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Radar Hydrology: New Z/R Relationships for Klang River Basin, Malaysia

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Abstract—**The use of Quantitative Precipitation Estimation (QPE) in radar-rainfall measurement for hydrological purposes is significantly important. For more than 50 years, radars have been deployed to monitor and estimate the precipitation routine in several countries. However in Malaysia, radar application in QPE is still new and needs to be explored. This paper focuses on the Z/R derivation work of radar-rainfall estimation. The work developed new Z/R relationships for the Klang River in the Selangor area for three different classes of rain events, namely low (<10mm/hr), moderate (>10mm/hr, <30mm/hr) and heavy (>30mm/hr). Looking at the high potential of Doppler radar in QPE, the newly formulated Z/R equations will be useful in improving the measurement of rainfall for any hydrological application, especially for flood forecasting.**

Keywords:Radar, Quantitative Precipitation Estimation, Z/R development, flood forecasting

I. INTRODUCTION

For more than 50 years weather radars have been utilized as substitute tools to improve rainfall measurement in hydrology (Uijlenhoet R, 2001). In Malaysia, the radar is one of the tools being used to observe the precipitation routine. The utilization of weather radar in quantitative precipitation estimates (QPE) however is still new. The study on radars in hydrological application recently shows that the radar has a potential value in developing better rainfall measurement products. Waleed et al. (2009) studied calibrating radar-derived rainfall data for rainfall-runoff modeling in the Upper Bernam river basin in Perak and found that the watershed river flow can be better estimated by using radar-derived rainfall data.

In most locations, rain gauge stations are available as a rain measurement system. Although the results are nearly accurate, they also experience problems such as no coverage for certain remote regions, point measurement is not representative of areas, differences in gauge designs and also the wind effect. Concurrently, forecasting by satellite is also favourable since it has good space and time resolutions, observations made are in near real time and are consistent. On the other hand, satellite measurements can be misleading because they measure cloud top properties instead of rain, having too coarse spatial and temporal resolutions, and large data is needed to complete the forecasting. Joss and Waldvogel (1990) explained that the advantage of using radar for precipitation measurement is the coverage of a large area in real time. At the same time, radars also experience difficulty in achieving an accurate estimation for hydrological applications. However with the existence of long radar data sets, these data could be also applied for climatological applications (Overeem et al., 2008). Ultimately, the biggest advantages of weather radar is the ability to detect cloud and precipitation structures and also the process of the rainfall system itself by providing real-time regional information (Peng et al.,2009).

Radar rainfall products are very important for flood prediction models, validation of satellite remote sensing and also for statistical characterization of extreme rainfall events. However the sources of error in radar rainfall estimation should be critically checked.

The use of weather radars in Malaysia is still limited to rainfall observation routines. Coupling the weather radar with the use of radar-rainfall estimates with a hydrological model can be a problem especially with heavy rainfall. It also plays an important part in the hydrology and hydraulics of flooding. Borga, M. (2008) emphasized that it is associated with several parameters such as orography, attenuation, vertical profile of reflectivity and also Z-R relationships (the quantitative use of radar measurements that find the relationship between radar reflectivity and rain intensity).

II. Z/R RELATIONSHIP FOR RADAR-RAINFALL MEASUREMENT

Precipitation types (convective, stratiform or mixed types) are one of the main parameters for Z-R relationships due to variations of rain patterns. Muramoto et al (2003) and Uijlenhoet (2001) elucidated that the relationship between radar reflectivity factor (Z) and precipitation rate (R) are important in estimating rainfall since an error of only a few dBZ in the Z-R relationship may cause over or underestimates of rainfall rates. Thus, the application of an optimal Z-R relationship needs to be understood in radar rainfall estimation.

The Z-R relationship is highly dependent on the precipitation types; whether it is convective, stratiform or mixed types (Chen et al, 2008). Event type is one of the major influences of Z-R relationship that must be studied accordingly. In addition, the location of areas also plays an important factor in applying Z-R relationships to radar rainfall measurements. Various Z-R relationships are created according to the event types (convective, stratiform) and locations. Different equations are suitable for different atmospheric conditions. Thus, it is appropriate to ensure the radar conversion system uses the correct/suitable Z-R equations for radar-rainfall measurement purposes. Many studies have shown that with inappropriate use of Z/R relations, the rainfall estimates are proved to be inaccurate (Zogg, 2006). In order to minimize both underestimation and overestimation of light and heavy rainfall respectively, newly developed Z-R relationships are needed in Malaysia to obtain better estimation and rainfall prediction for forecasting purposes.

As is widely known, there is no universal Z- R relationship that can be applied to all cases of rainfall events. Thus, the focus of this paper will be on the validity of Z-R relationships which were tuned to fit the rain gauge measurements that turn into inaccuracies. For optimization of the Z-R relationship, a systematic space parameter should be explored. The present technique used in Malaysia for Z-R relationship is the statistical approach and in this research, optimization and neural network models are expected to improve the Z-R equation for Malaysia's climate condition.

The importance of the Z-R relationship in quantitative precipitation estimation (QPE) is very significant. The rain rate (R) obtained from the equation is the main key parameter for many hydrological applications such as rainfall-runoff estimation, water catchment capacity calculation, flood forecasting, watering for agriculture and many other hydrological purposes. Thus the conversion of rain-rate from radar reflectivity factor (Z) plays a crucial part in ensuring better precipitation estimation in the radar hydrology system. The best or the most appropriate Z-R relation must be adopted in order to obtain higher accuracy in radar-rainfall measurement. Many Z-R equations have been established according to 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.

Z-R relationships vary from one experiment to another due to the ambiguity characteristic in the drop size distribution (DSD). From the weather radar, Z is proportional to Di^6 where Di is the diameters of individual raindrops in a sample volume while R is proportional to Di^3. It is evident that the radar measurement is biased when dealing with larger rain drops (Hunter, 2009). The variation in distribution of rainfall drop size in both space and time will result in invalid calibration when applied to different rain events. (Chumchean et al, 2003).

Classification of the precipitation types will reduce the error in Z-R conversion by diminishing the variability in the distribution of rainfall drop sizes. A method proposed by Steiner et al (1995) used a storm classification technique to distinguish between convective and stratiform regions within the rainfall event. It has been found that less than 10% of the monthly rainfall statistics are affected by this method. In addition, the Z-R relationship is also affected by different rainfall rates. R Sen et al. (2009) proved that in his study that various functional relations are obtained for different rates of reflectivity and rainfall rates. He found that a single Z-R relationship may not be valid at higher rainfall rates and suggested to deploy time series analysis in order to establish better relations between radar reflectivity and rainfall rates.

Battan (1973) presented sets of Z-R equations for different types of rain including equations for drizzle, widespread rain and thunderstorms from various researchers. This information confirmed that the selection of the Z-R equation for particular locations is crucial in order to increase the accuracy of the radar measurement of rainfall. The use of the Marshall-Palmer equation for the Z-R relationship is no longer appropriate for rainfall estimation and the most suitable Z-R relationship for particular locations shall be developed.

In this paper, new Z/ R relationships have been derived according to three main rainfall events (low, moderate and heavy rainfall classes) for the Klang River Basin in Selangor, Malaysia. Statistical measurements have also been performed to compare the error between rain gauge and radar derived rainfall in terms of mean error, mean absolute error, RMSE and bias. The results show significant improvement with the new developed Z/R relationships in producing better rainfall estimation.

III. CASE STUDY AND DATA COLLECTION

The Klang River Basin in Selangor has experienced flooding for more than a decade. Since it is located in the midst of one of the busiest areas in Malaysia - between Selangor and Kuala Lumpur - it suffers from urbanization and a high population. The size of the Klang River Basin is 1288km2 big with a total stream length of approximately 120km. Located at 3°17'N, 101°E to 2°40'N,101°17'E, it covers areas in Sepang, Kula Langat, Petaling Jaya, Klang, Gombak and Kuala Lumpur. In the case study, only the upper river basin is targeted within an area of 468km2 (Petaling Jaya, Klang, Gombak and Kuala Lumpur). Most of the flooding in the Klang River occurred from soil erosion problems and high rainfall intensity adds to the serious degrading. Since 1998, more than RM20 millions have been spent on flood mitigation on this river. It is essential to study the rainfall intensity effect for the Klang River Basin, and the combination of radar and rain gauge will improve the rainfall estimation. Hence, it can be deployed for further hydrological work.

Radar reflectivity data were obtained from S-band Terminal Doppler Radar in KLIA, which are operated by MMD (Malaysia Meteorological Department) and located at an elevation of 37 m MSL. The conventional radar data are collected every 10 minutes up to the effective range of 230 km for three elevation scans (PPI) with elevation angles of 1.0°, 2.0° and 3.0°. Ground clutter is removed in radar data calibration. The 1°×2 km resolution maps were collected every 10 minutes and converted into rainfall intensity by means of the classical Marshall and Palmer relationship (***$Z=200R^{1.6}$***) using IRIS software Program. The Doppler radar, which is situated in Bukit Tampoi, Dengkil, about 10 km to North KLIA was first introduced in 1998. The prime function of TDR is to detect and to alert KLIA on the wind shear problem and also microburst scenario. Both conventional and Doppler radars can detect rainfall intensity through its signal reflectivity.

The Hydrological data such as rainfall, river discharge and water levels were obtained from the Hydrology Division, DID, Malaysia. 25 rain gauge stations have been selected in this studies which are located near the catchment area: Klang River Basin, Selangor. In this study, hourly rainfall data from DID were used and covered from January 2009 until December 2009. There were more than 100 events throughout the months. For Z/R development purposes, three categories of rainfall have been included; low rainfall (< 10mm/hr), medium rainfall (>10mm/hr but <30mm/hr) and heavy rainfall (> 30 mm/hr).

IV. METHODOLOGY: Z/R DERIVATION

There are 3 techniques commonly adopted to derive relationships for Z-R.

1. Drop Size Distribution (DSD) (Blanchard,1953)
2. Statistical Method (Marshall et al.,1947;Zawadzki,1975;Wilson and Brandes,1975;Austin,1987;Krajewski WF, Smith JA, 2002)
3. Matching Probability Method (Calheiros and Zawadzki,1987;Rosenfeld et al,1994)

The statistical method requires a combination of data from radar and rain gauge stations. The Z-R relationship will then be obtained by measuring both data simultaneously. One of the techniques used in statistical estimation for Z-R equation is the optimization method that relates measured values of radar reflectivity to rainfall rate. The approach is motivated by observation of sampling properties and not driven by DSD control of Z-R relations. In the optimization-based approach, some measures of 'closeness' of the radar rainfall products and the surface rainfall reference data obtained by rain gauges is minimized. The optimization approach determines the relationship by using reflectivity data measured by radar and rainfall data by rain gauges stations.

The Z-R relationship is deduced from radar reflectivity data and the surface rainfall rate using rain gauges. The 'best' values of *A* and *b* parameters are obtained by establishing the optimal curve fitting in the graph between reflectivity and rainfall rate. Issues arising from the method are merely from strong wing disturbance and partial evaporation of rain falling. The values of A and B coefficients can also be determined from literature with certain restrictions. The optimization approach implements algorithm and uses the Z-R relationship as an empirical formula to obtain unknown Z-R parameters. For particular application, the products are optimized in an appropriate manner according to the criteria.

V. NEW Z/R RELATIONSHIPS

At present, the KLIA weather radar has been using the classic Marshall Palmer equation (***$Z=200R^{1.6}$***) to convert reflectivity to rainfall rate in mm/hr. The data shows that more than 80% of the data obtained from the radar were overestimated when compared to rain gauge observations. The need for new Z/R is crucial in order to improve the results. Applying the optimization approach, new Z/R relationships have been derived for three types of rainfall events, namely: low (<10mm/hr), moderate (>10mm/hr, <30mm/hr) and heavy (>30mm/hr). The classification is important to observe the rainfall rates in terms of error measurement.

For low rainfall, the original data can exceed more than 30mm/hr when being converted with MP equation. Using solver analysis, the new Z/R, which is $Z=180R^{1.9}$, is obtained. The results show reduction in the data and improve the accuracy of hourly rainfall data. Figure 1 below shows the plot between estimated radar rainfall with $Z= 200R^{1.6}$, the new $Z=180R^{1.9}$ and rain gauge data for January 2009 until December 2009. Statistical measurements resulted from both relationships are shown in Table 1. Great reduction can be observed while using the new Z/R relationship.

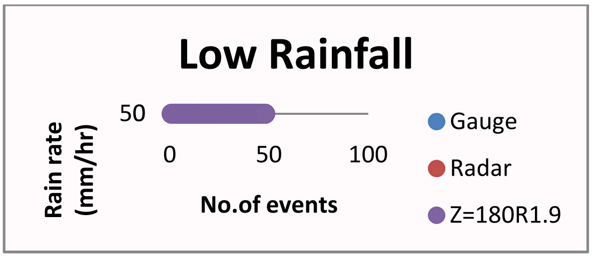

Figure 2. Plotted graph for original and new Z/R relationships compared to rain gauge

For moderate type of rainfall, the intensity of which is more than 10 mm/hr but less than 30 mm/hr, the best Z/R obtained from optimization work is $Z= 212R^{1.9}$. Results produced are significantly better than radar rainfall with $Z=200R^{1.6}$ when compared to rain gauge data. It can be seen from Figure 2 that the original radar rainfall gave maximum reading until 80 mm/hr with 20 mm/hr data for rain gauge. The new Z/R modified the results with better estimation. Table 2 shows the statistical measurement for moderate types of rainfall events.

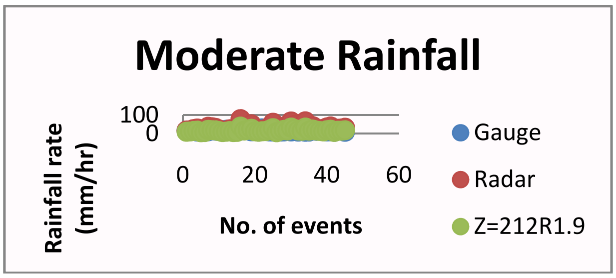

Figure 3. Plotted graph for original and new Z/R relationships compared to rain gauge

The data for heavy types of rainfall which consist of rain events more than 30mm/hr of intensity show interesting results. Most of the radar rainfall data were overestimated by more than 50% compared to rain gauge. It can reach until the maximum value of 200 mm/hr. The new Z/R, which is Z= 262R1.9, greatly reduces the disparity between radar rainfall and rain gauge values. Obvious improvement can be observed from Figure 3 and the error measurements are shown in Table 3.

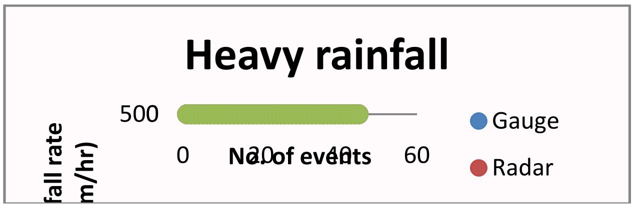

Figure 4. Plotted graph for original and new Z/R relationships compared to rain gauge

The improvements of using new Z/R relationships are described in Figure 5, 6 and 7 for different types of rainfall events respectively. The correlations increased between the radar reflectivity and the converted rainfall rates using the modified Z/R. The bigger the values of reflectivity, the bigger the difference of rain rate for the Marshall Palmer equation and newly derived equations. For example for the same reflectivity of 45dBZ (low rainfall), MP gives rain rate of approximately 20mm/hr while the new modified Z/R estimates around 10 mm/hr (see Figure 4). Better results can also be estimated from moderate and heavy types of rainfall events. With correlation more than 0.8, the newly developed Z/Rs have a huge potential in reducing errors between radar rainfall and rain gauge data.

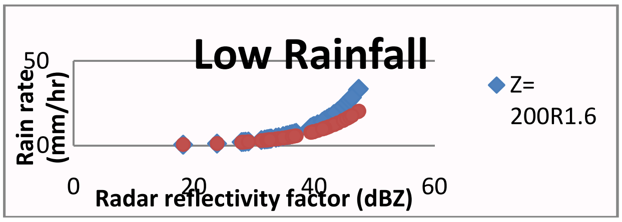

Figure 5. Regression graph between reflectivity (dBZ) and rain rate (mm/hr) for low type of rainfall

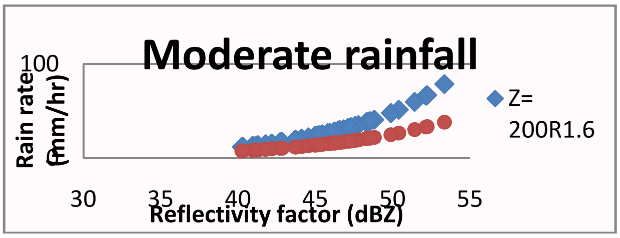

Figure 6. Regression graph between reflectivity (dBZ) and rain rate (mm/hr) for moderate type of rainfall

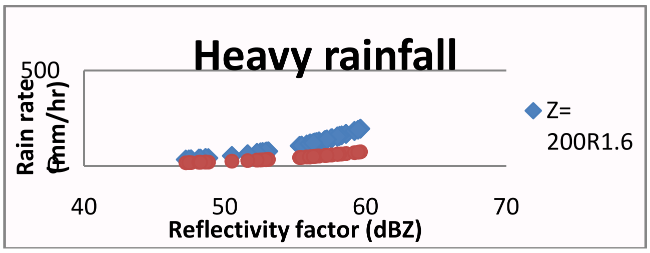

Figure 7. Regression graph between reflectivity (dBZ) and rain rate (mm/hr) for heavy type of rainfall

VI. Conclusions

The rain has been classified into three categories depending on the rain intensity. It shows that the bigger the rainfall intensity, the error also increases. To improve the results, new Z/Rs have been derived by using the optimization approach. The modified equations show significant improvement in the rainfall rates obtained and the errors are also minimized. The rain regimes are very important characters since the Z/R relationships are hugely dependent on location and type of rain.

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