

Combining radar and rain gauge rainfall estimates for flood forecasting using conditional merging method

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Abstract

Radar rainfall estimates are increasingly applied to flood applications. Early warning with the use of radar rainfall estimates and hydrologic models is crucial for minimizing flood and flash flood-related hazard. The strength of radar rainfall data, the ability to capture spatial rainfall information, is the weakness of rain gauge data and the weakness of radar rainfall data, inability to accurately capture rainfall amounts at a single location, is the strength of rain gauges. Therefore By merging the two datasets, the result is gauge adjusted radar rainfall data, a dataset that maintains volume accuracy at the gauge locations while retaining spatial information from Radar. The main idea of gauge adjustment is combine the individual strengths of the to measurement systems.

In this paper describes a short overview over the gauge adjustment methods applied in operational fields. And the technique employed is a conditional merging technique(CM). To evaluate the this method, statistics and hyetograph for rain gauges and radar rainfalls are compared using hourly radar rainfall data from the Imjin-river, Gangwha, rainfall radar site. Results show that rainfall field estimated by Condional Merging method give the best results in a statistics and qualitative way.

Keyword: Radar, Radar rainfall, Conditional merging, Gauge rainfall, Flood forecating

1. INTRODUCTION

Among various input data to hydrologic models, rainfall measurements arguably have the most critical influence on the hydrologic model's performance. Therefore, the most significant input a hydrologic model is a rainfall volume. Traditionally, hydrologic model have relied on point gauge measurements to provide the rainfall data. For years, hydrologists and engineers have tried to infer rainfall volume over a watershed by spatially interpolating point rainfall data from sparsely placed rain gauges. Rainfall distributions from rain gauges are typically estimated by assuming a spatial geometry tied to point rain gauge observations using, for example, Thiessen polygons, Inverse distance squared weighting or Kriging technique. Unfortunately, the spatial distributions inferred by these rainfall estimation techniques have little connection with how rain actually falls, too often, these estimation techniques put the wrong amount of rainfall in the wrong place at the wrong time. So what is the best way to get an accurate view of the volume of rainfall falling over a watershed? Theoretically, you could place enough gauges to completely eliminate errors in the spatial interpolation of rainfall, but that would be prohibitively expensive. A better solution is to use radar rainfall estimates from RADAR in conjunction with the existing rain gauge network.

The use of radar rainfall data for hydrologic model has been motivated by the need to define and accurately measure the spatial rainfall field and potential provision of short-term quantitative rainfall forecasts. Especially, Radar rainfall estimates are increasingly applied to flood forecasting. Early warning with the use of radar rainfall estimates and hydrologic models is crucial for minimizing flood and flash flood-related hazard. The strength of radar rainfall data, the ability to capture spatial rainfall information, is the weakness of rain gauge data. And the weakness of radar rainfall data, inability to accurately capture rainfall amounts at a single location, is the strength of rain gauges. Therefore by merging the two datasets, the result is gauge adjusted radar rainfall data, a dataset that maintains volume accuracy at the gauge locations while retaining spatial information from Radar. The main idea of gauge adjustment is combine the individual strengths of the to measurement systems.

In this paper describes a short overview over the gauge adjustment methods applied in operational fields. And the technique employed is a conditional merging technique(CM). To evaluate the this method, statistics and hyetograph for rain gauges and radar rainfalls are compared using hourly radar rainfall data from the Imjin-river, Gangwha, rainfall radar. Results show that rainfall field estimated by CM method gives the best results in a statistics and qualitative way.

2. Basic Concept of Radar Rainfall Adjustment and Current Research

Many researches are on going to estimate accurate spatially distributed rainfall. Steiner et al.(1999) report many sources of error in radar rainfall estimation, and they suggest adjustment of radar and rain gauge rainfall to remove error from wrong Z-R relation and radar such as beam blocking, attenuation, wrong radar calibration, VPR error. The exponent of Z-R equation is considered as a constant even though it has many errors (Steiner and Smith, 2000) and there is no correlation between the type of rainfall and the exponent (Amitai et al., 2002).
Understanding of radar rainfall adjustment is confused with radar calibration. Radar rainfall adjustment is a statistical process to estimate more accurate radar rainfall using comparison of gauge rainfall with radar rainfall while radar calibration is some kind of electromagnetic process to guarantee stability of radar observation. Radar rainfall adjustment can reflect meteorological condition such as type of rainfall, attenuation, variation of VPR. Several approximations were suggested to use radar rainfall adjustment(Koistinen and Puhakka, 1981).

(1) Gauge measurement are accurate for gauges,s locations
(2) Radar successfully measures relative spatial and temporal variabilities of rainfall (Hitchfeld and Bordan, 1954).
(3) Gauge and radar measurement are valid for the same location in time and space.

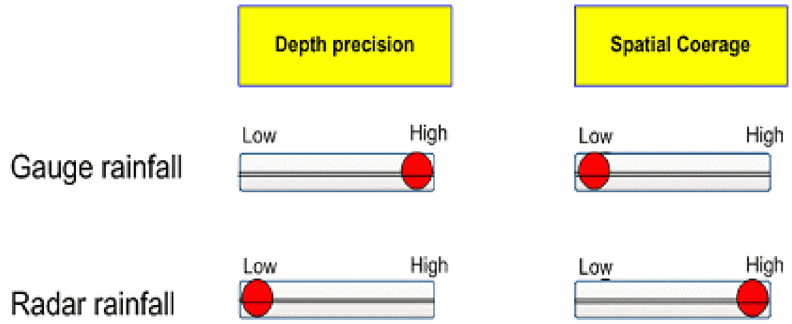


Figure 1. Comparison with Radar and Gauge Rainfall

Radar rainfall adjustment can classify "Gauge to Radar(G/R) ratio" method and "Sophisticated" method(Barbosa, 1994). Hitchfeld and Bordan(1954) insist that radar observation still needs gauge observation to make up for the weak point in the radar rainfall even if it can measure variation of rainfall in large area exactly. G/R method is generally used for supplementation of radar rainfall since developed. The first application of G/R method was carried out by Wilson and Brandes(1979) to correspond to cumulative radar and gauge rainfall. Wilson(1970) proved that information from gauge observation can make up accuracy of radar rainfall within 1,000mi^2.

Last 20 years radar rainfall adjustment is applied practically in England. Real time radar rainfall adjustment process system using radar rainfall and gauge rainfall was developed in online network(Collier et al., 1983) from the foundation project Dee Weather Radar Project(Harrold et al., 1973). Collier(1986b) reported using adjusted radar rainfall can get better result than using gauge rainfall only. The system has been using for FRONTIER system(Brown et al., 1991) and NIMROD(Golding, 1998) that using radar rainfall data for flood forecasting.

A kind of sophisticated method include optimal interpolation(Daley, 1991) and application of objective analysis well known as Kriging method(Krajewski, 1987; Seo, 1998; Pereira et al., 1998). Another form of the method is application of Kalman filter to estimate spatial bias of radar rainfall occurred when compared with gauge rainfall(Ahnert et al., 1986). The method using Kalman filter is applied to WSR-88D's rainfall estimation algorithm in USA to calculate mean field bias(MFB) using radar rainfall and gauge rainfall. The same algorithm as WSR-88D is used for practical operation such as input data for hydrologic model, complement of missing data of gauge observation in Czech Republic(Salek, 2000).

3. G/R Method and Conditional Merging Method

3.1 G/R Method

G/R method called MFB method that is used generally and Korea Meteorological Administration calculates correction factor f between gauge and radar rainfall to adjust radar rainfall. MFB method can classify single and multiple parameter gauge adjustment method. In this paper, just multiple parameter gauge adjustment method is mentioned.

To apply multiple parameter gauge adjustment method, the correction factor f is calculated each location of gauge using rainfall data and then the factor is used to adjust radar rainfall at every grid in radar umbrella. The method using multiple parameter gauge data is developed to get a better result than single parameter gauge data for radar rainfall adjustment. Multiple parameter method is using equation (1) to adjust radar rainfall and Figure 2 shows basic concept of the method.

$$\overline{C} = \frac{\sum \frac{C_i}{D_i}}{\sum \frac{1}{D_i}} \tag{1}$$

where, C_i is correction factor of each point, D_i is distance between gauge which gives C_i and radar grid. Equation (1) is a calculation method of correction factor using interpolation and equation (2) is a radar rainfall adjustment equation using correction factor.

$$R\_{adj} = R\_{ori} \times \overline{C} \tag{2}$$

where, R_{adj} is an adjusted radar rainfall using mean correction factor, R_{ori} is an unadjusted radar rainfall.

Point	1	2	3	4	5
Gauge Rainfall (G)	G_1	G_2	G_3	G_4	G_5
Radar Rainfall (R)	R_1	R_2	R_3	R_4	R_5
Correction Factor (C=G/R)	$C_1=G_1/R_1$	$C_2=G_2/R_2$	$C_3=G_3/R_3$	$C_4=G_4/R_4$	$C_5=G_5/R_5$

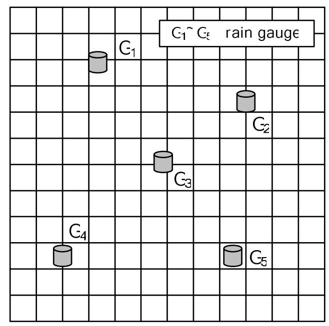


Figure 2. Radar Rainfall Adjustment Using Multiple Parameters

3.2 Conditional Merging Method

Hydrologist and Engineers have been interested to estimate spatially distributed rainfall using merging method from several observation system. In the early days, they focused in correction of rainfall bias using correction factor(Brandes, 1975) and prefer "adjustment" rather than "merging" in terminology. Through numerical experiment Krajeski(1987) suggested Co-kriging method and Seo(1998) presented spatially distributed rainfall using the method. Also Seo(1998b) estimated rainfall data using radar and gauge rainfall data in ungauged basin. Todini(2001) suggested Bayesian merging technique that connecting Kalman-filtering and Kriging method. The most difficult part of operational application of merging method was that estimate error structures of gauge and radar rainfall. It can be estimated from real time rainfall data supplementation and historic rainfall data analysis after assuming that rainfall data has stability.

Radar produces an unknown rainfall field observation. And it has many well known errors(Austin, 1987; Habib and Krajewski, 2002) but it still keeps real covariance of the rainfall field. The data from radar is used as a boundary condition of limited spatial information estimated using interpolation method of spaces between gauges. Using this method, the rainfall field that keeps both real rainfall field's structures and point rainfall data at gauges can be estimated. The first conditional merging method that estimates rainfall field's spatial structure from radar data and rainfall from merging of gauge rainfall and real rainfall field was suggested by Ehret(2002) and Pegram(2002). The method seems like ordinary Kriging method suggested by Chiles and Delfiner(1999), but the biggest difference is that radar data is used only for rainfall field not rainfall depth. This connection is started from the assumption that radar can measure exact spatial condition(structure) of rainfall not rainfall depth. Figure 3 shows flowchart of conditional merging method and figure 4 shows the main concept of the method. Equation (3) ~ (9) shows error structures of adjusted radar data estimated by conditional merging method.

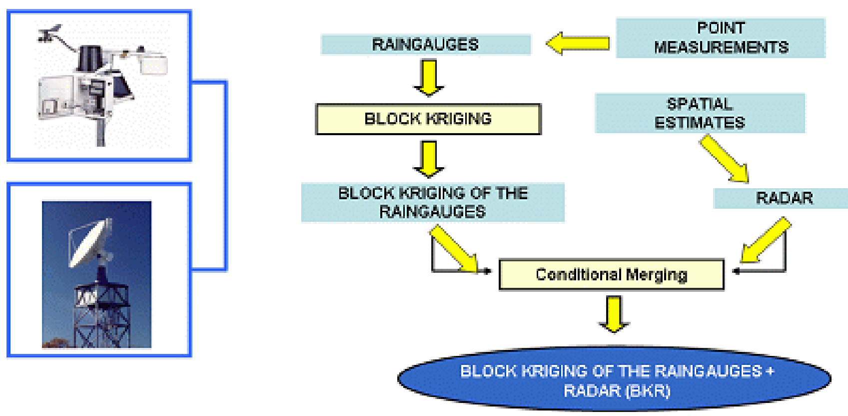


Figure 3. Flowchart of Conditional Merging Method

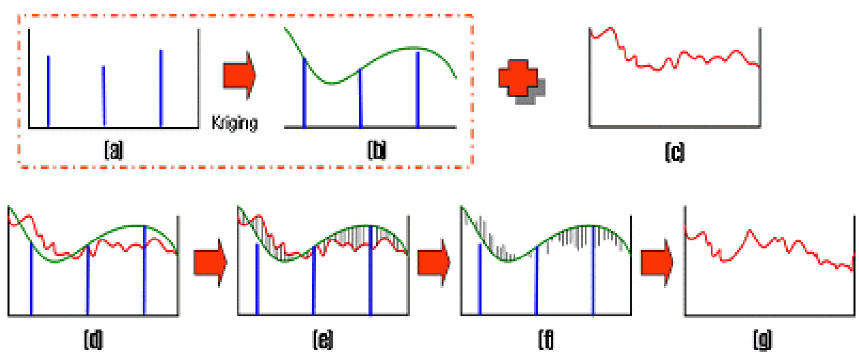


Figure 4. Main Concept of Conditional Merging Method (Pegram, 2002)

$$Z(s) = G_k(s) + [Z(s) - G_k(s)] \quad (3)$$

$$R(s) = R_k(s) + [R(s) - R_k(s)] \quad (4)$$

$$M(s) = G_k(s) + [R(s) - R_k(s)] \quad (5)$$

$$E[Z(s) - M(s)] = E[(Z(s) - G_k(s)) - (R(s) - R_k(s))] \quad (6)$$

$$\begin{aligned} var[Z(s) - M(s)] &= E\{[(Z(s) - G_k(s)) - (R(s) - R_k(s))]2\} \\ &= var[Z(s) - G_k(s)] + var[R(s) - R_k(s)] \\ &\quad - 2cov[(Z(s) - G_k(s))(R(s) - R_k(s))] \quad (7) \\ &= \beta(1 - \rho) \quad (8) \end{aligned}$$

$$\beta = var[Z(s) - G_k(s)] + var[R(s) - R_k(s)] \quad (9)$$

where, Z(s) is true rainfall field at locations, $G_k(s)$ is the Kriged (mean field) estimate of Z(s) from the rain gauge data, R(s) is the radar rainfall field, $R_k(s)$ is the Kriged (mean field) estimate of R(s) from the radar values at rain gauge locations, M(s) is the merged estimate of Z(s) and ρ is the correlation between $[Z(s) - G_k(s)]$ and $[R(s) - R_k(s)]$.

4. Application

4.1 Study Area and Radar Data

In this study, radar rainfall is estimated using Imjin-river rainfall radar data which is operated by Korea Ministry of Construction and Transportation(MOCT) to flood forecast in Imjin-river basin. The target area of the radar is the north of Imjin-river basin(a territory of North Korea) but a part of North Han-river and some small basins of Han-river basin such as Anseong-cheon, Yangyang-cheon, Kyeongan-cheon, Tan-cheon etc. are in radar umbrella. To select study area, it is considered that radar beam blocking, quality of hydro observation data, existence of flood alert system. And finally Anseon-cheon basin is selected for study area to examine validity of radar rainfall adjustment methods and it is shown in Figure 5.

Anseong-cheon basin that has 1699.6km^2 basin area and 66.4km river length lies middle-western part of Korea through N 36˚50´ ~ 37˚20´ and E 126˚50´ ~ 127˚00´. Selected rainfall events are 7/14/2002 00:00 ~ 7/15/2002 00:00, 7/22/2003 01:00 ~ 7/23/2003 23:00, 8/19/2003 10:00 ~ 8/20/2003 02:00 and 9/7/2003 03:00 ~ 9/8/2003 07:00. Table 1 shows summary of Imjin-river rainfall radar's characteristics and observation modes.

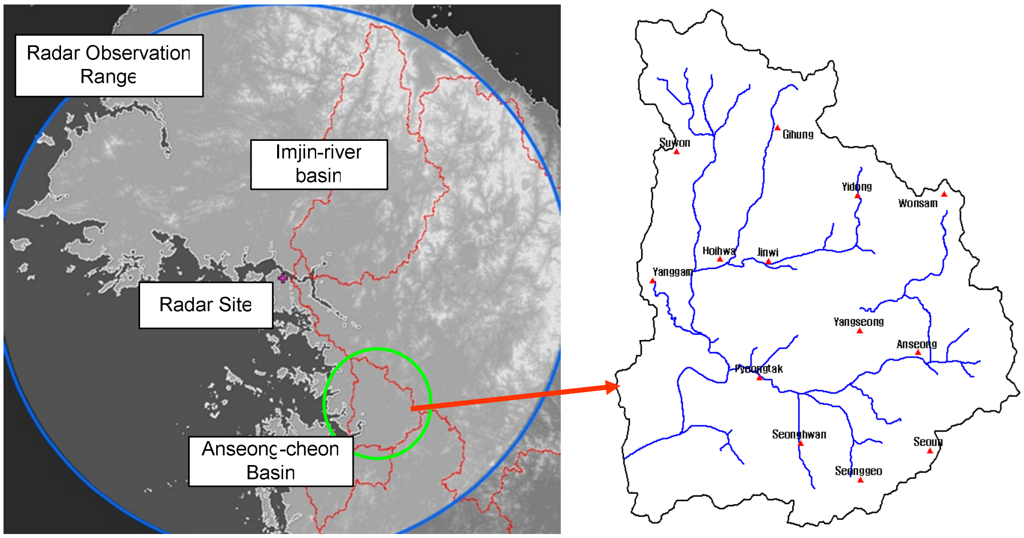


Figure 5. Anseong-cheon Basin

Table 1. Characteristics and observation mode of Imjin-river rainfall radar

Characteristics of Radar		Observation mode	
Radar	TDR-43250C (RADTEC(USA))	Scan Mode	Multi Elevation Volume Scan
Frequency	5.645GHz	Elevation Number	12(0.4°~2.2°)
PW/PRF	2μs / 500Hz	Z-R Equation	$Z = 31R^{1.71}$
Transmitter	Klystron	CAPPI Elevation	1 km
Peak Power	250kW	Antenna Velocity	15deg/sec (2.5RPM)
Signal Processor	RVP – 8	Observation Range	170km(max. 400km)
Antenna	Offset style(4.3*5.7) York Type		
Beam Width	0.95°		
Radar Control and Data Process	Sever-SGI02, OS-IRIX6.5, S/W-IRIS		

4.2 Radar Rainfall Process

Constant altitude plan position indicator(CAPPI) data interpolated using Bilinear method(Mohr and Vaughan, 1979) is used as a radar reflectivity data. And it is composed 10 elevation layers from 0.5km to 5km having horizontal and vertical resolution 1.0km, 0.5km respectively. Equation (10) ~ (11) are shown the equation to calculate the CAPPI. A bilinear interpolation along range and azimuth is performed at the projection point on each elevation plane using the four adjacent values(Eq. (10)). And then, a final linear interpolation is performed using the estimates at the projected points to obtain a reflectivity value at the interpolation location (Eq. (11)).

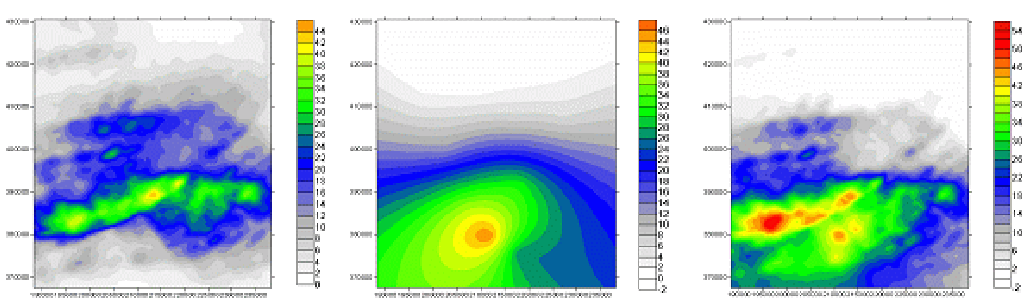
$$Z_e(R,\theta) = \frac{1}{\Delta R \Delta \theta}\{(R - R_i)[(\theta - \theta_j)Z_e(i+1, j+1) - (\theta - \theta_{j+1})Z_e(i+1, j)] - (R - R_{i+1})[(\theta - \theta_j)Z_e(i, j+1) - (\theta - \theta_{j+1})Z_e(i, j)]\} \quad (10)$$

$$Z_e(R,\theta,\phi) = \frac{1}{\Delta\phi}[(\phi - \phi_k)Z_e(R,\theta,\phi_{k+1}) - (\phi - \phi_{k+1})Z_e(R,\theta,\phi_k)] \quad (11)$$

where, R and θ are the slant range and azimuth of the projection point, Δ_R is the range spacing and Δ_θ is the angular distance between radar beams θ_j and θ_{j+1} and ϕ is the elevation angle of (R,θ,ϕ) and $\Delta\phi$ the angular distance between elevation scans ϕ_k and ϕ_{k+1}.

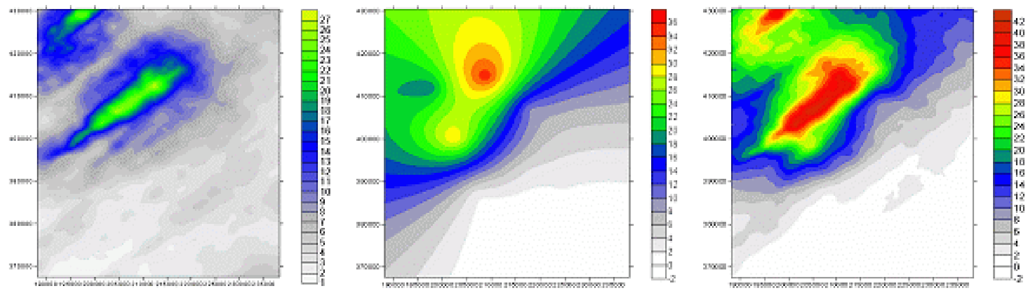
4.3 Radar Rainfall Adjustment using Conditional Merging Method

Adjusted radar rainfall is estimated using conditional merging method and figure 6 ~ 9 show raw radar rainfall, Kriged gauge rainfall, and adjusted radar rainfall using conditional merging method for each rainfall event. As shown in the figures, radar rainfall adjusted using conditional merging method still has characteristics both spatial variation of rainfall distribution from radar rainfall and rainfall depth from gauged rainfall. Especially, in 7/22/2003 event, adjusted radar rainfall has corrected rainfall depth keeping its spatial distribution while raw radar rainfall shows under measured rainfall against gauged rainfall.



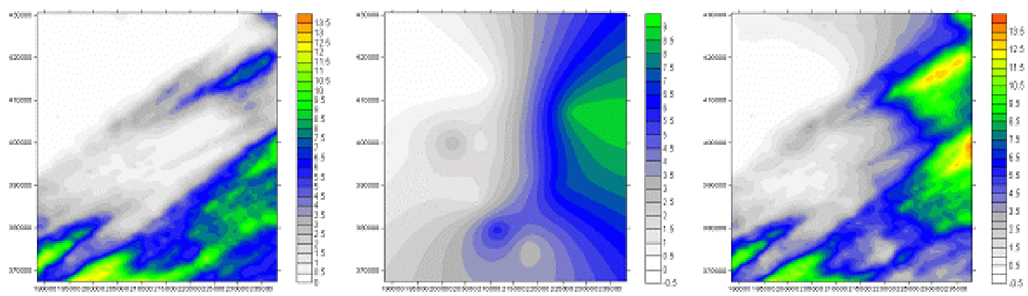
(a) Raw radar rainfall (b) Gauged rainfall (c) Adjusted rainfall

Figure 6. The Comparison of Each Rainfall's Distribution (7/14/2002 08:00)



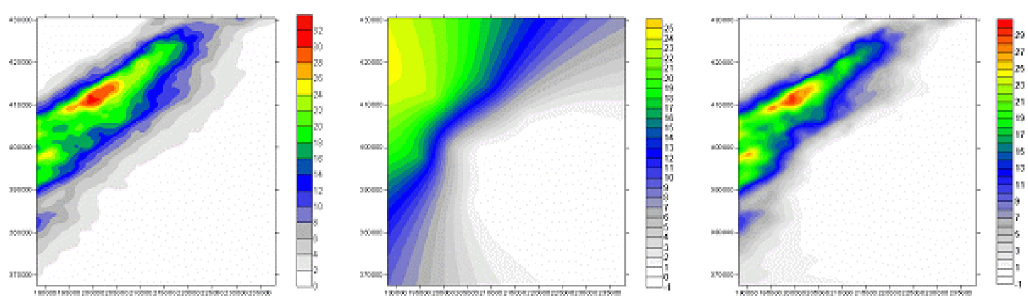
(a) Raw radar rainfall (b) Gauged rainfall (c) Adjusted rainfall

Figure 7. The Comparison of Each Rainfall's Distribution (7/22/2003 13:00)



(a) Raw radar rainfall (b) Gauged rainfall (c) Adjusted rainfall

Figure 8. The Comparison of Each Rainfall's Distribution (8/19/2003 20:00)



(a) Raw radar rainfall (b) Gauged rainfall (c) Adjusted rainfall

Figure 9. The Comparison of Each Rainfall's Distribution (9/7/2003 20:00)

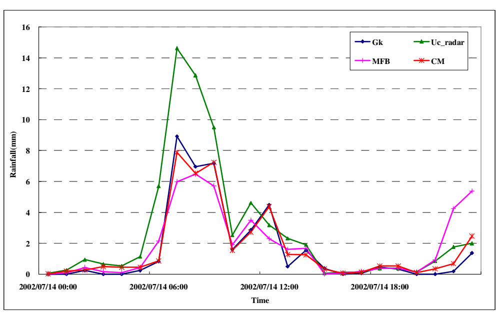
4.4 Comparison of Adjustment Result

To verify practical use of adjusted rainfall as an input data for hydrologic models, areal rainfall hyetograph, cumulative rainfall and estimated efficient coefficient(mean relative error, MRE and fractional standard error, FSE) are compared. Comparison of estimated areal rainfalls for

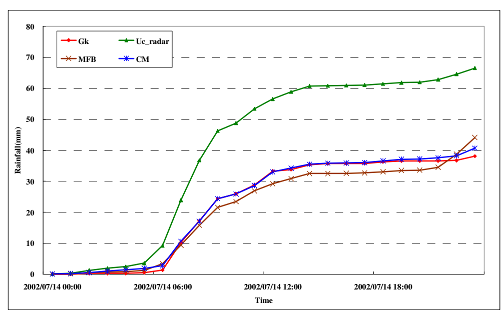
Dongyeongyo, Hoihwa, Gongdo stage gauge in Anseong-cheon basin are shown in Figure 10 ~ 12 and Figure 13 shows comparison of point rainfalls at selected gauges in Anseong-cheon basin. As shown in Figure 10 ~ 13, using conditional merging method can get better adjustment result then MFB. Conditional merging method shows good fitting both areal and point rainfall. However, MFB method shows good fitting for areal rainfall except some time period while it shows not good fitting for point rainfall. Also the comparison of efficient coefficient in Table 2, 3 show conditional merging is better than MFB. MRE and FSE can calculate using Equation (12) and (13) respectively.

$$MRE = \frac{\frac{1}{N_i}\sum_{i=1}^{N_t}(R_i - G_i)}{\frac{1}{N_i}\sum_{i=1}^{N_t} G_i} \tag{12}$$

$$FSE = \frac{[\frac{1}{N_i}\sum_{i=1}^{N_t}(R_i - G_i)^2]^{0.5}}{\frac{1}{N_i}\sum_{i=1}^{N_t} G_i} \tag{13}$$

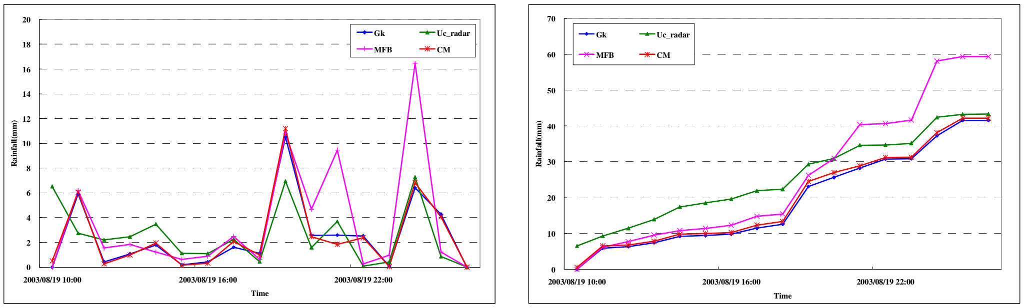


(a) Hyetograph



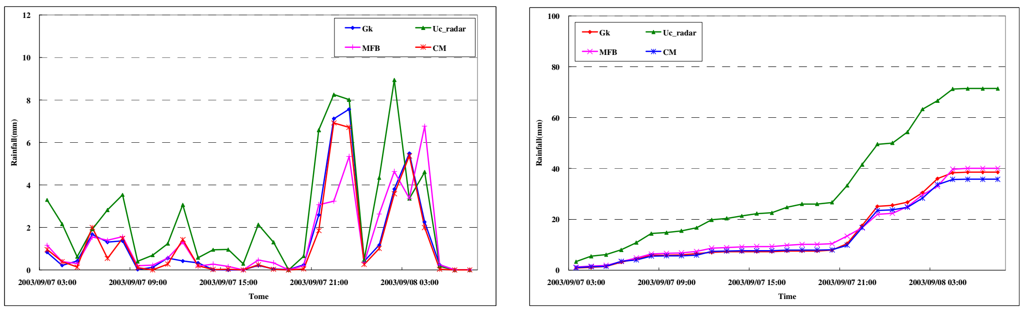
(b) Cumulative rainfall

Figure 10. Comparison of Areal Rainfall (Dongyeongyo, 7/14/2002)



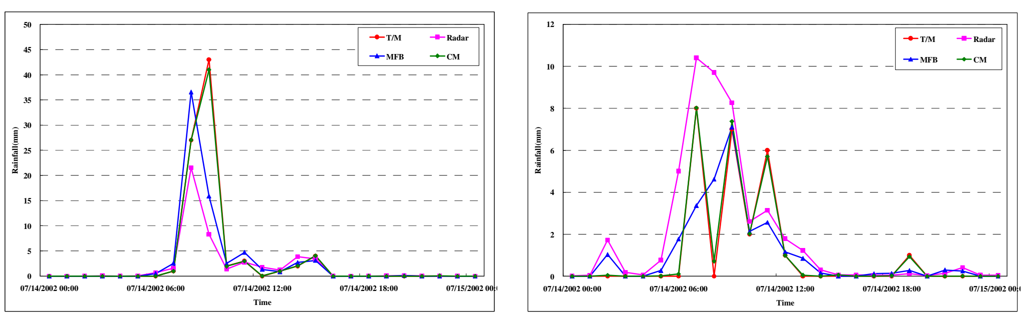
(a) Hyetograph (b) Cumulative rainfall

Figure 11. Comparison of Areal Rainfall(Hoihwa, 8/19/2003)

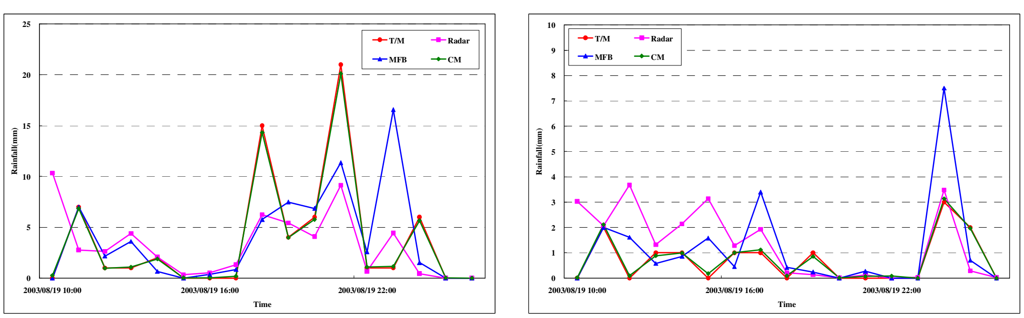


(a) Hyetograph (b) Cumulative rainfall

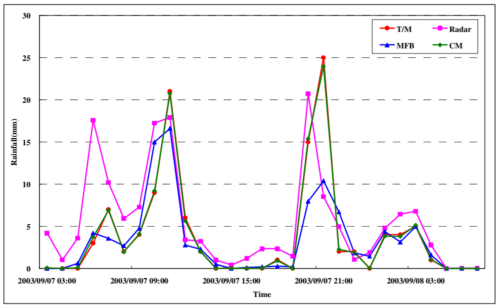
Figure 12. Comparison of Areal Rainfall(Gongdo, 9/07/2003)



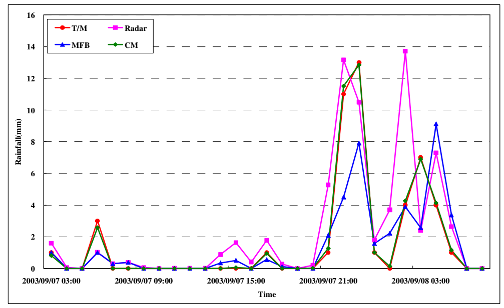
(a) Seoun(7/14/2002) (b) Giheung(7/14/2002)



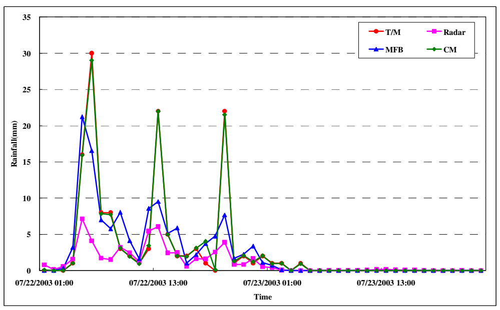
(c) Seonghwan(8/19/2003) (d) Suwon(8/19/2003)



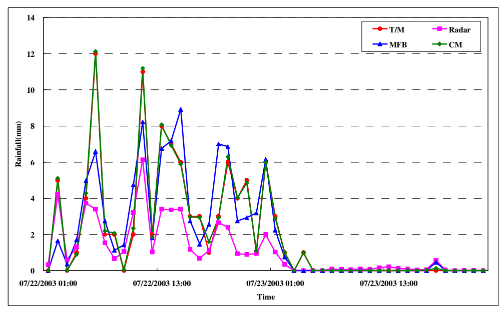
(e) Giheung(9/7/2003)



(f) Seoun(9/7/2003)



(g) Yanggam(7/22/2003)



(h) Wonsam(7/22/2003)

Figure 13. Comparison of Point Rainfall(Selected event)

Table 2. MRE and FSE for Unadjusted and Adjusted Areal Radar Rainfall(7/22)

	Raw Radar		MFB		CM	
	FSE	MRE	FSE	MRE	FSE	MRE
Dongyeongyo	0.9804	-0.0004	1.6454	0.9637	0.3075	0.0999
Pyeongtaek	1.0469	0.1830	1.7664	0.7987	0.3358	0.0068
Gongdo	1.0240	0.1931	1.8907	0.8464	0.3231	0.0014
Hoihwa	0.8247	0.0737	1.5536	0.9400	0.2422	0.0849
Songsan	1.1989	-0.0724	1.9396	1.0073	0.4708	0.1241

Table 3. MRE and FSE for Unadjusted and Adjusted Point Radar Rainfall(7/22)

	Raw Radar		MFB		CM	
	FSE	MRE	FSE	MRE	FSE	MRE
Gihung	1.5879	-0.5696	1.0869	-0.0729	0.1353	0.0070
Suwon	1.5488	-0.5055	1.2009	0.0043	0.4001	0.0595
Anseong	1.4233	-0.3687	1.3130	-0.1392	0.2561	0.0608
Yanggam	1.8882	-0.5937	1.3120	-0.0904	0.1637	0.0154
Yangseong	1.5030	-0.3507	1.3082	0.0692	0.2911	0.0716
Wonsam	1.0168	-0.4623	0.7097	-0.0169	0.0646	0.0187
Jinwi	1.4916	-0.4449	1.1444	-0.0576	0.1785	0.0336
Yidong	1.1824	-0.3641	0.9187	-0.0789	0.1998	0.0490
Pyeontaek	1.3605	-0.3548	1.0115	-0.0642	0.3611	0.0835
Hoihwa	2.0078	-0.5832	1.6068	-0.1103	0.1982	0.0120

6. Conclusion

Several radar rainfall adjustment methods are reviewed and conditional merging method is selected in this paper. The method is used to adjust radar rainfall observed at Imjin-river radar site. Adjustment results are presented and compared using statistics and hyetographs. The conclusion of this paper is that:

(1) Anseon-cheon basin in Imjin-river rainfall radar umbrella is selected for application of conditional merging method after checking gauge observation network and flood alert system operating.

(2) After comparison with raw radar rainfall, Kriged gauge rainfall, and adjusted radar rainfall using conditional merging method, it is found that adjusted radar rainfall shows reasonable rainfall field with rainfall depth for each rainfall event. Especially, 7/22/2003 event shows rainfall depth adjustment of under estimated radar rainfall of raw radar rainfall keeping spatial distribution.

(3) Comparison with MFB method used widely to adjust radar rainfall and conditional merging method is performed in this study. The result shows that conditional merging method shows better adjustment result than MFB for point and areal rainfall.

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