



Improving radar rainfall estimation accuracy in the composite area of Takhli and Sattahip radars using spatial and hourly time-varying bias adjustment

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Abstract

In estimating rainfall over the composite coverage area of the Takhli and Sattahip radars, the use of a composite Z–R relationship may still result in residual errors due to differences in the physical characteristics of rainfall. These differences can be attributed to the effects of the Earth's curvature, variations in terrain characteristics, and event-to-event differences in rainfall, including variations in the spatial distribution of raindrops over time. In this study, a total of 267 rainfall events occurring between August 2018 and August 2020 were collected and analyzed. The dataset consisted of hourly rainfall measurements from 47 automatic ground-based telemetry stations and radar reflectivity data obtained within a 240 km detection range of the Takhli and Sattahip radars. These data were used to determine pixel-specific bias adjustment factors that varied on an hourly basis using the Inverse Distance Weighting (IDW) method. The adjustment factors were estimated from neighboring pixels with known values derived from both radar observations and automatic ground-based telemetry stations located within a 20 km radius of each target pixel. The results showed that the Composite radar rainfall intensity estimated using the $Z = 138R^{1.6}$ relationship for the Takhli radar and the $Z = 170R^{1.6}$ relationship for the Sattahip radar, combined with the proposed hourly time-varying bias adjustment factors, provided the greatest improvement in radar rainfall estimation accuracy over the composite coverage area of the Takhli and Sattahip radars. This approach yielded the lowest RMSE (Root Mean Squared Error), MAE (Mean Absolute Error), and BIAS values compared with the other bias adjustment methods. The proposed approach improved rainfall estimation accuracy by 50.24%, 16.83%, and 8.33% in terms of RMSE, MAE, and BIAS, respectively, compared with the unadjusted composite rainfall intensity estimated using the $Z = 138R^{1.6}$ relationship for the Takhli radar and the $Z = 170R^{1.6}$ relationship for the Sattahip radar.

Keywords: Rainfall intensity, Bias adjustment, Radar reflectivity, Inverse Distance Weighting (IDW), Automatic ground-based telemetry station

1. Introduction

Rainfall data are essential for meteorological and hydrological applications, as well as for water resources development and management. Although the required level of rainfall information may vary among different projects, a common objective is to obtain information describing the amount and spatial and temporal distribution of rainfall, rather than relying solely on point rainfall measurements at specific locations [1]. Point rainfall observations alone cannot adequately capture the spatial and temporal variability of rainfall. Furthermore, because rain gauge stations are often sparsely distributed, rainfall measurements obtained from rain gauges may not always provide a representative estimate of the actual rainfall occurring over a given area [2-3].

In recent years, remote sensing techniques, particularly meteorological radar, have received increasing attention for investigating the spatial characteristics and temporal evolution of rainfall. Weather radar can provide detailed rainfall information over a broad area within the radar coverage and continuously monitor rainfall as soon as precipitation occurs. It can therefore provide rainfall observations with high spatial and temporal resolution over extensive areas [4-9]. When radar-derived rainfall estimates are integrated with rainfall observations from automatic ground-based telemetry stations, the accuracy of rainfall estimation at the ground surface can be further improved [10-13].

However, radar rainfall estimation is subject to several sources of uncertainty. These can generally be classified into three major components. First, uncertainties in radar reflectivity measurements may arise from several sources, including Ground Clutter, Beam Blockage, and Beam Attenuation [14-18]. These errors should be addressed before radar reflectivity data are used to derive the Z–R

relationship. Second, errors may result from the use of an inappropriate relationship between radar reflectivity and rainfall intensity measured at automatic ground-based telemetry stations, commonly expressed as the Z–R relationship ($Z=aR^b$). The parameters a and b are not constant and may vary depending on the characteristics and distribution of raindrop populations [19–23]. Third, additional uncertainties may be associated with the effects of Earth curvature and variations in terrain characteristics. Moreover, individual rainfall events may exhibit different raindrop distributions at different times, resulting in temporal variations in the physical characteristics of rainfall. Even when an appropriate Z–R relationship is applied, residual errors may remain because radar-derived rainfall represents rainfall estimated above the ground surface, rather than the equivalent rainfall actually reaching the ground.

Therefore, a further bias adjustment is required to convert radar-derived rainfall above the ground into rainfall amounts representative of rainfall reaching the ground surface. Previous studies have proposed various approaches for determining radar rainfall bias adjustment factors. [24–28] proposed a single, spatially uniform adjustment factor (G/R) for the entire study area. This approach is appropriate for areas with a sufficiently dense network of rain gauges that are widely and uniformly distributed throughout the study area. [29] reported that rainfall events occurring in different areas exhibit different raindrop distributions and consequently proposed an adjustment factor that varies spatially according to areas with different rainfall distribution characteristics. [30–31] identified a distance-dependent error in radar rainfall measurements and consequently proposed a range-dependent adjustment factor based on the distance from the radar station. [32–39] demonstrated that rainfall events occurring at different times can exhibit different raindrop distributions, resulting in temporal variations in the physical characteristics of rainfall. Accordingly, these studies proposed time-dependent adjustment factors, particularly hourly adjustment factors. [40–41] found that rainfall characteristics vary among different areas due to the influence of spatially heterogeneous terrain conditions and therefore proposed zone-based adjustment factors. In addition, [42–43] indicated that the effects of Earth curvature and the increasing radar beam width with range cause the height and volume of the atmosphere sampled by the radar to increase with distance from the radar station. These studies therefore proposed adjustment factors that vary with both distance and time, referred to as range-dependent hourly adjustment factors.

Accordingly, the objective of this study is to determine a non-uniform hourly bias adjustment factor for each pixel within the composite coverage area of the Takhli and Sattahip radars. The proposed pixel-based and hourly time-varying bias adjustment is intended to reduce the residual errors associated with Earth curvature, spatially varying terrain characteristics, and temporal variations in raindrop distributions among different rainfall events and time periods. These factors contribute to variations in the physical characteristics of rainfall and may result in discrepancies between radar-derived rainfall above the ground and rainfall actually reaching the ground surface.

The resulting bias adjustment factors will subsequently be applied to correct the Composite radar rainfall intensity estimated using the five methods investigated in study [44]. These methods comprise: Method 1, rainfall intensity estimated solely from the Takhli radar using the relationship $Z=138R^{1.6}$; Method 2, rainfall intensity estimated solely from the Sattahip radar using the relationship $Z=170R^{1.6}$; Method 3, Composite rainfall intensity estimated using the relationship $Z=200R^{1.6}$ proposed by Marshall and Palmer [45]; Method 4, Composite rainfall intensity estimated using the relationship $Z=300R^{1.4}$ proposed by Woodley and Herndon [46] and Method 5, Composite rainfall intensity estimated using the relationship $Z=138R^{1.6}$ for the Takhli radar and $Z=170R^{1.6}$ for the Sattahip radar. The application of the proposed bias adjustment factors is expected to improve the accuracy of Composite radar rainfall intensity derived from all five methods, thereby providing more accurate estimates of rainfall reaching the ground surface.

2. Materials and methods

2.1 Data study

The composite area of the Takhli and Sattahip radars encompasses the area located within the 240 km observation range of both the Takhli and Sattahip radars, as shown in Figure 1. In this study, a total of 267 rainfall events occurring within the 240 km observation range of the Takhli radar were collected. The Takhli radar is an S-band dual-polarization radar operated by the Department of Royal Rainmaking and Agricultural Aviation, with observations conducted at 6-minute intervals and at an elevation angle of 1.3°. The Sattahip radar is an S-band Doppler radar operated by the same agency, with observations conducted at 6-minute intervals and at an elevation angle of 1.5°. Radar reflectivity (Z) data were obtained in the form of volume files, while rainfall observations were collected from automatic ground-based telemetry stations operated by the Hydro-Informatics Institute (HII). The data covered the period from August 2018 to August 2020. For each rainfall event included in the study, corresponding rainfall observations from both radar stations and the automatic ground-based telemetry stations were required to be available. In addition, both datasets had to undergo quality control and bias correction procedures as follows:

2.1.1 Quality control and bias correction of radar reflectivity data from the Takhli and Sattahip radars

The radar reflectivity data from the Takhli radar at an elevation angle of 1.3° and the Sattahip radar at an elevation angle of 1.5°, which were identified as the appropriate scanning elevation angles for the two radars based on study [44], were subjected to quality control and bias correction. However, the radar reflectivity data from both radars were still affected by radar beam contamination from permanent ground targets (ground clutter). Therefore, ground clutter maps were generated from the radar reflectivity data to identify pixels affected by ground clutter. The reflectivity values of pixels identified as ground clutter were subsequently corrected using the reflectivity values of neighboring pixels through an interpolation method [47–48]. The results of the radar reflectivity correction for ground clutter contamination for the Takhli and Sattahip radars are presented in Figures 2 and 3, respectively.

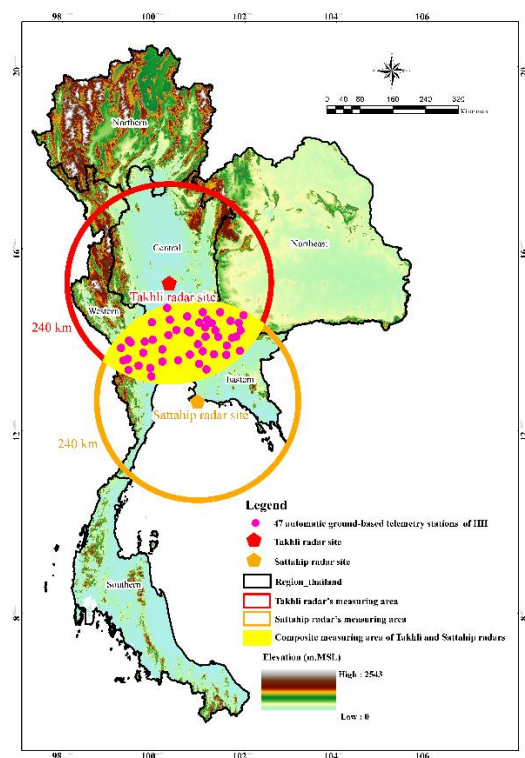


Figure 1 Composite area of the Takhli and Sattahip radars within the 240 km observation range

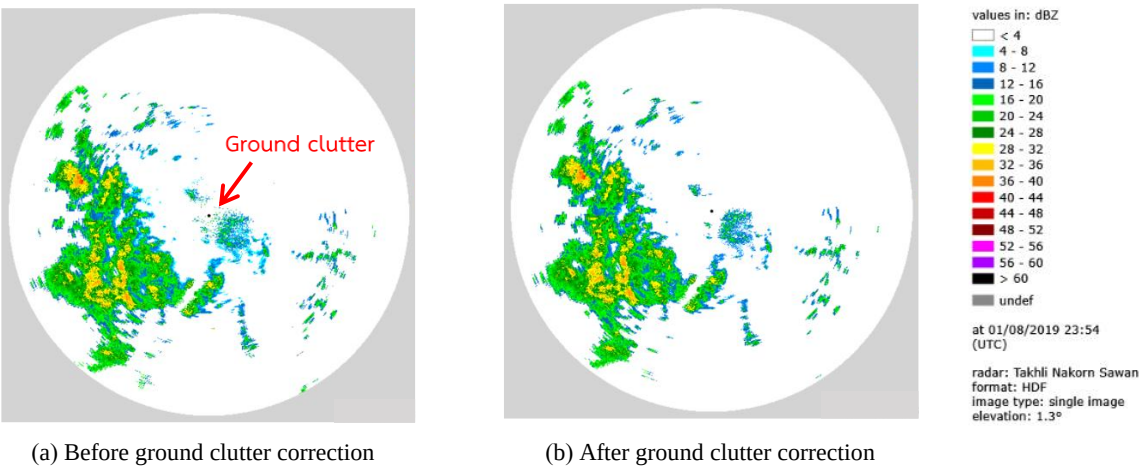


Figure 2 Takhli radar reflectivity data before and after ground clutter correction on August 1, 2019, at 23:54 UTC

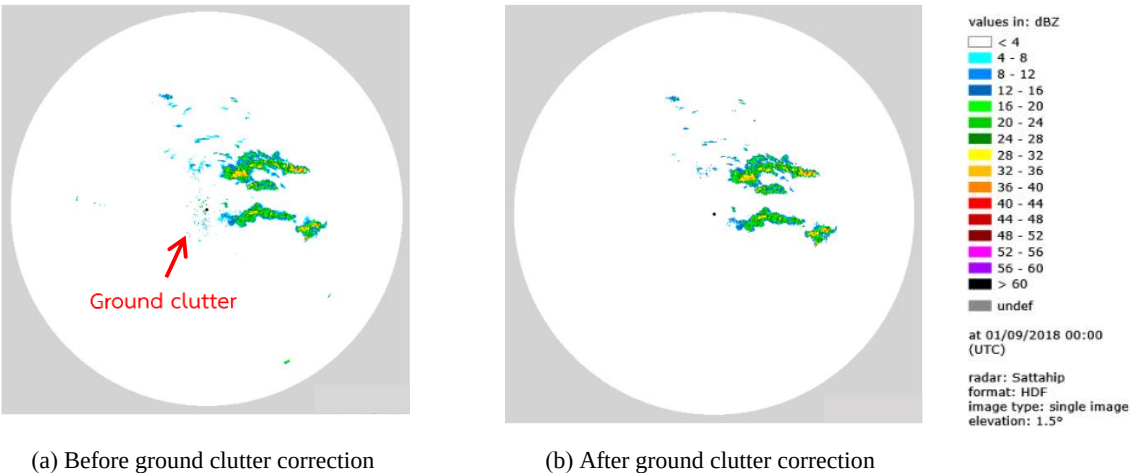


Figure 3 Sattahip radar reflectivity data before and after ground clutter correction on September 1, 2018, at 00:00 UTC

The impact of beam blockage, which occurs when the radar beam is obstructed by permanent targets, causes the radar reflectivity measured in areas behind the obstruction to be lower than normal. Therefore, a correction was performed using monthly accumulated rainfall data to identify the locations affected by beam blockage. The radar reflectivity values of pixels located within the beam-blockage areas were then corrected by estimating their values from those of neighboring pixels using an interpolation method [47–48]. The results of the radar reflectivity correction for beam blockage effects for the Takhli and Sattahip radars are presented in Figures 4 and 5, respectively. In addition, attenuation occurs when radar-wave energy is absorbed as the radar beam propagates through atmospheric gases, water vapor, oxygen, and precipitation [49], resulting in a reduction in radar-wave energy. The sensitivity of radar signals to attenuation depends on the wavelength of the transmitted radar beam. Attenuation is a significant concern for X-band and C-band radars, which have wavelengths of approximately 2.5 and 5.5 cm, respectively, whereas it is generally not a significant issue for S-band radars, which have a wavelength of approximately 10.7 cm [50]. Therefore, because both the Takhli and Sattahip radars are S-band radars, their radar reflectivity measurements are considered to be minimally affected by attenuation. To avoid including radar reflectivity signals that are not associated with precipitation echoes, only radar reflectivity values greater than 15 dBZ were selected for analysis. Conversely, to minimize the inclusion of echoes associated with hail, radar reflectivity values greater than 53 dBZ were capped at 53 dBZ [51].

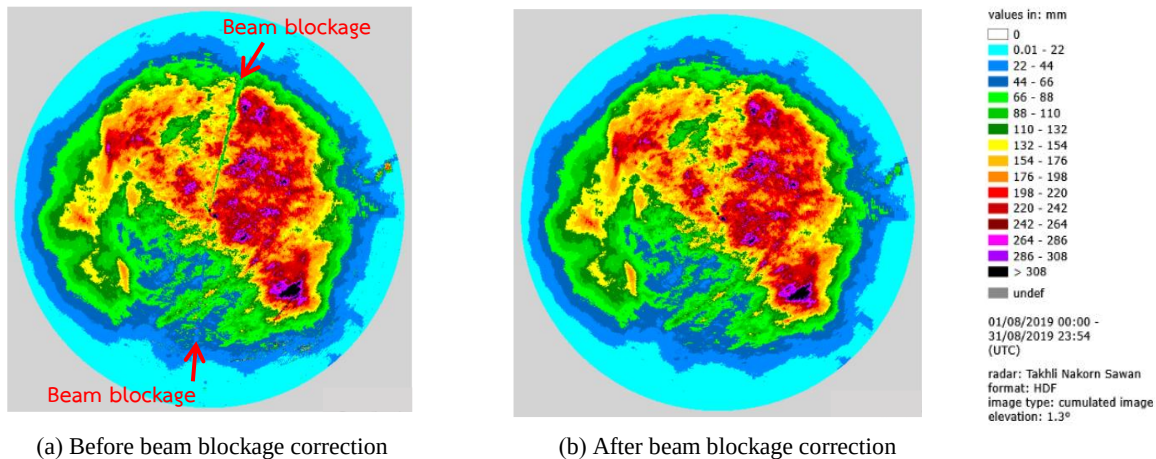


Figure 4 Monthly accumulated rainfall estimated from the Takhli radar for the August 1, 2019 rainfall event before and after beam blockage correction

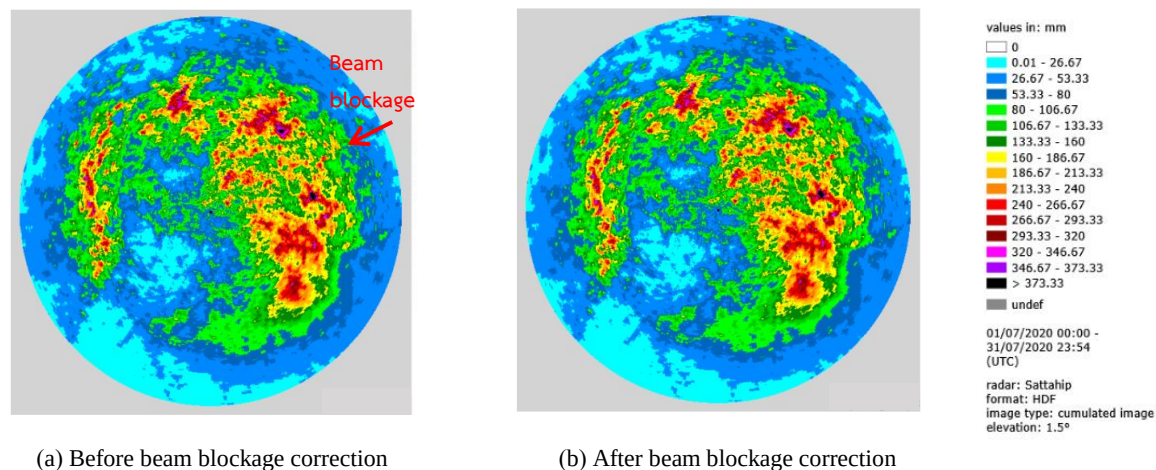


Figure 5 Monthly accumulated rainfall estimated from the Sattahip radar for the July 1, 2020 rainfall event before and after beam blockage correction

2.1.2 Quality control of hourly rainfall data from automatic ground-based telemetry stations

The hourly rainfall data from the automatic ground-based telemetry stations included in this study were required to meet the quality-control criteria based on the double mass curve method, with an R^2 value greater than 0.90. A total of 47 automatic ground-based telemetry stations with data collected during the period from August 2018 to August 2020 were subjected to quality control. The results indicated that all 47 automatic ground-based telemetry stations passed the quality-control criteria and were therefore included in the analysis.

2.2 Analysis of hourly time-varying radar rainfall intensity bias adjustment factors at each pixel within the composite area

The radar rainfall intensity at each pixel within the composite area of the Takhli and Sattahip radars was estimated for a total of 267 rainfall events occurring between August 2018 and August 2020 using the five rainfall estimation methods described in Study [44]. However, residual errors remained in the radar rainfall estimates due to the effects of Earth's curvature and variations in

topography. In addition, the spatial and temporal distributions of raindrops differed among rainfall events, resulting in variations in the physical characteristics of precipitation. Furthermore, the radar rainfall intensity estimated using the five methods represents rainfall intensity measured aloft rather than the equivalent rainfall intensity at the ground surface, as measured by automatic ground-based telemetry stations. These residual errors can be regarded as a systematic difference between radar rainfall and ground-based rainfall observations at corresponding geographic locations. Such systematic differences can be reduced by applying a bias adjustment derived from ground-based rainfall observations. The bias adjustment (G/R) is calculated as the ratio of accumulated rainfall measured by an automatic ground-based telemetry station (G) to the corresponding accumulated rainfall estimated from radar (R). This approach has been widely used to adjust radar rainfall estimates to better represent ground rainfall observations. Previous studies [24-28] have proposed calculating a single, spatially constant G/R bias adjustment factor for the entire study area. This approach is suitable for areas with a large number of rain gauges that are well distributed and provide adequate spatial coverage across the study area. [29] found that rainfall events occurring in different areas exhibit different spatial distributions of raindrops and therefore proposed calculating bias adjustment factors according to areas with distinct rainfall distribution characteristics. [30-31] identified distance-dependent errors in radar rainfall measurements and consequently proposed a distance-based bias adjustment method. [32-39] found that rainfall events occurring at different times exhibit different raindrop distributions, resulting in variations in the physical characteristics of precipitation, and therefore proposed time-dependent bias adjustment methods, particularly hourly bias adjustment factors. [40-41] found that rainfall events occurring in different areas exhibit different raindrop distributions due to variations in terrain characteristics and consequently proposed zone-based bias adjustment methods. Furthermore, [42-43] found that the effects of Earth's curvature and the increasing radar-beam width with distance cause the height and atmospheric sampling volume of radar rainfall measurements to increase with increasing distance from the radar station. Therefore, these studies proposed a distance- and time-dependent bias adjustment method, namely hourly distance-based bias adjustment factors, to improve the accuracy of radar rainfall estimation.

This study analyzed non-uniform hourly bias adjustment factors for radar rainfall intensity within the composite area at each individual pixel. The analysis accounts for differences in terrain characteristics among pixels, as well as the effects of Earth's curvature and the increasing radar-beam width with distance, which cause the height and atmospheric sampling volume of radar rainfall measurements to increase with distance from the radar station. Hourly rainfall intensity data from automatic ground-based telemetry stations and radar rainfall intensity data within the composite area, estimated using each of the five rainfall estimation methods, were used at pixels where automatic ground-based telemetry stations were located. In this study, a pixel containing an automatic ground-based telemetry station is defined as a pixel for which both radar rainfall intensity data and ground-based rainfall intensity data are available. The bias adjustment factor for each target pixel was determined on an hourly basis using rainfall intensity data from neighboring pixels where both radar and ground-based rainfall observations were available. Only pixels located within a radius of 20 km from the target pixel were considered. This spatial search radius was selected because differences in terrain characteristics can result in differences in the spatial distribution of raindrops among areas. Therefore, rainfall intensity data from radar and automatic ground-based telemetry stations located close to the target pixel are expected to provide the most representative information for the target pixel because of their relatively similar spatial characteristics. In addition, the selected radius is consistent with the mean distance between each pixel in the composite radar domain and the pixels containing automatic ground-based telemetry stations for which both radar and ground-based rainfall intensity data were available. The mean distance was 16.54 km. Accordingly, this study selected rainfall intensity data from pixels containing automatic ground-based telemetry stations, where both radar and ground-based rainfall intensity data were available, and located within 20 km of the target pixel for the bias adjustment analysis. The hourly, pixel-based bias adjustment factors were then calculated using the IDW method. The fundamental principle of IDW is that pixels with known rainfall intensity data located closer to the target pixel have a greater influence on the estimated bias adjustment factor than those located farther away. Thus, the weighting assigned to each bias adjustment factor is inversely proportional to the distance between the target pixel and the pixel containing the corresponding radar and ground-based rainfall intensity observations, as shown in Equation 1.

$$(G/R)_{i,t} = \frac{\sum_{l=1}^{N_{i,t}} \frac{G_{l,t}}{d_{l,t}}}{\sum_{l=1}^{N_{i,t}} \frac{R_{l,t}}{d_{l,t}}} \quad (1)$$

where:

$(G/R)_{i,t}$ is the bias adjustment factor at pixel i for the rainfall event during hour t .

$G_{i,t}$ is the rainfall intensity measured by the automatic ground-based telemetry station located at pixel i during hour t (mm).

$R_{i,t}$ is the radar rainfall intensity at pixel i , estimated using each of the five rainfall estimation methods, during hour t (mm).

$d_{i,t}$ is the distance between pixel i , where both radar rainfall intensity and automatic ground-based telemetry rainfall intensity data are available, and the target pixel for which the bias adjustment factor is to be estimated during hour t (m).

$N_{i,t}$ is the total number of pixels with known radar rainfall intensity and automatic ground-based telemetry rainfall intensity data located within a 20 km radius of the target pixel for which the bias adjustment factor is to be estimated during hour t .

2.3 Analysis of bias-corrected radar rainfall

The hourly varying bias adjustment factors $(G/R)_{i,t}$ at each individual pixel (non-uniform hourly bias adjustment) are applied to correct the radar rainfall intensity at each pixel within the composite area of the Takhli and Sattahip radars, as estimated using each of the five rainfall estimation methods. The bias-corrected radar rainfall at each pixel is assumed to be equivalent to the rainfall amount reaching the ground surface and can be calculated using Equation 2.

$$\text{Bias-corrected radar rainfall (mm/h)} = (G/R)_{i,t} \times \text{Pre-adjustment radar rainfall (mm/h)} \quad (2)$$

For this study, the methods for estimating radar rainfall intensity at pixels within the composite area of the Takhli and Sattahip radars were evaluated using a total of 10 methods. These comprised the five unadjusted radar rainfall intensity estimation methods adopted from Study [44] and the five bias-adjusted radar rainfall intensity estimation methods proposed in this study, as follows:

- Method 1:** Radar rainfall intensity estimated using the equation $Z=138R^{1.6}$ from the Takhli radar only.
- Method 2:** Radar rainfall intensity estimated using the equation $Z=170R^{1.6}$ from the Sattahip radar only.
- Method 3:** Composite radar rainfall intensity estimated using the equation $Z=200R^{1.6}$.
- Method 4:** Composite radar rainfall intensity estimated using the equation $Z=300R^{1.4}$.
- Method 5:** Composite radar rainfall intensity estimated using the equation $Z=138R^{1.6}$, for the Takhli radar combined with the equation $Z=170R^{1.6}$ for the Sattahip radar.
- Method 6:** Radar rainfall intensity estimated using the equation $Z=138R^{1.6}$, from the Takhli radar, combined with the hourly bias adjustment method.
- Method 7:** Radar rainfall intensity estimated using the equation $Z=170R^{1.6}$, from the Sattahip radar, combined with the hourly bias adjustment method.
- Method 8:** Composite radar rainfall intensity estimated using the equation $Z=200R^{1.6}$, combined with the hourly bias adjustment method.
- Method 9:** Composite radar rainfall intensity estimated using the equation $Z=300R^{1.4}$, combined with the hourly bias adjustment method.
- Method 10:** Composite radar rainfall intensity estimated using the equation $Z=138R^{1.6}$, for the Takhli radar and the equation $Z=170R^{1.6}$ for the Sattahip radar, combined with the hourly bias adjustment method.

These ten methods were evaluated to identify the most appropriate radar rainfall intensity estimation method at pixels within the composite area of the Takhli and Sattahip radars. The evaluation was conducted using 267 rainfall events occurring between August 2018 and August 2020. For each method, the estimated radar rainfall intensity at pixels containing automatic ground-based telemetry stations was compared with the rainfall intensity measured by the corresponding ground-based telemetry stations at the same time. The most appropriate method was identified based on the lowest values of RMSE (Root Mean Squared Error), as shown in Equation 3, MAE (Mean Absolute Error), as shown in Equation 4, and BIAS, as shown in Equation 5.

$$RMSE = \sqrt{\frac{1}{N \times N_t} \sum_{t=1}^{N_t} \sum_{i=1}^N (R_{i,t} - G_{i,t})^2} \quad (3)$$

$$MAE = \frac{1}{N \times N_t} \sum_{t=1}^{N_t} \sum_{i=1}^N |R_{i,t} - G_{i,t}| \quad (4)$$

$$BIAS = \frac{1}{N \times N_t} \sum_{t=1}^{N_t} \sum_{i=1}^N R_{i,t} - G_{i,t} \quad (5)$$

where:

$R_{i,t}$ is the radar rainfall intensity at pixel i , estimated from the suggested (Z - R) relationship equation, in hours t (mm) with an automatic ground-based telemetry station located.

$G_{i,t}$ is the rainfall intensity measured by an automatic ground-based telemetry station at pixel i , with an automatic ground-based telemetry station located, in hours t (mm).

N is the total number of pixels with an automatic ground-based telemetry station located.

N_t is the number of rain periods (h).

3. Results and discussion

The results of the analysis to identify the most appropriate radar rainfall intensity estimation method for the composite area of the Takhli and Sattahip radars were evaluated based on the RMSE, MAE, and BIAS statistics. The radar rainfall intensity estimated at pixels within the composite area where automatic ground-based telemetry stations were located was compared with the rainfall intensity measured by the corresponding ground-based telemetry stations for all ten methods, as shown in Figures 6-8 and Table 1, respectively.

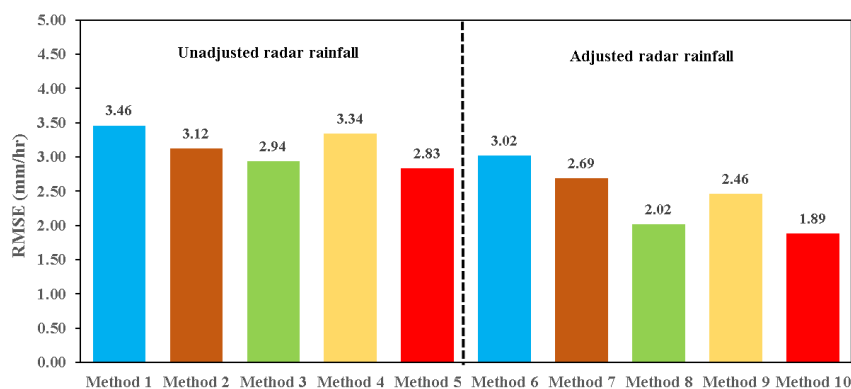


Figure 6 RMSE values of the 10 radar rainfall intensity estimation methods compared with rainfall intensity measured by automatic ground-based telemetry stations

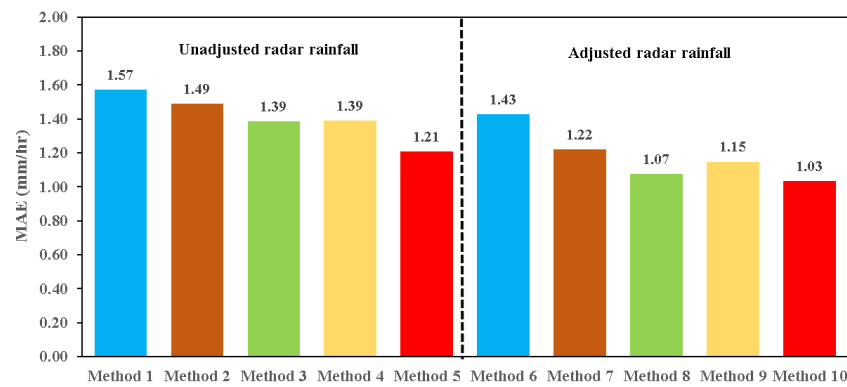


Figure 7 MAE values of the 10 radar rainfall intensity estimation methods compared with rainfall intensity measured by automatic ground-based telemetry stations

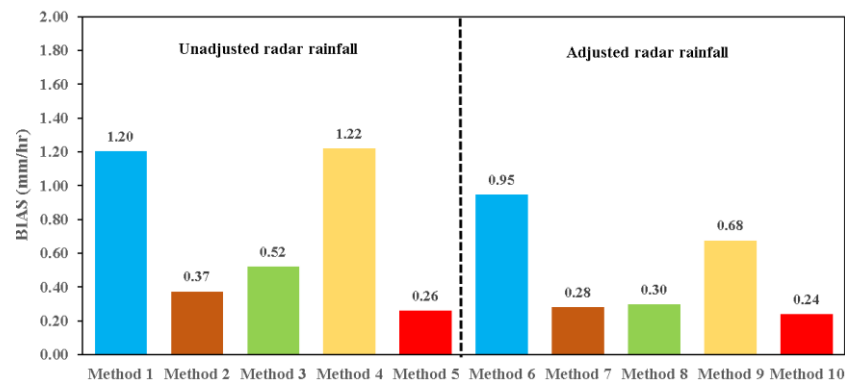


Figure 8 BIAS values of the 10 radar rainfall intensity estimation methods compared with rainfall intensity measured by automatic ground-based telemetry stations

Table 1 Results of the RMSE, MAE, and BIAS analysis for 10 radar rainfall intensity estimation methods at composite pixels of the Takhli and Sattahip radars compared with rainfall intensity measured by automatic ground-based telemetry stations

Radar rainfall intensity estimation method	RMSE (mm/h)	MAE (mm/h)	BIAS (mm/h)
Method 1: Radar rainfall intensity estimated using the equation $Z=138R^{1.6}$ from the Takhli radar only.	3.46	1.57	1.20
Method 2: Radar rainfall intensity estimated using the equation $Z=170R^{1.6}$ from the Sattahip radar only.	3.12	1.49	0.37
Method 3: Composite radar rainfall intensity estimated using the equation $Z=200R^{1.6}$.	2.94	1.39	0.52
Method 4: Composite radar rainfall intensity estimated using the equation $Z=300R^{1.4}$.	3.34	1.39	1.22
Method 5: Composite radar rainfall intensity estimated using the equation $Z=138R^{1.6}$ for the Takhli radar combined with the equation $Z=170R^{1.6}$ for the Sattahip radar.	2.83	1.21	0.26
Method 6: Radar rainfall intensity estimated using the equation $Z=138R^{1.6}$ from the Takhli radar, combined with the hourly bias adjustment method.	3.02	1.43	0.95
Method 7: Radar rainfall intensity estimated using the equation $Z=170R^{1.6}$ from the Sattahip radar, combined with the hourly bias adjustment method.	2.69	1.22	0.28
Method 8: Composite radar rainfall intensity estimated using the equation $Z=200R^{1.6}$, combined with the hourly bias adjustment method.	2.02	1.07	0.30
Method 9: Composite radar rainfall intensity estimated using the equation $Z=300R^{1.4}$, combined with the hourly bias adjustment method.	2.46	1.15	0.68
Method 10: Composite radar rainfall intensity estimated using the equation $Z=138R^{1.6}$ for the Takhli radar and the equation $Z=170R^{1.6}$ for the Sattahip radar, combined with the hourly bias adjustment method	1.89	1.03	0.24

The results showed that, among the unadjusted composite radar rainfall intensity estimation methods, Method 5, which combines the equation $Z=138R^{1.6}$ for the Takhli radar with the equation $Z=170R^{1.6}$ for the Sattahip radar, provided more accurate rainfall estimates than Method 1-4. This finding is consistent with previous studies [52-56], which reported that composite radar rainfall estimation can improve the accuracy of radar rainfall estimation by reducing errors in radar reflectivity measurements from the Takhli and Sattahip radars caused by the effects of Earth's curvature and the increasing radar-beam width with distance. However, the radar rainfall intensity estimated using Method 5 still contained residual errors because the estimated radar rainfall represents precipitation measured above the ground surface and does not yet correspond to the equivalent rainfall reaching the ground surface. Therefore, the residual errors in above-ground radar rainfall estimates should be corrected to obtain rainfall amounts that are more representative of ground rainfall. Accordingly, this study applied the non-uniform hourly bias adjustment to the radar rainfall intensity estimated using the five rainfall estimation methods and proposed Methods 6–10. The results demonstrated that Method 10, which estimates radar rainfall intensity at composite pixels using the equation $Z=138R^{1.6}$ for the Takhli radar and the equation $Z=170R^{1.6}$ for the Sattahip radar, combined with the hourly bias adjustment method, produced the lowest RMSE, MAE, and BIAS values.

These results indicate that Method 10 is the most appropriate radar rainfall intensity estimation method for the composite area of the Takhli and Sattahip radars. This method provides the greatest reduction in the residual errors associated with the difference between radar rainfall estimates and rainfall reaching the ground surface, compared with the other nine radar rainfall intensity estimation methods.

4. Conclusions

1) The unadjusted composite radar rainfall intensity estimated using the equation $Z=138R^{1.6}$ for the Takhli radar combined with the equation $Z=170R^{1.6}$ for the Sattahip radar in Method 5 still contained residual errors because the estimated radar rainfall represents precipitation above the ground surface and does not correspond to the equivalent rainfall reaching the ground surface. Applying the pixel-based hourly time-varying radar rainfall bias adjustment in Method 10 helped reduce these residual errors. When the bias-corrected radar rainfall intensity from Method 10 was compared with the unadjusted radar rainfall intensity from Method 5 against rainfall intensity measured by automatic ground-based telemetry stations, the results showed improvements in rainfall estimation accuracy of 50.24%, 16.83%, and 8.33% based on RMSE, MAE, and BIAS, respectively.

2) The composite radar rainfall intensity estimated using the equation $Z=138R^{1.6}$ for the Takhli radar and the equation $Z=170R^{1.6}$ for the Sattahip radar, combined with the hourly bias adjustment method in Method 10, improved the accuracy of radar rainfall intensity estimation based on RMSE by 83.50%, 65.52%, 56.02%, 77.08%, 50.24%, 60.37%, 42.76%, 6.90%, and 30.50%, improved the accuracy of radar rainfall intensity estimation based on MAE by 51.93%, 44.20%, 33.95%, 34.33%, 16.83%, 38.01%, 17.99%, 3.87%, and 11.03%, improved the accuracy of radar rainfall intensity estimation based on BIAS by 401.25%, 55.83%, 116.67%, 407.92%, 8.33%, 294.58%, 16.67%, 23.33%, and 181.67%, compared with the radar rainfall intensity estimated using Methods 1, 2, 3, 4, 5, 6, 7, 8, and 9, respectively.

3) The application of the proposed Method 10 for rainfall intensity estimation over the composite area for future rainfall events is subject to the limitation that concurrent rainfall data from automatic ground-based telemetry stations and radar rainfall data are required to derive hourly time-varying bias adjustment factors. Therefore, the effectiveness of the proposed method depends on the availability and spatial density of ground-based rainfall monitoring stations within the study area. Nevertheless, hourly adjustment of radar rainfall can help reduce the residual errors arising from the difference between radar-measured rainfall in the atmosphere above the ground and rainfall reaching the ground surface, thereby improving the consistency of radar-derived rainfall intensity with rainfall measurements from ground-based stations.

4) The proposed Method 10 can be applied as a guideline for rainfall intensity estimation over the composite areas of other weather radars, thereby increasing the spatial coverage of rainfall information. However, the method should be further refined and calibrated to account for the characteristics of each study area, the density of rainfall monitoring stations, and the specific characteristics of each radar. Accurate and high-resolution spatial radar rainfall data can be applied to hydrological applications, such as spatial rainfall analysis, monitoring and assessment of water conditions, and planning and management of water resources, thereby improving the efficiency of water resource management in the area.

5. Acknowledgements

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