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SUBANG RADAR CAPPI DATA PROCESSING AND Z-R OPTIMIZATION FOR QUANTITATIVE PRECIPITATION ESTIMATES (QPE) OVER LANGAT RIVER BASIN

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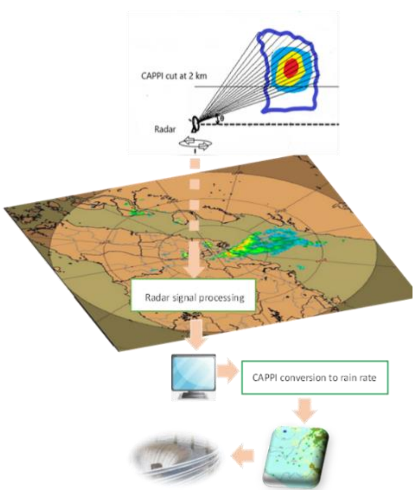
Graphical abstract



Abstract

The main advantage of radar data over point gauge rainfall is its ability to provide continuous spatial and temporal resolution of rainfall details over a large area. Weather radar transmits electromagnetic wave, interacts with raindrops and reflects some of the intercepted power (backscattering) that is subsequently converted into rainfall intensity. Despite its advantages, indirect rainfall estimation using radar reflectivity factor suffers from various sources of error such as ground clutter, partial beam occultation, beam blockage and attenuation effects. Literatures on the use of radar quantitative precipitation estimates (QPE) in Malaysia have been increasing since the past 15 years ago. However, none of the previous work have detailed out the sources of radar data used and its processing for rainfall rate conversion. This paper will discuss the fundamentals in radar data acquisition and processing for rainfall input to a case study of Langat river basin, Malaysia. The methodology in raw radar data processing is decribed in details and the use of CAPPI data for rainfall estimation over Langat river basin is discussed. The findings indicate a good performance of the radar CAPPI data as an alternative source to the rainfall measurement for Langat river basin with correlation coefficient between radar rainfall and gauged rainfall ranging from 0.69 to 0.75. Improvement on radar rainfall estimates is also recommended by newly derived optimized Z-R equations based on monsoon season. The results presented in this study are encouraging, especially for the application of water resources management for the river basin.

Keywords: Radar rainfall, CAPPI data, water resources management, Langat river basin

Abstrak

Kelebihan utama data anggaran hujan dari radar berbanding dari tolok hujan ialah keupayaannya untuk memberikan resolusi spatial dan temporal taburan hujan yang berterusan di kawasan yang luas. Radar cuaca menghantar gelombang elektromagnet, berinteraksi dengan titisan hujan dan memantulkan beberapa kuasa yang dipintas (*backscattering*) yang kemudiannya ditukar kepada intensiti hujan. Di sebalik kelebihannya, anggaran hujan tidak langsung menggunakan faktor pemantulan radar mengalami pelbagai punca ralat seperti kekusutan gangguan, okultasi rasuk separa, sekatan rasuk dan kesan pengecilan. Literatur mengenai penggunaan anggaran kerpasan kuantitatif radar (QPE) di

Malaysia telah meningkat sejak 15 tahun lalu, namun sebelum ini tidak banyak yang memperincikan sumber data radar yang digunakan dan pemprosesannya untuk penukaran kepada kadar hujan. Kertas kerja ini akan membincangkan asas dalam pemerolehan data radar dan pemprosesan input hujan kepada kajian kes lembangan sungai Langat, Malaysia. Metodologi dalam pemprosesan data radar mentah dihuraikan secara terperinci dan penggunaan data CAPPI untuk anggaran hujan di lembangan sungai Langat dibincangkan. Penemuan menunjukkan prestasi yang baik bagi data radar CAPPI sebagai sumber alternatif kepada pengukuran hujan untuk lembangan sungai Langat dengan pekali korelasi antara hujan radar dan hujan terukur antara 0.69 hingga 0.75. Penambahbaikan pada anggaran hujan radar juga disyorkan oleh persamaan Z-R teroptimum yang baru diperoleh berdasarkan musim tengkujuh. Keputusan yang dibentangkan dalam kajian ini adalah memberangsangkan terutamanya untuk aplikasi pengurusan sumber air untuk lembangan sungai.

Kata kunci: Hujan radar, data CAPPI, pengurusan sumber air, lembangan Sungai Langat

1.0 INTRODUCTION

Hydrological model is an essential tool in water resource management of a river basin. Radar and rain gauge are the two widely used sensor devices in estimating rainfall input for hydrological models [1, 2]. Rain gauge is considered the primary input to most of the hydrological models; however, issues of rain gauge maintenance, sparsely distribution network, and instrument accuracy limit the use of rain gauge.

Weather radar transmits electromagnetic wave, interacts with raindrops and reflects some of the intercepted power (backscattering) that is subsequently converted into rainfall intensity. The volume of rainfall sampled by radar depends on the distance from radar and elevation. The main advantage of radar rainfall over point gauge rainfall is its ability to provide continuous higher spatial and temporal resolution of rainfall details over a large area. This comprehensive and detailed rainfall representative will enhance the reliability of the hydrological model. Other areas of application of radar rainfall in operational hydrology include storm hazard assessment, flood forecasting, warning and monitoring [3, 4] of land surface hydrological processes, and verification of sub-grid rainfall parameterizations for satellite-based, atmospheric and global circulation models [5, 6].

Nevertheless, rainfall estimation or quantitative precipitation estimate (QPE) using radar suffers from various sources of error such as ground clutter, partial beam occultation, beam blockage and attenuation effects. In addition, recalibration or replacement of radar hardware can cause drift of bias [7], which can be resolved using improved radar technology such as dual polarization measurements [8] and VPR correction technology [9].

Merging radar and rain gauge data is a commonly adopted technique to reduce error between radar rainfall estimates and the gauged rainfall. Qiu *et al*. [10] discussed that Mean Field Bias (MFB) modification is the easiest technique in which the correction factor is calculated as the ratio of the cumulative gauge rainfall, G and the accumulated radar rainfall estimates, R over the specified time duration at the specified locations. Other radar-gauge merging methods include co-kriging [11] kriging with external drift [12] and conditional merging [13].

The use of radar rainfall estimates as input to hydrological model is getting more attention by the authorities in Malaysia, especially for enhancing the national flood forecasting and warning system [14, 15]. Since the past 15 years, researchers in the country have explored the use of radar QPE and have expanded its application [16, 17]. Most of the previous work have focused on improving the performance of radar QPE as an alternative to rainfall input without going into details on the radar data sources and processing [18, 19, 20]. None of the previous literatures have described the complexity of exploiting and optimizing this advanced remote sensing technology of indirect rainfall estimates. This paper will present the fundamentals in radar data acquisition and processing to estimate rainfall. Though radar instrument and processing system may vary from one country to another, the underlying concepts and fundamentals would be much the same and are applicable to other places. Detailed descriptions of Constant Altitude Plan Position Indicator (CAPPI) radar product and rain rate derivation are presented for a case study of Subang radar covering the Langat river basin, Malaysia. The performance of the estimated radar rainfall is also evaluated based on some statistical measures. Additionally, an attempt was made to derive optimum Z-R equations for monsoon seasons. The derived radar rainfall estimates are validated to ensure its quality and performance before using them as data input to a water resource management system (an intelligence support system) for Langat river basin.

2.0 METHODOLOGY

Subang radar is located near the Sultan Abdul Aziz Shah Airport in Subang, Selangor with the latitude of 3.145160 N and the longitude of 101.55820 E. The photo of the radar is presented in Figure 1 and its characteristics are detailed in Table 1. The transmitter is magnetron based, which is a solid-state modulator with RVP8/RCP8 digital signal processor and digital receiver.

Figure 1 Subang Doppler Radar

Table 1 Characteristics of Subang Radar

Type of Radar	S-band
Model	Meteor 600S (SELEX)
Reflector	28 foot diameter
Frequency	2796 Mhz
Polarization	Horizontal/Vertical
Coverage elevation	PPI up to 2.5 ° / VOL up to 32°
Azimuth	360 ° continuous
Beam width	1 ° maximum on axes
PRF	250 Hz /600 Hz
Pulse width	2.0 µs /0.8µs
Peak power	850 KW at transmitter output
Max Range	300 Km
Radar Control and Processing Software	IRIS (Vaisala)

2.1 Ingest Files as Compressed Polar Data

The Subang radar control and processing software at the time of study are managed by Interactive Radar Information System (IRIS). The system runs the radar and signal processing, processes the polar volume measurement and generates ingest files and raw data to various different products. The main product is collection of all raw ingests data acquired during a run of a single task volume scan which contains the raw signal processor output parameters in polar coordinates [21].

2.2 CAPPI Data

The PPI (Plan Position Indicator) product shows the distribution of data on a constant elevation angle surface while Constant Altitude Plan Position Indicator (CAPPI) is a horizontal cut through the atmosphere which requires a PPI volume scan at multiple elevation angles. The number of angles and their spacing depend on the range and height of the CAPPI to be produced. An example of CAPPI radar display is shown in Figure 2.

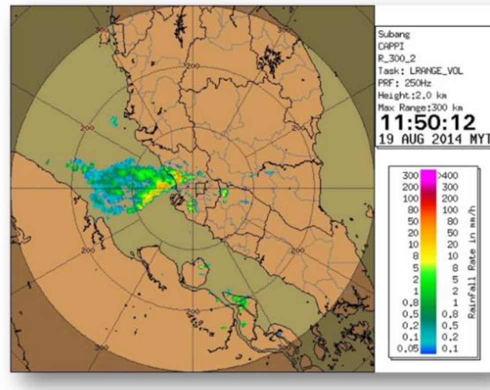


Figure 2 An example of CAPPI data from Subang Radar

The volume scans of the Doppler radar are derived at 10-minute intervals using radar beam at 11 different elevation angles (0.70, 1.50, 2.50, 3.50, 4.50, 5.50, 6.90, 9.20, 120, 15.60, 200). The CAPPI data used in this study had been extracted at a nominal elevation of 2.0 km and spatial resolutions of 0.83 x 0.83 km, 10-minute resolution. The reflectivity data are in a Cartesian grid with 720 km x 720 km extent. Since each CAPPI file was read every 10 minutes, six CAPPI files must therefore be obtained in order to get the hourly radar rainfall. Figure 3 shows the illustration of CAPPI data cut at 2 km. The figure also illustrates the flow of the data to be converted to hourly QPE and used as input to hydrological model of a river basin.

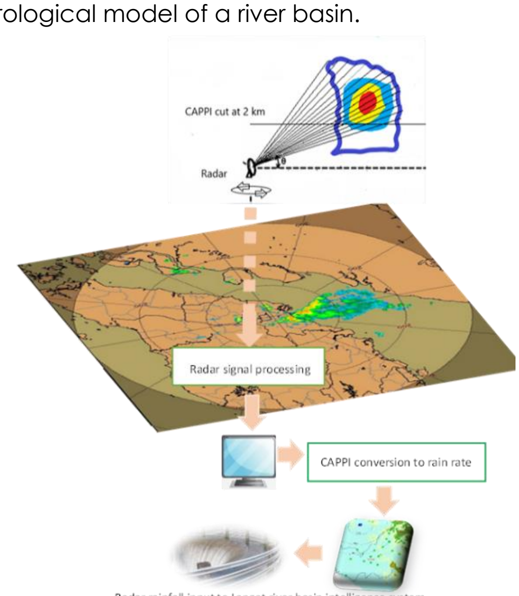


Figure 3 Illustration of CAPPI cut at 2 km altitude and data conversion to hourly radar QP

The radar CAPPI file examples are provided in Figure 4 which show examples of the data files received in binary code. This file can be converted into human readable values by using productx (by IRIS Vaisala). This study had developed its own algorithm to convert the binary code into the human readable text. Each file name indicates the radar (eg: SG for Subang), year, date and time.

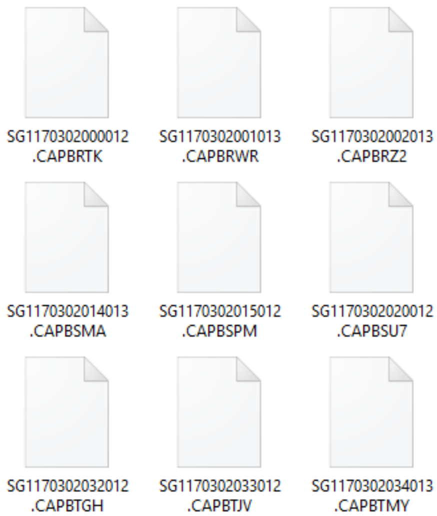


Figure 4 Transferred CAPPI Data from SG radar dated 2.3.2017

47	1.95482	103.15903	1.000
49	1.95482	103.16653	1.000
49	1.95482	103.17403	1.000
43	1.95482	103.18153	1.000
40	1.95482	103.18903	1.000
41	1.95482	103.19653	1.000
45	1.95482	103.20403	1.000
52	1.95482	103.21152	1.000
56	1.95482	103.21902	1.000
42	1.95482	103.22652	1.000

(a)

65535	1.05830	105.83495	2.000
65535	1.05830	105.84246	2.000
65535	1.05830	105.84997	2.000
65535	1.05830	105.85748	2.000
65535	1.05830	105.86499	2.000
65535	1.05830	105.87250	2.000
65535	1.05830	105.88001	2.000
65535	1.05830	105.88752	2.000
65535	1.05830	105.89503	2.000

(b)

Figure 5 Conversion of CAPPI Binary Code into (a) dBZ at 1 km cut (b) DB_RAINRATE2 at 2 km cut

2.3 Conversion of CAPPI Reflectivity Data to Rain Rate (mm/h)

The CAPPI binary radar data transferred can be divided into several data types. Once the binary data have been converted into readable value as shown in Figure 5(a) and (b), they can be analyzed for further processing. The first column in the figure is the value of the reflectivity at the particular pixel. The second and third columns are latitude and longitude that indicate the location of the pixel while the fourth column is the height of CAPPI cut in km. If the data type is CAPPI DB_dBZ2 (2-byte reflectivity), the dBZ is calculated as follows:

$$dBZ = (N - 32768) / 100 \qquad \text{Equation 1}$$

where N is the unsigned radar data output from the CAPPI file.

The reflectivity values in dBZ at 10-minute interval are then converted into rainfall using the Marshall-Palmer equation as used by the Meteorological Malaysian Department. Reflectivity, Z is measured in dBZ. The dB is called a decibel and was originally devised to express power ratios which is shown as follows:

$$dB = 10 \log[P1/P2] \qquad \text{Equation 2}$$

where P1 and P2 are the two power levels being compared and log is base 10.
Mathematically, reflectivity is defined as;

$$Z(dBZ) = 10 \log [z/[1mm^6/m^3]] \qquad \text{Equation 3}$$

where z is the measured backscattered power received by the radar.
Using the Marshal-Palmer equation adopted by the MMD

$$z = 200\, R^{1.6} \qquad \text{Equation 4}$$

Hence, to calculate the rainfall intensity, R for Z= 40 dBZ

$$z = \text{antilog}\,(40/10)$$
$$R = (z/200\}^{(1/1.6)}$$
$$= 11.53 \text{ mm/h}$$

If the data type is DB_RAINRATE2 as shown in Figure 5(b), the data is already in rain rate which is calculated using Marshall Palmer equation and is stored as float values. We have proposed conversion algorithm of the float values to rain rate (mm/h) as below:

If x = 0 or 65535
    Rainrate= 0
If x < 4096
    Rainrate=(x-1)/10000 mm/h
Else
    Rainrate={ (x (mod 212) + 212) x 2(x/4096) } - 1}/10000 mm/h

2.4 Conversion from Polar to Cartesian Coordinates

A radar produces its measured data in polar coordinates as shown in Figure 3 i.e. in range-azimuth format (r, φ), where each point on a plane is determined by a distance and an angle from the reference point (radar location). The radar raw data must first be converted in the Cartesian X-Y-format using the trigonometric function:

$$X = r \cos \varphi$$
$$Y = r \sin \varphi$$

Polar to Cartesian conversion is conducted by averaging the reflectivity (in mm^6 mm-3 units) returned from all the range bins falling within a given pixel. The reflectivity data are in a Cartesian grid with 720 km x 720 km extent. Since the radar covers up to 300 km radius; therefore, each pixel size would be 0.833 x 0.833 km.

2.5 Z-R Relationship Optimization for Different Monsoon

In this study, an attempt was made to derive suitable Z-R equations for different monsoon. Optimization of Z-R relationship was conducted by using Simplex algorithm and solver analysis. Through this approach, the smallest difference between radar reflectivity and gauged rainfall data was targeted.

$$Z=aR^b \quad \text{Equation 5}$$

$$logZ = loga + b * logR$$
$$\log R = \frac{\log Z - \log a}{b}$$
$$logRg = log\,(raingauge) \quad \text{Equation 6}$$

In this mode the smallest sum of square error is calculated by optimizing the log a and b coefficients. Sets of paired radar-gauge data were divided into two main monsoons namely Southwest Monsoon (May – Sep 2017) and Northeast monsoon (Nov-Mac 2017).

2.6 Performance Analysis

The performance of radar data in estimating rainfall can be analyzed by using pairs of gauged rainfall values versus the radar rainfall estimates for collocated time and closest pixel to gauge locations as provided in Table 2. The length of record is from 1st January until 31st December, 2017. More than 50000 CAPPI files were processed and hourly radar QPE was derived. Outliers and missing pairwise data have been omitted. The Root Mean Square Error (RMSE), Mean Absolute Error (MAE) and Pearson Correlation have been applied to measure the performance of radar rainfall estimates.

Table 2 Representative Rain Gauge Involved

Raingauge station with name	Distance to Subang Radar
Site 3218101 TNB Ponsoon	39 km
Site 2714001 Kg. Tali Air Morib	45 km
Site 3118105 Balai Polis	29 km
Site 3119002 Lalang Sg Lui	39 km
Site 3119104 Genting Peres	41 km
Site 2817003 Kg Jenderam	45 km

3.0 RESULTS AND DISCUSSION

3.1 Overall performance

Figure 6 shows the case study area of Langat river basin, the rain gauges utilized in this study and their positions in relation to the Subang radar (in the centre of the scanning circle). The rain gauges considered are provided in Table 2 along with their distances (in km) from radar. We have identified the radar pixels which are the closest to the coordinates of the rain gauges considered through calculating the Cartesian coordinates of the pixels and knowing the Cartesian coordinates of the rain gauges.

Figure 6 shows the Pearson correlation coefficient r, value at the selected stations indicating the strength of relationship between gauge rainfall and radar rainfall estimates. The correlation for all six stations indicates good positive relationship between radar rainfall and gauged rainfall data with a maximum value of 0.75 and a minimum value of 0.69 for each bivariate correlation being significant at the 0.01 level (two tailed) as shown in Table 3. The observation also indicates that there are many events in which the radar rainfall estimations are higher than the gauged rainfall. However, some events indicate higher gauged values. It can also be observed that the correlation between radar rainfall estimates and gauged rainfall is better when the distance of stations to radar is closer. This observation can be due to the radar sample volume which is partially or completely filled with mixed phase or close to the minimum detectable signal. At further distances, the width of a range-bin can be bigger than the pixel width but have less rainfall as compared to pixels which are closer to radar where there are many radar resolution bins. This situation can influence the correlation and estimation accuracy of radar rainfall estimates, thus increasing errors as the distance from radar increases. Studies by [14, 15, 22] also found that the inaccuracy of radar rainfall estimates increase as it gets further away from the radar.

Table 3 Performance measurement for each rainfall station

Station	RMSE	MAE	r
Site 3218101 TNB Ponsoon	0.47	1.64	0.73
Site 2714001 Kg. Tali Air Morib	0.34	2.23	0.69
Site 3118105 Balai Polis	0.46	2.36	0.75
Site 3119002 Lalang Sg Lui	0.49	1.92	0.75
Site 3119104 Genting Peres	0.46	2.18	0.71
Site 2817003 Kg Jenderam	0.48	2.11	0.74
Areal Rainfall Comparison	0.39	1.03	0.82

Figure 7 shows the scatter plots of radar QPE versus gauged rainfall for each rainfall station with lines of discrepancy ratio (DR). Table 4 summarized the performance of the radar rainfall in the discrepancy ratios of 0.5-2.0 for two categories, namely rainfall intensity 0.1 mm/hr and above and as well as 1.0 mm/hr and above. It is observed that the radar QPE can be better estimated for rainfall which is higher than 1.0 mm/hr and the discrepancy ratio for all stations are more than 65%. The larger variance for the lower range of rainfall intensity could be due to ground clutter or noises interference in the radar signal. This wider variance can be reduced by setting a minimum threshold of radar reflectivity to be converted to into rainfall intensity such as 20 dBZ since it is typically the point at which light rain begins [22].

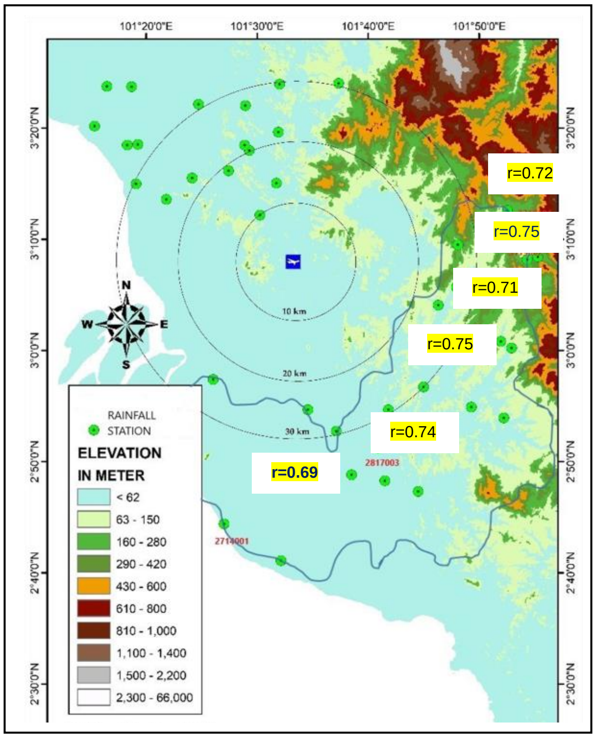


Figure 6 Langat River Basins and the location of Subang Radar and rainfall stations with value of r

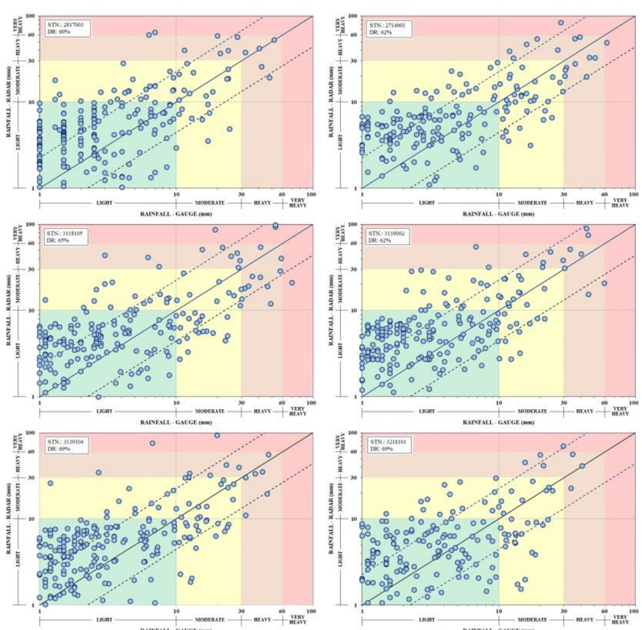


Figure 7 Radar-gauge comparison and discrepancy ratio for Station (a) 3118105 and (b) 2714001 (c) 2817003 (d) 3119002 (e) 3119104 (f) 3218101

It can be observed from the graph that the higher the rainfall intensity, the better the radar rainfall estimates as indicated by the heavy and very heavy regions. This result is encouraging, especially for the application of radar data as an input to various hydrological processes, such as flood modelling, flood forecasting system, dam management and water resources planning.

Table 4 DR value for different range of rain intensity

Station ID	In the range of DR value	
	0.1 mm/hr and above	1.0 mm/hr and above
2817003	54%	74%
2714001	54%	74%
3118105	49%	66%
3119002	47%	71%
3119104	52%	77%
3218101	46%	69%

The performance is improved for areal rainfall values which is obtained by taking the arithmetic average of rainfall over the river basin. The Pearson correlation indicates positive strong relationship between the areal radar rainfall estimates and gauged rainfall with r = 0.82 as shown in Figure 8. However, as displayed in Table 5, the radar QPE from Subang radar had overestimated the rainfall values with higher mean, median and maximum values. Figure 9 provides the bar graph of areal rainfall comparison which shows higher radar QPE values during certain event as compared to the gauged rainfall. The findings are different from other studies done in the country where the radar QPE had underestimated the gauged rainfall [14, 15].

Table 5 Descriptive statistic of areal rainfall data

	Areal average Radar Rainfall depth (mm)	Areal average Rainfall depth (mm)
N	6075	6075
Mean	0.56	0.27
Median	0.13	0.02
Std. Dev.	1.70	1.21
Variance	2.90	1.47
Minimum	0.00	0.00
Maximum	49.89	25.62

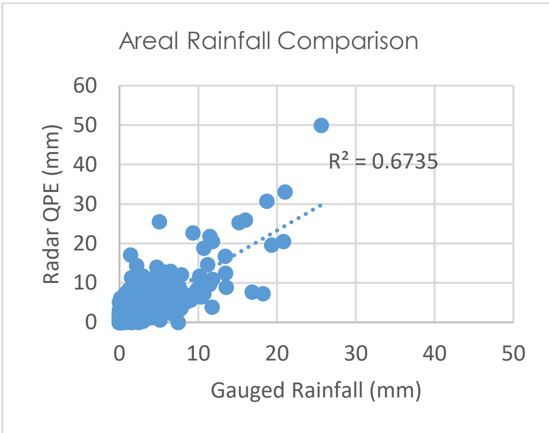


Figure 8 Radar-gauge comparison in terms of areal rainfall values from Jan-Dec 2017

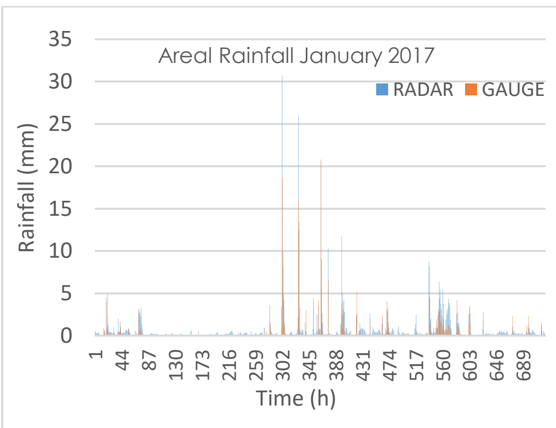


Figure 9 Radar-gauge comparison in terms of areal rainfall values from Jan-Dec 2017

3.2 Z-R for Different Monsoon

An attempt to improve the radar rainfall equation was made using optimization technique of the radar-gauge pairs for different categories of monsoon. Using optimization technique, two (2) equations have been derived as the followings:

Southwest Monsoon: $Z=215\ R^{1.6}$ Equation 7

Northeast Monsoon: $Z=200\ R^{1.8}$ Equation 8

The performance measurement done using different sets of data had shown reduced error; however, bias is a little bit higher which can be seen in Table 6.

Table 6 Performance measurement of new derived equation based on monsoon

	Radar MP $Z=200\ R^{1.6}$	Southwest Monsoon Optimum Z/R $Z=215\ R^{1.6}$	Radar MP $Z=200\ R^{1.6}$	Northeast Monsoon Optimum Z/R $Z=200\ R^{1.8}$
RMSE	5.7	5.37	8.35	4.85
Bias	0.9	0.94	0.73	1.02
MAE	2.81	2.74	4.52	3.31

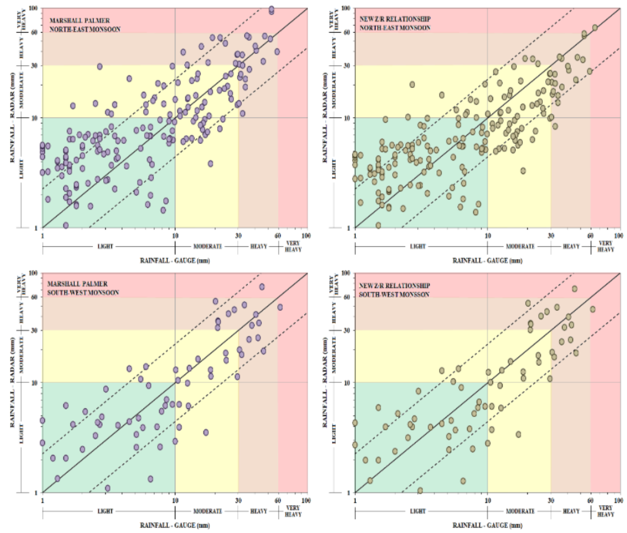


Figure 10 DR plot showing performance of newly derived equations for Southwest Monsoon and Northeast Monsoon

Figure 10 shows improved DR for radar rainfall calculated using the newly derived equation as compared to radar rainfall using the Marshall Palmer equation for both main seasons. Though the plotted points on the graph do not seem to differ much, Figure 11 displays better illustration of improved values of total monthly rainfall calculated using the newly derived equation (NE monsoon) for January 2017 which was measured at six (6) rainfall stations. The graph indicates that the radar rainfall derived from MP equation had overestimated the total rainfall, while the newly derived equation estimates was closer to the gauged rainfall value. Previous studies done had shown that the radar rainfall estimates can be enhanced by applying the optimum and suitable Z-R equation derived for different types of rainfall or region of interest. Many Z-R equations have been derived based on the types of rain (stratiform or convective), locations (higher latitude or lower latitude) and other meteorological factors. Battan [24] quoted a list of 69 such empirical power law Z–R relationships derived for different climatic settings in various parts of the world. Derivation of the suitable Z-R relationship was done using three common approaches, which was based on: (i) raindrop size distribution (DSD) [25,26], (ii) statistical method [27,28] and (iii) Probability Matching Method [29]. The advantage of the statistical method, such as optimization technique used in this study, is the availability of many archived data of radar QPE and gauged rainfall. DSD-based technique has the limitation of possible inaccurate radar reflectivity information that truly represents the rainfall due to the limited sampling spots over a large area [30].

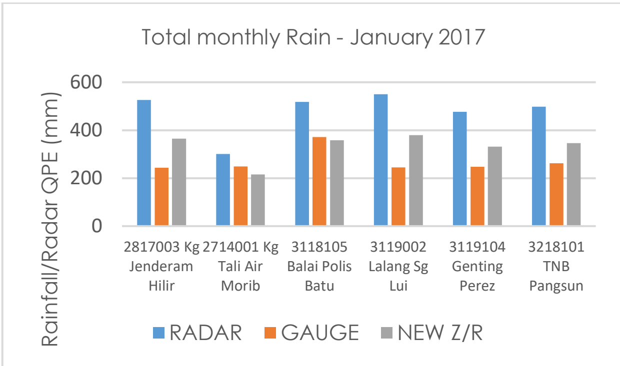


Figure 11 Radar-gauge rainfall comparison between radar QPE (MP) gauge rainfall and radar QPE (Northeast Z/R) for total monthly rainfall value

3.3 Use of Radar-rainfall for Langat Intelligence System

The improved radar QPE can then be prepared as input to the hydrological model employed by the Langat Intelligence system in producing predicted flow from the basin. The predicted flow will provide information on whether water should be released from the dam at the monitoring station. The details of the hydrological model and the intelligence system is not the scope of this paper.

The radar QPE derivation system developed is illustrated in a flowchart as shown in Figure 12. The flowchart indicates the processing and algorithm required in producing the hourly radar QPE. An example of radar display from the system is shown in Figure 13.

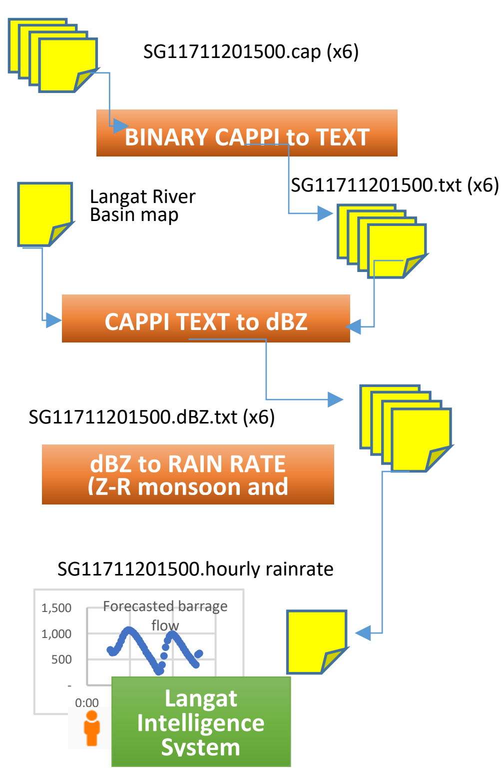


Figure 12 Radar QPE derivation system flowchart

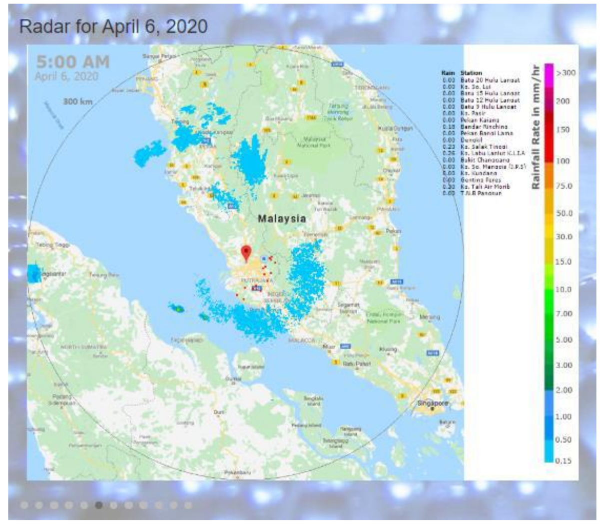


Figure 13 Radar display for the intelligence system

4.0 CONCLUSION

In this study, we investigated the performance of rainfall estimates using CAPPI data from Subang radar to be used as input to the hydrological model of a water balance intelligence system. Elaborated description of raw radar CAPPI data acquisition and processing to derive hourly QPE had been presented to provide insights on the use of this significant alternative of rainfall measurement. Though radar instrument and processing system may vary from one place to another, the underlying concepts and fundamentals are pretty much the same and can be applied elsewhere. The performance of the radar QPE had been assessed based on some statistical measures. The study found that the radar QPE had slightly overestimated the observed rainfall. Additionally, we tried to improve the radar rainfall by formulating new Z-R equation based on monsoon. Archived radar-gauge rainfall data from 2017 were grouped between two main monsoons, namely Southwest Monsoon (May – Sep 2017) and Northeast monsoon (Nov-Mac 2017). The derived new Z-R equations may sometime overestimate or underestimate the hourly time series events; however, the total monthly estimation is improved when using the new equation. The radar QPE were validated to ensure its quality and performance before using them as data input to the hydrological model of a water resources management system for Langat river basin.

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