Z-R RELATIONSHIP IN BANDUNG AREA FROM DISDROMETER DATA

Persamaan Z-R di Wilayah Bandung dari Data Disdrometer

Rahmawati Syahdiza[1)]*, Sholehhudin Al Ayubi[2)], Halda Aditya Belgaman[1)], Budi Harsoyo[2)], Edi Riawan[3)], Nyayu Fatimah Zahroh[1)], Erwin Mulyana[1)], Faisal Sunarto[1)]

[1)] Research Centre for Climate and Atmosphere - National Research and Innovation Agency.
[2)] Directorate of Laboratory Management, Research Facilities in Science and Technology Areas - National Research and Innovation Agency.
[3)] Atmospheric Science Research Group, Bandung Institute of Technology (ITB).
*E-mail: rahmawati.syahdiza@brin.go.id

Abstract

The radar measures reflectivity (Z), proportional to N D^6, where N represents drop concentration and D is its diameter, leading to an empirical relationship of $Z = aR^b$. However, the drop size distribution is not perfectly exponential as assumed, and variations depend on the pseudo-constants (a) and (b). Consequently, radar-derived rainfall estimates may lack accuracy. An Intensive Observation Period was conducted in the Bandung area from 23 October 2021 to 27 April 2022, involving the deployment of several instruments. Drop size distribution data from a Laser Precipitation Monitor (LPM) or optical disdrometer from Thies-Clima were used to refine the ZR relationship, resulting in $Z=397R^{1.37}$ for Bandung area. Comparison with Marshall-Palmer and Rosenfeld indicates distinct rain microphysical features in Bandung. Monthly Z-R analysis shows consistency in the (b) coefficient of 1.4 and (a) ranging from 321-443. Rain type classification reveals the dominance of stratiform rain. Significant diurnal variation in Bandung shows the majority peak in both precipitation frequency and intensity occurring from 12:00 to 23:00 LT, predominantly associated with stratiform rain. In contrast, heavy rain events during 00:00–11:00 LT are dominated by convective and mixed rain.

Keywords: Disdrometer, Precipitation Estimation, Radar reflectivity.

Intisari

Radar menghitung reflektivitas (Z) yang nilainya equivalen terhadap N D^6, dengan N merupakan konsentrasi butir hujan dan D adalah diameter butir hujan. Persamaan ini menghasilkan hubungan empiris antara reflektivitas radar terhadap estimasi curah hujan yang dideskripsikan sebagai $Z = aR^b$. Namun realitanya, distribusi ukuran tetes awan hujan tidak selalu sempurna mengikuti persamaan eksponensial seperti yang diasumsikan, dan variasinya bergantung pada pseudo-konstanta (a) dan (b). Oleh karena itu, estimasi curah hujan dari radar tidak selalu akurat. Selama periode 23 Oktober 2021 hingga 27 April 2022 dilaksanakan pengamatan intensif lapangan (Intensive Observation Period – IOP) di Bandung, beberapa instrument meteorologi dipasang salah satunya Laser Precipitation Monitor (LPM) atau disdrometer optik buatan Thies-Clima. Data distribusi ukuran butir hujan dari disdrometer digunakan untuk memperbaiki hubungan ZR. Hasil penelitian menunjukkan hubungan Z-R dengan $Z=397R^{1.37}$ untuk area Bandung. Perbandingan dengan persamaan Marshall-Palmer dan Rosenfeld menunjukkan fitur mikrofisika hujan yang berbeda dengan kedua persamaan tersebut. Analisis Z-R bulanan menunjukkan konsistensi pada koefisien (b) sekitar 1.4 dan (a) berkisar antara 321-443. Klasifikasi tipe hujan memperlihatkan dominasi hujan stratiform di area Bandung. Pola variasi harian signifikan terlihat di Bandung dengan mayoritas puncak frekuensi dan intensitas presipitasi terjadi dari pukul 12:00 hingga 23:00 WIB, yang didominasi oleh hujan stratiform. Sebaliknya, kejadian hujan lebat pada pukul 00:00–11:00 WIB didominasi oleh hujan konvektif dan campuran (mixed rain).

Kata Kunci: Disdrometer, Estimasi Presipitasi, Reflektivitas Radar.

1. INTRODUCTION

Radar has been known providing high-quality data, makes it the best option to measure areal rainfall. Therefore, radar is potentially the best way of measuring localized rainfall. However, confidence is lacking in the quantitative values of rainfall derived from the radar; Collier (2019) stated that the level of performance of the radar has remained largely unchanged since 1978. This is due to the relationship between *Z-R* is not represented well.

The radar measures reflectivity (Z) proportional to $N\ D^6$. With N is the drop concentration and D is its diameter. This leads to an empirical relationship of *Z-R*. In meteorology, this relationship is defined as $Z=aR^b$, where R is rainfall rate. However, the problem is that the drop size distributions are not perfectly exponential as assumed. Therefore, radar-derived rainfall estimates may not be very accurate. However, despite the limitations, radar is still the best way to measure area rainfall more accurately in comparison to satellite data.

The pioneer and widely known *Z-R* equation is Marshall and Palmer (1948) later in this manuscript will be refer as MP, characterized $Z = 200R^{1.6}$. However, later investigations showed a tendency of this equation does not fit with local nature of rainfall over the maritime continent. Up to today, many forms of *Z-R* relationship have been found depicting different types of rainfall in different locations. Fabry (2015) stated that this variation, which depends on pseudo-constants (*a*) and (*b*), is based on the dynamical and microphysical processes controlling precipitation formation and hence varies a little from one region to another.

There are two most known methods to construct *Z-R* for precipitation estimation. The first method is by comparing direct radar reflectivity with rain gauge data. The other method is by using drops size distribution (DSD) data. The rainfall rate and reflectivity are both functions of the raindrop size distribution. There has been considerable research on using disdrometer data to calibrate rain-rate estimation from radar reflectivity measurements or identify a suitable empirical equation of *Z-R* (Cerro *et al.*, 1997; Atlas *et al.*, 1999; Campos and Zawadzki, 2000; Bringi *et al.*, 2001; Park *et al.*, 2005; Rico-Ramirez *et al.*, 2007; Hazenberg *et al.*, 2014). The study results show that the DSD data from the disdrometer has excellent potential in radar adjustment, reflectivity monitoring, and identification key sources of errors in radar rainfall estimation.

In Indonesia, Marshall-Palmer ($Z = 200R^{1.6}$) and Rosenfeld *et al.*, 1993 with $Z = 250R^{1.2}$ equations are usually applied for the radar quantitative precipitation estimation (QPE) for stratiform rain and convective rain, respectively. Several related studies have been conducted to construct new *Z-R* relationships in different locations in Indonesia. The pioneering research about the *Z-R* relationship in Indonesia was conducted by Mueller and Sims (1966), who reported the *Z-R* relationship at Bogor with $Z = 311R^{1.44}$. This result was derived from at least one year of DSD data obtained by raindrop camera. Later, Kozu *et al.* (2006) used almost two years of data (Aug 2001 – July 2003) of disdrometer and radar instrument. The result pointed out in Kototabang during (DJF-MAM-JJA-SON) the *b* value of the Z-R equation is consistent with Marshall Palmer (MP) in the range of 1.47 – 1.5 and the (*a)* value in the range of 167-225. These values indicate a subtle seasonal variation without notable distinctions in *Z-R* relationships across various monsoon seasons. On the other hand, the new *Z-R* shows strong diurnal variation influenced by the heat contrast between ocean and land and the effects of mountains, leading to the initiation of local convection in the afternoon. Arida *et al.* (2012) used five months (Nov 2009 – March 2010) of the C-Band Doppler radar reflectivity and rain gauge data. The result shows the *Z-R* in Soroako is $Z = 96.16R^{2.066}$ is found for all rain cases, while for the stratiform rain the *Z-R* equation is $Z = 61.94R^{1.55}$ with (*b*) value shows consistency with MP while for convective rain $Z = 1.58R^{0.52}$. The *a* and *b* values in convective rain is remarkably small which accompanied by enormous error. The significant error indicates that the Z-R relationship shows significant variation with time, particularly for convective rain.

Marzuki *et al.* (2013) observed DSD from Parsivel Optical Disdrometer in Kototabang, Pontianak, Manado, dan Biak. Each location provided different data lengths, from the shortest with 147 days data and the longest with 318 days data. The study results suggest that for light rain cases, the Z-R relationship is consistent with the MP equation. In contrast, during heavy rain, the Z-R shows regional variations. The Z-R equation in Pontianak is generally close to the Z-R equation reported for continental locations, while Z-R in other locations is similar to maritime locations. Later, Marzuki *et al.* (2018) continued the study and added two other locations: Padang and Sicincin. The study results reveals that the coefficient of (a) and (b) from the Z−R equations vary from 200 to 400 and 1.36-1.47. The b coefficient shows a tendency to fix value of 1.4. All locations showed strong diurnal variation in Z−R relationships. In Biak and Manado, coefficient *a* during 00–11 local time (LT) is larger than during 12–23 LT. However, Sicincin, Padang, Kototabang, and Pontianak show the opposite pattern with coefficient *a* during 00–11 local time (LT) is smaller than during 12–23 LT.

Hutapea *et al.* (2021) constructed a new ZR with $Z = 110R^{1.6}$ using December 2014 – February 2015 C-band radar data compared it with a rain gauge from AWS in Surabaya. Lestari *et al.* (2022) also found a similar *ZR* equation with $Z=102.7R^{1.75}$ using C-band radar and disdrometer data in Jakarta from 2010-2020. The similar geography of both megacities, might be one of the reasons why they have a similar *ZR* relationship.

Despite various studies focused on improving radar's quantitative precipitation estimation (QPE) in several locations in Indonesia, to the authors' knowledge, no related research has been conducted for the Bandung area. One of the main reasons might be due to the unique nature of the dataset of DSD. An (Intensive Observation Period) was conducted in Bandung during 2021-2022. Several instruments like Disdrometer, Sodar, Radiometer and AWS (Automatic Weather System) were installed in the meteorological station Department of Meteorology, Institut Teknologi Bandung (ITB) (-6.89, 107.61, 800m asl) from 23 October 2021 up to 27 April 2022. In addition, Radar polarimetric Furuno WR-2100 X-band Dual-polarisation Doppler Radar is also installed in Lembang, Bandung (-6.807, 107.616, 1300 m ASL) from 20 Oktober to 21 November 2021. The availability of this high-accuracy data of DSD from the disdrometer will be used to construct a new *Z-R* equation fitted to local nature in Bandung.

2. METHODOLOGY

2.1. Observation Site and Study Domain

The study domain is focused on the Bandung area. The Thies Clima disdrometer and the Automatic Weather System (AWS) used for this study were installed at the ITB meteorological station (-6.89, 107.61, 800 m ASL). The location of the observation site is shown in Figure 1. Both data are part of an Intensive Observation Period campaign in Bandung during 23 Oktober 2021 – 27 April 2022. This data covers one month of transitional periods to the wet season (November), one wet season (December – January – February), and two months of transitional periods to the dry season (March and April).

Bandung is located in a basin surrounded by mountainous areas, resulting with the area being heavily influenced by local circulation. The complex terrain influences the vigorous diurnal intensity of convective clouds triggered by the wind valley circulation. Previous study by Oigawa *et al.* (2017) shows the convection initiated at noon over the summit of the southern mountain of Bandung and caused widespread rainfall across the northern part of the basin during the evening, with the precipitation over Bandung basin reaches its peak around 18 LT.

2.2. Data

This research uses two datasets, which are drop size distributions (DSD) data collected by the disdrometer and rain rate data obtained from the Automatic Weather Station (AWS) installed at the meteorological station at Institut Teknologi Bandung (ITB). The LPM data provided one-minute data while the AWS data is only available in five-minute range. Previous research by Vuerich *et al.* (2009) and Lestari *et al.* (2022) points out the importance of one-minute data for estimating heavy rain rates over short periods. Therefore, in this study, the new Z-R relationship will be constructed based on a one-minute data sample from Laser Precipitation Monitor (LPM) data. Furthermore, the AWS uses a tipping bucket rain gauge sensor for the rain rate measurement. Tipping bucket rain gauges (TBR) have a 0.2 mm bucket, which means in one minute, the tip is either 0, 1, or 2 tips, and the rain rate is either 0 mm/hr, 12 mm/hr, or 24mm/hr for each minute. Therefore, the TBR is not very accurate since it has a coarse resolution and weaknesses in measuring low rainfall rates over short intervals. This could affect the new Z-R if the majority of data of low rain rate is removed by the AWS data since it will only consider rain 0.2 mm or rain rate from 12 mm/hr over one-minute and 2.4 mm/hr over five-minutes. Therefore, using direct rain rate data from a rain gauge will result in a bias Z-R. In this study, the rain rate from AWS will only be used for crosschecking and verifying the rainfall pattern from the disdrometer data.

2.3. Method

2.3.1. Data quality control

Since DSD is a function of time intervals, intrinsic noise may occur in the processes. Therefore, the disdrometer will need time to get a reasonable number of drops in each size bin. For this research, the drop counted is accumulated for one minute. The DSD data with small data samples are excluded from the data analysis. The data are removed if the drop counted from the one-minute DSD data is below ten drops. This process removes implausible points of unphysical data, such as very high dBZ with a low rain rate. Then, the rainfall rate derived from the DSDs is crosschecked and verified with the AWS data. The data from the disdrometer are considered spurious if the accumulated rainfall does not agree with these rain gauges. For data analysis, we disregarded very light rain with a rain rate below 0.1 mm/hr to reduce statistical and quantization errors.

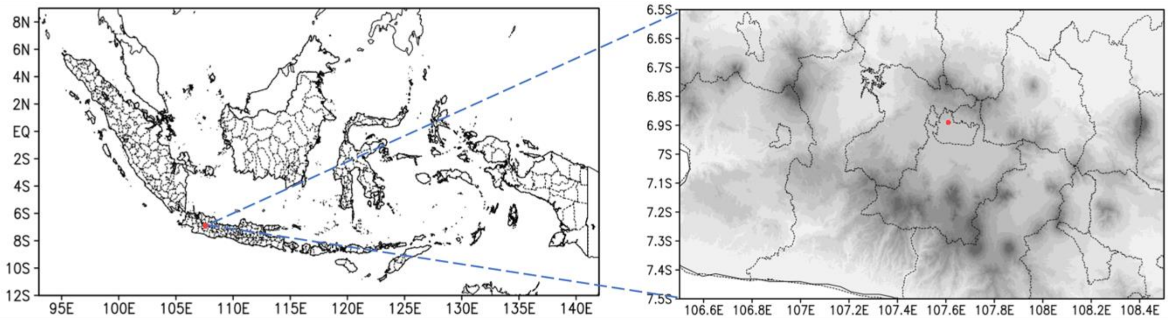

Figure 1. Study area domain shows the Bandung basin. The Thies-Clima disdrometer and the Automatic Weather System (AWS) were installed at the Department of Meteorology, Institut Teknologi Bandung (ITB) meteorological station marked by the red dot.

2.3.2. Data processing and analysis

The drop size distributions (DSDs) data are converted to reflectivity (*Z*) by using equation:

$$Z\ (mm^6\, m^{-3}) = \Sigma\ N_i\, D_i{}^6 \qquad (1)$$

N_i is the concentration in m^{-3} drops of diameter D_i (mm) summed overall drop sizes within a unit volume. N_i is referred to raindrop size distribution. As the value of *Z* ($mm^6\ m^{-3}$) can vary greatly, depending upon the target, the radar reflectivity factor can be defined using a logarithmic scale with:

$$Z\ (dBZ) = 10\ log_{10}\ Z \qquad (2)$$

The rainfall rate (*R*) is calculated by the volume of the drop times the fall speed of the raindrop (terminal velocity) by using the equation:

$$R = \Sigma Ni\ \frac{\pi}{6}\ Di^3 v_t \qquad (3)$$

To match the dBZ, the *R* is also converted to dBR by:

$$dBR = 10\ log_{10}\ R \qquad (4)$$

The *Z* and *R*, are then plotted in a log-log plot (dBZ and dBR) to construct the *Z-R* relationship. Mueller and Sims (1966) stated that the reflectivity should be treated as the independent variable for the rainfall rate estimation from the measurement of radar reflectivity. On the contrary, if rainfall is considered as the independent variable, it will result in a smaller exponent and a larger coefficient for the identical dataset. Therefore, in this study, the *Z-R* relationship is generated by using linear regression on log-transformed values of dBR over dBZ. The best-fit line of the data is the linear regression in the form of:

$$y = mx + c \qquad (5)$$

with *c* as the intercept value of the y-axis and *m* as the slope of the data, or in this case, the linear regression equation for the log-transformed values would be:

$$log\ 10\ (Z) = b * log\ 10(R) + log\ 10(a) \qquad (6)$$

When (6) is fitted to (5), with X in dBR and Y in dBZ, the intercept of the data (*c*) gives (*a*) coefficient in dB (dBa) or log10(*a*) and the slope (*m*) is (*b*) coefficient.

Statistical analysis of the data is also calculated to quantify the new *Z-R* equation. The r^2 indicates the correlation between the data, 0 means no correlation, and 1 means perfect correlation of the data. Root Mean Square Error (RMSE) is the standard deviation of the *dBR*. It shows how far the dBR from the regression line data points are (the spread of the data).

Further analyses are conducted by investigating the *Z-R* in different rain events. The main classification is defined using the rain rate and its standard deviation over ten consecutive data samples; this method is modified from previous studies by Chen *et al.* (2013) and Pu *et al.* (2020). The classification uses the Thies-Clima rain intensity data; based on the rain rates of 10 consecutive one-min samples, specifically, for sample of the rain rate from t_i – 5 NS (Number of Sample) to t_i + 5 NS are higher than 5 mm/hr and the standard deviation is more than 1.5 mm/hr, the rain is considered as convective rainfall. If the rain rates are greater than 0.5 mm/hr and the standard deviation is less or equal to 1.5 mm/hr, the rain events are considered stratiform rainfall, and the rest of the rain event (rain rate > 0.1 mm/hr) is classified as mixed rain type. Further analysis was also conducted by plotting the monthly *Z-R* to see the monthly variation of the *Z-R* equation. The monthly *ZR* are plotted using all the one-minute sample throughout the month. The diurnal variation is also studied by grouping the data into 00–11 LT and 12–23 LT.

3. RESULTS AND DISCUSSION

3.1. General relationship of Z-R in Bandung

The new *Z-R* relationship is constructed using the whole data period (see Figure 2). Since all the one-minute samples are combined for the plot, with 20.405 samples, the data are colored by the point density to showcase the distinct pattern of the data spread. The point density describes the number of points in a given area. The dark blue shade indicates lower density, and the yellow shade is higher density. The yellow shade implies the majority occurrence of rain. The graph shows that the x-axis is displayed from -10 to 20; the *x* value is in dBR. Therefore -10 dBR equals 0.1 m/hr, 0 dBR means 1 mm/hr rainfall, 10 dBR is 10 mm/hr, and 20 is 100 mm/hr rainfall. The plot also compares other *Z-R* equations from previous research in Indonesia along with Marshall Palmer (MP) and Rosenfeld equations.

Generally, the *Z-R* relationship in Bandung marks by the magenta line shows *a* value around 399 and the *b* is 1.37. The r^2 between dBZ and dBR is 0.91, indicates a good correlation between *Z-R*. The RMSE (dBR) with the fit line is at 2.2 dB, this value indicates the error of the rain rate estimation with the fitting line is around 66 %. The values with the regression line show that the data concentrated far better around the line of best fit (magenta line) than in previous research. The small fractional error of *b* indicates the excellent relationship between the data and the vast amount of the data. Despite the error of around 66%, using $Z = 399R^{1.37}$ for radar quantitative precipitation estimation (QPE) in the Bandung area is generally better.

The error in dBR shows that the spread of the data is due to the different occasions of rain. The dot's color shows that the *Z-R* relationship changes coherently from one rain to the next. For example, the most obvious is the outlier dots outside the main scatterplot. The scatter of these dots will have a completely different *Z-R* relationship, which indicates a different rain behavior. The colour of the dots shows that most of the rain (darker yellow shade) is below 30 dBZ and 3 dBR (below 2 mm/hr). The point density indicates that the light rain dominates the rain events in Bandung throughout the dataset (Z < 30 dBZ and R < 3 dBR).

Figure 2 also shows the *Z-R* comparison with previous studies. Marshall-Palmer (1948) marked by black line and Rosenfeld (1993) marked by yellow line are plotted due to the frequent use of Indonesia's operational radar. The error with MP and Rosenfeld, respectively, by 2.8 and 3.1 dB, indicates that the rain behavior in Bandung has distinctly different characteristics from MP and Rosenfeld. Therefore, using those equations for radar QPE in Bandung will entirely result in the wrong estimation, particularly for moderate to heavy rain events. As a comparison Other Z-R in different location in Indonesia such as Bogor (BGR) by Mueller and Sims (1966), Soroako (SOR) by Arida *et al.* (2012), Kototabang (KT), Padang (PDG), Pontianak (PT), Manado (MND), Biak (BK) by Marzuki *et al.* (2018), Surabaya (SBY) by Hutapea *et al.* (2021) and Jakarta (JKT) by Lestari *et al.* (2022) also plotted as comparison. As shown in Figure 2, the Z-R in Bandung shows a similar value of *b* by around 1.4 with almost all other locations in Indonesia (Bogor, Kototabang, Padang, Pontianak, Manado dan Biak). The *a* coefficient in Bandung is the highest among other ZRs around 399. Marzuki *et al.* (2018) stated that higher *a* values usually associated with a higher concentration of large size drops in the area.

Despite the big spread between the data and other *Z-R* equations, *Z-R* in Bandung shows the closest similarity with Pontianak (PT) to other locations marked by the lowest error (dBR) of 2.1. Marzuki *et al.* (2013) stated that this equation is close to the *Z-R* relationship reported for continental locations. The small error value followed by Bogor and Padang by 2.3 dBR, but the analysis from the *a* and *b* values from these two locations, *Z-R* in Bandung is more similar to Bogor due to the closer *a* value of around 300 and *b* value of 1.4. This signifies that besides the similarity of the mountainous area's topography, these two locations also show similar rain microphysical characteristics. The other notable result is that *Z-R* in Pontianak and Padang produces closer error to Bandung despite the disparity of the topography of low land area versus high terrain area. On the other hand, Kototabang produces slightly higher error despite their similarities in mountainous topography. Surabaya, Soroako, and Jakarta exhibit the highest errors by 4.1 and 4.0 dBR; the big spread is expected due to the difference in the geographical background between these areas, with Jakarta and Surabaya as big cities situated near the coastal area with low land topography. Lestari *et al.* (2022) also noted that the possible cause of the difference in the *Z–R* relationship between Jakarta and other locations in Indonesia could be related to the high levels of pollution and associated aerosol–deep convection interactions.

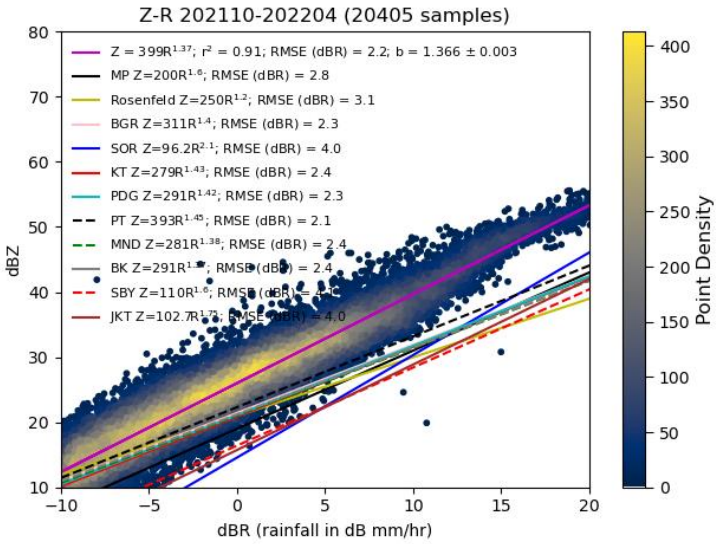

Figure 2. Z-R relationship from the one-minute data (23 October 2021 – 27 April 2022). The scatter of the data in a log-log plot. x-axis in dBR and y-axis in dBZ. The magenta line is the fitting line of the data. Other Z–R from previous studies is also plotted as comparison MP (black), Rosenfeld (yellow), Bogor (pink), Soroako (blue), Kototabang (red), Padang (cyan), Pontianak (black-dash), Manado (green-dash), Biak (grey-dash), Surabaya (red-dash), and Jakarta (brown). The color bar represents the point density. A dark blue shade indicates lower density, and a yellow shade is higher density. (r^2) is the correlation of the data. b is the slope of the data. dBa is the intercept with the y-axis. RMSE is the standard error in terms of dBR.

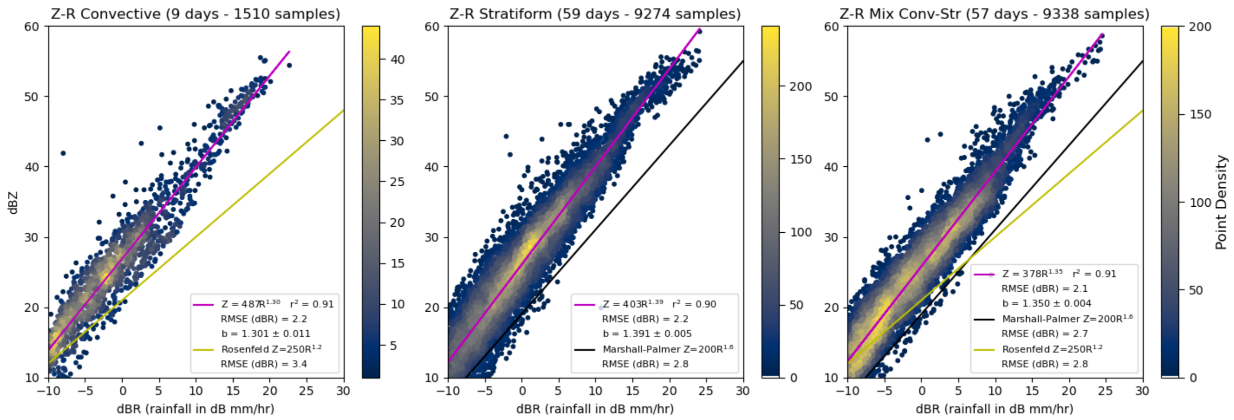

Figure 3. Z-R relationship is categorized into different rain types, i.e., convective, stratiform, and mixed rain. The Z-R was constructed from the one-minute data (23 October 2021 – 27 April 2022). The scatter of the data is in a log-log plot, with the x-axis in dBR and the y-axis in dBZ. The magenta line is the fitting line of the data. The black line is derived from the Marshall-Palmer equation. The yellow line is derived from the Rosenfeld equation. The colorbar represents the point density. A dark blue shade indicates a lower density, and a yellow shade is higher density. (*r^2*) is the correlation of the data. b is the slope of the data. dBa is the intercept with the y-axis. RMSE (dBR) is the standard error in terms of dBR.

3.2. Z-R Relationship in Different Rain Cloud Types

The rain rate and dBZ data are categorized into convective, stratiform, and mixed rain to better characterize the *Z-R* in different rain events. Figure 3 reveals the convective rain, spanning over 9 days and consisting of 1510 samples. Notably, these samples are statistically low compared to other categories, with stratiform rain occurrence over 59 days - 9274 samples and mixed conv-str, consisting of 57 days - 9338 of one-minute rain samples. The *Z-R* equation for each category is $Zconv = 487R^{1.30}$, $Zstr = 403R^{1.39}$, and $Zmix = 378R^{1.35}$ for convective, stratiform, and mixed rain types, respectively. In general, the equations show robust results with the consistency of *b* coefficient by around 1.3. Notably, the highest *a* coefficient is found in convective rain. This value is expected as convective rain typically contains larger drops (Sauvageot and Lacaux, 1995). Consequently, the highest error by 3.4 dBR is also expected in convective rain due to the significant variation or spread of the scatter, signifying that each convective rain event has its own unique *Z-R* characteristics.

In the stratiform rain category, the point density indicates the most dominant rain is moderate rain events marked by the darker yellow shade with reflectivity below 30 dBZ and rain rate 3 dBR. The scatterplot of stratiform rain also shows a significant number of severe rain events with reflectivity above 50, reaching up to 60 dBZ and rain-rate of around 15 – 25 dBR. This result demonstrates that stratiform rain produces more severe rain than convective rain events. The mixed rain category shows a slightly similar pattern of uniform shape of the dots in stratiform rain category. On the other hand, the majority of the rain are light rain with reflectivity below 20 dBZ and rain rate of -6 dBR. Extreme rain rate was also recorded from the mixed rain category despite the lower number of occurrences compared to the stratiform rain. Comparison with Rosenfeld and MP produce error (dBR) by 3.4 and 2.8 dB for convective and stratiform rain type. The mixed rain category in both equations produces errors of 2.8 and 2.7 dB respectively. This result shows that when we compared to the specific rain category, neither Marshall-Palmer nor Rosenfeld's equation fit the rain microphysical feature in Bandung.

3.3. Monthly variation of Z-R Relationship

Table 1 summarizes the *Z-R* monthly equation; the data covers six months from November 2011 – April 2022. The error from the *Z-R* equation in different locations in Indonesia along with Marshall-Palmer and Rosenfeld are calculated to Bandung data as a comparison for their performance evaluation. Across the analyzed period, in general, the correlation of the data stands consistently high in range 0.87-0.92, signifying a strong positive relationship between the variables (*Z* and *R*). Notably, the monthly variations demonstrate a consistent pattern in the *b* coefficient, with an approximate deviation in range of 1.30-1.39. In general, the (*a*) coefficients vary from 329–443. However, the (*a*) coefficient exhibits a less distinct pattern, potentially attributed to the limited six-month dataset, making it challenging to discern a clear trend. However, this result shows similar result with Kozu *et al.* (2006) which also shown that no distinct seasonal pattern of the ZR in Kototabang. The monthly plot of ZR in Bandung shows high (*a*) values, indicates the microphysical properties of the raindrop size in Bandung consistently large each month, with the largest drops are observed during March and December. The highest error is also observed during the wet month of December. Additionally, when applying *Z-R* from other locations to the *Z-R* dataset, shows consistent results with the general *Z-R* (refer to Section 3.1). The *Z-R* for Pontianak consistently produces the lowest errors (dBR) across all months, while Soroako, Surabaya, and Jakarta exhibit the highest errors consistently.

The monthly plot is also classified into convective, stratiform, and mixed rain types to investigate the *Z-R* relationship further. As shown in Table 2, The convective rain events only occurred during November 2021, January 2021, March 2022 and April 2022. From those months, most convective rain events are recorded during March 2022, with 812 convective rain samples. In general, the highest error for different cloud type also produces by the convective rain type further confirm the variation in time of convective rain. The sample number reveals stratiform rain dominating the rain events during November and April, while mixed rain during November and March. Comparison with MP and Rosenfeld shows consistent results with the general data (refer to Section 3.2) with Rosenfeld produce error (dBR) in the range of 3.1 – 3.9 dB for convective rain, MP with error of 2.4 – 3.3 dB in stratiform rain, in mixed rain 2.6 – 3.5 dB for Rosenfeld equation, and 2.4 – 3.5 dB for MP equation in mixed rain category.

Table 1. Monthly *Z-R* equation in the Bandung area from November 2011 – October 2022. Error from *Z-R* equation in different locations in Indonesia along with Marshall-Palmer and Rosenfeld calculated to Bandung data as a comparison for their performance.

		202111	202112	202201	202202	202203	202204
BDG	Z-R	Z=403R1.37	Z=439R1.31	Z=410R1.30	Z=329R1.37	Z=443R1.38	Z=354R1.39
	Corr	0.92	0.87	0.9	0.89	0.91	0.89
	RMSE (dBR)	2.0	2.6	2.1	2.1	1.9	2.4
MP – RMSE (dBR)		2.6	3.4	3.1	2.6	2.9	2.7
ROS – RMSE (dBR)		3.1	3.5	2.9	2.7	3.1	3.2
BGR – RMSE (dBR)		2.1	2.7	2.3	2.1	2.2	2.4
SOR – RMSE (dBR)		3.7	4.8	4.6	4.0	4.1	3.7
KT – RMSE (dBR)		2.2	2.9	2.4	2.1	2.3	2.4
PDG – RMSE (dBR)		2.2	2.8	2.4	2.1	2.3	2.4
PT – RMSE (dBR)		1.9	2.5	2.1	2.1	1.9	2.3
MND – RMSE (dBR)		2.3	2.9	2.4	2.2	2.4	2.5
BK – RMSE (dBR)		2.2	2.9	2.4	2.2	2.3	2.5
SBY – RMSE (dBR)		3.9	4.7	4.4	3.8	4.3	3.8
JKT – RMSE (dBR)		3.8	4.7	4.5	3.9	4.2	3.8

Table 2. Monthly *Z-R* equation in the Bandung area from November 2011 – October 2022. The monthly data were categorized into convective, stratiform, and mixed rain events for further analysis. Error from *Z-R* Equation with Marshall-Palmer and Rosenfeld equation also calculated to Bandung data as a comparison for their performance evaluation.

		202111	202112	202201	202202	202203	202204
CONVECTIVE							
BDG	Z-R	$Z=607R^{1.30}$	-	$Z=459R^{1.28}$	-	$Z=459R^{1.27}$	$Z=346R^{1.50}$
	Corr	0.93	-	0.95	-	0.86	0.95
	RMSE (dBR)	2.0	-	1.6	-	2.4	1.8
	Sample num	307	-	177	-	812	99
ROS – RMSE (dBR)		3.8	-	3.1	-	3.3	3.5
STRATIFORM							
BDG	Z-R	$Z=437R^{1.36}$	$Z=507R^{1.34}$	$Z=369R^{1.36}$	$Z=299R^{1.41}$	$Z=504R^{1.39}$	$Z=348R^{1.43}$
	Corr	0.92	0.91	0.89	0.86	0.94	0.89
	RMSE (dBR)	2.0	2.2	2.2	2.1	1.8	2.4
	Sample Num	2714	1079	621	1478	811	1860
MP – RMSE (dBR)		2.7	3.5	2.8	2.3	2.8	2.7
MIXED							
BDG	Z-R	$Z=361R^{140}$	$Z=367R^{1.28}$	$Z=421R^{1.20}$	$Z=399R^{1.31}$	$Z=410R^{1.38}$	$Z=365R^{1.28}$
	Corr	0.93	0.83	0.89	0.88	0.91	0.89
	RMSE (dBR)	1.9	3.0	2.0	2.2	1.7	2.2
	Sample Num	3293	864	447	1397	2075	958
ROS – RMSE (dBR)		2.9	3.5	2.8	2.6	2.7	2.8
MP – RMSE (dBR)		2.4	3.4	3.5	2.8	2.7	2.7

3.3. Diurnal variation of Z-R Relationship

The log-log plot of dBR and dBZ (Figure 4) shows a significant diurnal variation, with most of the rain events in Bandung happens during 12–23 LT, with 17,511 samples accounting for 86 % of the total rain events. While the occurrence of rain during 00–11 LT is around 14% with 2,894 samples. This result shows consistent results with Oigawa *et al.* (2017) that the precipitation over the Bandung basin reached its peak around 18 LT and dissipated before 00 LT. Similar results were also shown by Marzuki *et al.* (2018) with the peak rain rate at Sicincin, Padang, Kototabang, Pontianak, and Manado also detected during the second half of the day (12–23 LT). During 12–23 LT, the majority scatter point of the data shows a more uniform pattern, indicates that most of the rain during this period is dominated by stratiform rain.
The classification of the data in different rain type during 00–11 LT and 12–23 LT confirm more prominent diurnal variation with majority of the convective rain, stratiform and mixed rain frequency is higher during 12–23 LT respectively (see Figure 5). The samples number during this period along with the rainfall rate, reveals stratiform rain was predominant and accounted for more than 50 % of the rain frequency. This rain classification further confirms the uniform shape in the 12–23 LT in Figure 4. The rain classification during 00–11 LT shows the heavy rain events dominated by convective and mixed rain type marked by the number of dots with reflectivity above 50 dBZ and rain rate above 17 dBR. The point density during this period pointed out most of the rain in stratiform rain are moderate rain with *Z* around 28 dBZ and R around 3 dBR. On the other hand, in mixed rain type the rain events dominated by light rain with *Z* around 12 dBZ and rain of -8 dBR. The *Z-R* in different cloud type shows consistency in (b) value in range of 1.27-1.38, and the highest (*a*) coefficient accounted for convective rain in both periods. This results furtherly indicate that higher (*a*) usually associated with larger drop size (Sauvageot and Lacaux, 1995; Marzuki *et al.* 2018).

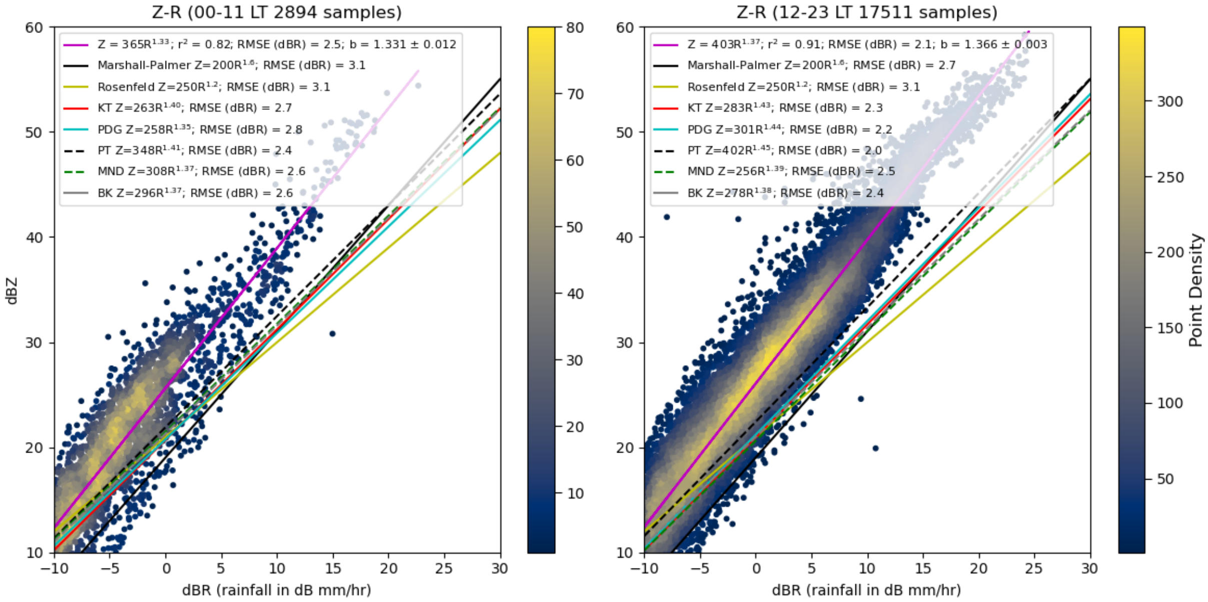

Figure 4. *Z-R* relationship for 00–11 LT and 12–23 LT from the one-minute data throughout the data period (23 October 2021 to 27 April 2022). The scatter of the data is in a log-log plot, with the x-axis in dBR and the y-axis in dBZ. The magenta line is the fitting line of the data. Other *Z–R* from previous studies is also plotted as a comparison: MP (black), Rosenfeld (yellow), Bogor (pink), Soroako (blue), Kototabang (red), Padang (cyan), Pontianak (black-dash), Manado (green-dash), Biak (grey-dash), Surabaya (red-dash), and Jakarta (brown). The colorbar represents the point density. Dark blue shade indicates lower density, and yellow shade is higher density. (r^2) is the correlation of the data. b is the slope of the data. dBa is the intercept with the y-axis. RMSE (dBR) is the standard error in terms of dBR.

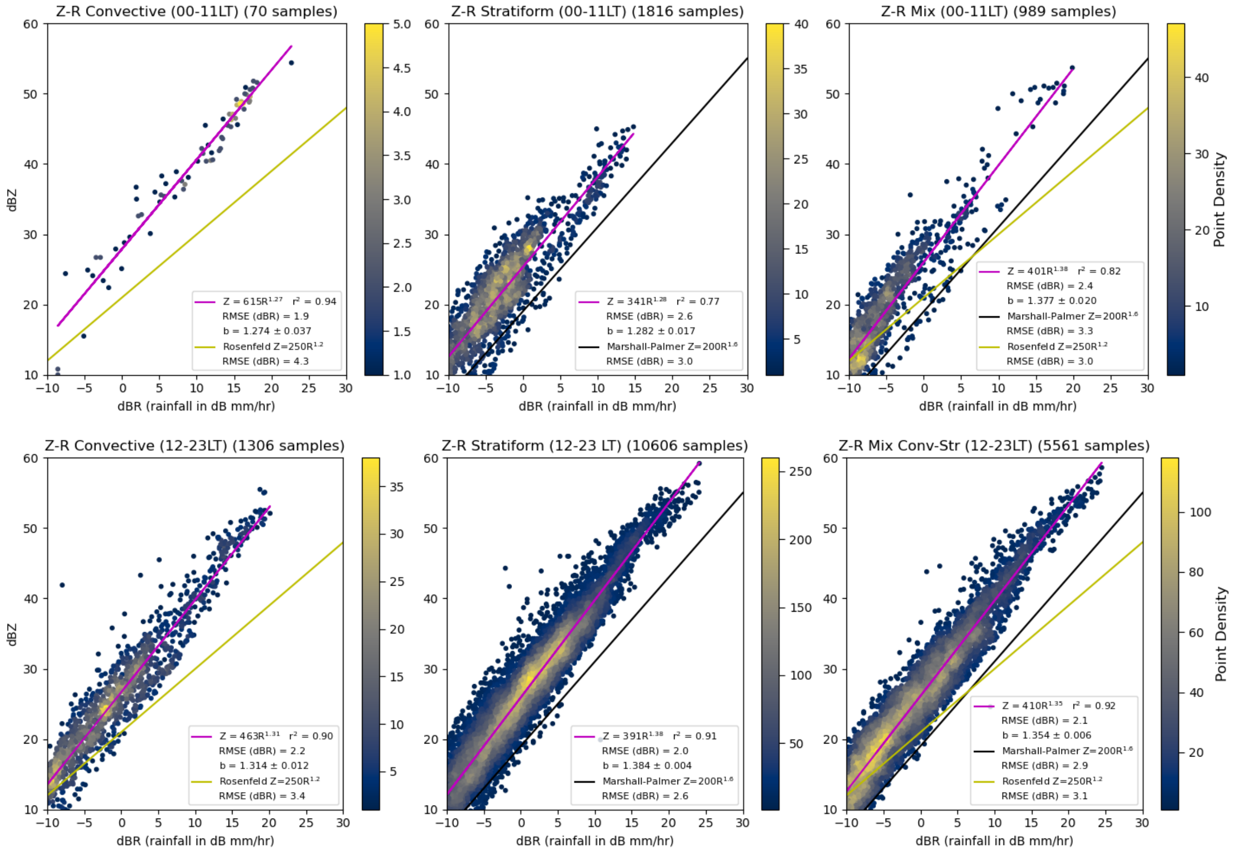

Figure 5. *Z-R* relationship for 00–11 LT and 12–23 LT for different rain classification (convective, stratiform and mixed rain) throughout the data period (23 October 2021 to 27 April 2022). The scatter of the data is in a log-log plot, with the x-axis in dBR and the y-axis in dBZ. The magenta line is the fitting line of the data. The black line is derived from the Marshall-Palmer equation. The yellow line is derived from the Rosenfeld equation. The colorbar represents the point density. A dark blue shade indicates lower density, and a yellow shade is higher density. (r^2) is the correlation of the data. b is the slope of the data. dBa is the intercept with the y-axis. RMSE (dBR) is the standard error in terms of dBR.

4. CONCLUSIONS

Drop size distribution data from Thies Clima disdrometer from 23 October 2021 - 27 April 2022 in Bandung reveals the Z-R equation with $Z = 399R^{1.37}$ with a high correlation of 0.91 and 2.2 dBR error (around 66 % error). Compared with a previous study in other locations, the *Z-R* equation in Bandung produces the highest (*a*) coefficient, and shows the closest similarity with Pontianak with an error of 2.1 dB. Comparison with Marshall Palmer and Rosenfeld produces higher error by 2.8 and 3.1 dB, indicates the rain microphysical feature in Bandung is very different from MP and Rosenfeld.

The classification of different rain types reveals the occurrence of rain in Bandung dominated by stratiform rain. The *Z-R* equation of each rain type suggests a deviation of (b) in range of 1.30-1.39 and (*a*) value in range of 378-487. The scatterplot for each rain reveals the stratiform and mixed rain shows more similarity with uniform shape, while the convective rain events are more sporadic. The rain type classification also reveals that heavy to severe rain in Bandung is mainly related to stratiform rain. Comparisons with Marshall Palmer and Rosenfeld further confirm that stratiform rain in Bandung shows different characteristics from Marshall Palmer, and convective rain also shows different characteristics from Rosenfeld.

The monthly *Z-R* shows a strong relationship between variables (*Z* and *R*) with a correlation of around 0.9. The *Z-R* marked consistency in (b) coefficient with an approximate deviation of 1.30-1.39 and the (*a*) range from 329-443. The highest (*a*) coefficient of 443 observed in March were potentially influenced by convective rain events, with $Z=570R^{1.21}$ further confirmed in the monthly rain classification with 812 samples of convective rain. The monthly plot shows consistent results with the general *Z-R* equation.

Significant diurnal variation is evident in Bandung, with the majority of the precipitation frequency and rain rate happening during 12–23 LT, dominating 86 % of the total rain events. The rain classification reveals stratiform rain was predominant and accounted for more than 50 %. These findings align with Oigawa *et al.* (2017), which stated that widespread precipitation in Bandung peaks at around 18 LT and dissipated before 00 LT. The occurrence of rain during the

00–11 LT period is around 14 %. The majority of the rain events are light to moderate rain. In contrast with the 12–23 LT the heavy rain events during the 00–11 LT dominated by convective and mixed rain.

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