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CLIMATOLOGICAL CALIBRATION OF RADAR Z-R RELATIONSHIP FOR PAHANG RIVER BASIN

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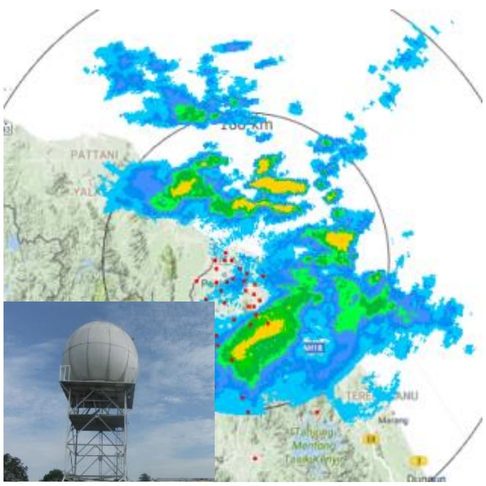
Graphical abstract



Abstract

Flood disaster due to prolonged heavy rainfall had caused millions ringgit of property losses, infrastructure damages and numerous deaths in the east coast region of Peninsular Malaysia. One of the efforts taken to improve disaster preparedness in this region is by enhancing the flood forecasting and warning system (FFWS) using rainfall input from weather radar. Weather radar has the advantage of its ability to provide good spatial and temporal resolution of rainfall estimates but comes with inherent associated errors. In this study, the radar rainfall estimates were improved by climatological calibration of reflectivity-rain (Z-R) relationships for Pahang river basin. The reflectivity data for period of one year from Kuantan radar station and the hourly rainfall depths at 67 rainfall stations located in the basin for the same periods were used. Correlation analysis between radar and gauged rainfall indicates that the further the distance from the radar, the weaker the R^2 coefficient value. Two Z-R equations were derived using optimization method for distance (1) 0-100 km and (2) above 100 km from Kuantan radar. The results in the form of $Z = 24R^{1.7}$ and $Z = 5R^{1.6}$ represents the average relationship for Kuantan radar for distance (1) and (2). The radar rainfall estimates using the newly derived climatological Z-R equations enhanced the FFWS for Pahang river basin.

Keywords: Radar, Rainfall Estimates, Climatological Z-R Relation, Flood Forecasting

Abstrak

Bencana banjir akibat hujan lebat yang berpanjangan telah menyebabkan berjuta-juta ringgit kerugian harta, kerosakan infrastruktur dan kematian di kawasan pantai timur Semenanjung Malaysia. Salah satu usaha yang diambil untuk meningkatkan persediaan menghadapi bencana di kawasan ini adalah dengan meningkatkan sistem ramalan banjir dan amaran (FFWS) menggunakan input hujan dari radar cuaca. Radar cuaca mempunyai kelebihan keupayaan untuk menyediakan resolusi spatial dan temporal yang baik bagi anggaran hujan tetapi banyak kesilapan berkaitan. Dalam kajian ini, anggaran hujan dari radar telah diperbaiki dengan penentukuran klimatologi reflektiviti-hujan (Z-R) bagi lembangan sungai Pahang. Data reflektiviti untuk tempoh satu tahun dari stesen radar Kuantan dan data hujan setiap jam di 67 stesen hujan di lembangan bagi tempoh yang sama telah digunakan. Analisis korelasi antara radar dan hujan menunjukkan bahawa lebih jauh jarak dari radar, lebih lemah nilai pekali R^2. Dua persamaan Z-R kemudian diperoleh menggunakan kaedah pengoptimuman untuk jarak (1)

0-100 km dan (2) di atas 100 km dari radar Kuantan. Dapatan dalam bentuk Z = 24R1.7 dan Z = 5R1.6 mewakili persamaan purata bagi radar Kuantan untuk jarak (1) dan (2). Anggaran radar hujan menggunakan persamaan klimatologi Z-R yang baru diperolehi akan meningkatkan FFWS bagi lembangan sungai Pahang.

Kata kunci: Radar, Anggaran hujan, Climatological ZR Perhubungan, Ramalan Banjir

1.0 INTRODUCTION

Floods have been the most common natural disaster in east coast Peninsular Malaysia especially during the monsoon season; generally due to the prolonged heavy rainfall occurrences. The nature of rainfall distribution which can be significantly non-uniform over a river basin requires the use of more advanced rainfall measuring techniques other than the telemetric raingauges, especially for inputs to flood forecasting and warning system (FFWS). Weather radar can provide reliable and promising alternative in rainfall estimation. Weather radar has been used to provide rainfall inputs to flood forecasting operation for many river basins around the world [1, 2]. The main advantage of the radar rainfall over point gauge rainfall is its ability to provide good spatial and temporal resolution rainfall information with a continuous detailed view of the rainstorm over a large area. However, the indirect estimation of rainfall using radar reflectivity factor is associated with various sources of error such as ground clutter, partial beam occultation, beam blockage and attenuation effects.

Estimation of radar rainfall could be done using various techniques. The most common technique is by using radar equation known as power law Z-R relationship expressed as $Z=aR^b$ where a and b are coefficients that depend on space and time. The relationship is based on the fact that the radar reflectivity factor Z (physical quantity measuring electromagnetic waves power reflected by raindrops) and the rain rate R are related to each other via the raindrop size distribution. Z is proportional to D_i^6 where D is the diameters of individual raindrops in a sample volume while R is proportional to D_i^3 . The widely known Z-R relationship is given as $Z=200R^{1.6}$ derived by Marshall & Palmer [3] based on the theoretical relationship between reflectivity factor, rain intensity and drop size distribution (DSD). Nevertheless, there is no universal relation that is truly representing all cases of rainfall events since DSD has ambiguous characteristics and largely varying in both space and time. Many Z-R equations have been derived following the types of rain (stratiform or convective), locations (higher latitude or lower latitude) and other meteorological factors. The suitability of the chosen equations is normally validated with available rain gauge data sets. Borga [4] emphasized that one of the errors in radar rainfall are associated with Z-R relationships. The Z-R relationship is heavily dependent on two main factors which are drop sizes distribution (DSD) and rainfall location (tropics, continental or oceanic country). Various Z-R relationships have been created according to the event types (convective, stratiform) and locations. Different equations are suitable for different atmospheric conditions.

Battan [5] listed more than 50 Z-R relationships according to space and rain events. Errors that are associated with Z-R can be modified by determining the most suitable equation for that specific events and place. Suitable Z-R equations should be carefully selected in order to reduce both the overestimation and underestimation for low and heavy rainfall respectively. Review shows that there are three common approaches used by researchers to derive the Z-R relationship. The first one is based on drop size distribution (DSD) [3, 6]. The second common method is the Statistical Method as used by [7, 8, 9] while the third method is the Probability Matching Method [10, 11].

Studies on improvement of radar rainfall data quality are still ongoing as indicated by the work done by [12, 13, 14]. In Malaysia, the research on radar rainfall as alternative input to flood forecasting system is getting more significant [15, 16]. Several studies had looked into deriving suitable Z-R equations for different regional areas. Each study produced optimized Z-R relationship which represents the whole river basin [16, 17].

The paper describes a study done on the use of radar to produce quantitative precipitation estimates (QPE) or radar rainfall as input to national flood forecasting and warning system (NaFFWS) for Pahang River Basin. One of the objectives of the research work is to study the correlation between the distance from radar with the radar rainfall estimation accuracy. Subsequently, the main objective of the study is to improve radar rainfall estimates through climatological calibration of Z-R relationship based on distance from the radar.

2.0 METHODOLOGY

Archived data of radar CAPPI files from Kuantan Doppler radar were collected from the Malaysian Meteorological Department (MMD). The Doppler radar is located at the Kem Tentera Batu Sepuluh, Kuantan at latitude 030 45' 24 and longitude 1030 11' 54 as shown in Figure 1. The characteristics of Kuantan Radar is provided in Table 1.

Figure 1 The Kuantan Doppler Radar

Table 1 Characteristics of Radar

Type of Radar	**S-band**
Model	EEC WSR 74S
Reflector	14 foot diameter
Frequency	2700-2900 Mhz
Polarization	Horizontal
Coverage elevation	PPI up to 2.5 ° / VOL up to 32°
Azimuth	360 ° continuous
Beam width	2 ° maximum on axes
PRF	250 Hz /600 Hz
Pulse width	2.0 μs /0.8μs
Peak power	650 KW at transmitter output
Max Range	300 km
Radar Control and Processing Software	IRIS (Vaisala)

The radar data were retrieved from the server at the Drainage and Irrigation Department (DID) which were transferred from the MMD. The data were CAPPI files of R(13) product data type. Linux and *productx* application were used in processing and converting the data into readable rain-rate form. The polar radar format was converted to Cartesian coordinate with map resolution of 2x2 km per pixel. Each CAPPI file was read every 10 minutes, therefore six CAPPI files must be obtained to get the hourly radar rainfall. Hourly rainfall data from 67 rainfall stations in Pahang river basin for the period of November 2014 until November 2015 were obtained from the Drainage and Irrigation Department (DID) of Malaysia.

Optimization of Z-R relationship was done by using Simplex algorithm and solver analysis. Through this approach, the smallest difference between radar reflectivity and gauged rainfall data was targeted.

$Z=aR^b$ Equation 1

$$logZ = loga + b * logR$$

$$\log R = \frac{\log Z - \log a}{b}$$

$$logRg = log\,(raingauge)$$ Equation 2

In the beginning stage, log a and coefficient b are assumed to be 1 before optimization work started. Thus, log R will be calculated based on the formula above by setting up the log a = 1 and b = 1. After that, the error between log R and log Rg will be attained by normal subtraction followed by square of the error.

Error = $\log R_g - \log R$

Error2 = $(\log R_g - \log R)^2$ Equation 3

In this mode the smallest sum of square error is calculated by optimizing the log a and b coefficients. Solver analysis will find the optimum value for log a and b in the equation that gives the smallest difference between log R_g and log R. Statistical measurement used to check the performance of the improved Z-R relationship are mean absolute error, root mean square error and bias.

Mean absolute error (MAE)

$MAE=\frac{1}{n}\sum_{i=1}^{N}|Rg - Rr|$ Equation 4

Root Mean Square (RMSE)

RMSE = $\sqrt{\frac{1}{n}\sum_{i=1}^{N}(Rg - Rr)^2}$ Equation 5

Bias **=** Average values rain gauge/average values radar rain rate Equation 6

3.0 RESULTS AND DISCUSSION

Radar rainfall processed directly from the CAPPI files received from the MMD using the Marshall-Palmer equation ($z = 200R^{1.6}$) were compared with the gauged rain data from 1st. November 2014 until 30th November 2015. More than 50000 CAPPI files were processed and analyzed for 67 rainfall stations. Each of the hourly data of gauged rainfall and hourly calculated radar rainfall at the closest pixel location were paired and results of comparison are shown as in Figure 2. The correlation analysis indicates that the closer the distance from the radar at Kuantan (KN radar), the better correlation of the radar rainfall with the gauged rainfall data. The R^2 value can reach up to 0.83 closed to Kuantan radar and 0.7 at many closer areas. However, although the correlation is good, the radar rainfall values are much lower than the gauged rain indicating an underestimation of the rainfall. In addition, the further away from the radar the weaker the reflectivity as indicated by the graphs of gauged rainfall versus radar rainfall as in Figure 3 and 4.

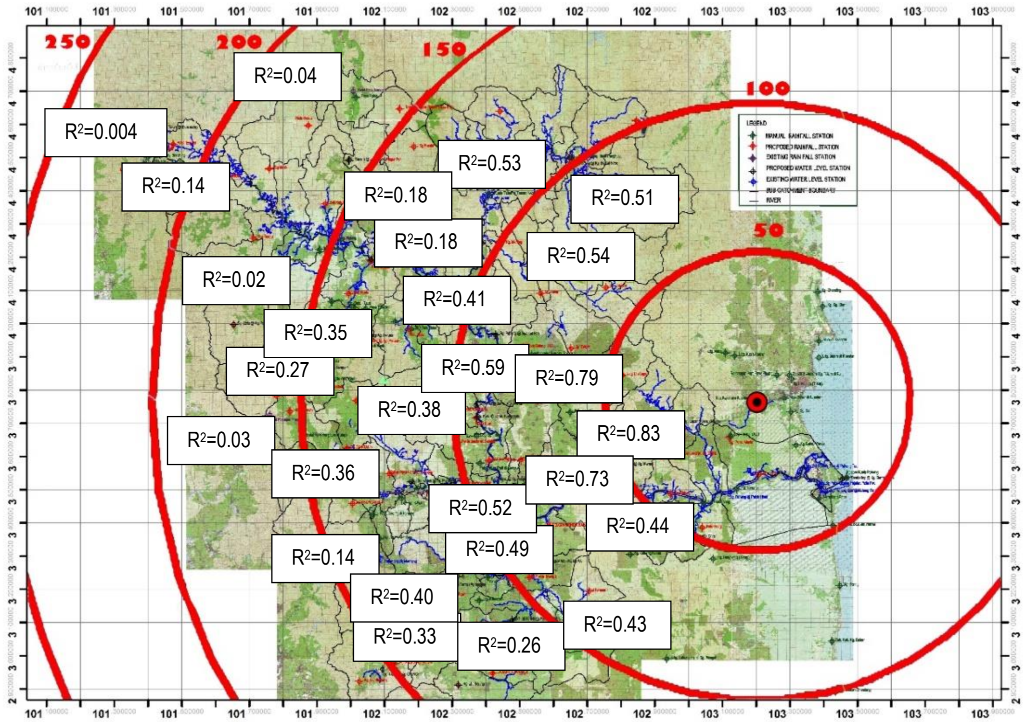
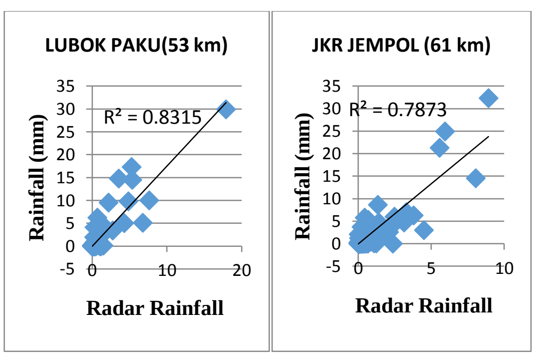
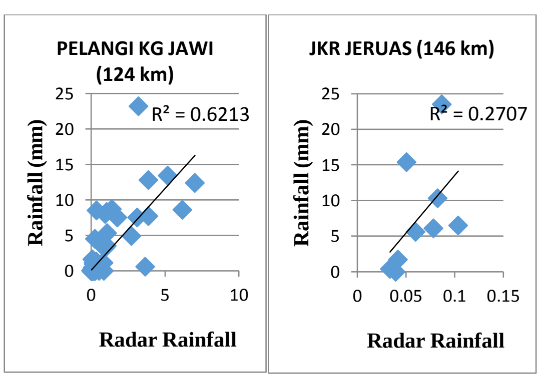


Figure 2 The correlation (indicated by coefficient R^2) between radar rainfall and gauged rainfall shown for various distances from Kuantan radar



(a) (b)

Figure 3 The correlation between radar rainfall and gauged rainfall for (a) Station Lubok Paku (b) Station JKR Jempol



(a) (b)

Figure 4 The correlation between radar rainfall and gauged rainfall for (a) Station Pelangi Kg Jawi (b) Station JKR Jeruas

The plots show low (underestimate) radar rainfall calculated from the reflectivity factor (using the Marshall Palmer equation) as compared to the gauged rainfall. Though the correlation is good, for instance R^2=0.79 at JKR Jempol, the reflectivity factor reads value about 10 mm for 30 mm (33%) of gauged rainfall. Correlations are quite satisfactory for farther distance from KN radar, for example as shown by the analyis for station Pelangi Kg Jawi located 124 km from the KN radar. The graph indicates 0.62 coefficient correlation, but the radar underestimates the rainfall value with x-axis (radar rainfall) shows range of 0-10 mm for y-axis (gauged rainfall) of 0-25 mm. For much longer distance location from the KN radar, not only the correlation is poorer but also the reflectivity factor is weaker. The decreasing values of reflectivity further distance from the radar indicates radar signal attenuation where the radar beam will lose power due to absorption by rainfall from nearer storm and underestimates the further away rainfall.

The poor correlation could be due to several radar limitations commonly discussed in radar rainfall review. The limitation includes (i) the spread of radar beam is above the cloud, thus it missed observing the rain present below the cloud. This limitation can be improved by inspection of the instrument setting since the error is caused by the instrument settings and the method of scanning for weather targets. Other limitations are (2) radar beam is blocked by terrain, such as hills and high-rise buildings and (3) radar beam loses its power due to absorption by rain from the nearest storm and underestimates the rain of storm located far from radar.

Regardless of the limitation, radar is indeed a very powerful tool to provide rainfall estimation. The best range coverage would be within 40-180 km distance from the radar. The datasets used for Z-R optimization were chosen from the period of 1st. November 2014 until 31st November, 2015. The optimization method was applied using solver analysis on 250 sets of data. The analysis was done for two parts of the river basin (1) distance 0-100 km and (2) above 100 km distance from KN radar. Results are provided in Table 2 and 3. The optimized Z-R relation is $Z=24R^{1.7}$ for distance 0-100 km and $Z=5R^{1.6}$ for distance above 100 km from KN radar.

Table 2 Optimized Z-R, performance measurement and validation for distance 0-100 km from KN radar

DISTANCE 0-100 km from KN Radar	**$Z=24R^{1.7}$**	
	Marshal Palmer ($Z=200R^{1.6}$)	Optimized Z-R Equation $Z=24R^{1.7}$)
RMSE	15.96	7.04
Bias	3.78	1.21
Mean Absolute Error	11.37	4.93

Table 3 Optimized Z-R and performance measurement for distance above 100 km from KN radar

DISTANCE above 100 km from KN Radar	**$Z=5R^{1.6}$**	
	Marshal Palmer ($Z=200R^{1.6}$)	Optimized Z-R Equation $Z=5R^{1.6}$)
RMSE	11.59	7.74
Bias	8.78	0.88
Mean Absolute Error	8.03	4.96

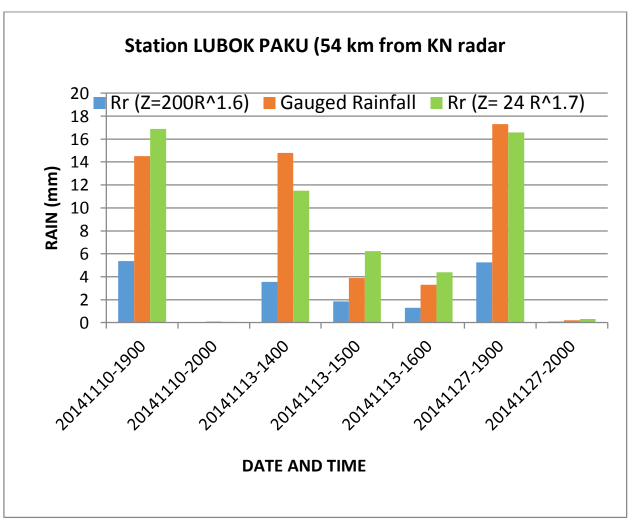


Figure 5 Comparison between gauged rain and radar rainfall from optimized Z-R relation and Marshal Palmer for Station Lubok Paku (distance 0-100 km)

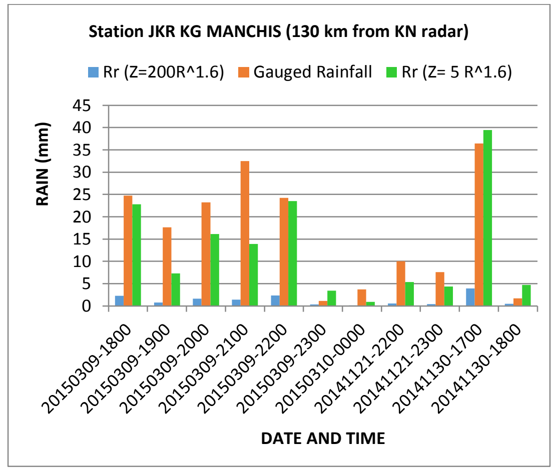


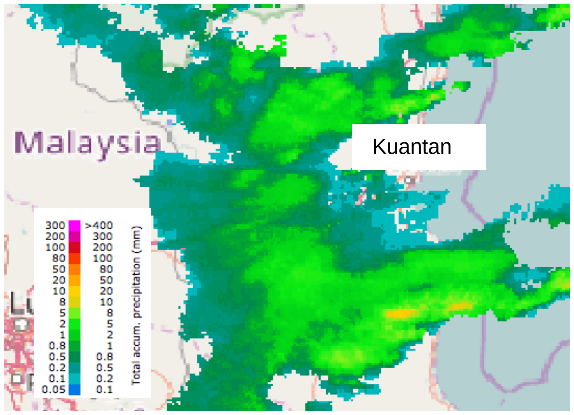
Figure 6 Comparison between gauged rain and radar rainfall from optimized Z-R relation and Marshal Palmer for Station JKR Kg Manchis (distance above 100 km)

The new equations were tested to other 56 pair of datasets not used in the optimization analysis. The results indicate a higher value of radar rainfall if using the equation. Figure 5 and 6 show bar graphs of comparison between the gauged rain, radar rainfall using Marshall Palmer equation ($Z = 200^{1.6}$) and the derived new Z-R relation.

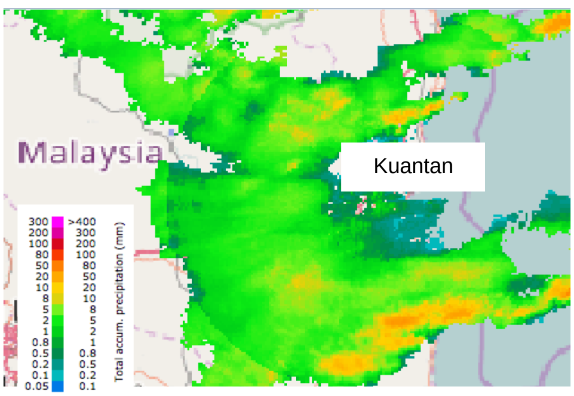
Though the equation performs better there are still high rainfall events not captured well at certain locations. Nevertheless, the radar rainfall has been improved if using the new Z-R equations as indicated by the root mean square error, bias and mean absolute error provided in Table 2 and 3.

The results are compared to the equations derived for Kluang Radar, Alor Star Radar, and Butterworth Radar in the previous study done by the MetMalaysia [17]. The study found that the necessary values used were $Z=13R^{1.3}$ for Kluang Radar, $Z=2.3R^{2.2}$, for Alor Star Radar and and $Z= 0.004R^{4.9}$ for Butterworth radar respectively. The results were compared with the Marshall Palmer Equation $Z= 200^{1.6}$, and also from the Rosenfeld study $Z= 250R^{1.2}$ and was found that the derivation of the new Z-R relationship is better than the Marshall Pamer Z-R equation and the Rosenfeld Z-R equation. The findings of the study indicate the parameter a is reduced to a small value, similar to the finding in this current study; a much lower values as compared to a=200 in Marshal Palmer equation. Similar findings were resulted from studies done in Singapore and Thailand [18,19]. New Z-R relationship ($\boldsymbol{Z}=61.75R^{1.61}$) is derived using rainfall rate data from rain gauge in a study done at Nanyang Technological University [18] whereas a climatological *Z-R* relationship in the form $Z = 74R^{1.6}$ is found to be suitable for radar rainfall prediction for the upper Ping river basin [19]. The studies show that parameter a varies largely in different regions and much lower values are found to be more suitable to tropical rainstorm.

The radar rainfall values were then translated into radar display. Figure 7 shows a comparison of radar rainfall display from KN radar for an event dated 26.12.2014 at 12:00 (a) using the Marshall Palmer equation (b) using the new Z-R distance 0-100 and above than 100 km. The radar display for new improved Z-R for distance 0-100 km and distance above 100 km from KN radar shows closer proximity with the gauged rainfall values as verified by the point gauged values at the rainfall stations



(a)



(b)

Figure 7 Display from KN radar for events dated 26.12.2014 at 12:00 (a) using the Marshall Palmer (b) using the two new Z-R equations for distance 0-100 and above than 100 km

4.0 CONCLUSION

The use of radar rainfall from Kuantan radar as input to the flood forecasting and warning system for Pahang River Basin requires the climatological calibration of Z-R equations for improved rainfall estimates. Correlation analysis results show that the further distance from the Kuantan radar, the lower the estimates of rainfall by the radar. Subsequently, two climatological Z-R were derived based on distance: 1) 0-100 km and 2) above 100 km from the KN radar. The comparison between the gauged rainfall and radar rainfall using new Z-R equations and Marshall Palmer equations indicate improved radar rainfall estimates using the new equation. This study aims to investigate the suitable *Z-R* relationship for radar rainfall estimation in Pahang river basin to minimize the errors caused by *Z-R* conversion. The newly derived climatological Z-R relationship represents the average relationship for Kuantan radar. To further improve the accuracy of radar rainfall estimation, further calibration using gauged- radar rainfall ratio [16] is recommended. Other techniques for radar rainfall estimation error reduction can be found in [20, 21, 22]. The improved radar rainfall estimates can then be used as the input data for the FFWS for Pahang river basin.

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