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Development of a window correlation matching method for improved radar rainfall estimation

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Abstract

The present study develops a method called window correlation matching method (WCMM) to reduce collocation and timing errors in matching pairs of radar measured reflectivity, Z_e, and gauge measured rainfall intensity, R, for improving the accuracy of the estimation of Z_e–R relationships. This method is compared with the traditional matching method (TMM) and the probability matching method (PMM). The relationship Z_e=18.05 $R^{1.45}$ obtained from 7×7 km of space window and both present and 5 min previous time of radar observation for time window (S77T5) produces the best results for radar rainfall estimates for orographic rain over the Mae Chaem Watershed in north of Thailand. The comparison shows that the Z_e–R relationships obtained from WCMM provide more accuracy in radar rainfall estimates as compared with the other two methods. The Z_e–R relationships estimated using TMM and PMM show large overestimation and underestimation, respectively, of mean areal rainfall. Based on the overall results, it can be concluded that WCMM can reduce collocation and timing errors in Z_e–R pairs matching and improve the estimation of Z_e–R relationships for radar rainfall. WCMM is therefore a promising method for improved radar-measured rainfall, which is an important input for hydrological and environmental modeling and water resources management.

1 Introduction

Rainfall is measured based on three sensors – rain gauge, weather radar and satellite. Rain gauges are traditionally used for measuring rainfall at the ground level. Gauge-measured rainfall is often regarded as the true or reference rainfall. However, inaccurate rainfall estimates based on rain gauges are due to inadequate spatial coverage or configuration and inadequate gauge density especially in mountainous regions (Borga, 2002). Satellites are an attractive alternative to observe rainfall at global scale from the space with large spatial and temporal resolution. However, it is difficult to apply satellite

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rainfall in small scale basins (less than 10^3 km^2) and in real time operation (Linsley et al., 1988; Collier, 1996). In addition to that, the accuracy of satellite rainfall estimation decreases when the time scale is reduced (i.e., from monthly to daily to sub-daily). Weather radar overcomes some of the disadvantages associated with rain gauges and satellites as it provides a rain field with high spatial and temporal resolution and large areal coverage. Also, it measures rainfall closer to the ground level than the satellite. Application of radar measured rainfall in hydrological and environmental modeling, including real-time hydrological forecasting, has become an active area of research by hydrologists (Collinge and Kirby, 1987; Bell and Moore, 1998; Sun et al., 2000; Vieux, 2003).

In measuring rainfall by radar, $Z-R$ relationships are widely used to convert radar measured reflectivity to rainfall intensity, hence the accuracy of the estimation of $Z-R$ relationship is important (Rosenfeld et al., 1993; Collier, 1996; Atlas et al., 1997). The true radar reflectivity (Z), which can be measured by distrometer, is determined based on the drop size distribution (DSD) of rainfall and is related with rainfall intensity (R) to estimate the true $Z-R$ relationship (Atlas, 1964; Battan, 1973). However, non-availability of raindrop size distribution information restricts the determination of the true $Z-R$ relationship based on DSD.

Chlheriros and Zawadzki (1987) and Rosenfeld et al. (1990) applied a regression analysis technique to determine the relationship of synchronous datasets between measured rainfall intensity by rain gauge and measured or effective reflectivity by weather surveillance radar (Z_e) at the pixel over the rain gauge (defined as the traditional matching method, TMM, in this paper). However, in reality perfect synchronization between Z_e and R is unachievable, except at the closest range and nearest to the ground. The non-synchronous Z_e-R pairs are due to: 1) the large discrepancy between the sample volume of the rain gauge and the radar, 2) timing and geometric mismatches, and 3) the large variability of the $Z-R$ relationships mainly due to differences of rainfall characteristics, locations and times (Joss et al., 1970; Battan, 1973; Chumchean, 2004). These problems reduce the accuracy of Z_e-R conversion for radar rainfall estimates.

To overcome these problems in TMM, the probability matching method (PMM) was developed to match non-synchronous datasets of Z_e and R using cumulative density functions (CDF) (Chlheriros and Zawadzki, 1987; Atlas et al., 1990; Rosenfeld et al., 1993). The PMM eliminates the sampling volume, collocation and timing errors by matching Z_e and R pairs of non-synchronous Z_e and R datasets that have the same CDF. This method provides better results in estimating Z_e–R relationships for non-synchronous Z_e and R datasets as compared to TMM (Atlas et al., 1997). However, Krajewski and Smith (1991) found that TMM is still significantly superior, providing much higher rain estimation accuracy, as compared to PMM for estimating Z_e–R relationships of synchronous Z_e–R pairs. The advantage of PMM is that there is no requirement of concurrent Z_e and R datasets while the disadvantages are that this technique does not represent the real physical process of rainfall and it does not use joint probability between Z_e and R datasets.

The accuracy of radar rainfall estimates is particularly important when these estimates must be computed as input to a hydrological model (Borga, 2002). The Z_e–R conversion error is an important issue which affects the accuracy of the estimation of Z_e–R relationship and radar- measured rainfall. In order to minimize synchronization and collocation uncertainties in Z_e–R pairs matching and to address the shortcomings of PMM, this study aimed to develop a method to improve estimation of the Z_e–R relationships of non-synchronous Z_e–R pairs by accounting collocation and timing errors. This developed method is compared with other two methods, namely TMM and PMM. The accuracy of radar rainfall estimates is evaluated using rain gauge-based estimates of point rainfall and mean areal rainfall. The area in this study is a mountainous watershed in the north of Thailand where rain gauge observations are available from a dense rain gauge network and digital radar data is available from a weather radar installed in the vicinity.

2 Study area and data collection

2.1 Description of the study area

The study area, Mae Chaem Watershed is located in the north of Thailand with a geographical area of 3853 km^2 (Fig. 1). The study watershed is contained within 18°06′–19°10′ N and 98°04′–98°34′ E which comprises mountainous and forested terrain. The highest point in the Mae Chaem Watershed is the Doi Inthanon summit, 2565 m above the mean sea level, the highest altitude in Thailand. The lowest point in the watershed is 282 m above the mean sea level. The water flows through the Mae Chaem Watershed areas for 135 km before joining the Ping River, one of the tributaries of the Chao Phraya River, the main river of Thailand. Rainfall in this region is characterized by a large seasonal and inter-annual variation. The average annual rainfall in the study area varies from 1000 to 1200 mm and more than 80% of it occurs during the southwest monsoon and tropical cyclones. Kuraji et al. (2004) and Dairaku et al. (2002) reported that the rainfall in the Mae Chaem Watershed is orographic. The average annual runoff at the watershed outlet is 1075×10^6 m^3 and about 70% of it occurs during the rainy season from May to October.

2.2 Gauge and radar data

The GEWEX Asian Monsoon Experiment - Tropics (GAME-T) project from 1996–2001 established a rain gauge network in the Mae Chaem Watershed to observe rainfall in this mountainous area since 1997 (Kuraji et al., 1998). Automatic tipping bucket type rain gauges (20 cm orifice diameter and 0.5 mm per tip) with pulse-count time-recording data loggers (one second time resolution) were installed at 13 sites in the watershed. At the outlet of the watershed (Fig. 1), a river flow gauging station (P.14) is also being operated by the Royal Irrigation Department (RID) of Thailand.

Radar data in this research was obtained from the meteorological radar installed in 1991 on top of a mountain at Om Koi (17°47′53′′ N, 98°25′57′′ E) in northern Thai-

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land (Fig. 1). The Bureau of the Royal Rainmaking and Agricultural Aviation, Thailand, operates the Om Koi Radar station for routine observations. The radar is an S-Band Doppler weather surveillance radar system (DWSR-88S model), with the following principal characteristics: frequency 2.7–2.9 GHz, wavelength 10.8 cm, peak power 500 kW, antenna diameter 6.1 m and beam width 1.2°. The data was obtained at 5 min interval with a 250 km observation range, 1 km radial resolution, and 1° azimuthally resolutions. The radar reflectivity data used in this study was extracted from the CAPPI (Constant Altitude Plan Position Indicator) radar product at an elevation of 3.0 km above the mean sea level.

The continuous gauge record of rainfall during 15–18 September 1999 at each of the 13 rain gauges is used to calculated rain intensity values of 5 min duration and they are paired with the corresponding 5 min reflectivity values measured by radar for determining the Z_e–R relationship. All the rainfall events within the 86 h of 13 individual rainfall measuring sites are used to develop the representative Z_e–R relationship for the whole study watershed of 3853 km^2. Table 1 presents the characteristics of rainfall observed at the 13 rain gauge stations in the study watershed.

3 Z_e–R matching techniques

3.1 Traditional matching method (TMM)

The approach of TMM is matching the value of Z_e over a rain gauge station with R at the corresponding time of measurement (Fig. 2). This method assumes that the raindrops fall absolutely vertical from the atmosphere to the rain gauges and the radar rain intensity at the measured altitude is the same as at the surface (Chlheriros and Zawadzki, 1987).

3.2 Probability matching method (PMM)

The probability matching method was proposed by Chlheriros and Zawadzki (1987) to bypass sampling volume, timing and collocation problems in radar-gauge point comparison. In PMM, it is assumed that the radar observed reflectivity has the same probability of occurrence as the gauge-measured rain intensity (Atlas et al., 1990; Rosenfeld et al., 1993). The setting of Z_e–R pairs using this method is therefore based on matching CDF of gauge rainfall intensities and radar measured reflectivity values as described in Eq. (1) and shown in Fig. 3.

$$\int_{R_i}^{\infty} P(R)dR = \int_{Z_{ei}}^{\infty} P(Z_e)dZ_e, \tag{1}$$

where $P(R)$ is the probability density function of gauge-measured rainfall intensities and $P(Z_e)$ is the probability density function of measured reflectivity values by radar. To construct CDF of Z_e and R, the datasets of Z_e and R are determined as explained earlier in TMM. R_i and Z_i having the same CDF values are matched as pairs and then these pairs are used to determine the Z_e–R relationship. This method eliminates timing errors because PMM does not make use of the actual time at which each pair of R and Z_e occurred and the geometric errors are eliminated as long as raindrops at the radar pixel over the rain gauge fall absolutely vertical. However, the disadvantage of PMM is that this method does not consider the joint distribution or inter-association between Z_e and R.

3.3 Window correlation matching method (WCMM)

WCMM was developed to match Z_e–R pairs when collocation and timing errors are present (non-synchronous Z_e–R datasets). These errors are caused by wind and the height of radar measurement, respectively. This method attempts to account for the physical process of rainfall as the raindrops rarely fall absolutely vertically due to wind effects, and also radar measurements are taken at a height much higher than the ground, therefore it is necessary to consider the travel time of raindrops. The concept of this method is the extension of possible matching areas of Z_e from the traditional matching method for searching and finding optimal Z_e that gives the best correspondence with R. The possible matching areas in this method consist of the space and time windows as shown in Fig. 4. The purpose of the space window is to reduce geometric mismatch that is affected by wind, while the time window is to account for timing error which is mainly affected by the height of radar measurement.

The process of WCMM consists of matching Z_e values within the space and time windows to reference gauge rainfall intensity and searching the value of Z_e of the radar pixel that gives the maximum correlation coefficient (r) as expressed in Eqs. (2) and (3). This Z_e value is then assigned to match the reference gauge rainfall intensity. This Z_e–R pair is called "The optimal Z_e–R pair".

$$r = \frac{\mathrm{cov}Z_eR}{s_{Ze}s_R}, \tag{2}$$

$$\mathrm{cov}Z_eR = \frac{\sum_{i=1}^{n}((Z_i - \overline{Z_e}) \times (R_i - \overline{R}))}{(n-1)}, \tag{3}$$

where Z_i is Z_e value of non-zero Z_e–R pair i, $\overline{Z}$ is the mean value of Z_e data, R_i is R value of non-zero Z_e–R pair i, $\overline{R}$ is the mean value of R data, S_{Ze} is the standard deviation of Z_e data, S_R is the standard deviation of R data and n is the number of non-zero Z_e–R pairs over the 86 h of the 13 rain gauge sites. The WCMM process is illustrated in Fig. 5. The size of the space and time windows must be large enough to account for collocation and timing errors.

For the value of r=1, the Z_e–R pairs are perfectly synchronized, while a value of r=0, means that the Z_e–R pairs do not have a relationship at all. The WCMM allows matching the values of Z_e of the radar pixels surrounding the reference rain gauge or measured in the previous time intervals with R.

4 Evaluation of Z_e–R relationships

4.1 Comparison of various WCMM scenarios

Twelve WCMM scenarios were investigated in this study for matching Z_e–R pairs and identifying the optimal Z_e–R pairs. The sizes of the space windows used were 3×3, 5×5, 7×7 and 9×9 radar grid pixels which cover an area of 9, 25, 49 and 81 km^2, respectively, above the rain gauges. The time windows of radar measurements were set to three sizes which consist of present time that is at the same time as rain gauges measurement (0 min), a combination of present time and 5 min previous time (0 and −5 min) and a combination of present time, 5 and 10 min previous times (0, −5 and −10 min). These scenarios are defined in Table 2. The number of Z_e values for finding optimal Z_e that gives the best correspondence with R with respect to the given space and time windows are presented in parenthesis in Table 2.

Fifteen rain intensity values of 5 min duration which vary from 0.5 to 7.5 mm/5 min (6 to 90 mm/h) with the increment of 0.5 mm/5 min (6 mm/h) were considered over the 86 h period with the 13 rain gauges stations. This gave a total of 627 non-zero Z_e–R pairs. The scatter plots of these Z_e–R pairs for the twelve WCMM scenarios are depicted in Fig. 6. It is found that when the space and time window size is increased, the degree of scatter of Z_e–R pairs reduces. However, it can be seen that the scatter plot of the 9×9 km of the space window (S99) has no significant improvement as compared to the 7×7 km of the space window (S77). Similarly, the increase in time window from 5 to 10 min previous time also has not reduced the degree of scatter of Z_e–R pairs. The degree of fitness of the relationship of Z_e–R pairs based on various WCMM scenarios was measured in terms of correlation coefficient (Eqs. 2 and 3) and the results are presented in Table 3.

The r values increase significantly when the space window in WCMM is expanded from 3×3 to 5×5 km for the different time windows considered. The percentage increase varies from 10.68–28.88%. However, the r values have slightly increased when the space window is enlarged to 7×7 km. The change is about 2% as compared to 5×5 km of the space window. Further increase in the space window to 9×9 km has very small increase in the *r* values. On the other hand, when the time widow is extended from present time to previous 5 min of radar measurement, the *r* values have increased slightly except in the S33T5 scenario (Table 2) where an increase of 18.79% as compared with S33T0 is observed. The increases in r values for the other scenarios are about 2–3%. The results indicate a small increase in *r* values when previous 10 min of radar observation is added in the time window of WCMM. The increase in the *r* values is less than 0.5%. The use of 9×9 km of the space window and previous 10 min of radar observations in the time window has no significant improvement in the relationship of Z_e–R pairs. Based on the results, it can be concluded that when the space and time window size of WCMM are increased, the relationship between Z_e and R is improved. Moreover, the S77T5 scenario (using a 7×7 km of the space window and a combination of present time and previous 5 min radar scan in time window) is sufficient to correct collocation and timing errors in Z_e–R pairs.

4.2 Estimation of *a* and *b* parameters in Z_e–R relationship

The relationship between Z_e–R is usually represented in term of empirical power law equation (Marshall and Palmer, 1948; Joss et al., 1970; Collier, 1996; Rosenfeld et al., 1993) as below,

$$Z_e = aR^b, \tag{4}$$

where Z_e is measured radar reflectivity in mm^6/m^3, R is rainfall intensity in mm/h, and *a* and *b* are parameters. The parameters *a* and *b* in the power law equation were estimated for different WCMM scenarios and the results are presented in Table 4.

Table 4 indicates that with increase in space and time window size of WCMM, the value of parameter *a* decreases whereas the value of parameter *b* increases. However, parameter *b* does not vary much as compared to parameter *a*. Moreover, the values of parameters *a* and *b* remain nearly the same when the space window is expanded from 7×7 km to 9×9 km and also when the time window is extended from previous 5 min to 10 min of radar measurement. It can be said that increasing the space window to 9×9 km and adding the previous 10 min of radar observation in the time window in WCMM has no significant change in the values of parameters a and b in $Z_e - R$ relationship considered in the study. These results also suggest that 7×7 km of the space window and a combination of present time and previous 5 min radar scan in time window in WCMM can account for collocation and timing errors that occurred due to wind effects and the difference in height of measurements by radar and rain gauges.

4.3 Comparison of radar- and gauge-measured rainfall

In order to find out which space and time window sizes in WCMM give the best results for radar rainfall estimates as compared with the gauge rainfall, the performances of estimated $Z_e - R$ relationships from different WCMM scenarios are also evaluated in this study with two approaches described in the following sections.

4.3.1 Point rainfall estimates

The estimations of radar rainfall intensities of 5 min duration over 13 rain gauges in the Mae Chaem Watershed using the estimated $Z_e - R$ relationships for different WCMM scenarios were compared with the observed gauge rainfall intensities as point rainfall measurements. The performance of different estimated $Z_e - R$ relationships was evaluated using the mean absolute error (MAE) as expressed below,

$$\mathrm{MAE} = \frac{1}{n} \sum_{i=1}^{n} |R_i - G_i|, \quad (5)$$

where R_i is radar rainfall intensity in mm/h or total depth of radar rainfall in mm, G_i is gauge rainfall intensity in mm/h or total depth of gauge rainfall in mm and n is the number of data pairs. The results of MAE are presented in Table 5. It is seen that the increase in the space window in WCMM from 3×3 to 5×5 and 7×7 km decreases MAE of radar-measured rainfall. However, further increase to 9×9 km has no improvement in MAE for all the time window scenarios analyzed. Furthermore, when the time window in WCMM is extended from present time to previous 5 min, MAE also reduces. However, relatively much less reduction in MAE is observed when previous 10 min of radar observation in the time widow is considered compared to the present time and previous 5 min of radar scan in the time widow in WCMM.

In addition, the total depths of rainfall of 13 rain gauges over 86 h are compared with radar rainfall estimates using MAE statistic (Eq. 5) as also presented in Table 5. The results are similar to the comparison of radar and gauge rainfall intensity. The enlargement of space and time windows from 3×3 to 7×7 km and present time to previous 5 min improves the estimation of Z_e-R relationship and radar rainfall. Using 9×9 km of space window and previous 10 min of radar scanning in time window also has no significant reduction in MAE. Therefore, in this study, it can be concluded that the Z_e-R relationship estimated based on S77T5 provides the best estimates of point radar rainfall as compared with the rain gauge data with MAE of 6.59 mm/h for rainfall intensity and 8.56 mm for the total rainfall depth.

4.3.2 Mean areal rainfall estimates

A comparison of cumulative mean areal rainfall (CMAR) estimates over the whole area of the Mae Chaem Watershed during 15–18 September 1999 (86 h) obtained using the Thiessen polygon technique with 13 rain gauges data (dense rain gauge network) and from the radar data using the different Z_e-R relationships that are estimated based on several WCMM scenarios (Table 4) is presented in Table 6. The percentage difference of cumulative mean areal rainfall (PD_{CMAR}) between the radar and the rain gauge data is determined using Eq. (6) and the results are also given in Table 6.

$$PD_{CMAR}(\%)=\frac{\left(CMAR_{radar}-CMAR_{gauge}\right)}{CMAR_{gauge}}\times 100 \tag{6}$$

In Eq. (6), $CMAR_{radar}$ and $CMAR_{gauge}$ are the cumulative mean areal radar and guage rainfall, respectively, in mm. The positive and negative values of PD_{CMAR} mean that cumulative mean areal radar rainfall is overestimated and underestimated, respectively, compared to the estimates based on the Thiessen polygon technique using the 13 rain gauges data. Among the WCMM scenarios, the results from S77T5, S77T10, S99T5 and S99T10 are closest to the estimates based on rain gauge data with a difference of only −3% over a period of 86 h. Again, from these results, it is concluded that increasing in the space window from 7×7 to 9×9 km and extending the previous 10 min of radar measurement in the time window in WCMM causes no significant improvement in the mean areal radar rainfall estimates. From these results, it is also confirmed that the S77T5 scenario provides the best results of radar measured rainfall in the present study.

4.4 Comparison of Z_e–R pair matching techniques

The Z_e–R relationship estimated from S77T5 is compared with those estimated from the other two techniques, namely TMM and PMM. The Z_e–R pairs scatter plot of TMM is shown in Fig. 7a. It can be seen that Z_e is poorly related to R with r of 0.376. The Z_e and R datasets of TMM were used in PMM to determine the CDF of gauge rainfall intensities and measured radar reflectivity data. The Z_e and R that have the same CDF values are matched as pairs as shown in Fig. 7b. Regression analysis was used to estimate the parameters$a$ and b of the empirical formula of Z_e–R relationship for TMM and PMM and the results are presented in Table 7. The performance of the Z_e–R relationships derived from the three matching techniques was evaluated in terms of point rainfall and mean areal rainfall estimates by comparing them with the rain gauge data (see Sect. 4.3). The analysis results are also given in Table 7.

The estimated Z_e–R relationship from TMM gives the largest MAE of 63.10 mm/h and 108.94 mm in point radar rainfall estimates, as compared to the estimates based on the other two methods, due to unsynchronized Z_e–R pairs used in TMM (Fig. 7a). The Z_e–R relationship by PMM provides improved estimates of point rainfall compared to those based on TMM. However, the Z_e–R relationship determined based on S77T5 gives the best results of point rainfall estimates.

The cumulative mean areal rainfall estimates based on different Z_e–R pair matching techniques and rain gauges data are compared in Fig. 8. The cumulative mean areal rainfall based on the radar data using Z_e–R relationship obtained from TMM is much overestimated, a value of 216.0 mm compared to 72.9 mm with the Thiessen polygon method using 13 rain gauges data. The cumulative mean areal rainfall based on PMM is underestimated with the percentage difference of −39.6% when compared with the Thiessen polygon method. The Z_e–R relationship determined based on S77T5 shows only −3% differences in the cumulative mean areal rainfall estimates as compared with the estimates based on rain gauge data.

5 Conclusions

In this study, a method called window correlation matching method (WCMM) was developed to correct collocation and timing errors in Z_e–R pair matching to reduce Z_e–R conversion error in radar-measured rainfall. This method was compared with other two methods, namely the traditional matching method (TMM) and the probability matching method (PMM). The investigations were based on 5 min rain gauge and radar data of orographic rain occurring during 15–18 September 1999 over the Mae Chaem watershed in the north of Thailand.

In order to find out which space and time windows in WCMM give the best results for radar rainfall estimates, the size of the space and time windows was varied. The comparison among various WCMM scenarios shows that when the space and time window sizes are increased, the relationship between Z_e and R improves. Using 7×7 km of space window and a combination of present and 5 min previous time of radar observation in the time window (S77T5) provides the best correlation in the matching of Z_e–R pairs. The variation of the space and time widow sizes also affects the accuracy of the estimation of Z_e–R relationship. The relationship Z_e=18.05 $R^{1.45}$ obtained from

S77T5 gives the best results of point rainfall estimates with MAE of 6.59 mm/h for rainfall intensity and 8.56 mm for the total depth of rainfall. Also, this Z_e–R relationship provides the best estimation of mean areal radar rainfall with the percentage difference of cumulative mean areal rainfall of −3% as compared with the gauge rainfall. These results confirm that S77T5 is large enough to account for collocation and timing errors in Z_e–R pair matching that occur due to wind effects and the difference in height of measurement of rainfall by radar and rain gauges.

The Z_e–R relationship obtained from TMM provides poor estimation of radar rainfall because of geometrical mismatch and timing errors. The PMM improved the radar rainfall estimates compared to TMM because PMM is based on probability density functions of radar reflectivity values and gauge-measured rainfall intensities which are derived from the observations. However, this method does not consider the joint probability between Z_e and R. From the comparison among the three Z_e–R pair matching techniques, it can be concluded that the Z_e–R relationship obtained from WCMM provides better estimates of point rainfall and mean areal rainfall than TMM and PMM.

Further, the development of WCMM attempts to represent the real physical process of rainfall as the raindrops rarely fall absolutely vertically due to wind effects and also radar measurements are taken at a height much higher than the ground so raindrops take time to reach to the ground. However, this matching technique does not take into account the error of variation of measured reflectivity in vertical profile which is a further area of research. WCMM is therefore a promising method for improved real time radar-measured rainfall input for hydrological and environmental modeling in watersheds, especially those lacking rain gauge data or completely ungauged.

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Table 1. Characteristics of rainfall observed at 13 rain gauges in the study watershed.

Period	15–18 September 1999
Rain type	Orographic
Duration (h)	86
Maximum gauge-measured rain intensity of 5 min duration (mm/h)	90.0
Maximum gauge-measured rain intensity of 1 h duration (mm/h)	38.5
Accumulated gauge mean areal rainfall by Thiessen polygons (mm)	72.9

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Table 2. WCMM scenarios analyzed and the number of Z_e values.

Space window (km)	Time window (min) 0	0, −5	0, −5, −10
3×3	S33T0 (9)	S33T5 (18)	S33T10 (27)
5×5	S55T0 (25)	S55T5 (50)	S55T10 (75)
7×7	S77T0 (49)	S77T5 (98)	S77T10 (147)
9×9	S99T0 (81)	S99T5 (162)	S99T10 (243)

Note: The figure in parenthesis is the number of Z_e values considered in the analysis.

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Table 3. Correlation coefficient of Z_e–R pairs for different WCMM scenarios.

Space window (km)	Time window (min) 0	0, −5	0, −5, −10
3×3	0.644	0.765	0.769
5×5	0.830	0.848	0.850
7×7	0.845	0.868	0.870
9×9	0.846	0.869	0.870

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Table 4. Parameters *a* and *b* in Z_e–R relationship (Eq. 4) for different WCMM scenarios.

Space window (km)	Time window (min)					
	0		0, −5		0, −5, −10	
	a	*b*	*a*	*b*	*a*	*b*
3×3	42.44	1.157	30.59	1.298	30.48	1.302
5×5	26.35	1.305	19.04	1.422	19.00	1.424
7×7	18.60	1.423	18.05	1.450	18.02	1.451
9×9	18.58	1.425	18.04	1.450	18.02	1.451

Table 5. Mean absolute error (MAE) in rainfall intensity and rainfall depth for different WCMM scenarios.

Space window (km)	Time window (min)					
	0		0, −5		0, −5, −10	
	Rain intensity (mm/h)	Rain depth (mm)	Rain intensity (mm/h)	Rain depth (mm)	Rain intensity (mm/h)	Rain depth (mm)
3×3	13.81	48.14	9.41	29.79	9.32	27.32
5×5	9.15	22.28	7.58	12.42	7.50	12.36
7×7	7.80	13.31	6.59	8.56	6.58	8.54
9×9	7.78	13.27	6.59	8.56	6.58	8.54

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Table 6. Cumulative mean areal rainfall (CMAR) and PD_{CMAR} for different WCMM scenarios.

Space window (km)	Radar, Time window (min): 0, CMAR (mm)	0, PD_{CMAR} (%)	0, −5, CMAR (mm)	0, −5, PD_{CMAR} (%)	0, −5, −10, CMAR (mm)	0, −5, −10, PD_{CMAR} (%)	Rain gauge (mm)
3×3	83.8	15.0	78.6	7.8	78.3	7.4	
5×5	80.5	10.4	75.4	3.4	75.2	3.2	
7×7	76.9	5.5	70.7	−3.0	70.7	−3.0	72.9
9×9	76.8	5.3	70.7	−3.0	70.7	−3.0	

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Table 7. Performance of Z_e–R relationships by different Z_e–R pair matching techniques.

Z_e–R matching method	Parameter		MAE		CMAR	PD_{CMAR}
	a	*b*	(mm/h)	(mm)	(mm)	(%)
TMM	45.85	0.861	63.10	108.94	216.0	196.3
PMM	95.52	1.134	11.30	34.28	44.0	−39.6
S77T5WCMM	18.05	1.450	6.59	8.56	70.7	−3.0

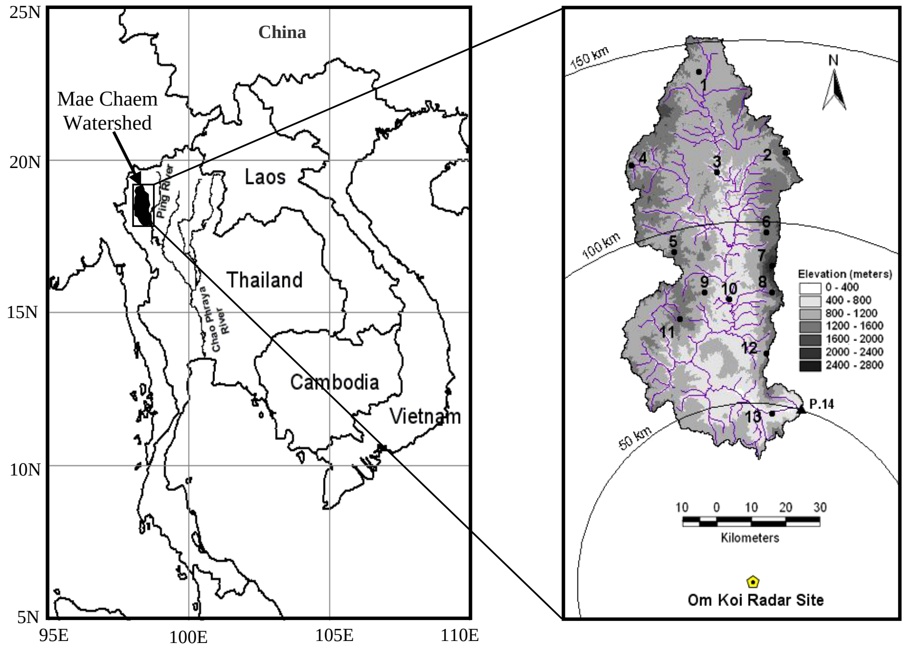

Fig. 1. Mae Chaem Watershed and locations of radar and gauge stations.

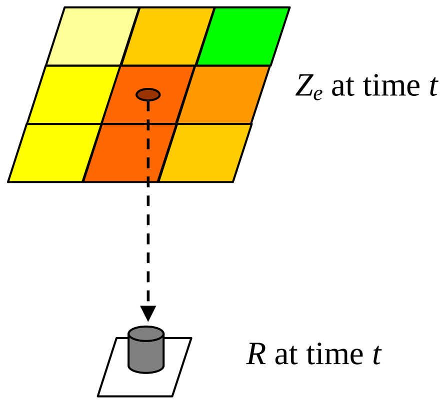

Fig. 2. The traditional $Z_e - R$ matching method (TMM).

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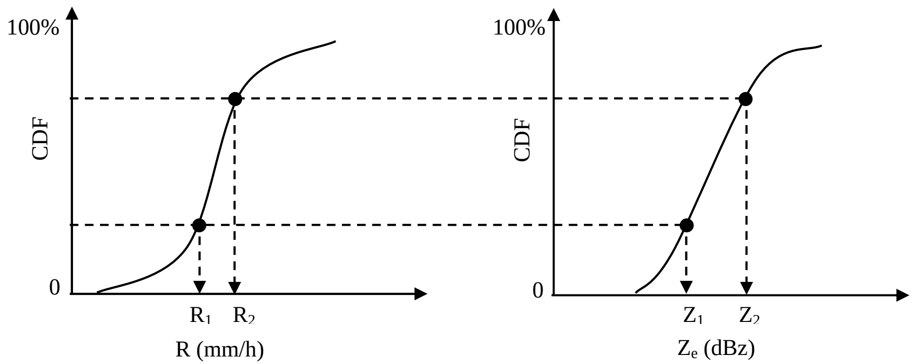

Fig. 3. The probability matching method (PMM).

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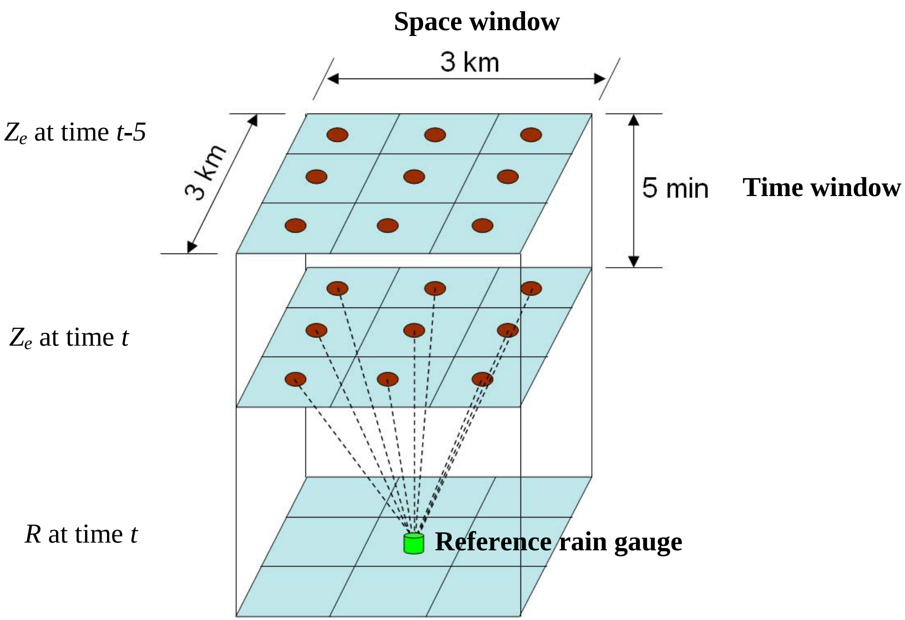

Fig. 4. The concept of window correlation matching method (WCMM).

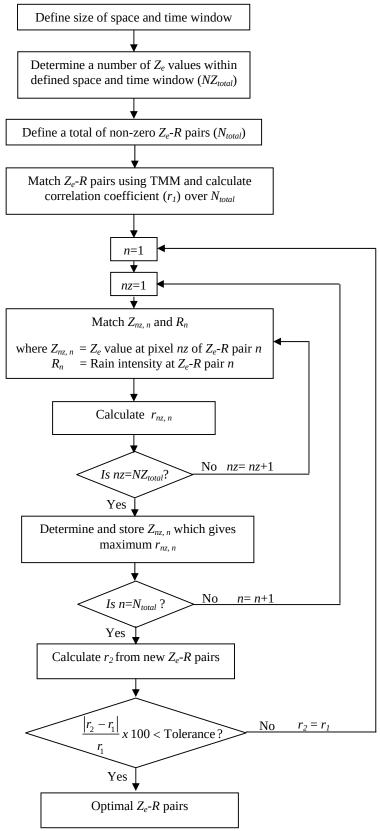

Fig. 5. The WCMM process.

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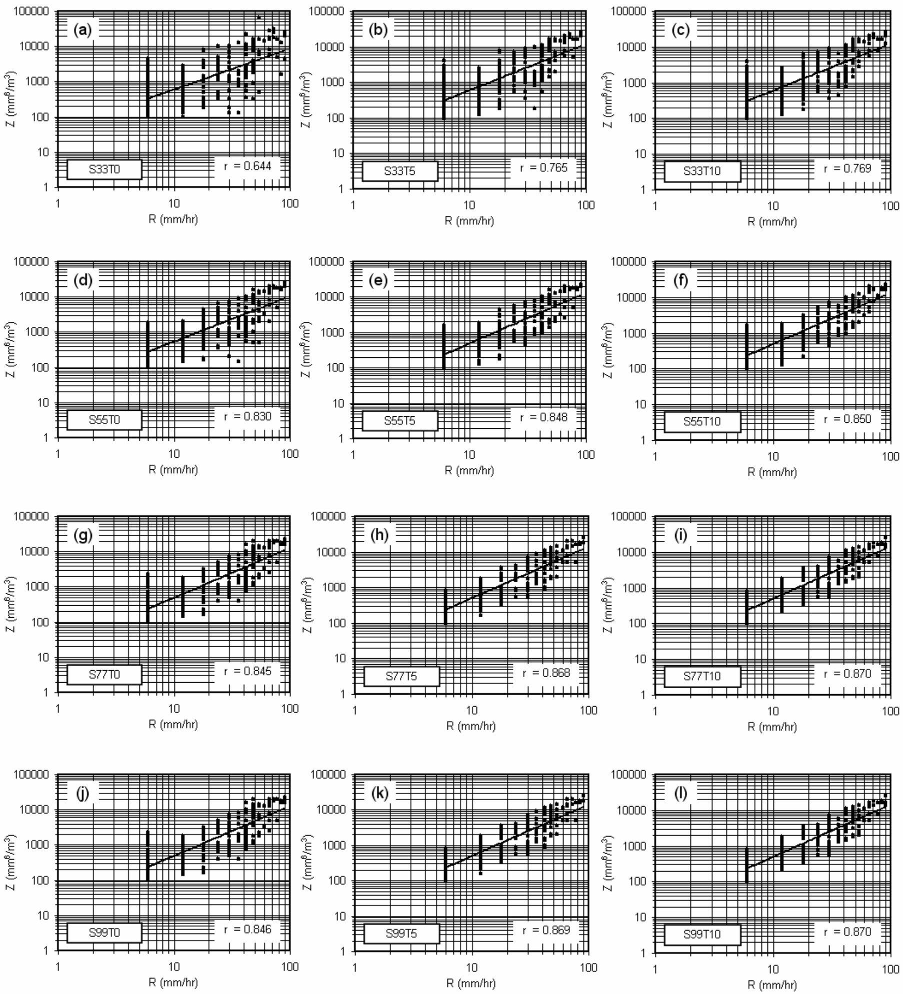

Fig. 6. Scatter plots of Z_e-R pairs for different WCMM scenarios during 15–18 September 1999.

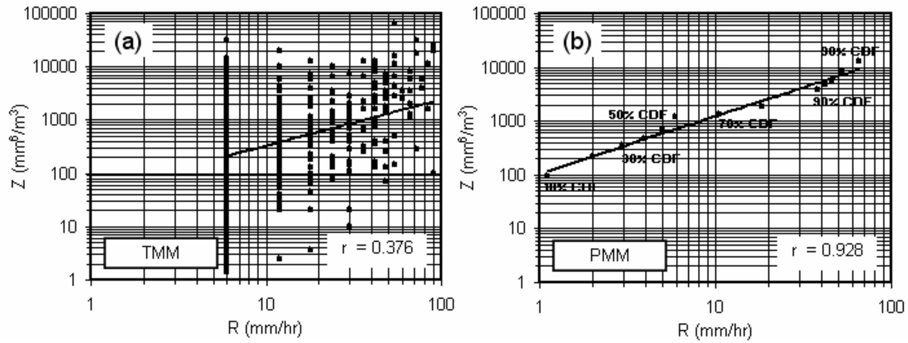

Fig. 7. Scatter plot of Z_e–R pairs based on TMM **(a)** and PMM **(b)** during 15–18 September 1999.

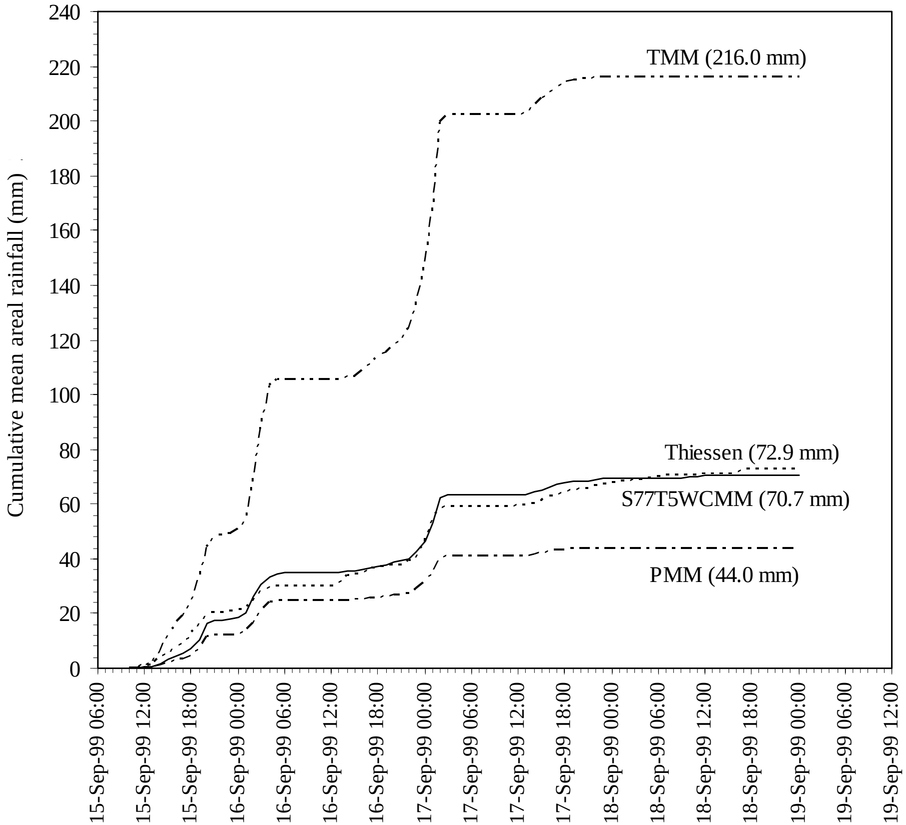

Fig. 8. Cumulative mean areal rainfall estimates based on different Z_e–R pair matching techniques.

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