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Calibration and Performance Evaluation of Radar QPE and QPF in Klang River Basin

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Abstract

Accurate hydrological data is crucial for the use of sustainable environmental monitoring and disaster management purposes. The flood that occurred in December 2021 in the Klang River Basin serves as a valuable lesson on the significance of accurate rainfall forecasts to anticipate any undesirable catastrophe from taking place. The usage of weather radar to forecast quantitative rainfall has been challenging, especially now that the climate is experiencing unpredictable changes. In this study radar quantitative precipitation estimates (QPE) and quantitative precipitation forecast (QPF) in Klang River Basin have been calibrated using the mean field bias (MFB) and mean assessment factor (MAF) correction techniques. The performance analysis compares the radar QPE and QPF with mean areal gauge rainfall using Thiessen Polygon Method and point gauges of 21 rainfall stations located in the basin. Results show that the MFB correction technique performs better than the MAF technique with higher correlation coefficient and less error. Radar QPF performance assessment indicates improved accuracy in calibrated values especially for shorter lead time, but the correctness is inconsistent.

1. Introduction

Accurate hydrological data is crucial for disaster management purposes. A major flood that was faced by Malaysians at the end of December 2021 has become a lesson learned for the government and society. The incident taught about the importance of staying alert and being prepared to face floods as global climate change has a tremendous effect on the weather patterns in Malaysia nowadays. Among the effects present in the urban hydrological environment are a reduction in precipitation concentration time, a decreasing storage rate, and an increase in water flow [1]. The severity of the damage to urban areas has changed and has been hastened by the change in climate. On December 17, 2021, almost every state in the center of the peninsula, as well as the eastern and western coasts of Malaysia, received rainfall for four days straight, which resulted in a flood disaster. The central state in Malaysia, which is Selangor, including Kuala Lumpur, is one of the badly affected states in the flood event.

The extreme change in weather patterns in Klang Valley is also mainly caused by climate change globally. A tropical depression known as Tropical Depression 29W first emerged over the South China Sea on December 15th and has been lurking over the Strait of Malacca since December 17th, which may have been the cause of the flood that year. Usually, the Titiwangsa mountain range shields the western section of the peninsular from the winds that come from Malaysia's northeast [2], but this time, Typhoon Rai and Tropical Depression 29W together enhanced the monsoon's impacts, allowing the rains to spread further west than usual. This demonstrates that the inherent variability and the numerous meteorological mechanisms are among the factors that cause rainfall to be one of the most challenging variables to forecast. Therefore, the accuracy of rainfall forecasting needs to be improved, as its low performance in predicting rainfall beforehand can become one of the main causes of flood tragedies.

Accurate quantitative prediction of future rainfall events is one of the most challenging problems faced by hydrometeorologists. This is because the prediction or forecast of hydrology includes the implementation of hydrological and meteorological principles [3]. Low performance of the rainfall forecast could lead to hydrometeorological disasters. Accurate weather forecasts, especially rainfall forecasts, have become crucial due to the recent change in climate. Extreme weather patterns caused by the said factor have resulted in increased occurrences of localized torrential rainfall that leads to flash floods. To lower flood-related hazards and property losses, effective disaster prevention efforts are becoming increasingly crucial.

Over the years, radar quantitative precipitation estimation (QPE) has been found to be reliable for flood forecasting purposes such as issuing warnings for extreme events and climate modeling [4], [5]. Radar QPE is found to be ideal for hydrological modeling for its extremely high spatial and temporal precision of rainfall information [6]. Real-time flood forecasting frequently applies to the QPE of weather radar for better rainfall prediction. With the aid of radar QPE and hydrological modeling, an effective early warning system can be implemented, which is highly essential for minimizing the effects of flood-related risks. Additionally, data from rain gauge networks can enhance radar based QPE, either through adjustments or by combining data from various sources [7]. Many researchers have discussed variational methods to improve the accuracy of radar QPE, namely the Kalman filter method, bias adjustment, Kriging method, Bayesian merging method, and many others [8], [9], [10], [11],[12]. These methods mainly require the merging of radar QPE with rain gauge data to achieve high-resolution precipitation estimations. Generally, radar QPE that is derived using those acquired using the space-time interpolation method, which produces both unadjusted and adjusted estimates, gives a better estimation than any other extrapolation or interpolation method.

Subsequently, quantitative precipitation forecast (QPF) utilizes numerical weather prediction models to predict rainfall. Over the years, researchers have developed new techniques to enhance the accuracy of QPF. One such approach involves using radar data, which is adjusted using measurements from rain gauges and corrected for errors. By combining numerical weather prediction models and radar-based extrapolation, known as nowcasting, it is possible to generate precise quantitative precipitation forecasts (QPFs) with lead times ranging from a few hours to several days. Nowcasts specifically refer to short-term rainfall forecasts with a lead time of only a few hours, although the term "rainfall forecasts" can encompass both short-term and long-term predictions.

The main contribution of the study is the performance evaluation of radar-based QPF in nowcasting a flood event and comparison analysis of two (2) radar QPE correction techniques namely the MFB and MAF, using the Klang River Basin flood event in December 2021 as a case study.

2. Methodology

2.1 Study Area

Klang River Basin is located between latitudes 2°55'N and 3°25'N and longitudes 101°20'E and 101°50'E. It has a total catchment area of approximately 1,288 km2, with a channel length of 120 km. The river travels past Kuala Lumpur and Selangor before finally going into the Straits of Malacca. The river includes 11 major tributaries, namely the Gombak River and Batu River, which are in the upper basin, as well as the Kerayong River, Damansara River, Keruh River, Kuyoh River, Penchala River, and Ampang River.

With an average annual rainfall of between 1900 mm and 2600 mm, the basin receives precipitation during the Northeast monsoon from November to March, the Southwest monsoon from May to September, and two inter-monsoon periods, which are in April and October. The daily mean humidity is between 80 and 85%, while the monthly mean temperature is between 26 and 28 °C. Up until today, the possibility of flooding in the Klang River basin has been concerning whenever there is an event of continuous heavy rain in the catchment area.

2.2 Data Collection

For this study, the data used is mainly secondary data, which are rain gauge measurements and radar rainfall data. All data are gained from two sources: rain gauge measurements are collected from the Department of Irrigation and Drainage (DID), while radar rainfall from RaINS [13] is transferred from the Malaysia Meteorological Department (MMD). The selection of rainfall stations is made by considering both the availability of rainfall data from rain gauge measurements and RaINS radar data that are collected by DID and MMD, respectively. This means that only rainfall stations that have rainfall data availability at the same temporal and spatial scale for each rain gauge and RaINS radar are selected for this analysis. Fig. 1 and Table 1 show the location of rainfall stations included in this study.

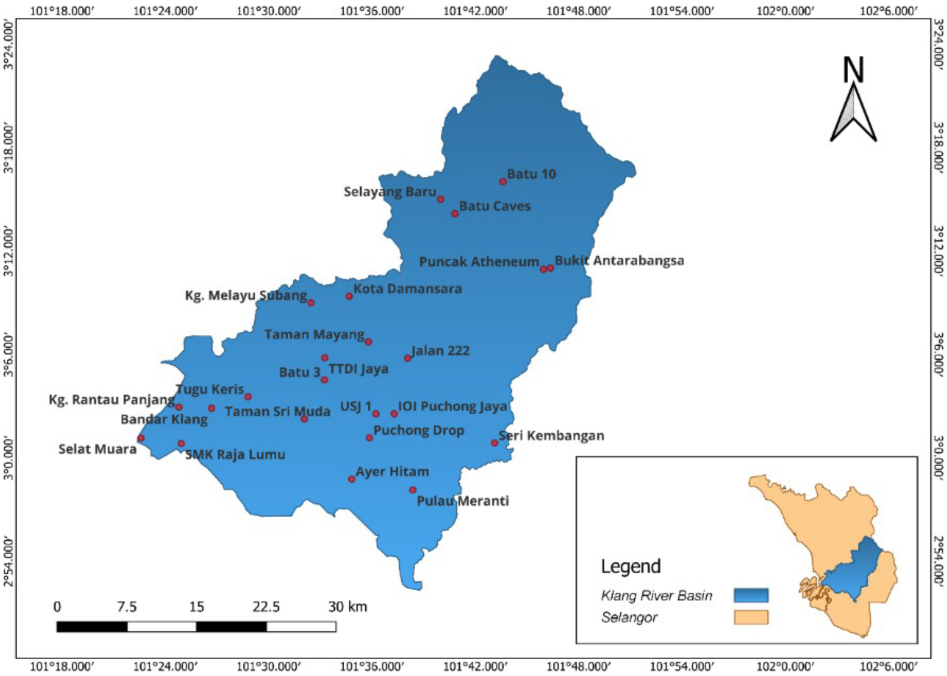


Fig. 1 *Map of selected rainfall stations*

Table 1 *List of selected rainfall stations*

Gauge No	Rainfall station	Sub basin	Longitude	Latitude
18	Jalan 27 Selayang Baru	Sg.klang	101.6663	3.25022
20	Batu 10 Gombak	Sg.Salak	101.7267	3.26728
21	Sg Selayang	Sg.Batu	101.6802	3.23627
43	Tugu Keris	Sg.Klang	101.4801	3.05917
48	Selat Muara	Sg.Klang	101.3764	3.01928
58	Bandar Klang	Sg.Klang	101.4448	3.04806
60	Kg Rantau Panjang	Sg.Klang	101.4132	3.04914
62	S.M.K Raja Lumu	Sg.Klang	101.4154	3.01403
74	Taman Mayang	Sg.Damansara	101.5964	3.11228
80	Kota Damansara	Sg.Selangor	101.5780	3.15639
81	Ayer Hitam Puchong	Sg. Klang	101.5804	2.97961
83	Puchong Drop	Sg.Klang	101.5974	3.01953
84	USJ 1	Sg.Klang	101.6038	3.04277
94	Kg Melayu Subang	Sg.Damansara	101.5409	3.15006
96	TTDI Jaya	Sg.Damansara	101.5542	3.09694
97	Batu 3	Sg.Damansara	101.5539	3.07561
98	Taman Sri Muda 1	Sg.Klang	101.5345	3.03772
99	Seri Kembangan	Sg.Kuyoh	101.7187	3.01450
100	Jalan 222	Sg.Penchala	101.6344	3.09653
101	IOI Puchong	Sg.Selangor	101.6214	3.04275
104	Pulau Meranti	Sg.Rasau	101.6394	2.96911

2.3 Statistical Analysis of Uncalibrated Radar QPE Against Rain Gauge Rainfall

The performance of radar QPE is quantitatively compared using correlation coefficient, r, bias error, and root mean square error (RMSE). The evaluation is done by considering two conditions which one is to consider radar

QPE at the point of the rain gauge location; another is to consider radar QPE for entire mean areal basin. The empirical formula for the performance evaluation is described in Eq. (1), (2) and (3):

$$r = \frac{n \times (\sum(X,Y) - (\sum(X) \times \sum(Y)))}{\sqrt{(n \times \sum(X^2) - \sum(X)^2) \times (n \times \sum(Y^2) - \sum(Y)^2)}} \quad (1)$$

$$Bias = \frac{1}{N} \sum_{i=1}^{n} (G_i - R_i) \quad (2)$$

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^{n} (G_i - R_i)^2} \quad (3)$$

where Gi or X is the observed rain gauge rainfall value, Ri or Y is the estimated value at the rain gauge location, which is radar rainfall, n is the number of rain gauges while N is the rainfall data.

2.4 Radar QPE Calibration Methods

2.4.1 Mean Field Bias Correction (MFB)

Detailed explanation of this calibration technique has been explained by previous scholars [14]. MFB adjustment is basically the most popular and straightforward method in radar meteorology, which the correction factor is easily determined by contrasting a spatially average ratio of rain gauge readings with the radar accumulations at gauged locations over the specified time. A mean field bias correction algorithm aims to reduce the gross error in the truncated 1-h precipitation accumulation as observed against the automatic rain gauge observation. The assumption here is that the radar estimation is affected by uniform multiplicative errors. The bias-adjusted precipitation estimation calculated on an hourly basis from the uncorrected radar data by applying Eq. (4) and (5):

$$C_{MFB} = \frac{\sum_{i=1}^{n} G_i}{\sum_{i=1}^{n} R_i} \quad (4)$$

$$R_{adjusted} = C_{MFB} \ x \ R_i \quad (5)$$

2.4.2 Mean Assessment Factor Correction (MAF)

Mean assessment factor (MAF) correction is another alternative to Mean Field Bias method. Thistechnique has been fully explained in [15]. MAF aims to enhance radar data by identifying and correcting for a radar dataset's long-term bias. CMAF is the long-term arithmetic mean ratio of rain gauge and radar rainfall estimates over n 60-minute time intervals at the i'th rain gauge. The correctionfactor can be calculated using Eq. (6).

$$C_{MAF} = \frac{1}{n} \frac{\sum_{i=1}^{n} G_i}{\sum_{i=1}^{n} R_i} \quad (6)$$

$$R_{adjusted} = C_{MAF} \ x \ R_i \quad (7)$$

The correction factors are obtained at hourly time step. The arithmetic mean ratio for the whole n 60-minute time intervals of radar rainfall and rain gauge rainfall is calculated before the highest factor is selected as the correction factor. The corrected radar estimation is calculated by multiplying the correction factor by the radar value using Eq. (7) at each grid location.

2.4.3 Verification of Uncalibrated and Calibrated Radar QPF

The collection of secondary RaINS radar data from MMD includes the uncalibrated radar QPF [13]. The radar QPF consists of 3-hour forecast from the actual time for the duration of flood event in Klang River Basin from 16th through 18th December 2021. The uncalibrated and calibrated radar QPF are analyzed with various ranges of rainfall threshold. Performance analysis of two rainfall events is presented in this paper in which nowcasts of each selected event are compared against the radar QPE at actual time and the gauge rainfall as the true value.

3. Results and Discussion

This section will discuss the findings of accuracy analysis for uncalibrated and calibrated radar QPE against gauge rainfall at point gauge and mean areal basin, as well as verification of uncalibrated and calibrate radar QPF, respectively.

3.1 Comparison of Radar QPE with Gauge Rainfall at Mean Areal Basin

The comparison of the uncalibrated radar QPE with the rain gauge rainfall is analyzed at mean areal basin by considering two different method which are arithmetic mean method and Thiessen polygon method. The comparison is shown in Fig. 2 (a) and (b).

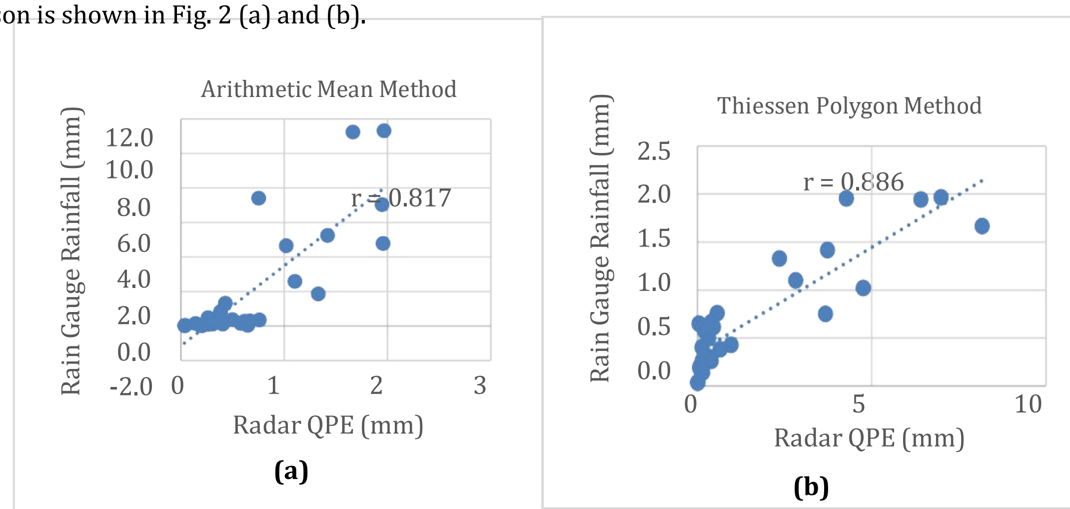


Fig. 2 *Comparison between mean areal uncalibrated radar QPE with mean areal rain gauge rainfall; (a) Using Arithmetic Mean Method; (b) Using Thiessen Polygon Method*

Table 3 *Calculation of correlation r, bias and RMSE error for both comparison*

Method	r	Bias	RMSE
Arithmetic Mean Method	0.817	1.59	0.66
Thiessen Polygon Method	0.886	1.10	0.43

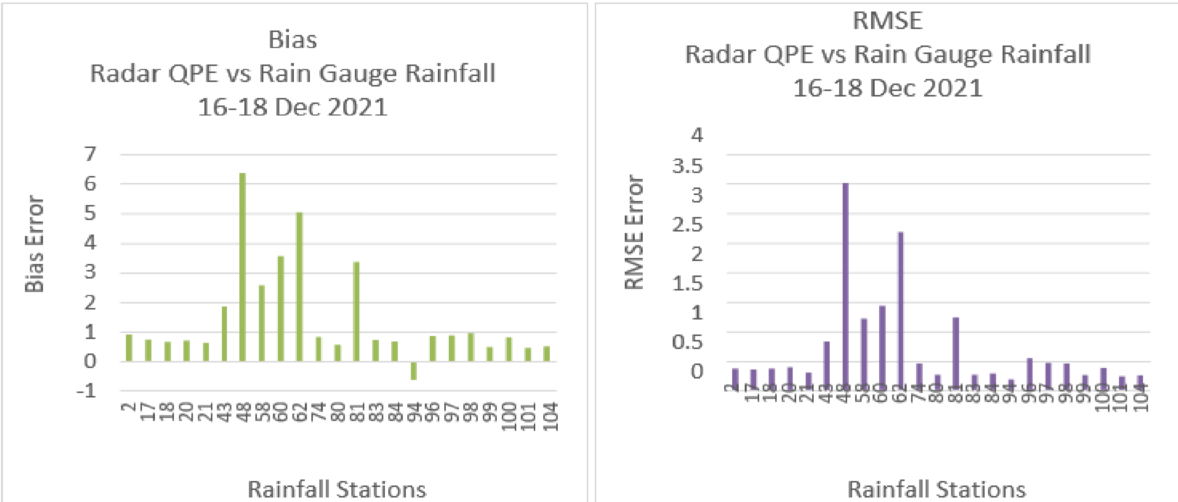
The comparison of radar QPE with Thiessen averaged areal rain gauge rainfall shows better result with correlation r value of 0.886, lower bias error of 1.10 and RMSE error of 0.43 as shown in Table 3. The comparison of radar QPE with arithmetic mean areal rain gauge rainfall still show good result but slightly lower performance with correlation r of 0.817, bias error 1.59 and RMSE error of 0.66. This result indicates that radar QPE comparison with observed value using Thiessen polygon method performs better than the arithmetic mean method. This is because calculation for arithmetic mean method is very simple and suitably used to calculate average rainfall in a catchment area less than 500 km^2. Thiessen polygon method on the other hand is a very accurate method that calculates average rainfall by considering the representative area for each rain gauge.

3.2 Comparison of Uncalibrated Radar QPE with Gauge Rainfall at Point Station

The uncalibrated radar QPE will be further compared with rain gauge rainfall at every point gauge to determine the accuracy of the estimated radar rainfall against the true value of gauge rainfall at smaller point scale (based on closest pixel [12]) at each rainfall station. The results of the comparison are presented in Table 4 while the bias error and RMSE error are presented in Fig. 3.

Table 4 *Calculation of correlation coefficient, r, at point rain gauge*

Gauge No.	Correlation coefficient, r	Gauge No.	Correlation coefficient, r
18	0.5155	81	0.9521
20	0.2680	83	0.7697
21	0.5772	84	0.8059
43	0.8973	96	0.7969
48	0.9428	97	0.7709
58	0.9579	98	0.8468
60	0.7536	99	0.5761
62	0.6567	100	0.8253
74	0.5530	101	0.8774
80	0.7372	104	0.7087



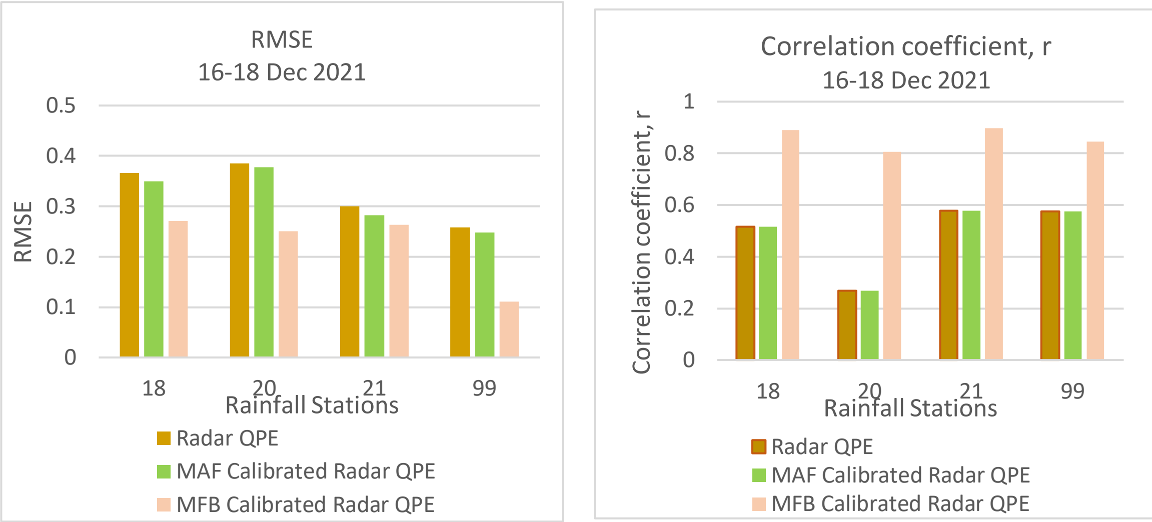
(a) **(b)**

Fig. 3 *(a) Bias error; (b) RMSE error of the rainfall comparison at every rainfall station*

Based on the bias error for all stations in Klang River Basin, Gauges 43, 48, 58, 60, 60, 62 and 81 have the highest bias error which exceeds 2.0 despite the gauges show good correlation coefficient values of 0.947, 0.971, 0.979, 0.868, 0.811 and 0.976 respectively. These rain gauges are stationed at Tugu Keris, Selat Muara, Bandar Klang, Kg Rantau Panjang, S.M.K Raja Lumu and Ayer Hitam Puchong which all respective stations are located at the downstream of Klang River Basin. From the scatter graph of all the said rain gauges, it can be observed that the rain gauges recorded a higher rainfall value of almost doubled than the weather radar. Overall, other rain gauges achieve strong correlation coefficient above 0.8 with minor bias and RMSE error with lower than 1.0 except for four rain gauges with r value of 0.516, 0.268, 0.577 and 0.576 namely Gauge 18, 20, 21 and 99 that are stationed at Jalan 27 Selayang Baru, Batu 10 Gombak, Sg Selayang and Seri Kembangan respectively.

3.3 Comparison of Calibrated Radar QPE with Rain Gauge Rainfall

By referring to the comparison made in the previous section, the uncalibrated radar QPE for Gauge 18, 20, 21 and 99 will be improved by using MFB and MAF techniques. Fig. 4(a) shows that RMSE value of MAF correction is higher than the MFB calibrated radar QPE but lower than the raw radar QPE. This indicates that although the MAF calibration can estimate closer radar rainfall value to the rain gauge value, the estimation however disperses greater than the MFB calibrated radar QPE. Fig.4(b) illustrates that MFB correction method can improve the correlation coefficient between radar QPE and gauge rainfall. Due to this satisfactory performance, the subsequent analysis will adopt the MFB correction technique to improve the radar QPF



(a) **(b)**

Fig. 4 *(a) RMSE error; (b) Correlation coefficient, for radar QPE vs MFB calibrated radar QPE vs MAF calibrated radar QPE against rain gauge rainfall at point gauge station (with lower correlation)*

3.4 Comparison of Mean Areal Rainfall and Radar QPF with Rain Gauge Rainfall

The radar data has been processed using QGIS to produce the mean areal radar rainfall value of each nowcasted rainfall considered. The comparison of the radar QPF involving 1-hour, 2-hour and 3-hour ahead of predicted rainfall with the gauge rainfall as the true value is analyzed. The value of observed rainfall is considered from the Thiessen areal averaged gauge rainfall values at selected timesteps which has been calculated in the previous analyses. Two (2) comparison events are presented in this paper. Fig. 5 illustrates an example from the analysis done for light rainfall events while Fig. 6 shows an analysis for rainfall events with partly high rainfall intensity distribution.

Table 5 *Relative error of uncalibrated 1-hour, 2-hour and 3-hour nowcast in comparison with rain gauge rainfall on 17th December 2021 12:00*

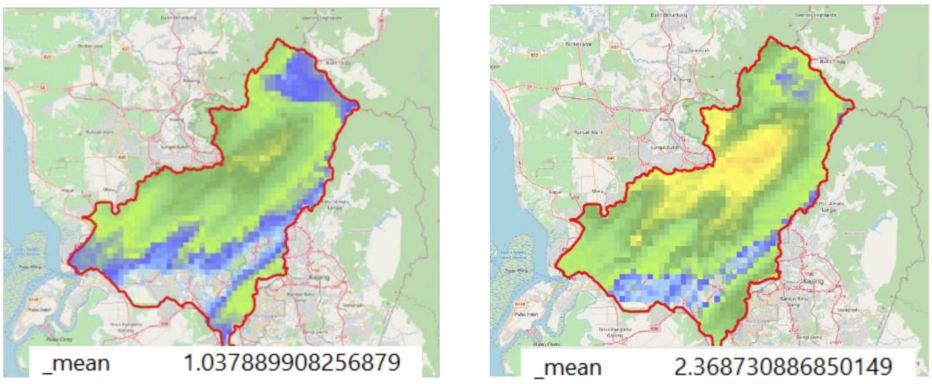
Date & Time	Rain Gauge (mm)	1-hour Nowcast (mm)	Relative Error	2-hour Nowcast (mm)	Relative Error	3-hour Nowcast (mm)	Relative Error
17/12/2021 12:00	2.36	1.04	0.56	0.92	0.61	1.17	0.50

Table 6 *Relative error of calibrated 1-hour, 2-hour and 3-hour nowcast in comparison with rain gauge rainfall on 17th December 2021 12:00 hours*

Date & Time	Rain Gauge (mm)	1-hour Cal. Nowcast (mm)	Relative Error	2-hour Cal. Nowcast (mm)	Relative Error	3-hour Cal. Nowcast (mm)	Relative Error
17/12/2021 12:00	2.36	2.37	0.00	2.12	0.10	2.65	0.12

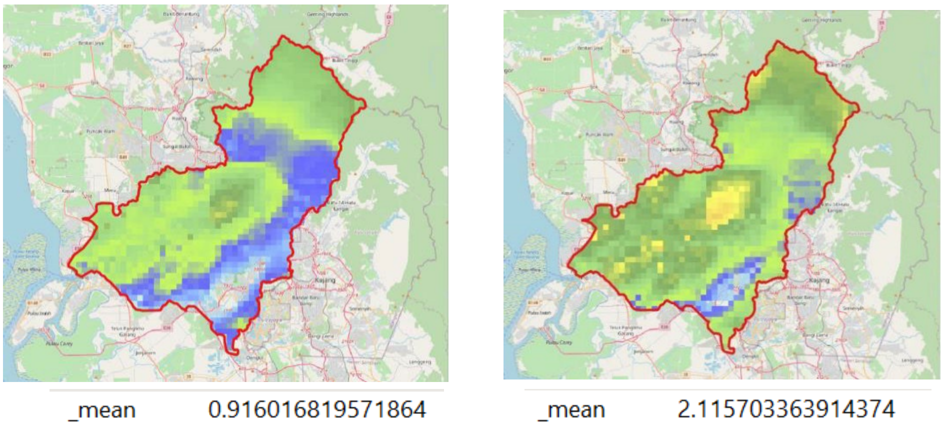
The rainfall event on 17th December 2021 12:00 hours is categorized under light rainfall with the value of 2.36 mm. The performance of uncalibrated radar QPF in predicting future rainfall is relatively low and fluctuating where the radar QPF under forecasted rainfall 3-hour ahead at 1.17 mm, then reduced to 0.92 mm at 2-hour ahead and increased again to 1.04 mm at 1-hour nowcast as shown in Table 5. Referring to Table 5, the relative error of the uncalibrated radar QPF in forecasting rainfall is 0.56, 0.61 and 0.50 for 1-hour nowcast, 2-hour nowcast and 3-hour nowcast respectively. The performance of the radar QPF, however, greatly improved after being calibrated where the relative error dropped to 0.00, 0.10 and 0.12 of the respective nowcasted time as shown in Table 6.

Event = E1
Rainfall Event = 17th December 2021 12:00 hours
Observed Rainfall = 2.36 mm



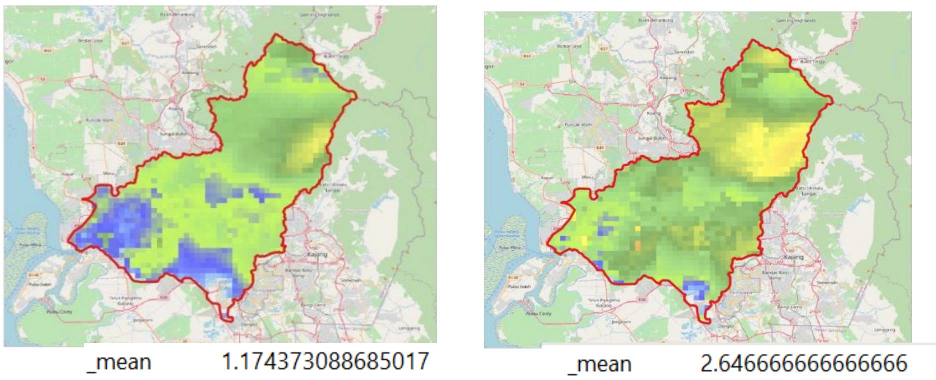
Uncalibrated 1-hr nowcast Calibrated 1-hour nowcast

(a)



Uncalibrated 2-hour nowcast Calibrated 2-hour nowcast

(b)

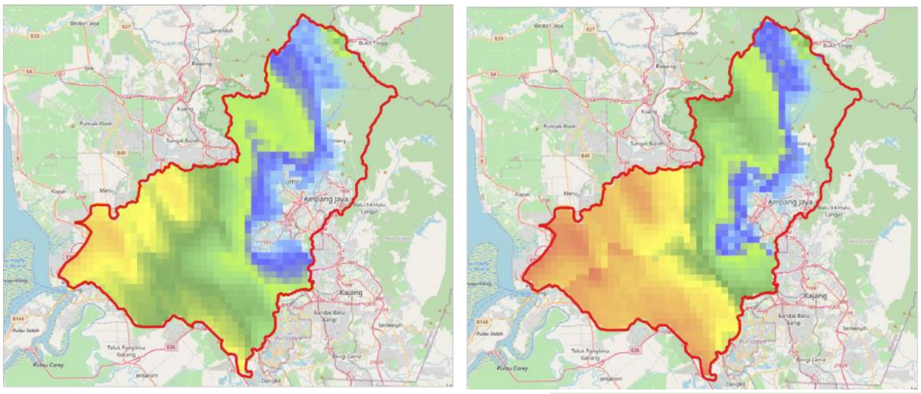


Uncalibrated 3-hour nowcast Calibrated 3-hour nowcast

(c)

Fig. 5 *Comparison of uncalibrated and calibrated (a) 1-hour; (b) 2-hour; (c) 3-hour radar nowcast in Klang River Basin on 17th December 2021 at 12:00*

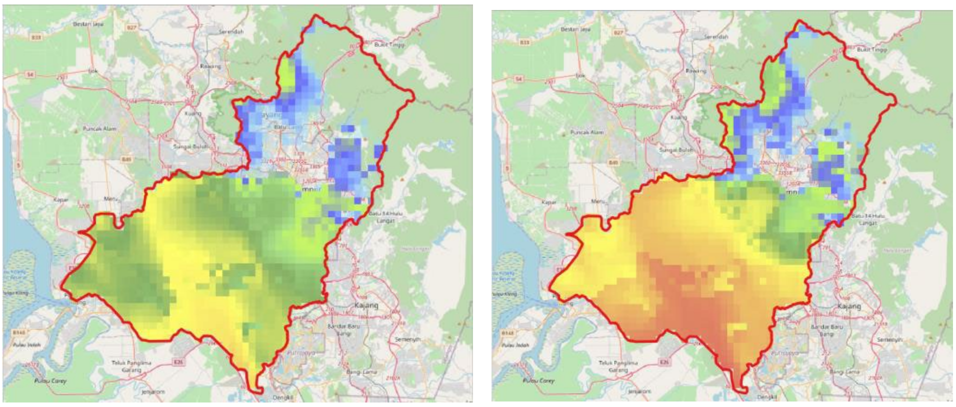
Event= E2
Rainfall Event= 17th December 2021 20:00 hours
Rain Gauge Rainfall= 8.17 mm



_mean 2.107334869431642 _mean 5.954623655913979

Uncalibrated 1-hour nowcast Calibrated 1-hour nowcast

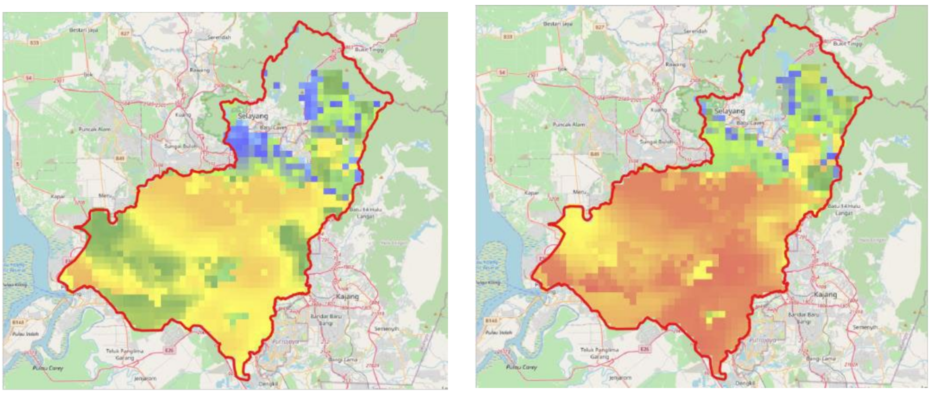
(a)



_mean 2.466524105754276 _mean 7.795419906687402

Uncalibrated 2-hour nowcast Calibrated 2-hour nowcast

(b)



_mean 4.742948021722268 _mean 13.284468580294799

Uncalibrated 3-hour nowcast Calibrated 3-hour nowcast

(c)

Fig. 6 *Comparison of uncalibrated and calibrated (a) 1-hour; (b) 2-hour; (c) 3-hour nowcast in Klang River Basin on 17th December 2021 at time 20:00*

For timestep 17th December 2021 at time 20:00 during event E2, mean areal rainfall of 8.17 mm is observed. Fig. 6 shows a clear comparison of uncalibrated and calibrated radar QPF with the actual time of rain gauge rainfall. The performance of radar QPF in predicting future rainfall is relatively low where the rain event is under forecasted. The rainfall is forecasted to be 4.74 mm with relative error of 0.42 at advanced 3-hour, 2.47 mm with relative error 0.70 at 2-hour nowcast and 2.11 mm with highest relative error of 0.74 for 1-hour ahead actual time. After the calibration of radar QPF has been done, the performance increased significantly but the accuracy fluctuates. Radar rainfall is forecasted to be 13.28 mm with highest relative error of 0.63, then the error dropped massively to 0.05 which is almost accurate to the actual time with 7.80 mm at 2-hour nowcast, then the relative error become greater again with 0.27 when radar rainfall is under forecasted at 5.95 mm.

4. Conclusion

At larger spatial scale, which is at mean areal basin, analysis shows that interpolation of Thiessen polygon method of gauge rainfall indicates better accuracy of radar rainfall estimation compared against the observed value to the arithmetic mean method. For the comparison of radar rainfall with the gauge rainfall at point scale, it is observed that the performance of radar rainfall estimation is satisfactory at most gauges with correlation factors exceed 0.6 which surpassed the strong category of correlation, with low bias error and RMSE value. On the other hand, the calibration of radar QPE using MAF correction method overall shows closer radar rainfall estimation to the rain gauge value with lower bias error and RMSE compared to MFB calibration, only those gauges that located at the downstream area have higher bias error and RMSE than MFB calibration despite the high correlation coefficient r analyzed. The occurrence of bias errors is mostly due to other uncertainties that disturb the performance of radar QPE. Additionally, by referring to the accuracy analysis of radar QPF, analysis show satisfactory results where calibrated radar nowcast achieves lower relative error in comparison with the actual rainfall. The analysis also suggests that earlier lead times have superior nowcast values, which may be attributed to the extrapolation factor of radar advection. Despite the considerable potential of radar QPF derived from RaINS, further efforts are required to enhance performance consistency.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Wardah Tahir;* ***data collection:*** *Hannani Hasni;* ***analysis and interpretation of results:*** *Hannani Hasni, Wardah Tahir;* ***draft manuscript preparation:*** *Noor Shazwani Osman. All authors reviewed the results and approved the final version of the manuscript.*

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