3.5   SENSITIVITY ANALYSIS OF VARIABILITY IN REFLECTIVITY-RAINFALL RELATIONSHIPS ON RUNOFF PREDICTION

Chakradhar Goud Malakpet, Emad Habib, Ehab A. Meselhe
University of Louisiana at Lafayette, Lafayette, Louisiana

Ali Tokay
Joint Center for Earth Systems and Technology, University of Maryland, Baltimore County, MD

1.   INTRODUCTION

Radar-rainfall information presents a significant potential for improving our ability to provide accurate and timely flood predictions. Similar to other measuring devices, radar data also has many uncertainties. One of the main sources of uncertainties is due to natural and sampling variations in the estimation of rainfall rates from radar reflectivity factors. The National Weather Service (NWS) WSR-88D estimates rainfall rates by employing a relationship between Reflectivity factor Z ($mm^6\ m^{-3}$) and rainfall rate R ($mm\ h^{-1}$) of the form $Z=AR^b$ (Ulbrich and Miller, 2001). Both Z and R are defined as different moments of the drop size distribution (DSD) in a sampled volume. Typical default values used by the NWS are A=300 and b=1.4 (for system with deep convection) and A=250 and b=1.2 (for tropical events). Earlier work by Atlas et al. (1999) showed that there can be dramatic changes in Z-R parameters between storms as well as within individual storms. The variability in Z-R relationship is attributed to changes in drop size distributions (DSD) of rainfall events. Lee. (2005) discussed the classification of DSDs according to the dominant physical processes observed by vertical profile of radar and its scale dependence. The Variability of Z-R relationships from storm to storm are due to differences in DSDs caused by governing types of storms (convective, tropical). Variability of Z-R relationships within a storm is due to different microphysical processes involved in the storm. Lee. (2005) showed that optimal Z-R relationships are obtained when the physical process is identified with a unique DSD. The scatter around the Z-R relationship for physical process converges showing a unique relationship.

The rainfall rate estimation from the Z-R relationships at different time-scales yield different parameter values, which affect the overall accuracy of the estimated rainfall rates. Application of estimated rainfall in hydrologic modeling for flood prediction will results in uncertainties in runoff predictions due to carrying of errors in non-linear processes like infiltration, surface and channel routing, etc.

The present work focuses on sensitivity analysis of runoff predictions to the time scale at which radar Z-R relationships are established and used to estimate radar-based rainfall information. Variability in Z-R relationships at different time-scales like climatological scale, storm scale, event scale and physical process scale are examined for three different rain periods with distinct rain characteristics. Each rain period is analyzed to derive Z-R relationships at time-scales using reflectivity from NWS radar at Lake Charles and rainfall data from JW-Disdrometer in study area. The dependence on Z-R estimation method (e.g., least square fitting method, bias correction and least root mean square error method) is also examined. Rainfall rates based on different estimation methods and time scales are used to simulate runoff at the outlet of a mid-size watershed in south Louisiana. The model results are compared to the reference values obtained by using rainfall estimated from disdrometer DSD measurements. The analysis is performed first using disdrometer reflectivity data, and then repeated using radar reflectivity measurements.

2.   STUDY SITE AND INSTRUMENTS

The study site for the analysis is the 35-Km^2 Issac-Verot (IV) watershed located in Lafayette, southwest Louisiana. The watershed is a sub-drainage area of Vermillion river basin which drains into the Gulf of Mexico. The IV watershed is a typically low-gradient watershed where open channel flow plays vital role in runoff prediction (Habib and Meselhe, 2006). The terrain elevation in the watershed, with reference to mean sea level, ranges from approximately 6 m near the outlet to 11.5 m at the catchment divide. The main

---
[1] Corresponding author address: Emad Habib, Civil Engineering Department, University of Louisiana at Lafayette, P.O. Box 7574, Lafayette, LA 70504; email: habib@louisiana.edu

channel in the watershed has a slope of 0.0008. The watershed is located within south Louisiana subtropical climate which is influenced by factors such as subtropical latitude, location along the Gulf of Mexico, prevailing southerly winds, and the northern continental landmass. The area is frequently subject to tropical storms in the summer and hurricanes in the summer and the fall. The average annual rainfall over the IV watershed is about 140 to 155 cm with monthly accumulations as high as 17 cm (6.6 inches). There are basically two main soil types in the IV Watershed: Coteau frost soil and Memphis frost soil. Both soils are texturally classified as silt loam with low to medium runoff capacity. The land-use in the watershed is composed of urban areas, cropland, pasture and some forest areas.

The Department of Civil Engineering at the University of Louisiana at Lafayette has deployed a dense experimental network of rainfall and runoff monitoring sites over the watershed. The watershed is covered with 13 tipping-bucket rain gauges with an orifice size of 12 inches. The gauges are provided with digital data loggers that record the time of occurrence of successive 0.254 mm tips. Raw data can be used to construct time series of rainfall intensities (or accumulations) at any desired time scale.

Drop size distribution (DSD) measurements are made by a JW impact-type disdrometer. The data is recorded as number of drops (n_i) in 20 intervals of drop diameters (D_i) ranging from 0.35 to 5.25 mm. The disdrometer-based reflectivity factor Z_D (mm^6 m^{-3}) and rainfall rate R_D (mm h^{-1}) can be computed as follows:

$$Z_D = 10^6 \sum_{i=1}^{20} D_i^{\,6} N(D_i) \Delta D_i \text{ , and} \qquad (1)$$

$$R_D = 0.6\pi \sum_{i=1}^{20} v(D_i) D_i^{\,3} N(D_i) \Delta D_i \text{ ,} \qquad (2)$$

where $N(D_i)$ (m^{-3} mm^{-1}) is the drop size distribution calculated from number of drops in each class interval (n):

$$N(D_i) = \frac{n_i}{v(D_i) A t \Delta D_i} \text{ ,} \qquad (3)$$

Where $v(D_i)$ (m s^{-1}) is the fall velocity of a drop of diameter D_i (cm), A (m^2) is the area of the disdrometer, t(s) is the sampling time (60s), and ΔD_i (cm) is the width of the ith diameter interval.

Streamflow measurements are collected at the outlet of the watershed and used to calibrate and validate the hydrologic model.

The Issac-Verot watershed is located about 116 Km east of the NWS WSR-88D site in Lake Charles and approximately at 87° azimuth. The lowest elevation angle of the radar beam is about 1.7 Km above the disdrometer site and is free of ground clutter. The average size of radar pixel above the watershed is 1 Km x 1.9 Km, with about 32 radar pixels encompassing the watershed.

3. STUDY STORMS AND DATA PROCESSING

Data used in the study is from JW impact-type disdrometer located in Issac Verot and from radar located at Lake Charles for the year 2004. The dataset comprises of continuous one-minute drop size distribution data, and 5 to 6-minute radar scans for the year 2004. For this study, we selected three main rainy periods observed at different seasons during the year. Each of these rain periods are associated with distinct rain characteristics and varied micro-physical phenomena which extended from few hours to days. The first rain period is June 22-27, 2004, which included of a sequence of high-intensity and short-duration convective squall line storms crossing the watershed on 24th and 25th June. The total rainfall accumulations recorded was 125 mm and 60 mm respectively. The second rain period used for the analysis is October 7-10, 2004. This period includes Tropical Storm Matthew, which was formed from a tropical wave in the southwestern Gulf of Mexico on October 6th and made landfall on south Louisiana on October 10th causing as much as 10 inches of rain. Storm Matthew resulted in significant runoff as high as 50 m^3/sec at the outlet. The third rain period used for the analysis is November 17-27, 2004. This is an extensively wet period of scattered and squall line storms, generating total rainfall accumulation of about 6 inches. Five distinct rain events are observed in this period with similar behavior in terms of total rainfall accumulations and rainfall rates. The runoff observed at the watershed outlet did not lead to very high discharge values but had consistent response to rainfall.

Since the disdrometric data is affected by uncertainties due to drop sorting and small sampling volume (Smith et al. 1993; Joss and Zawadzki 1997), one-minute DSD with rainfall intensity less than 0.1 mm/hr and total number of drops less than 10 are discarded to avoid the

under-sampling effect (Tokay et al. 2001). Time series plots of reflectivity and rainfall rate are constructed to study distribution of rain for the events. Radar data for events is extracted from level II data of NWS Radar at Lake Charles. The data from lowest elevation scan 0.5° is considered for the analysis to construct Reflectivity-rainfall relationships. Reflectivity data at different elevation angles is extracted over the disdrometer site to obtain the reflectivity vertical profile during each of the three rain periods.

There is high uncertainty in comparing the instantaneous radar reflectivity values (sampled every 5-6 minutes) with one-minute disdrometer data due to time and space scale differences. Radar provides an average reflectivity for each radar pixel, and if data is extracted from lowest elevation angle of 0.5°, the radar beam is at a height of 1.7 Km above the ground. Where as the disdrometer samples the rain at the ground level and sampling volume of JW disdrometer is 0.005 m^2. Assuming an average falling velocity, the time required for a raindrop to reach ground from a height of 1.7 Km is calculated to be around 5 minutes. Empirical analysis showed that maximum correlation between instantaneous radar and gauge observations was achieved at time shift of 5 minutes and averaging one-minute DSD's over 5 minutes. Therefore in the rest of this study, we adopted time shift of 5 minutes and averaging time of 5 one-minute DSD's.

4. METHODOLOGY

4.1 Hydrologic Model

In the current study, the Gridded Surface Subsurface Hydrologic Analysis (GSSHA) system is used to develop a rainfall-runoff model for the IV watershed. GSSHA is a fully distributed-parameter, process-based hydrologic model. It uses finite difference and finite volume methods to simulate different hydrologic processes such as rainfall distribution and interception, overland water retention, infiltration, evapotranspiration, two-dimensional overland flow, and one dimensional channel routing. GSSHA also provides a detailed modeling of the soil moisture profile in the unsaturated zone using different methods such as Green and Ampt and Richards' equation. Full description of GSSHA can be found in Downer and Ogden (2002 and 2004).

The model setup adopted in this study included the following options: two-dimensional diffusive wave approximation of the de Saint Venant equations for overland flow, one-dimensional explicit diffusive wave method for channel flow, Penman-Monteith equation for evapotranspiration calculations (Monteith, 1965), and the Green and Ampt infiltration with redistribution (GAR) method (Ogden and Saghafian, 1997) for flow simulation in the unsaturated zone. The GAR method includes soil moisture accounting which simulates the soil moisture redistribution along the soil profile during a runoff event, as well as the change in soil moisture due to evapotranspiration between rainfall events.

The watershed topographic and hydrologic properties are represented using a square 100x100 m^2 Cartesian grid. Topographic information for the watershed was obtained from recent high-resolution LIDAR data for the state of Louisiana (Craig and Philips, 2003). Channel dimensions were compiled from historical surveys and were checked and updated by conducting recent surveying measurements in 2004. Overland hydraulic properties are assigned at each grid pixel based on land use information. Soil hydraulic parameters necessary for the GAR method (e.g., saturated hydraulic conductivity, soil suction head, effective porosity), and evapotranspiration parameters were assigned based on spatial variations in the combined classifications of soil type and land use maps. Initial values of these parameters are selected based on literature sources and are adjusted through a model calibration and validation using several storms observed in watershed.

4.2 Reference rainfall runoff

The GSSHA rainfall-runoff model of IV watershed was used to simulate runoff responses at the outlet during the three considered rain periods. In our study we chose one-minute rainfall rates estimated from DSD of disdrometer as reference rainfall to drive the hydrologic model. The runoff predictions resulting from the hydrologic model driven by the reference rainfall rates are considered as reference hydrographs. The reference rainfall and runoff data are then used to assess the effect of estimating rainfall rates and the corresponding runoff values based on Z-R relations. The Z-R relations are constructed at different time scales and with using different estimation methods. The assessment is performed both visually and statistically.

4.3 Different Reflectivity-Rainfall Estimation Methods

The relationship between reflectivity and rainfall rate is defined by a power law $Z=AR^b$. Multiplicative factor A and exponent b are known as Z-R parameters. Steiner and Smith, 2000, discussed different ways to determine these factors from Z and R pairs. In current study we selected three different methods and investigated the differences in rainfall and runoff estimation caused by using each method. The first Z-R estimation method is the least square fitting method (LSF). This approach is based on estimating A and b values by optimizing the differences in logarithmic scale. The linear regression coefficients are computed using least-squares regression equations.

The second estimation method used in the analysis (FIX) is based on fixing the exponent and removing the overall bias of rainfall volumes. This approach estimates the multiplicative factor A by fixing the exponent value and adjusting the multiplicative value to equate the total rainfall accumulation with the estimated value. The multiplicative factor is given by

$$A = \left(\frac{\sum_{j=1}^{m} Z_j^{\frac{1}{b}}}{\sum_{j=1}^{m} R_j} \right)^b , \qquad (4)$$

The NWS uses default Z-R relationships for different rain events like A=300 and b=1.4 for most of the events and A=250 and b=1.2 for tropical storms. In our analysis we used the values of b=1.2 for Tropical Storm Matthew rain period and b=1.4 for other two rain periods.

The third estimation method (BIAS_RMSE) is based on bias removal and minimizing root-mean-square errors. This is similar to the FIX method where the multiplicative factor is estimated by choosing the exponent such that the total rainfall accumulations are made equal and rmse is minimized. A range is provided for b values from 0.5 to 4 in steps of 0.1. For each value of b, A is calculated from the above formula and rmse is calculated by

$$RMSE = 100\% \sqrt{\frac{1}{n-2} \sum_{j=1}^{n} \left[\frac{R_j - (Z_j/\alpha)^{1/\beta}}{R_j} \right]^2} \qquad (5)$$

Optimal A and b are chosen such that there is minimum rmse for that pair.

4.4 Estimation Time Scales

Lee and Zawadzki (2005) showed that the coefficients A and exponent b depend on the scale of Z and R used for the estimation. For example, if Z and R pairs are estimated at different time scales like climatological scale, storm scale, event scale and physical process scale, A and b values obtained at each scale represent the best fitting line for that particular time scale. Z-R relationships also depend on types of rainfall. Battan (1973) listed a total of 69 Z-R relationships for different rainfall types and locations. Each type of rainfall (eg: stratiform, convective and transitional) has its own Z-R relationship. Results from Lee and Zawadzki, (2005) showed that accurate rainfall rate estimation from radar reflectivity can be obtained when using a Z-R relationship that corresponds to the specific rainfall type. In this study we investigated the inaccuracies in rainfall estimation from radar reflectivity at different time scales and their impact on runoff prediction. For each time scale and estimation method, the estimated rainfall rates are used as input into the GSSHA model to assess the effect of uncertainties in rainfall estimation on runoff simulations during the three selected storms.

Climatological scale

Every region experiences different types of rainfall along the year depending upon the geographic location and climatic conditions of that region. The study area has a very diverse climate, which encounters varied rainfall types like convective thunderstorms in summer, scattered storms, convective squall line storms and hurricanes in summer and fall. To derive a climatological-representative Z-R relation, we use the entire dataset of 2004 which included about 60 storms with different rainfall characteristics. With one-minute Z-R pairs from disdrometer for all the storms in 2004, A and b values are estimated by different Z-R estimation methods (LSF, FIX and BIAS_RMSE). This relation is an integrated representation of all the storms in the region and ignores any variability present between and within the individual storms. Accordingly, there is only one Z-R relationship derived for each Z-R estimation method. For each rain period, the climatological relation is used to estimate rainfall rate values from disdrometer one-minute reflectivity data. The same relation is also used to estimate rainfall rates from the radar data.

Storm Scale

We also explore Z-R estimation time scale at storm level. In the current study storm scale is defined as the rain period which includes series of rain events. We have considered three rain periods (June 22-27, October 8-10 and November 17-27, 2004) for the analysis, and each period is called a storm scale. Variability of Z-R relationships within the storm and effects of using these relationships for rainfall rate estimation on runoff simulation are investigated. The reflectivity and rainfall rate data pairs are used separately for each storm to derive Z-R relationships that correspond to each particular storm. By estimating A and b values of Z-R relationship for each storm separately, all the variability that exists within each storm is eliminated and only variability between the storms is present.

Using Z-R pairs, Z-R relationships are derived for each rain period with different estimation methods. Accordingly, there is one Z-R relationship derived for each rain period and for each Z-R estimation method.

Event Scale

Rain period or storm scale is composed of time series of rain events. Event is defined as continuous rain period with 6 hours of no-rain period preceding and following the rain. The three rain periods considered for this study have more than one event in each storm. Although storm periods chosen for the study have distinct rain characteristics from each other like convective squall line storms and tropical storms, each storm period further has distinct separations which break them into events. Events normally are spanned from few hours to even few days. Events can be distinguished by plotting the time series of rainfall rates for each rain period. Continuous periods of rainfall intensity with clear separation of 6 hours are considered as separate rain events. Events separated by smaller time intervals are merged into one event. Reflectivity and rainfall rate data pairs from radar and disdrometer for each event are used to estimate Z-R relationships that correspond to the individual rain events. By estimating Z-R relationships for rain events separately, we are preserving the variability present within the storm .i.e. variability from one event to another, and eliminating variability existing within the rain event.

Physical Process Scale

In this section, we quantify the degree of variability of Z-R relationships caused by changes in physical process of rain events. As defined above, event is a continuous period of rain with clear separation of dry period before and after. Even within rain events, there exist different physical processes like stratiform and convective systems. Convective system is mainly composed of high intensity rainfall lasting for short duration. It has major contribution to the total rainfall accumulation. Stratiform phase is generally characterized by long period of drizzle as observed at ground level. These physical processes can be distinguished by the brightband signature evident in the vertical structure of the reflectivity (Fabry and Zawadzki 1995). In the current study, the vertical profile of reflectivity for the rain periods was developed by extracting time series of instantaneous reflectivity from different elevation angle scans of the radar pixel above the disdrometer. From the time series of vertical profiles of rain events, stratiform phase is distinguished by presence of clear brightband. In this period, reflectivity gradient decreases from brightband as it approaches ground. Convective phase is distinguished by rain period of high gradient of reflectivity extending deeper into the atmospheric column. In some cases, transitional phases between convective and stratiform are also identified. Reflectivity and rainfall rate pairs for all the periods of convective, stratiform and transitional phases in a rain event are put together so that there are three data pairs (convective, stratiform and transitional) within each single event. With three data pairs for each rain event, Z-R relationships are estimated separately which represent different physical processes. Some rain events are composed of only convective and stratiform phases, without transitional phase, in which case there will be only two Z-R data sets.

Rainfall rates are estimated from the reflectivity values by using the Z-R relationship that corresponds to the physical process to which the reflectivity data belongs. Estimated rainfall rates for each physical process in an event are combined in timely-squential order to get the time series of rainfall for the rain period. This time series is used as input precipitation data for the GSSHA model.

4.5   Statistical Assessment

By using the Z-R relationships at different time scales and different Z-R estimation methods,

rainfall rates are estimated for three rain periods. These rainfall rates are compared to the reference rainfall rates that are obtained from one-minute DSD disdrometric data. The differences in rainfall rates and accumulations between reference and estimated rainfall rates are assessed using the following statistical measures:

Overall bias (mm) in rainfall accumulation

$$bias = \frac{\sum (R - R_T)}{60},$$ (6)

Root mean square error (rmse) (mm/hr):

$$rmse = \left[\frac{1}{n-1} \sum \left(\frac{R - R_T}{R} \right)^2 \right]^{\frac{1}{2}},$$ (7)

Where R (mm/hr) is the rainfall rate estimated from DSD disdrometer data, and R_T (mm/hr) is corresponding rainfall rate transformed from radar reflectivity using Z-R relationship of a particular time scale, and n is the number of observations.

With rainfall rates estimated at different time scales and different estimation methods, runoff hydrographs are simulated using GSSHA and compared to the reference hydrographs, which were based on using one-minute rainfall rates from DSD disdrometric data. The differences are assessed in terms of overall bias in runoff volume, rmse of discharge values, and peak discharges:

$$bias\,(mm) = \frac{\left[\sum (Q - Q_{sim}) \right]}{A}$$ (8)

$$Rmse(m^3/s) = \left[\frac{1}{n-1} \sum \left(\frac{Q - Q_{sim}}{Q} \right)^2 \right]^{\frac{1}{2}}$$ (9)

Where, Q (m^3/sec) is reference runoff discharge, Q_{sim} (m^3/sec) is corresponding simulated discharge and A (m^2) is the area of the watershed and n is number of time steps between discharge values.

5. RESULTS

5.1 Disdrometer-Based Analysis

First, we present the results that are based on using one-minute disdrometric data for rainfall rate estimation by different time scales and different estimation methods. Different time scales of Z-R

estimation, namely climatological scale, storm scale, event scale and physical process scale are identified by the procedures explained in the above sections. For each time scale, one-minute reflectivity and rainfall rate pairs are calculated from DSD of disdrometer to estimate A and b values of Z-R relationships. These Z-R pairs are used to estimate A and b values by different Z-R estimation methods (LSF, BIAS_RMSE and FIX). Table 1 shows examples of these results for the Nov 17-27, 2004 rain period.

Default values of A and b used by NWS to estimate rainfall for convective storms are 300 and 1.4 respectively. Since the exponent of default Z-R relation used by NWS is 1.4, we used this exponent to fix the value of b and estimate A by removing the bias in the FIX method. The values of A and b obtained by using different time scales are quite different, which reflect the variability of Z-R relationships that exists between rain storms, events and physical processes. The values for physical processes are not showed in the table, since each event has three set of values. Rainfall rates estimated from reflectivity values using the Z-R relationships at different time scales and different estimation methods are compared with the reference values. Figure 1 shows an example of such comparison for the rain period October 7-10 in the form of a scatter plot. The effect of using estimated rainfall rates at different time scales and estimation methods on runoff simulation is shown in Figure 2. The results indicate that the BIAS_RMSE and FIX estimation methods were superior to the LSF method, especially at coarse estimation time scales. The LSF method yielded comparable results only when Z-R relationship was estimated at the physical process scale.

5.2 Radar-Based Analysis

The same analysis was repeated but using the radar data. Z-R relations were constructed based on pairs of radar-Z and disdrometer-R pairs for different time scales and estimation methods. These Z-R relations were then applied to estimate R and use it to drive the hydrologic model. A summary of the radar-based analysis is provided in Tables 2 to 4, and Figures 3 to 4.

6. SUMMARY AND CONCLUSIONS

In this study, we analyzed the sensitivity of runoff predictions to the time scale and the estimation method used to derive the reflectivity-rainfall rate relationships. We investigated several time scales that range from the finest scale of the

rainfall underlying physical process, to integrated storm and climatological scales. Three estimation methods are used to estimate the two parameters of the Z-R relationships at each estimation time scale. The methods include least-squares fitting, bias removal and minimization of random differences, and bias removal while fixing the exponent parameter. The analysis was first performed using disdrometric Z and R data, and then repeated using reflectivity data from the closest WSR-88D radar site. The following conclusions can be drawn form the study results:

(i) In agreement with previous studies, Z-R relations show significant variations across storms and within the same storm.

(ii) The estimated multiplier and exponent parameters of Z-R relations show strong dependence on the estimation time scale and on the method of estimation.

(iii) Use of least-squares fitting to estimate the Z-R relations based on either disdrometer or radar data resulted in relatively inaccurate rainfall estimates and rather poor runoff predictions. This was most evident when coarse estimation time scales (e.g., storm or event) were used. The method gives improved results only when the estimation is performed on a physical-process time scale.

(iv) Estimation based on bias removal and minimization of random differences (BIAS_RMSE) shows superior accuracy even when using coarse estimation time scale.

(v) Estimation time-scales that account for variations in the underling rainfall physical processes don't necessarily result in significant improvements in the accuracy of rainfall estimates and their corresponding runoff predictions.

(vi) A simple estimation method based only on bias removing and selection of a climatological representative exponent has resulted in acceptable rainfall estimates and runoff predictions.

7. BIBLIOGRAPHY

Atlas, D., C. W. Ulbrich, F. D. Marks Jr., E. Amitai, and C. R. Wiliams, 1999: Systematic variation of drop size and radar-rainfall relations. *J. Geophys. Res.,* **104** (D6), 6155-6199.

Battan, L. J., 1973: Radar observation of the atmosphere. The University of Chicago Press.

Craig, J., and H. Philips, 2003. LIDAR Technical Workflow. 3001 Inc., Gainesville, FL.

Downer, C.W., and F. L. Ogden, 2004: Prediction of runoff and soil moistures at the watershed scale: Effects of model complexity and parameter assignment. *Water Resour. Res.*, **(39)**(3), 10.1029/2002WR001439.

Fabry, F., and I. Zawadzki, 1995: Long term radar observations of the melting layer of precipitation and their interpretation. *J. Atmos. Sci.*, **(52)** 838-851.

Habib, E., and E. A. Meselhe, 2005: Stage-Discharge Relations for Low-Gradient Tidal Streams Using Data-Driven Models. *J. Hydr. Engrg.*, 132, 5, 482-492.

____, C. Malakpet, A. Tokay, and E. A. Meselhe, 2006: Analysis of surface and remotely-sensed rainfall observations during two tropical systems in south Louisiana. American Geophysical Union Joint Assembly, Baltimore, Maryland.

Joss, J., and I. Zawadzki, 1997: Raindrop size distribution again? Preprints, *28th Conf. on Radar Meteorology,* Austin, TX, Amer. Meteor. Soc., 326-327.Lee, G. W., and I. Zawadzki, 2005: Variability of drop size distributions: Noise and noise filtering in disdrometric data. *J. Appl. Meteor.,* **(44)** 634-652.

Monteith, J. L., 1965: Evaporation and environment. Symposium, Society of Experimental Biology, XIX, 205-234.

Ogden, F. L., and B. Saghafian, 1997: Green and Ampt infiltration and redistribution. *J. Irrigation and Drainage Engg.,* **(123)**, 386-393.

Smith, P. L., L. Zhong, and J. Joss, 1993: A study of sampling-variability effects in raindrop size observations. *J. Appl. Meteor.,* **(32),** 1259-1269.

Steiner, M., and J. A. Smith, 2000: Reflectivity rain rate and kinetic energy flux relationships based on raindrop spectra. *J. Appl. Meteor.* **(39)** 1923-1940.

Tokay, A., A. Kruger, and W. F. Krajewski, 2001: Comparison of drop size distribution measurement by impact and optical disdrometers. *J. Appl. Meteor.,* **(40)** 2083-2097.

Ulbrich, C. W., and N. E. Miller, 2001: Experimental test of the effects of Z-R law variations on comparison of WSR-88D rainall amounts with surface rain gauge and disdrometer data. *Weather Forecast* , **16,** 369-374.

TABLE 1. A and b values of Z-R relationships estimated from one-minute disdrometric reflectivity at different time scales and estimation methods for the rain period November 17-27, 2004.

Time Scale	Event	Estimation Method	A	b
Default			300	1.4
Climatological		LSF	241.58	1.55
		BIAS	371.42	1.30
		FIX	280.07	1.40
Storm		LSF	276.11	1.41
		BIAS	403.24	1.27
		FIX	268.57	1.40
Event	Event 1	LSF	240.98	1.39
		BIAS	338.59	1.11
		FIX	176.23	1.40
	Event 2	LSF	257.30	1.40
		BIAS	370.76	1.12
		FIX	226.59	1.40
	Event 3	LSF	231.18	1.48
		BIAS	275.75	1.46
		FIX	346.37	1.40
	Event 4	LSF	386.26	1.41
		BIAS	459.04	1.23
		FIX	273.39	1.4
	Event 5	LSF	391.77	1.36
		BIAS	505.21	1.28
		FIX	327.39	1.4

TABLE 2. A and b values of Z-R relationships estimated from instantaneous radar reflectivity at different time scales and estimation methods for the rain period October 7-10, 2004.

Time Scale	Event	Estimation Method	A	b
Default			250	1.20
Storm		LSF	72.47	2.19
		BIAS	50.24	1.79
		FIX	187.20	1.20
Event	Event 1	LSF	960.42	1.93
		BIAS	463.47	1.45
		FIX	537.41	1.20
	Event 2	LSF	32.77	2.28
		BIAS	47.02	1.81
		FIX	188.85	1.20
	Event 3	LSF	8.81	2.60
		BIAS	5.80	2.39
		FIX	133.59	1.20

TABLE 3. Statistics of estimated rainfall values for the rain period October 7-10, 2004, by using different estimation methods and different time scales.

Time Scale	Estimation Method	True rainfall Accumulation (mm)	Estimated rainfall Accumulation (mm)	Bias (ratio)	Rmse mm/hr	Correlation Coefficient	Coefficient of Efficiency
Default			182.68	0.22	4.44	0.78	0.55
Storm	LSF		137.47	0.41	4.63	0.80	0.40
	BIAS		232.89	0.00	3.81	0.80	0.65
	FIX	232.9	232.57	0.00	5.24	0.78	0.39
Event	LSF		172.60	0.26	4.02	0.82	0.58
	BIAS		232.85	0.00	3.59	0.83	0.69
	FIX		232.39	0.00	6.14	0.78	0.18

TABLE 4. Statistics of simulated runoff values for the rain period October 7-10, 2004, by using different estimation methods and different time scales.

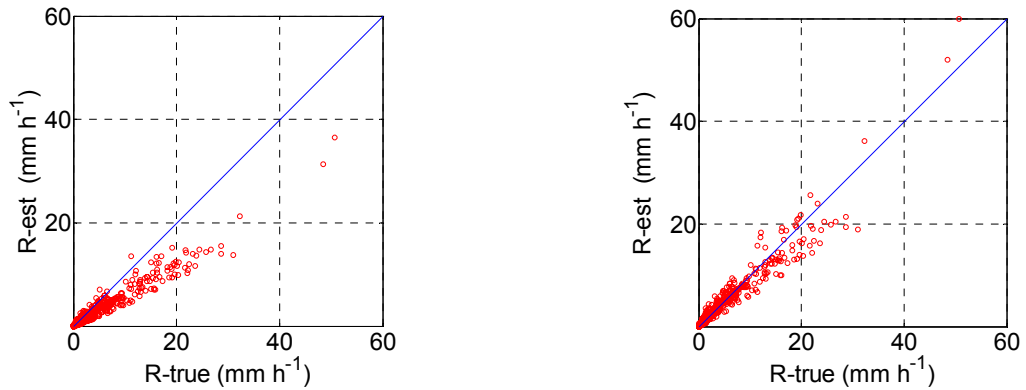| Time Scale	Estimation Method	True runoff Volume (mm)	Estimated runoff Volume (mm)	Bias (ratio)	Rmse (m3/sec)	Correlation Coefficient	Coefficient of Efficiency
Default			82.93	0.29	5.26	0.95	0.82
Storm	LSF		50.03	0.57	8.96	0.92	0.42
	BIAS		115.96	0.01	5.10	0.93	0.87
	FIX	117	118.47	-0.01	3.89	0.96	0.92
Event	LSF		77.41	0.34	6.08	0.96	0.75
	BIAS		121.34	-0.04	3.53	0.97	0.94
	FIX		122.81	-0.05	3.60	0.97	0.93

FIG. 1. Scatter plots of reference rainfall rates and estimated rainfall rates from climatological scale (left) and event scale (right) by using LSF estimation method.
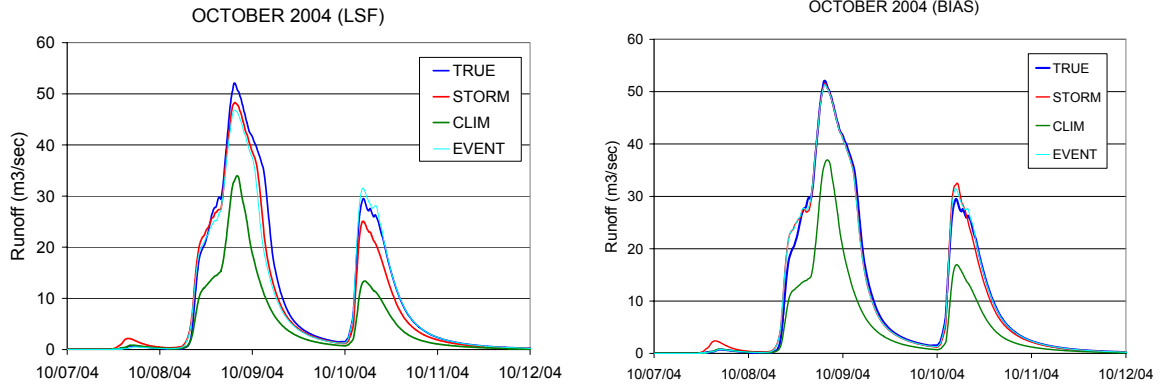
FIG. 2. Runoff hydrographs at watershed outlet for the rain period October 7-10, 2004 using rainfall rates estimated at all time scales by LSF (left figure) and BIAS (right figure) estimation methods.
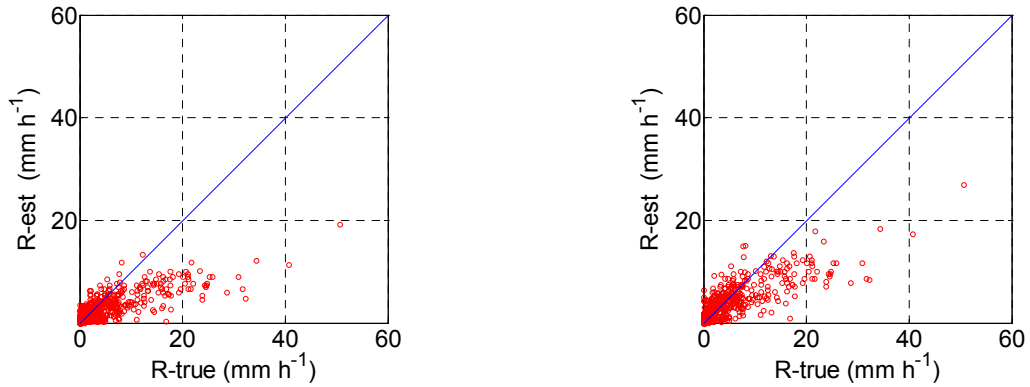

FIG. 3. Scatter plots of reference rainfall rates and estimated rainfall rates from radar reflectivity data for storm scale (left) and event scale (right) by using LSF estimation method for rain period October 7-10, 2004.
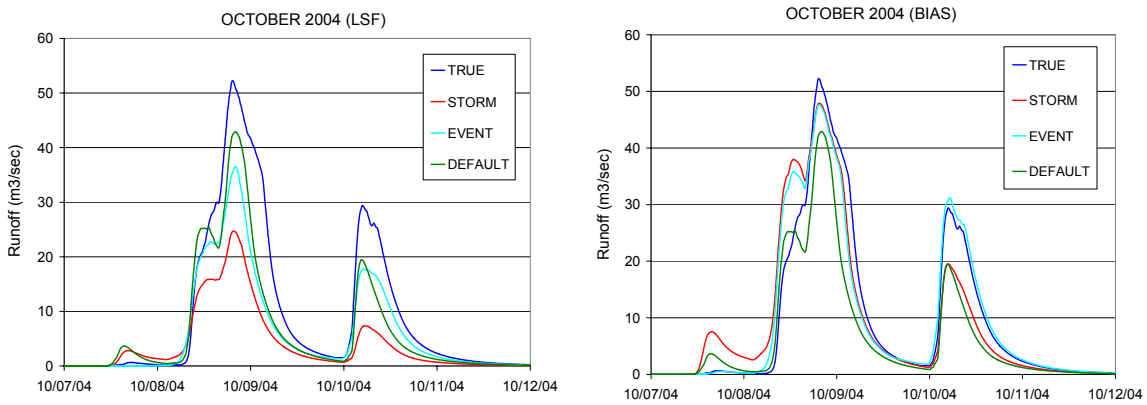

FIG. 4. Runoff hydrographs at watershed outlet for the rain period October 7-10, 2004 using rainfall rates estimated at all time scales by LSF (left figure) and BIAS (right figure) estimation methods.