(\overline{R_i} - \overline{G_i}) \tag{5}$$

Mean absolute error (MAE),

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|\overline{R_i} - \overline{G_i}| \tag{6}$$

Root mean square error (RMSE),

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(\overline{R_i} - \overline{G_i})^2} \tag{7}$$

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.

Repetition of calculating step 1 to 4 was done to several *Z-R* relationships until the best result gain. Whichever relationship gives the minimum of the four statistical measures will be chosen as the most suitable

Parameters A and b is the aim of this study, so the determination of A and b were done by trial and error and the after extensive trials of value of A and b. Finally, the calibration done with keeping the exponent b in the relationship fixed at 1.6 and parameter A was adjusted to minimise the error. From the literature, initial parameter A can be determined from the following equation.

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

where A_1 is the new multiplicative term A in *Z-R* relationship, A_o is the initial parameter A, m is the gradient of the regression line between the predicted and the observed rainfall obtained from the standard *Z-R* relationship (Z=200$R^{1.6}$), and b is the exponent in the *Z-R* relationship.

IV. RESULTS

Observed gauge rainfall data and radar rainfall data were analyse and the scatter plot of mean radar rainfall using Marshall-Palmer equation (Z=200$R^{1.6}$) and mean gauge rainfall are compared and illustrated in Fig. 4 below.

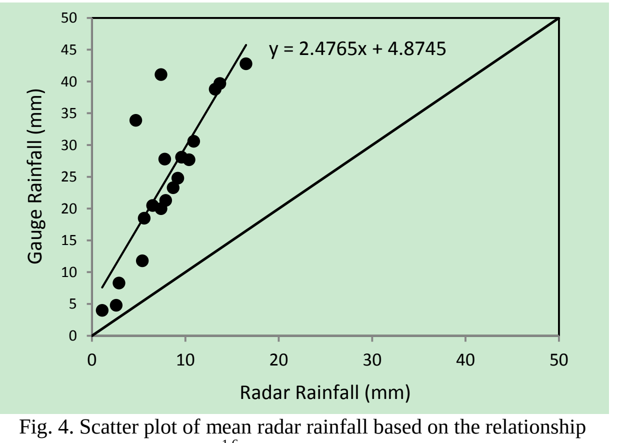

Fig. 4. Scatter plot of mean radar rainfall based on the relationship Z=200$R^{1.6}$ and mean gauge rainfall.

Fig. 4 shows that the radar rainfall data are under estimated than gauge rainfall. It can be seen from Fig. 5 below:

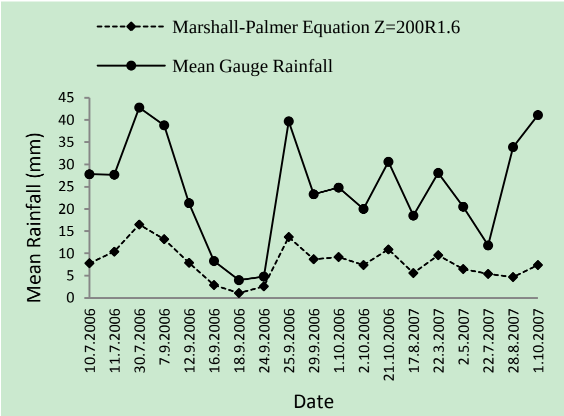

Fig. 5. Time series plot of mean gauge rainfall and radar rainfall using Marshall-Palmer Equation Z=200$R^{1.6}$.

The time series plot and the scatter plot shows that standard equation used by MMD should be replaced with the new equation. As mention earlier, multiplicative A can be determined using Equation 9. The m value in Equation 9 is equal to 2.4765 which is the value of the slope gained from Fig. 4. From the calculation done, the initial parameter A is equal to 46.9.

Calibration process started by using A as 50 and b 1.6 and the value of A was changed until the error were minimised. After several calculation made, the most suitable value for A is 40 and b is 1.6. The result shows that, new Z-R relationship gives the minimum value of error as shown in Table II.

TABLE II: Comparisons of the Statistical Measures Gained from the Different Z-R Relationships

Statistical Measures	Z = 200$R^{1.6}$	Z = 40$R^{1.6}$	Z = 50$R^{1.6}$	Z = 30$R^{1.6}$
ME (mm)	15.48	2.69	5.48	-1.515
MAE (mm)	15.48	3.75	5.73	5.425
RMSE (mm)	17.43	7.06	8.51	7.24
BIAS (mm)	0.54	0.89	0.77	1.063

The result of statistical measures shows that a new Z-R relationship gives significant reduction. The result shows the modified Z-R relationship can improve the accuracy of the mean daily radar rainfall compared to the standard equation. Fig. 6 shows the agreement between mean gauge rainfall and radar rainfall for calibrated event.

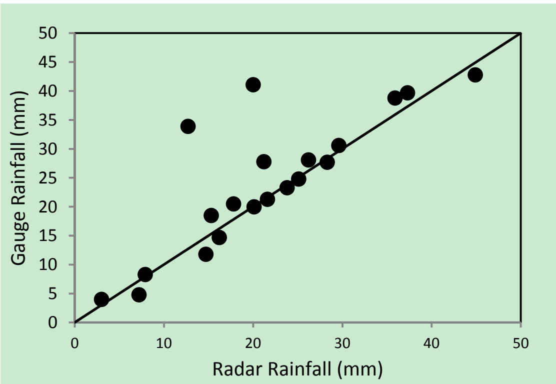

Fig. 6. Scatter plot of mean radar rainfall based on the relationship Z=40$R^{1.6}$ and mean gauge rainfall for twenty calibrated event.

Time series plot can show much better the closeness between mean gauge rainfall and radar rainfall for calibrated event by using the new relationship as illustrated in Fig. 7.

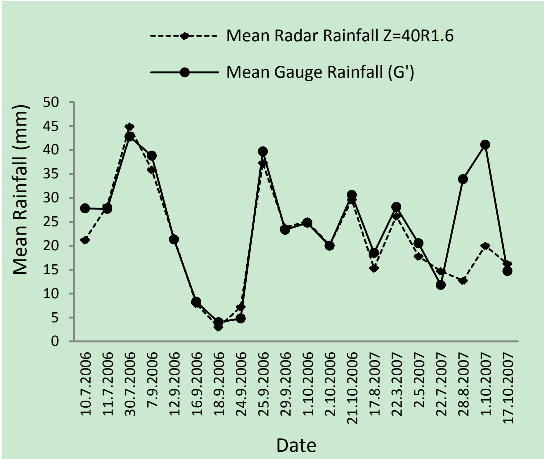

Fig. 7. Time series plot of mean gauge rainfall and radar rainfall using the relationship Z=40$R^{1.6}$

An agreement between estimated radar and gauge rainfall was examined using the Pearson correlation coefficient (r). The result shows the r value is equal to 0.824 which are acceptable.

Validation process is a process to validate the effectiveness of the calibrated equation chosen. In this study, the calibrated equation is Z=40$R^{1.6}$. Another 10 rainfall event was used in the validation process. Using the new equation, reflectivity data were converted to rainfall rate. Again, the radar rainfall rates were compared to gauge rainfall data. Results for validation process were shown in Table III, Fig. 8 and Fig. 9.

TABLE III: Statistical Result for Validation Process Using Z = 40$R^{1.6}$

Statistical Measures	Z = 40$R^{1.6}$
ME (mm)	2.65
MAE (mm)	3.29
RMSE (mm)	3.81
BIAS (mm)	0.85
r	0.97

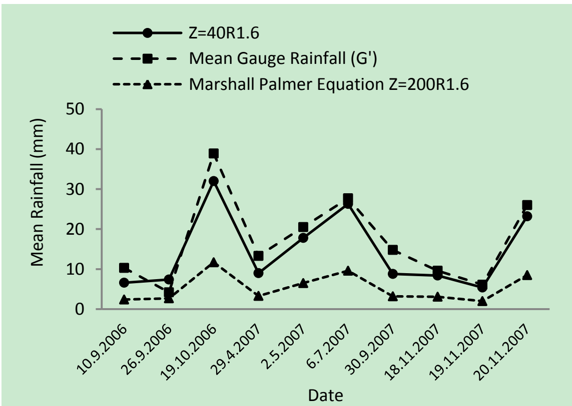

Fig. 8. Time series plot of mean gauge rainfall and radar rainfall using the relationship Z = 40$R^{1.6}$ comparing with Marshall-Palmer equation (Z=200$R^{1.6}$).

From the validation process, the result shows that new equation developed in this study can gives an accurate result comparing to standard Marshall-Palmer equation. Therefore, the calibrated equation Z=40$R^{1.6}$ is suitable to be used for an estimation of daily radar rainfall for Perlis river basin.

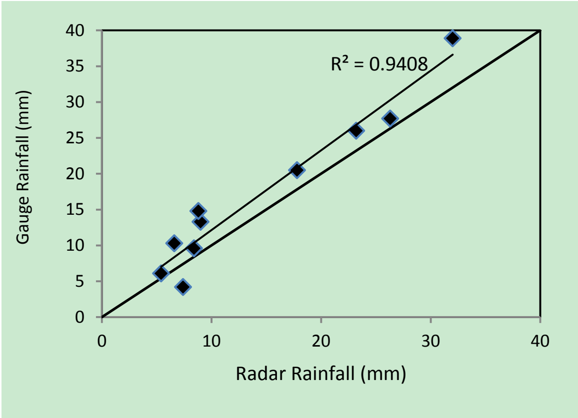

Fig. 9. Scatter plot of mean radar rainfall based in the relationship $Z = 40R^{1.6}$ and mean gauge rainfall.

V. Discussion

Overall result obtained had answered the objective of this study. New *Z-R* relationship was developed for Alor Star Radar. The equation proposed by Marshall-Palmer that was used currently by MMD shows that the estimation were lower than gauge rainfall whiles the new equation $Z=40R^{1.6}$ gives more accurate value. The parameter *A* were adjusted to minimise four statistical measures (ME, MAE, RMSE and Bias), while exponential *b* is fixed to 1.6.

Time series and scatter plot of mean radar rainfall and mean gauge rainfall has shown that new equation is appropriate equation for radar Alor Star. Moreover, validation process performed to ensure the calibrated equation can be used and the result also gives high correlation coefficient (*r*) and coefficient of determination (R^2) value.

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