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Spatial evaluation rainfall estimation on weather radar using Marshall–Palmer reflectivity–rainfall rate in Banten

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Abstract: Based on data from the National Disaster Management Agency (Ind.: Badan Nasional Penanggulangan Bencana – BNPB), throughout 2022, more than 91% of disaster events were hydrometeorological disasters, with floods at 43% and landslides at 17%. One of the factors for floods and landslides is high rainfall intensity. Automatic rain gauge (ARG) is a rainfall observation instrument that can accurately measure rainfall at observation points. However, it has problems such as communication systems that cause delays in data transmission, low instrument density, and inability to cover a wide spatial area, which can affect the accuracy of rainfall information. Weather radar is a remote sensing instrument that can estimate rainfall spatially so that weather radar observations can reach areas of the region that do not have ARG. However, before being used as rainfall information, estimation rainfall needs to be evaluated or calibrated. Evaluation of rainfall estimation on weather radar to ARG in Banten at a 30–120 km distance range, shows a coefficient of determination above 0.8. Based on the studies that have been conducted, increase of root mean square error (*RMSE*) is due to influence of radar observation range and observation distance on ARG. Adjustment of rainfall estimation improves the accuracy of rainfall estimation. Adjusting rainfall estimation can reduce *RMSE* by 50%.

Keywords: estimation, Marshall–Palmer, rainfall, reflectivity, weather radar

INTRODUCTION

Based on data from National Disaster Management Agency (Ind.: Badan Nasional Penanggulangan Bencana – BNPB), throughout 2022, more than 91% of disaster events were hydrometeorological disasters, with floods at 43% and landslides at 17%. For example, extreme rainfall in early 2020 caused floods and landslides in Banten, Special Capital Region of Jakarta (Ind.: Daerah Khusus Ibukota Jakarta – DKI Jakarta), and West Java. The BNPB recorded 47 fatalities and missing people. Banten is a province on Java Island with a relatively high historical disaster record (Tiwi *et al.*, 2023). One of the factors for floods and landslides is high rainfall intensity (Marengo *et al.*, 2021).

Rainfall is one of the weather parameters that influence various sectors such as transportation, tourism, agriculture, and disaster (Ananda, Hartanto and Kurniadi, 2023). Low rainfall intensity can cause drought, resulting in irrigation difficulties in agriculture (Yang, Liu and Yang, 2019), and high rainfall intensity

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can cause hydrometeorological disasters such as floods and landslides (Marengo *et al.*, 2021). Therefore, it is necessary to have rainfall observation instruments as a mitigation effort to minimise the impact and losses caused by rainfall in Banten. Based on Law No. 31 of 2009, Meteorological Climatological and Geophysical Agency (Ind.: Badan Meteorologi Klimatologi dan Geofisika – BMKG) is responsible for weather observation (Radjab *et al.*, 2020), one of the parameters observed is rainfall. Implementing rainfall monitoring, the BMKG has installed observation instruments such as automatic rain gauge (ARG) and weather radar.

The ARG is a rainfall observation instrument that can accurately measure rainfall at observation points (Qiu *et al.*, 2020; Xia *et al.*, 2020). However, it has problems such as communication systems that cause delays in data transmission, low instrument density, and inability to cover a wide spatial area. It can be affected by the accuracy of rainfall information (Nsabagwa *et al.*, 2019; Gyasi-Agyei, 2020). Weather radar is a remote sensing instrument that can estimate rainfall spatially so that weather radar observations can reach areas of regions that do not have ARG. However, weather radar has measurement limitations, such as attenuation and beam-blocking factors that can affect the quality of rainfall estimates produced.

Based on this, this study evaluates rainfall estimates using weather radar for rainfall measurement using ARG. This study aims to analyse the results of estimation evaluation on weather radar using Marshall–Palmer reflectivity–rainfall rate (Z–R) at eight ARG sites in Banten province. Analysis of rainfall estimation evaluation on weather radar shows the quality of weather radar based on maximum coverage of observation distance so that estimation can improve the accuracy of rainfall estimation and reach areas that do not have rainfall observation instruments.

MATERIALS AND METHODS

STUDY MATERIALS

This study used the period of rainfall data from December 1, 2022 to February 28, 2023. This period was chosen because it is a rainy season in Indonesia (Hartanto *et al.*, 2023). Rainfall data was obtained from eight ARG in Banten province, and rainfall estimation data on weather radar located at coordinates 6.1669°S, 106.6502°E. Data samples used in this study amounted to 12,150 for each observation location point. In Figure 1, the location distribution of automatic rain gauges (ARG) and weather radar used in this study can be observed.

In this study, we analyse the quality of rainfall estimates produced by weather radar in comparison to rainfall measurements taken by rain gauges. (Sevruk, Ondrás and Chvíla, 2009; Imhoff *et al.*, 2020). The location of the rain gauge and the distance from ARG to the weather radar can be seen in Table 1.

Weather radar is a remote sensing instrument that can measure rainfall spatially. The principle of weather radar is emitting electromagnetic waves to objects in the atmosphere, such as clouds and precipitation, and then receiving back waves (Binetti *et al.*, 2022; Curzio Di *et al.*, 2022).

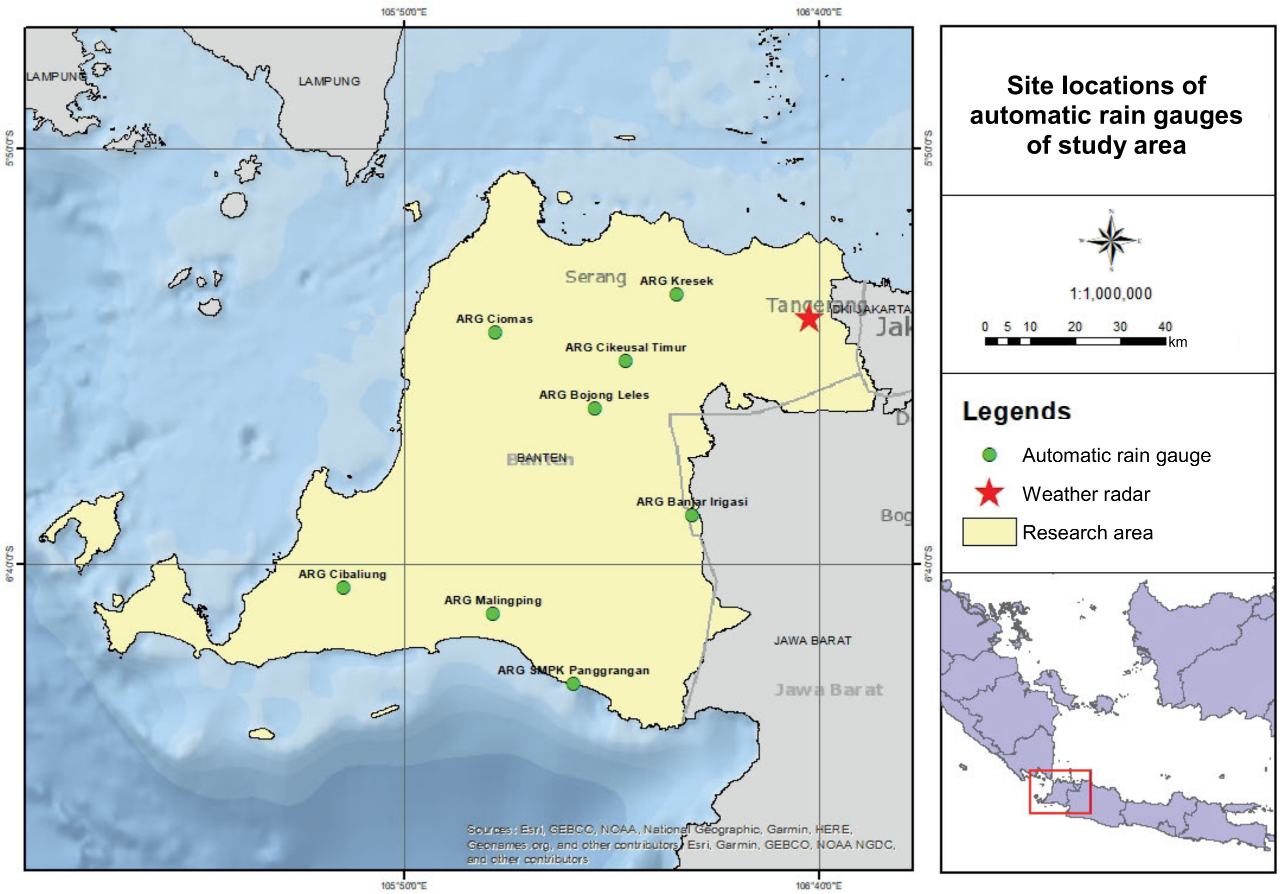

Fig. 1. Distribution map of automatic rain gauges (ARG) and weather radar in this study; source: own elaboration based on Esri, GEBCO, NOAA, National Geographic, Garmin, HERE, www.geonames.org

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Table 1. Eight automatic rain gauge (ARG) locations used in this study

ARG	Distance to weather radar (km)	Elevation (m)	Geographical coordinates	
			latitude	longitude
Kresek	31	10	–6.064	106.530
Cikeusal Timur	42	14	–6.765	106.010
Bojong Leles	52	22	–6.220	105.933
Banjar Irigasi	53	181	–6.628	106.160
Ciomas	71	155	–6.569	106.411
SMPK Panggarangan	97	4	–6.260	106.277
Malingping	99	32	–6.355	106.216
Cibaliung	120	173	–6.907	106.173

Explanations: SMPK = special agricultural meteorological station (Ind.: Stasiun Meteorologi Pertanian Khusus).
Source: own study.

Table 2. Specification of weather radar

Parameter	Value
Polarisation	single
Transmitter type	coaxial magnetron
Frequency	5.6 GHz
Tower height	20 m
Altitude	10 m
Pulse repetition frequency	600 Hz
Maximum range	200 km
Beam width	1°
Moment observed	reflectivity (unfiltered and filtered), radial velocity, spectral width

Source: own elaboration based on EEC (2013).

STUDY METHODS

Output data observation of weather radar is in volumetric (.vol) format. The observation consists of three primary data: reflectivity (Z in $mm^6 \cdot mm^{-3}$), velocity (V), and spectrum width (W). Data is then converted to NetCDF (.nc) files, and a data filter is applied to retrieve Z (Daliakopoulos and Tsanis, 2011; Tahir *et al.*, 2022). Weather radar observation image output is processed using the Marshall–Palmer Z–R relationship to produce rainfall estimates based on a predetermined location of the Marshall–Palmer Z–R relationship as described in Equation 1 and 2 (Marshall and Palmer, 1948; Mapiam and Sriwongsitanon, 2008).

$$Z = aR^b \tag{1}$$

where: Z = radar observation reflectivity ($mm^6 \cdot mm^{-3}$), R = rainfall intensity (mm), a and b = positive empirical constants whose values correspond to each weather radar location's geographical position and climatic characteristics (Ananda, Hartanto and Kurniadi, 2023).

$$Z = 200R^{1.6} \tag{2}$$

This data processing uses Python programming using Wradlib and Py-ART libraries, which support processing spatial data such as weather radar. The flowchart of this research can be seen in Figure 2.

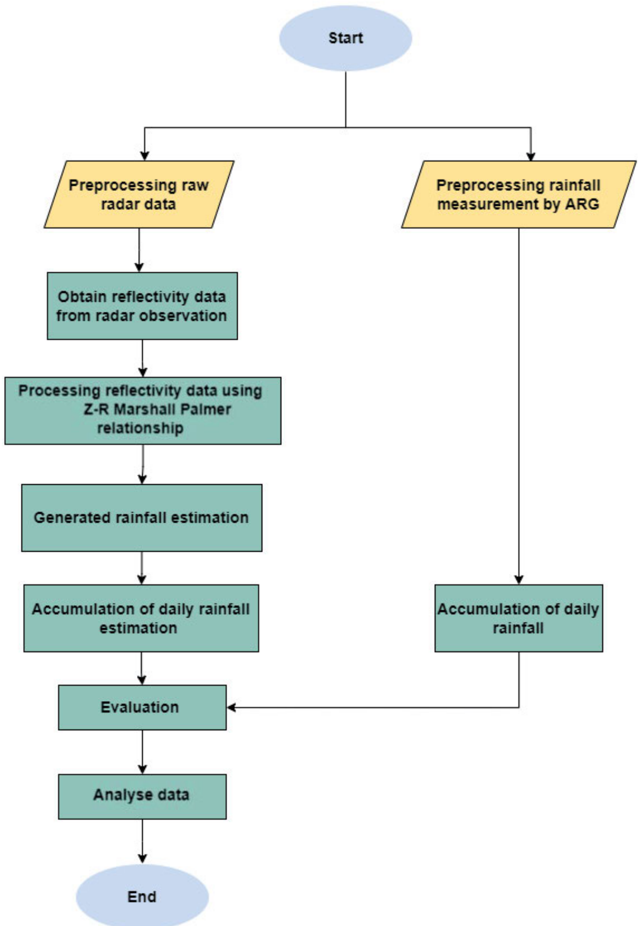

Fig. 2. Flowchart of this study; source: own study

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PARAMETER EVALUATION

The accuracy for estimation rainfall from weather radar was evaluated using the Marshall–Palmer *Z–R* relationship (Mahavik, Tantanee and Masthawee, 2021). The results of rainfall estimation were evaluated using rainfall measurements by ARG. The bias factor, used as an evaluation parameter in this study, is calculated as the mean value from a comparison of total amounts collected by radar and rain gauge for a given radar and time step (Sokol *et al.*, 2021). The bias factor can significantly reduce errors in radar estimation. It is assumed that the resulting bias in rainfall estimation on weather radar is influenced by multiplicative error (Ali, Deranadyan and Umam, 2020).

$$B_{x,\ y} = \frac{\sum_{i=1}^{n} R_{\text{gauge}}(x_i)}{\sum_{i=1}^{n} R_{\text{radar}}(x_i)} \tag{3}$$

where: $B_{x,y}$ = correction factor of rainfall estimation data based on x (longitude) and y (latitude) locations, R_{gauge} = rainfall data on the rainfall observation instrument, R_{radar} = estimation rainfall at location of rainfall observation instrument at locations x and y, n = number of radar data and rainfall observation instrument, i = number of iterations, x_i = order of radar data processing and rainfall observation equipment.

$$R_{\text{adj}} = B_{x,y}\, R \tag{4}$$

where: R = result of rainfall estimation obtained from Marshall–Palmer *Z–R* and Rosenfeld tropical equations, R_{adj} = corrected rainfall estimation value at rainfall equipment locations x and y.

The coefficient of determination (C_D) shows the relationship between weather estimation by weather radar and rainfall measurement by ARG on a scale from 0 to ±1. The value of R ranges from 0 to 1 where if C_D = 1, the variation of predictor variables can explain the variation of response variable by 100% (Harisuseno and Cahya, 2020).

$$C_D = \frac{\sum_{i=1}^{n}\left(R_{\text{radar}} - \overline{R_{\text{radar}}}\right)\left(R_{\text{gauge}} - \overline{R_{\text{gauge}}}\right)}{\sqrt{\sum_{i=1}^{n}\left(R_{\text{radar}} - \overline{R_{\text{radar}}}\right)^2\left(R_{\text{gauge}} - \overline{R_{\text{gauge}}}\right)^2}} \tag{5}$$

where: R_{radar} = rainfall estimation using radar at location of rainfall instrument observation, R_{gauge} = rainfall measurement at location of rainfall instrument observation.

Root mean square error (*RMSE*) is the standard deviation of the difference between rainfall estimation of weather radar and rainfall measurement of rain gauge (Hartanto *et al.*, 2023).

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(R_{\text{radar}} - R_{\text{gauge}}\right)^2} \tag{6}$$

RESULTS AND DISCUSSION

EVALUATION ESTIMATION

Implementing a *Z–R* relationship for estimating rainfall uses reflectivity variables from weather radar observations (Dinh *et al.*, 2023). The constant of the *Z–R* relationship contributes to decreasing accuracy of rainfall estimates from weather radar observations (Mahavik, Tantanee and Masthawee, 2021) so adjustments need to be made in order to improve accuracy (Ali, Lubis and Sa'adah, 2023). The Marshall–Palmer *Z–R* relationship is one of the rainfall estimators that does not pay attention to the area and can be used in all cloud categories (Aziding *et al.*, 2023). In weather service operations, Meteorological Climatological and Geophysical Agency (Ind.: Badan Metorologi Klimatologi dan Geofisika – BMKG) still uses Marshall–Palmer *Z–R* in estimating rainfall using weather radar observations (Hutapea *et al.*, 2021). Estimation of rainfall can reach areas that do not have rainfall observation instruments or rainfall information. However, before being used as rainfall information, estimation data needs to be evaluated or calibrated (Sharif, Habib and ElSaadani, 2020). In this research, weather radar estimation using the Marshall–Palmer *Z–R* relationship for eight ARG in Banten province was evaluated. In Figure 3, the rainfall estimation results for eight ARG in Banten province are shown on a scatter plot.

In Figure 3, orange dots represent the distribution of unadjusted rainfall estimation, and a dashed black line depicts a linear axis between rainfall estimation and rainfall by ARG. Orange dots and dashed black lines are below the diagonal axis (red line) on a scatter plot, indicating that the results of the rainfall estimates are underestimated compared to the actual rainfall data by ARG. An underestimation occurred at eight ARG in Banten. The accuracy of Marshall–Palmer *Z–R* can be improved by adjusting rainfall estimation using bias (Ali, Lubis and Sa'adah, 2023). In Figure 4, adjusted rainfall estimation in comparison to rainfall data by ARG in Banten province can be observed on a scatter plot.

In Figure 4, green dots represent the distribution of adjusted rainfall estimation, and a dashed black line depicts a linear axis between rainfall estimation and rainfall by ARG. Visually, the scatter plot in Figure 4 shows an increase in the accuracy of rainfall estimation after adjusting. This indication can be seen from orange dot as distribution of rainfall data and black dashed line as linear axis between adjusted rainfall estimation approaching the red line as a diagonal line. Increase of accuracy in estimation rainfall using Marshall–Palmer *Z–R* can be seen on Figure 4, the green dot as the distribution of rainfall data and the black dotted line as the linear axis, showing that the black dash line as a linear pattern of rainfall estimation data distribution can follow the red diagonal line pattern as rainfall data standar measured by ARG.

SPATIAL EVALUATION

In Table 3, the results of processing using the Marshall–Palmer *Z–R* relationship are shown. Based on the statistics, the highest determinant coefficient value in ARG Malingping is 0.90, with 99 km from weather radar. It is due to the scanning strategy of the Tangerang c-band weather radar having an optimum observation distance of 50–100 km (Ali *et al.*, 2021). Overall, within the distance range of 30–120 km, the coefficient of determination for eight ARG showed a high correlation. It can be seen that coefficient of determination is above 0.8. Distance and elevation can affect bias and RMSE values (Urban and Strug, 2021). Based on Table 3, the farther the weather radar observation, the more *RMSE* error value increases. It can be seen from ARG Kresek,

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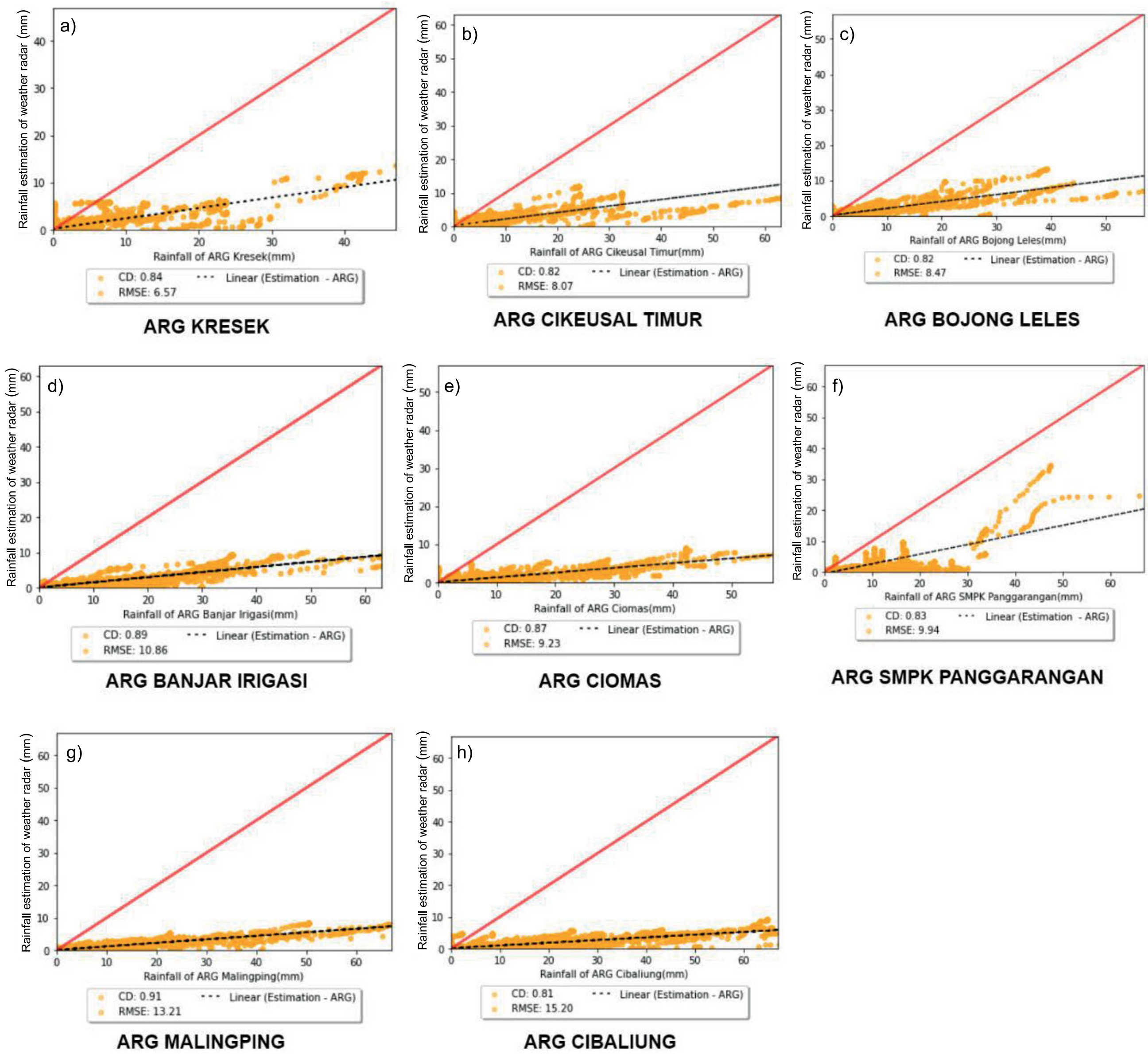

Fig. 3. Scatter plot of unadjusted rainfall estimation using the Marshall–Palmer reflectivity–rainfall rate (Z–R) to rainfall measurement by the automatic rain gauges (ARG): a) Kresek, b) Cikeusal Timur, c) Bojong Leles, d) Banjar Irigasi, e) Ciomas, f) SMPK Panggarangan, g) Malingping, h) Cibaliung; *CD* = coefficient of determination, *RMSE* = root mean square error; source: own study

which is 30 km from weather radar and produces the lowest bias and *RMSE* value of 3.68 and 6.57 mm daily in this study. However, after adjusting the estimation using bias, the bias factor is considered to reduce the error *RMSE* value (Ozkaya and Akyurek, 2019). The *RMSE* value on ARG Kresek became 6.05 mm daily. The decreased percentage of *RMSE* in ARG Kresek is not too significant, only 7.91%. This is due to the influence of ARG elevation of 10 m. The influence of distance and elevation of ARG contributes to the error of the rainfall estimator and potentially reduces the performance of the estimator (Pappa *et al.*, 2021).

ARG which has an elevation <25 m, produces a *RMSE* decrease below 20%. It can be seen in ARG Resek, which has an elevation of 10 m, and ARG SMPK Panggarangan, which has an elevation of 4 m, resulting in a *RMSE* decrease of 7.91% and 19.22%. Meanwhile ARG Cibaliung, 120 km from weather radar, has the highest bias value of 9.80 and *RMSE* value of 15.20 mm daily on unadjusted conditions. After adjusting rainfall estimation, the *RMSE* on ARG Cibaliung still had the highest *RMSE* of 8.92 mm daily and a decreased *RMSE* of 41.32%. Constant of Marshall–Palmer Z–R, different geographical conditions and uneven rainfall distribution can affect the accuracy of rainfall estimation. It happens when weather radar detects rain particles, but not all rainfall particles fall to land, where 10% become water vapour (Ali, Lubis and Sa'adah, 2023; Kalesse-Los *et al.*, 2023), so there is a difference in data from actual rainfall results and rainfall estimation. Increased accuracy and calibration of the Z–R estimator in producing rainfall estimates can reach areas that do not have a rainfall instrument network (Suwarno *et al.*, 2021).

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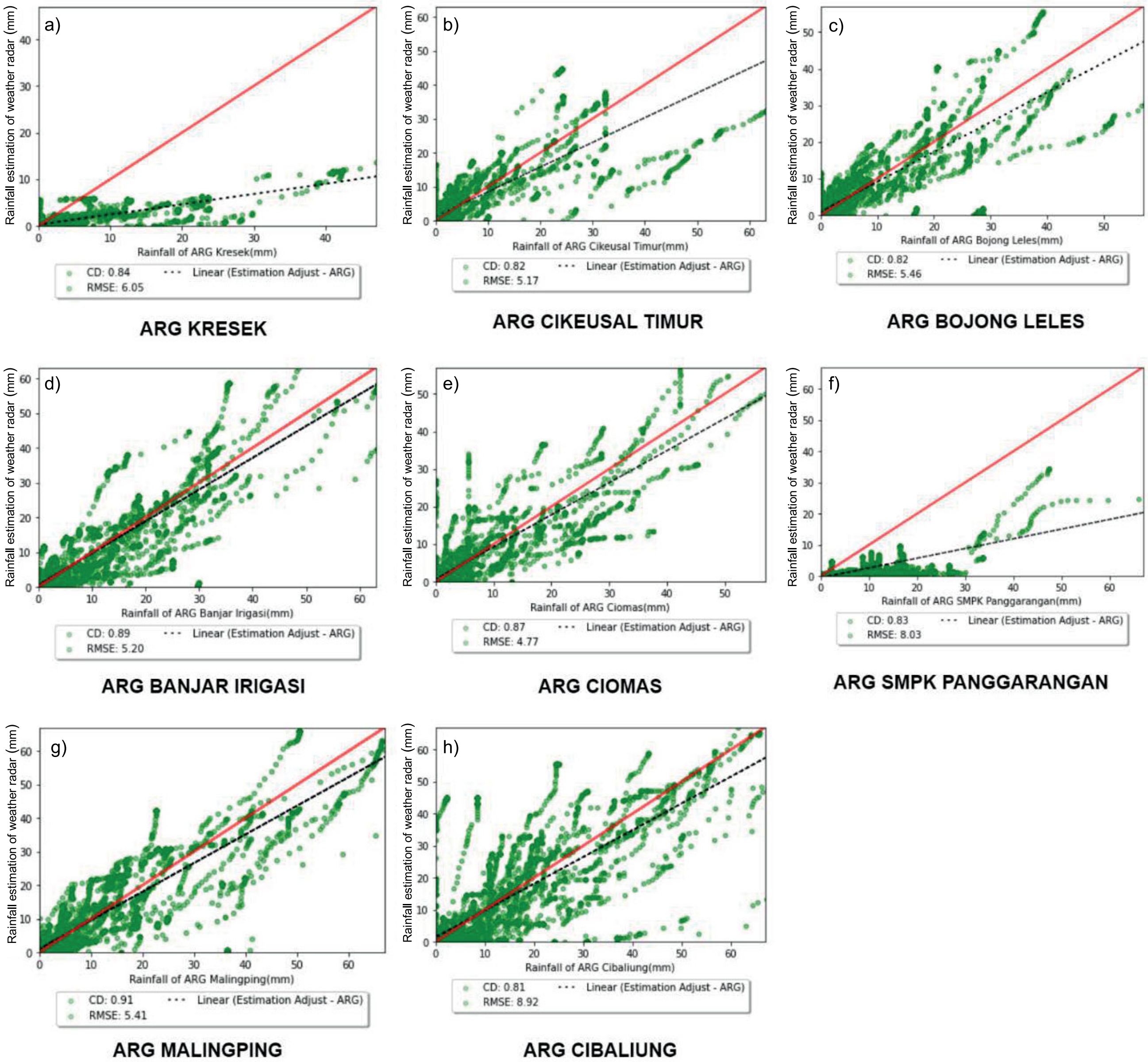

Fig. 4. Scatter plot of adjusted rainfall estimation using the Marshall–Palmer reflectivity–rainfall rate (*Z–R*) to rainfall measurement by the automatic rain gauges (ARG): a) Kresek, b) Cikeusal Timur, c) Bojong Leles, d) Banjar Irigasi, e) Ciomas, f) SMPK Panggarangan, g) Malingping, h) Cibaliung; *CD*, *RMSE* as in Fig. 3; source: own study

Table 3. Evaluation of rainfall estimation using the Marshall–Palmer reflectivity–rainfall rate (*Z–R*) relationship

ARG	Bias	C_D	*RMSE* (mm)		*RMSE* decrease (%)
			before bias	after bias	
Kresek	3.68	0.84	6.57	6.05	7.91
Cikeusal Timur	3.77	0.82	8.07	5.17	35.94
Bojong Leles	4.17	0.82	8.47	5.46	35.54
Banjar Irigasi	6.30	0.89	10.86	5.20	52.12
Ciomas	6.86	0.87	9.23	4.77	48.32
SMPK Panggarangan	6.66	0.83	9.94	8.03	19.22
Malingping	8.30	0.91	13.21	5.41	59.05
Cibaliung	9.80	0.81	15.20	8.92	41.32

Explanations: ARG = automatic rain gauge, SMPK as in Tab. 1, *RMSE* as in Fig. 3.
Source: own study.

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CONCLUSIONS

Evaluation of rainfall estimation on weather radar spatially to the automatic rain gauge (ARG) is influenced by the constant *Z–R* relationship, elevation of the ARG and range observation of weather radar to ARG. The coefficient of determination in the range of 30–120 km shows a value above 0.8, which indicates that rainfall estimation results produce a high correlation. Distance of weather radar and ARG can affect *RMSE* and bias, it can be observed that weather radar observations farther away result in higher *RMSE* and bias. Adjustment of rainfall estimation improves the accuracy of rainfall estimation. Adjusting rainfall estimation can reduce *RMSE* by 50%, but the elevation of ARG can affect the rate of *RMSE* decrease.

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CONFLICT OF INTERESTS

All authors declare that they have no conflict of interests.

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