Evaluation of the Effectiveness of Composite Radar Rainfall Estimation Using the Quality Index Technique in Mountainous Terrain with a Weather Radar Network in Northern Thailand

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Abstract

Radar measurements in mountainous regions with complex terrain present significant challenges due to beam blockage. Consequently, rainfall estimation based on data from a single weather radar station may be subject to substantial inaccuracies. The application of composite radar techniques, which integrate data from multiple radar stations, provides a potential approach for improving the accuracy of radar-based rainfall estimation. This study aims to evaluate the effectiveness of composite radar rainfall estimation in mountainous terrain using the quality index technique, considering three key environmental factors: 1) radar beam blockage, 2) radar beam height above the terrain, and 3) distance from the radar station. Data from three weather radar stations—Chiang Rai, Nan, and Phitsanulok—were utilized in the analysis. The effectiveness of radar-derived rainfall estimates was assessed by comparing them against measurements from automatic rain gauge stations for 21 rainfall events recorded during tropical storm Son-Tinh (between June and September 2018). The results indicate that the quality index-based composite radar technique yields superior performance on average compared to single-radar data. When combined with bias correction, the composite method enhances spatial rainfall representation, providing improved quantitative accuracy at all rainfall intensity levels, showing an improvement of approximately 25% compared to pre-correction estimates. This improvement is particularly pronounced in areas affected by beam blockage. Moreover, considering the impact of radar elevation angle adjustments may further enhance the effectiveness of radar-based rainfall estimation in mountainous regions.

Keywords: composite radar rainfall, quality index technique, mountainous terrain, beam blockage

1. Introduction

Flooding is a natural disaster that is difficult to predict and manage, especially without accurate and real-time rainfall data. Flood forecasting is crucial for early warning and disaster mitigation. However, the installation of rain gauge stations across Thailand's river basins remains limited due to uneven spatial distribution, particularly in mountainous regions where station deployment and data collection are challenging. Additionally, most rain gauges are non-automated and record daily rainfall data, which affects the timeliness of flood assessments and increases the risk of loss of life and property. This issue is especially pronounced in northern Thailand, where the terrain is predominantly mountainous, making the installation of rain gauge stations difficult. Challenges related to long-distance data transmission further contribute to the insufficient density of ground-based rain gauge stations, potentially compromising the accuracy of rainfall monitoring and flash flood risk assessment. To address these limitations, weather radar, a remote sensing technology developed for high-resolution rainfall estimation, offers an alternative data source for improved accuracy and detail.

Weather radar technology is an essential tool for indirectly estimating rainfall with high spatial and temporal resolution, making it suitable for near real-time rainfall modeling and short-term precipitation forecasting [1, 2]. It is particularly beneficial in regions with limited rain gauge networks. However, weather radars do not directly measure rainfall but instead rely on reflectivity data, which can be affected by factors like mountain blockage, beam height, and distance from the radar. As a result, relying on data from a single radar station may not be sufficient for high-resolution and accurate rainfall assessment.

Radar composite techniques integrate data from multiple radar stations to enhance the accuracy of rainfall estimation in overlapping signal areas. Traditional methods include the Maximum Value Method, Mean Value Method, Nearest Neighbor Method, and Distance Weighted Method. Among these, the Maximum Value Method is recognized for its effectiveness in assessing heavy rainfall [3]. However, this method selects the highest reflectivity value in overlapping pixels without filtering data quality, which may lead to overestimation if errors are not corrected using ground-based rain gauge data [4]. Therefore, the development of additional mechanisms for improving data quality is essential to enhance the accuracy of radar-based rainfall estimation.

Rainfall Estimation from Composite Radar Using Quality Index Techniques Rainfall estimation from composite radar using quality index techniques involves integrating data from multiple radar stations while accounting for the quality of data from each station. This approach aims to minimize errors and improve the accuracy of rainfall estimation. Ongoing refinements to this technique have focused on enhancing the precision of rainfall analysis by incorporating various indices, including radar-specific characteristics, distance from the radar station, radar measurement altitude above ground level, and signal attenuation due to mountainous terrain [5]. However, the application of QI techniques in Thailand remains challenging due to certain inherent limitations. Additionally, the use of different quality indices across radar stations may introduce variations in rainfall analysis results. In Thailand, the use of QI-based radar compositing remains limited, particularly in mountainous regions such as northern Thailand. Previous studies have primarily focused on flat terrains in Chao Phraya river basin [6] or have not explicitly addressed the complexities associated with radar performance in rugged landscapes. Consequently, it remains uncertain whether the QI technique can consistently improve rainfall estimation accuracy under these challenging conditions. This research evaluates the efficiency of composite radar using quality index techniques in comparison to the Maximum Value Method, aiming to identify the advantages and limitations of each approach. The study utilizes radar reflectivity data from a network of three radar stations: Chiang Rai, Nan, and Phitsanulok. These findings will contribute to the development of appropriate methodologies and improve the accuracy of radar-based rainfall estimation in mountainous regions.

2. Study Area

The radar network used in this study consists of three stations: Chiang Rai, Nan, and Phitsanulok, operated by the Thai Meteorological Department. These radar stations have a detection radius of 240 km, covering a total of 31 provinces in mountainous region. northern Thailand, as illustrated in Fig. 1.

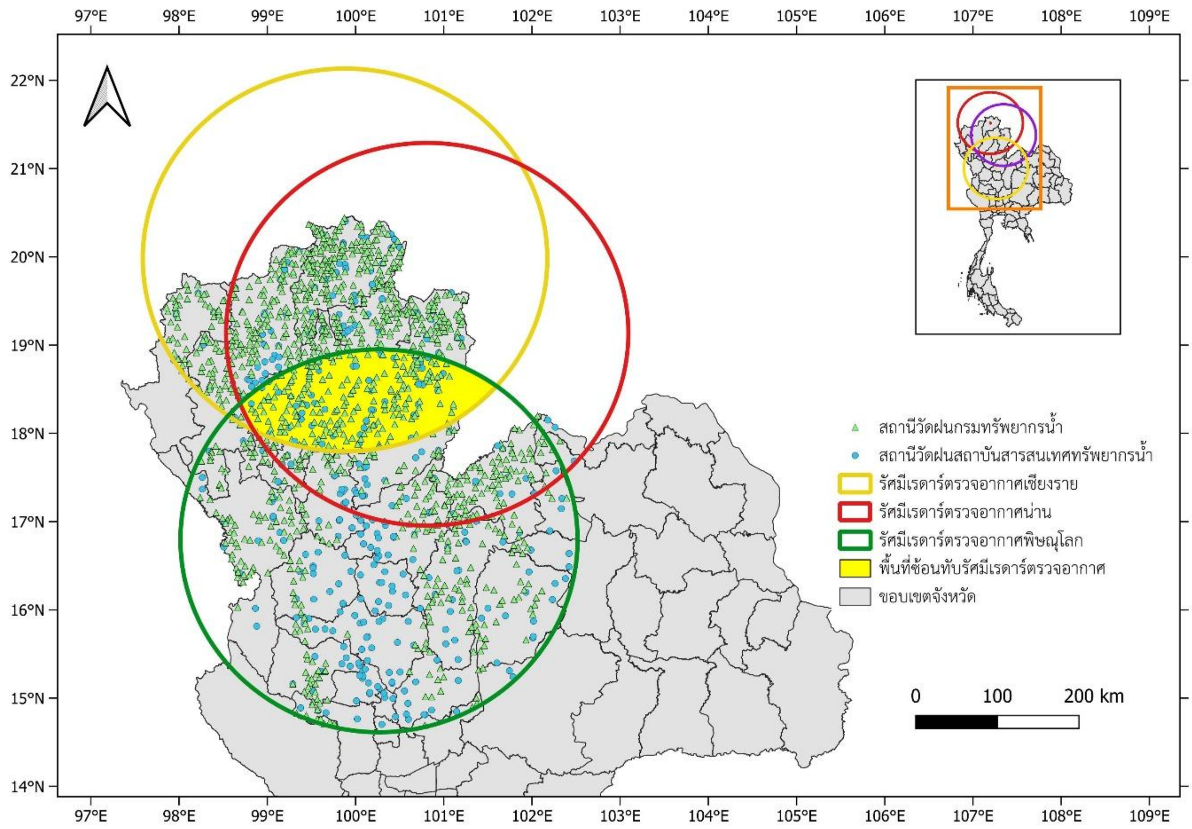

Fig. 1 Locations of the Chiang Rai, Nan, and Phitsanulok Radar Stations and the Automatic Rain Gauge Stations.

3. Data Collection and Quality Control

3.1 Radar reflectivity data

Radar reflectivity data were collected from the three radar stations during June–September 2018 at 15-minute intervals. The Chiang Rai, Nan, and Phitsanulok radars are C-band Dual Polarization radars that transmits the radiation with the wavelength of 5.3 cm and produces a beamwidth of 1.0°. The radar reflectivity data achieved from the three stations are in a Cartesian grid with 256 km x 256 km extent with 1 km^2 spatial resolution and 15-min temporal resolution.

To ensure data quality and minimize errors, quality control measures were applied to filter out potential noise or measurement inaccuracies. Reflectivity values below 15 dBZ were excluded to minimize radar noise, and those exceeding 53 dBZ were capped at 53 dBZ to mitigate hail-related errors [7]. These measures enhance the reliability and accuracy of radar reflectivity data analysis by minimizing noise-related errors and adjusting values affected by extreme weather conditions to a suitable range for rainfall estimation.

3.2 Rainfall data from automatic rain gauge stations

Hourly rainfall data were collected from automatic rain gauge stations operated by the Hydro-Informatics Institute (355 stations, 10-minute intervals) and the Department of Water Resources (1164 stations, 15-minute intervals) during June–September 2018. To ensure data reliability, quality control procedures were implemented by selecting only stations with at least 70% continuous data coverage throughout the rainy season. Data consistency was assessed using the Double Mass Curve method. These quality control measures ensure that the rainfall data used in this study are accurate and suitable for further analysis in rainfall estimation.

Based on the evaluation of rainfall data quality from automatic weather stations corresponding to radar reflectivity data from three radar stations, 21 rainfall events during tropical storm Son-Tinh were selected for further analysis. These events, occurring between June and September 2018, and ranged from light to very heavy rainfall (0.1–90.0 mm), were used to assess high resolution rainfall using the radar composite technique.

4. Theoretical Backgrounds

4.1 Radar data quality indices

4.1.1 Beam Blockage Fraction (BBF)

When the radar beam's elevation angle is lower than the terrain height, such as mountains, the radar beam is obstructed, leading to incomplete data. The Beam Blockage Fraction (BBF) index quantifies the proportion of the radar beam that is blocked by the terrain. A higher BBF value indicates a lower data quality. The index is calculated proposed by using Eq. (1) [8].

$$QI_{BBF} = \begin{cases} 1 - B & ; B \le B_{max} \\ 0 & ; B > B_{max} \end{cases} \tag{1}$$

Where B is the actual beam blockage fraction, and B_{max} is the maximum acceptable blockage fraction (percentage).

4.1.2 Distance to the radar station (DTR)

This index represents the degradation of radar data quality with increasing distance from the radar station. As the radar beam expands with distance, the accuracy of radar measurements decreases, and signal attenuation may occur. The index is computed using Eq. (2) [8].

$$QI_{DTR} = \begin{cases} 1.0 & ; \quad r < r_{min} \\ 1.0 - \frac{r - r_{min}}{r_{max} - r_{min}} & ; r_{min} \le r \le r_{max} \\ 0.0 & ; \quad r > r_{max} \end{cases} \tag{2}$$

Where r is the distance from the radar station, r_{min} is the minimum distance threshold, and r_{max} is the maximum reliable distance.

4.1.3 Height of the radar beam above the ground (HTG)

This index represents the variation in altitude between the terrain and the radar beam, which increases with distance. The radar beam altitude is calculated using Eq. (3), and the difference between this altitude and the terrain elevation is analyzed using Eq. (4) to determine 'h'. The maximum acceptable difference, h_{max}, is determined based on the maximum permissible altitude difference between the radar beam and the terrain. A larger altitude difference results in a lower quality index. The quality index is calculated using Eq. (5) [7].

$$H = \sqrt{r^2 + R'^2 + 2rR'sin\emptyset} - R' + H_0 \tag{3}$$

Where r is the distance from the radar station to the point of interest, $\emptyset$ is the radar beam's elevation angle, H_0 is the radar station's installation height, and R' is three-fourths of Earth's radius (6,374 km).

$$h = H - H_{dem} \tag{4}$$

Where H is the radar beam altitude, and H_{dem} is the terrain elevation from a digital elevation model.

$$QI_{HTG} = \begin{cases} 0.0 & ; \quad h < 0 \\ 1.0 - \frac{h}{h_{max}} & ; \quad 0 \le h \le h_{max} \\ 0.0 & ; \quad h > h_{max} \end{cases} \tag{5}$$

Where h is the altitude difference between the radar beam and the terrain (km), and h_{max} is the maximum acceptable altitude difference (km).

4.1.4 Overall quality index analysis

The overall radar data quality index integrates the indices for distance from the radar station, radar beam height above the terrain, and beam blockage fraction. It is computed using Eq. (6).

$$QI_{overall} = QI_{DTR} \times QI_{HTG} \times QI_{BBF} \tag{6}$$

4.2 Composite radar rainfall analysis using quality index method

4.2.1 Calibration of the Z-R relationship

Generally, rainfall estimation begins by converting measured reflectivity values into rainfall intensity or accumulation using the Z-R relationship, which is expressed as an exponential equation, as shown in Eq. (7).

$$Z = AR^b \tag{7}$$

Where Z is the reflectivity factor ($mm^6\ m^{-3}$), and A and b are parameters of the Z-R relationship. In this study. The traditional Z-R relationship proposed by Marshall and Palmer (1948) [9], with A set to 200 and b to 1.6, was used to calculate the initial radar rainfall in the radar compositing analysis [10].

4.2.2 Composite radar rainfall analysis

The radar rainfall estimates at each station is computed using the Z-R relationship as given in Eq. (7). The hourly accumulated radar rainfall is then calculated for the specified event to obtain the corresponding radar rainfall for all three radar stations. Composite radar rainfall is analyzed by averaging the radar rainfall data from all stations at the same grid point, weighted by the quality index values of each relevant radar station, as expressed in Eq. (8).

$$RR = \frac{\sum_{i=1}^{N} qi_i RR_i}{\sum_{i=1}^{N} qi_i} \quad (8)$$

Where qi_i represents the quality index of the radar station i, and RR_i is the hourly accumulated radar-estimated rainfall at the radar station i.

4.3 Hourly bias adjustment

The rainfall estimation based on the uncalibrated Z-R relationship may not be suitable for all selected rainfall events. Hourly Mean Field Bias Adjustment (HMFB) is a widely adopted standard method to enhance the accuracy of radar rainfall estimates. The adjustment is calculated using Eq. (9).

$$HMFB = \frac{\sum_{i=1}^{N} \mathrm{RG}}{\sum_{i=1}^{N} \mathrm{RR}} \quad (9)$$

Where N represents the number of data pairs between radar-estimated rainfall and automatic station rainfall, RR is the accumulated radar-estimated rainfall at the station i, and RG is the accumulated rainfall from an automatic gauge station at the station i.

5. Methodology

The procedure of this study consists of 3 steps, visualized in Fig. 2.

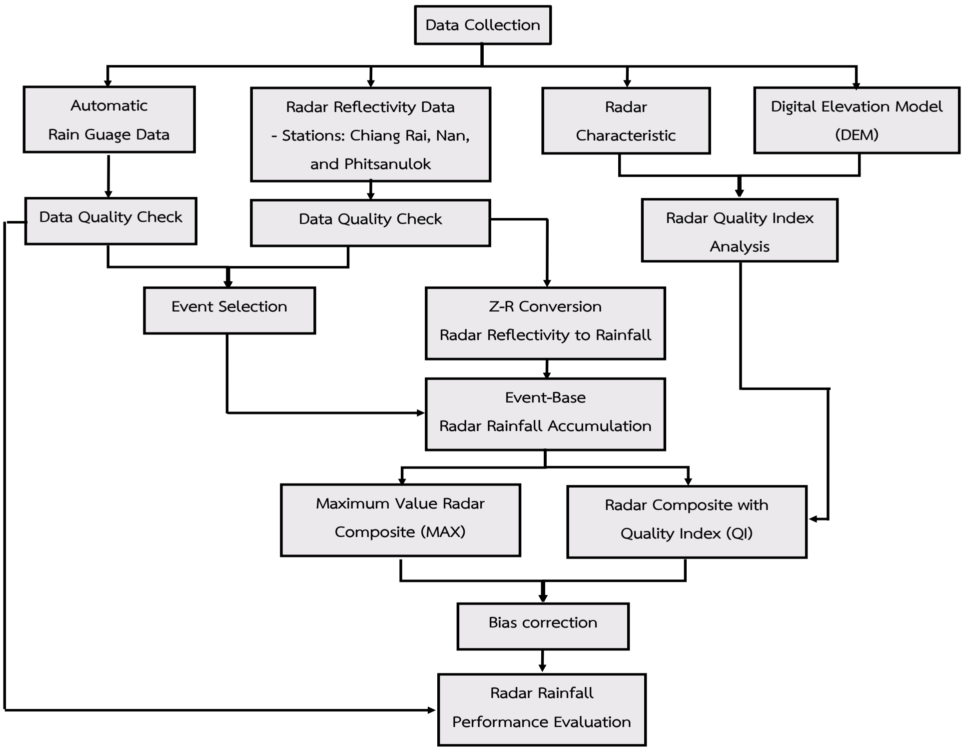

Fig. 2 A diagram of the procedure of this study.

5.1 Calculation of quality index for each radar station

5.1.1 Quality index based on radar beam blockage ratio

The quality index based on the radar beam blockage ratio is analyzed by calculating the radar beam blockage ratio (B). This process begins with assessing the radar beamwidth using radar data characteristics, such as elevation angle and beamwidth, to evaluate the increase in radar beamwidth with distance from the radar station. The cross-sectional beamwidth is then analyzed alongside Digital Elevation Model (DEM) data at various azimuth angles from 0 to 360 degrees to determine the radar beam blockage ratio (B). When the radar beam is obstructed by terrain, B is computed as the percentage of the total beamwidth that is blocked. In this study, B_{max} is set to 1, as defined in Eq. (5).

5.1.2 Quality index based on distance from the radar station

The quality index based on distance from the radar station is analyzed using the radial measurement distance of each radar station. All three radar stations have a maximum observation range of 240 km. Therefore, the QI_{DTR} for all stations is computed using Equation (2), with r_{min} and r_{max} set to 0 and 240 km, respectively.

5.1.3 Quality index based on radar beam height above terrain

This quality index is derived from the difference between the radar beam height and the terrain elevation. It is assessed using specific characteristics of each radar station, including the elevation of the radar installation, the radar observation range, and the elevation angle of each station. The radar stations in Chiang Rai, Nan, and Phitsanulok are installed at elevations of 390, 44, and 260 meters, respectively, and all three stations have an elevation angle of 1.0, 0.5, and 0.5 degrees.

The analysis process begins by calculating the radar beam height (H) using Eq. (3). Subsequently, the height difference between the radar beam and the terrain (*h*) is analyzed in conjunction with DEM data using Eq. (4) and (5). Due to variations in radar observation characteristics and terrain conditions, the spatial variability of *h* is determined. In this study, h_{max} for Chiang Rai, Nan, and Phitsanulok radars are 7.14 km, 7.73 km, and 6.77 km, respectively. After computing the three quality indices, the next step is to calculate the composite quality index using Eq. (6).

5.2 Hourly composite radar rainfall analysis

The sequence of composite radar analysis between Chiang Rai, Nan, and Phitsanulok radar stations for 21 rainfall events between June - September 2018 is as follows:

5.2.1 Analysis of instantaneous radar reflectivity data based on one-minute measurements from the three radar stations, interpolated using the Simple Linear Interpolation (SLI) method.

5.2.2 Conversion of reflectivity data from all three radar stations using the Z-R relationship equation ($Z = 200R^{1.6}$) to compute hourly accumulated radar rainfall.

5.2.3 Analysis of hourly composite radar rainfall using the quality index for each radar station, as computed in Eq. (8), for the 21 selected storm events.

5.2.4 Analysis of composite radar rainfall using the maximum value method for the same storm events as those analyzed with the quality index technique.

5.2.5 Bias correction of composite radar rainfall using rain gauge rainfall data located in the composited area. The composite radar rainfall analyzed using both the quality index technique and the maximum method is adjusted for bias and subsequently compared to evaluate the effectiveness of rainfall estimation. The bias correction factor is computed using the Hourly Mean Field Bias (HMFB) method, as shown in Eq. (9).

5.3 Performance evaluation of composite radar rainfall

The performance evaluation of composite radar rainfall for different case studies was conducted by analyzing the discrepancies between the estimated radar rainfall and observed rainfall from rain gauge stations at corresponding locations. The error between two sources of rainfall considered in this study is the Root Mean Square Error (RMSE), computed using Eq. (10).

$$RMSE = \sqrt{\frac{1}{\mathrm{N}}\sum_{t=1}^{\mathrm{N}}\sum_{i=1}^{\mathrm{N}}(R_{i,t} - G_{i,t})^2} \quad (10)$$

Where *N* is the total number of automatic rain gauge stations used in the computation, R_i,*t* is the radar rainfall estimates at rain gauge station *i* at time *t*, and G_i,t is the observed rainfall from the automatic rain gauge station *i* at time *t*.

The accuracy assessment case studies are as follows:

5.3.1 Evaluation of all rainfall events

This case study considers all 21 selected rainfall events to evaluate the accuracy of various composite radar rainfall estimation methods. The performance is compared against radar-based rainfall estimation using data from the Phitsanulok radar, which exhibits the highest error among the three stations.

5.3.2 Evaluation based on rainfall intensity

This case study investigates the impact of varying rainfall intensities on the effectiveness of composite radar techniques. Rainfall intensity is categorized into two levels based on the hourly rainfall classification of the Thai Meteorological Department: 1) Light to moderate rainfall (0.1 mm to 25.0 mm), and 2) Moderate to heavy rainfall (25.1 mm to 90.0 mm).

6. Results and Discussion

The evaluation of radar-based rainfall estimation before and after applying the radar composite technique using the quality index (QI) method, both qualitatively and quantitatively, under various case studies is presented as follows:

6.1 Quality index computation for each observation station

The analysis of the QI values for the radar stations in Chiang Rai, Nan, and Phitsanulok indicates that each station exhibits different QI values due to the unique characteristics of its radar hardware and various physical environmental factors in the observation area. Low QI values are predominantly found near the edges of the radar coverage and in areas where signals are significantly obstructed by mountains. However, when analyzing the overall QI by weighting the quality indices from all relevant stations, the results show a substantial increase in QI values in overlapping areas, reflecting the improved reliability of the composite technique. As illustrated in Fig. 3, the QI values range from 0 to 1, representing the lowest and highest data quality, respectively.

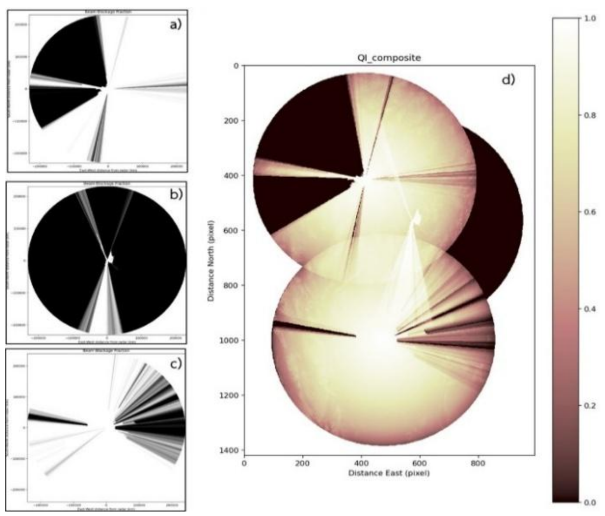

Fig. 3 Results of the quality index of the a) Chiang Rai, b) Nan, and c) Phitsanulok radars and d) the calculated overall quality index.

6.2 Qualitative assessment of radar composite performance

The radar composite analysis was conducted to evaluate the effectiveness of spatial rainfall distribution mapping using the composite method. This analysis compared two approaches: the maximum value (Max) method and the QI method. The study focused on continuous rainfall events and calculated composite radar rainfall accumulation for each event.

The results indicated that the Max method effectively delineates the edges of the rainfall area, particularly at the boundaries between the composite domain and the coverage area of a single radar station. This delineation occurs because the Max method selects the highest value from the involved radars. In contrast, the QI method employs a weighted approach, incorporating QI values from surrounding radar stations. This method produces a more continuous and realistic representation of rainfall clusters. The comparison between the two methods is clearly illustrated in Fig. 4 and 5, highlighting the differences in how the rainfall distribution is mapped.

Fig. 4 and 5 present a comparison of radar-derived rainfall distributions before and after bias correction. Prior to bias correction, the spatial distribution of rainfall appears limited and discontinuous, particularly in areas where data from multiple radar stations overlap. This discontinuity is likely due to inconsistencies in the raw radar data that have not been adjusted. After applying bias correction, the rainfall distribution becomes more continuous and spatially extensive. This improvement is especially evident in the outputs using the QI method, which enables a more seamless integration of radar data across overlapping coverage areas. As a result, the composite rainfall estimates appear more realistic and accurate, better reflecting the true spatial structure of rainfall.

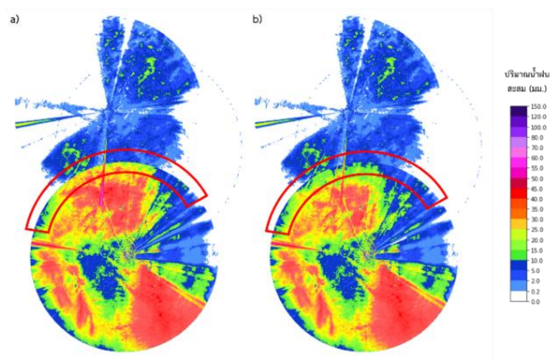

Fig. 4 Accumulated radar rainfall data before composite bias using a) Max and b) QI methods from 15 Jul 2018 at 07:00 PM to 18 Jul 2018 at 10:00 AM.

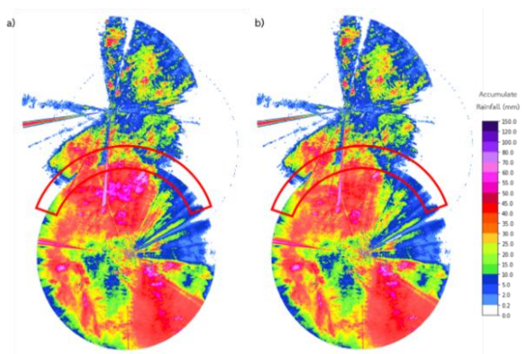

Fig. 5 Accumulated radar rainfall data after composite bias using a) Max and b) QI methods from 15 Jul 2018 at 07:00 PM to 18 Jul 2018 at 10:00 AM.

6.3 Quantitative assessment of radar composite performance

To quantify the discrepancies between different radar composite techniques in radar-based rainfall estimation, this study employs the root mean square error (RMSE) as a statistical index to compare the performance of the Max method and the QI method. An analysis of RMSE values across 21 rainfall events reveals that, after compositing with each technique, the hourly RMSE values vary, as illustrated in Fig. 6. The comparison of average hourly RMSE values before and after compositing indicates that the QI method initially exhibits lower performance than the Max method. However, after applying the HMFB correction technique, the QI-based composite significantly outperforms the Max method. This performance improvement is particularly evident when compared with using only the Phitsanulok radar station. As illustrated in Fig. 7, the performance improvements of the Max and QI composite methods compared to using the Phitsanulok radar alone. The Max method shows a modest improvement of 1.8%, while the QI method achieves a higher improvement of 10.9%. After applying the HMFB correction technique, the performance increases further to 6.1% for the Max method and 25.0% for the QI method.

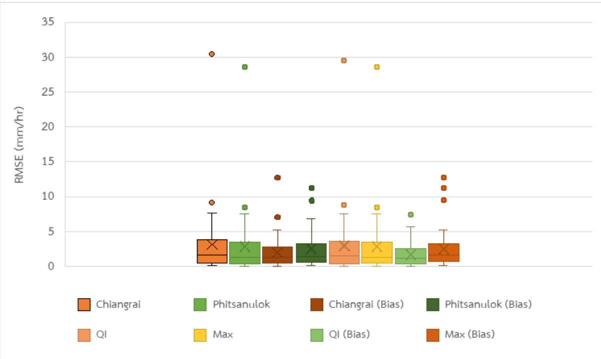

Fig. 6 Distribution of hourly average RMSE factors before and after composite of selected events.

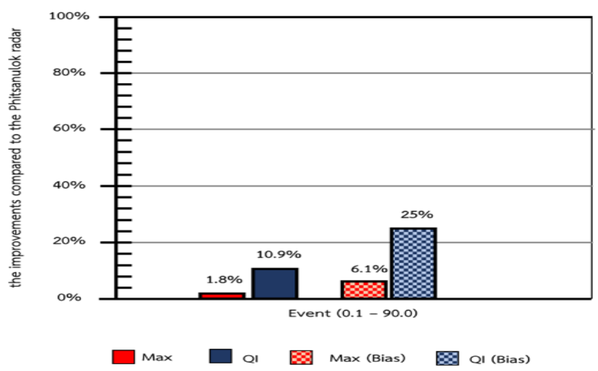

Fig. 7 Improved performance after composite compared with Phitsanulok radar.

7. Conclusion

1) The study, which covers the operational ranges of the Chiang Rai, Nan, and Phitsanulok weather radars, demonstrates that both the Quality Index (QI) method and the Maximum Value (Max) method provide higher accuracy compared to single-radar rainfall analysis. Among the three radars, the Phitsanulok weather radar exhibited the lowest accuracy in rainfall estimation. However, the application of bias adjustment techniques to enhance the accuracy of composite rainfall products significantly improved the reliability of rainfall simulations when compared with ground-based rain gauge measurements.

2) The application of three quality index techniques plays a crucial role in enhancing the reliability of rainfall data analysis. These techniques enable a continuous and spatially consistent representation of rainfall distribution patterns, aligning with the natural characteristics of rainstorms, even at the boundaries of overlapping radar coverage. A key advantage of this approach is its ability to reduce discrepancies between data collected from different radar stations, resulting in a more coherent and realistic depiction of rainfall. This contrasts with the Maximum Value Method, which often introduces discontinuities at measurement boundaries, potentially leading to incomplete or inconsistent rainfall data in certain areas. Therefore, the implementation of these three quality index techniques offers a more precise approach to rainfall data processing, mitigating inconsistencies across radar stations and enhancing the effectiveness of rainstorm monitoring and prediction.

3) For quantitative performance evaluation, the composite radar rainfall estimation using the QI method was found to be more effective than the Max method across the majority of events, particularly for light to moderate rainfall intensities. Based on both qualitative and quantitative assessments, the QI method is considered a suitable approach for composite radar rainfall analysis in the mountainous area. Integrating QI-based techniques with radar-based nowcasting algorithms and hydrological modeling could further enhance the accuracy of near real-time flash flood early warning systems in complex terrain.

Acknowledgement

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