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NOTES AND CORRESPONDENCE

Radar *Z–R* Relationship for Summer Monsoon Storms in Arizona

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ABSTRACT

Radar-based estimates of rainfall rates and accumulations are one of the principal tools used by the National Weather Service (NWS) to identify areas of extreme precipitation that could lead to flooding. Radar-based rainfall estimates have been compared to gauge observations for 13 convective storm events over a densely instrumented, experimental watershed to derive an accurate reflectivity–rainfall rate (i.e., *Z–R*) relationship for these events. The resultant *Z–R* relationship, which is much different than the NWS operational *Z–R*, has been examined for a separate, independent event that occurred over a different location. For all events studied, the NWS operational *Z–R* significantly overestimates rainfall compared to gauge measurements. The gauge data from the experimental network, the NWS operational rain estimates, and the improved estimates resulting from this study have been input into a hydrologic model to "predict" watershed runoff for an intense event. Rainfall data from the gauges and from the derived *Z–R* relation produce predictions in relatively good agreement with observed streamflows. The NWS *Z–R* estimates lead to predicted peak discharge rates that are more than twice as large as the observed discharges. These results were consistent over a relatively wide range of subwatershed areas (4–148 km^2). The experimentally derived Z–R relationship may provide more accurate radar estimates for convective storms over the southwest United States than does the operational convective *Z–R* used by the NWS. These initial results suggest that the generic NWS *Z–R* relation, used nationally for convective storms, might be substantially improved for regional application.

1. Introduction

Radar-based estimates of rainfall rates and areal accumulations are one of the principal tools used by the National Weather Service (NWS) to identify areas of extreme precipitation that could lead to flooding. Flash flooding is perhaps the most important severe weather event associated with convective storms over much of the southwestern United States (Doswell et al. 1996), making rainfall estimates from the NWS operational radars the most important product used by forecasters to warn the public of impending floods.

It is well known that radar rainfall estimates are often too high for intense convective storms (e.g., Crosson et al. 1996; Fulton 1999). This problem is related to the presence of hail and graupel in the radar beam sample volume, and the fact that cloud bases may be well above ground level resulting in the potential for significant

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evaporation between cloud base and the ground, especially over the southwestern United States. The fact that many radar systems in the Southwest are sited at elevations higher than much of the area to be monitored acerbates the above problems. The summer weather of this region is strongly affected by the North American monsoon (Douglas et al. 1993; Wallace et al. 1999), which results in frequent airmass thunderstorms that are highly convective, intense, localized, and of short duration. Flash floods frequently occur in these regions. These events are difficult to detect and it is also very difficult to issue adequate warnings for them (Maddox et al. 1995). Most storms in this section of the country are extremely continental in nature, implying that radar data obtained at and above elevations of 2–4 km MSL likely contain hail and/or graupel, making overestimation of rain rates at the surface a particularly vexing problem.

Radar-based rainfall estimates have been compared to gauge observations for 13 convective storm events over a densely instrumented, experimental watershed to derive an alternate reflectivity–rainfall rate (i.e., Z–R) relationship to that used operationally by NWS. The resultant Z–R relationship was applied to a separate, independent event that occurred over portions of the Phoenix metropolitan area. Additionally, the gauge data from the experimental network, the NWS operational rain estimates, and the alternate estimates resulting from this study were input into a hydrological model to “predict” watershed runoff for an intense and singular event.

2. Study areas and data

The two study areas are located in the semiarid climate regime of southern Arizona (Fig. 1a). The 148-km^2 Walnut Gulch Experimental Watershed (WGEW; see Goodrich et al. 1997) is located 50–70 km east-southeast of the Tucson Weather Surveillance Radar-1988 Doppler (WSR-88D) operational weather radar (wavelength, 10 cm; beamwidth, 1°; effective data bin length, 1 km), which is a part of the U.S. national weather radar network. The watershed is equipped with a dense network of rainfall gauges (Fig. 1b) managed by the U.S. Department of Agriculture’s Agriculture Research Service (USDA/ARS). Thirteen convective storms from the 1999 and 2000 monsoon seasons (June–August) were selected for study (Table 1). Rain data from 74 gauges located in the watershed area were used for development of a WGEW radar Z–R relation.

Because radar beams at the first and second tilts are partially blocked by intervening terrain before they reach the watershed, only the third tilt data (elevation angle of 2.4°) were used for the analysis (equivalent to approximately 3-km altitude above ground over the study area; average watershed elevation is roughly 1340 m above mean sea level). While this may seem quite high, the actual limitations of data available from the NWS radar network for real-time, operational rainfall estimation must be considered. Maddox et al. (2002) have shown that a very limited portion of the United States has NWS radar data available within 2 km of the surface. For the western United States, data for operational rainfall estimation are typically sampled near and above 3 km above ground level (see Fig. 5 in Maddox et al. 2002).

The second study area is the Phoenix metropolitan area, located northwest of the Phoenix NWS WSR-88D weather radar (Fig. 1a). Data from a summer storm in 2002 were used for this area (Table 1). The radar data segment used for the Phoenix storm was similar in size and distance (from radar) to that used for the WGEW events. Because there are no topographic blockage problems for the Phoenix study area, we were able to use radar data from the first three tilts (roughly equivalent to 1, 2, and 3 km above ground level) for the analyses. There are 34 rain gauges located and operated by the Flood Control District of Maricopa County within the radar sector studied (Fig. 1c). These gauge data were used for a single case evaluation of the WGEW-derived Z–R relationship for an area of Arizona quite different than the WGEW region (i.e., lower elevation and less complex terrain).

3. *Z–R* relationship

Radar reflectivity data (Z; mm^6 m^{-3}) are represented in polar coordinates centered at the radar station at a resolution of 1° × 1 km for different tilts with a time sampling interval of 5 min. Reflectivity data are commonly converted to estimated rain intensity data (R; mm h^{-1}) using a power law Z–R relationship in the form $Z = aR^b$. The relationship used by the NWS for convective rainfall (Fulton et al. 1998) is

$$Z = 300R^{1.4}. \tag{1}$$

An upper threshold is applied to reduce unreasonably large estimates caused by hail and graupel cores in thunderstorms (Fulton et al. 1998). The NWS upper threshold value is 53 dBZ (where 1 dBZ = 10log$Z$), which is equivalent to 104 mm h^{-1} according to (1). This means that all reflectivity values >53 dBZ are set equal to 53 dBZ before the rain rate is computed.

In this study, the exponent parameter (b) was set to the value of 1.4, while the multiplicative parameter (a)

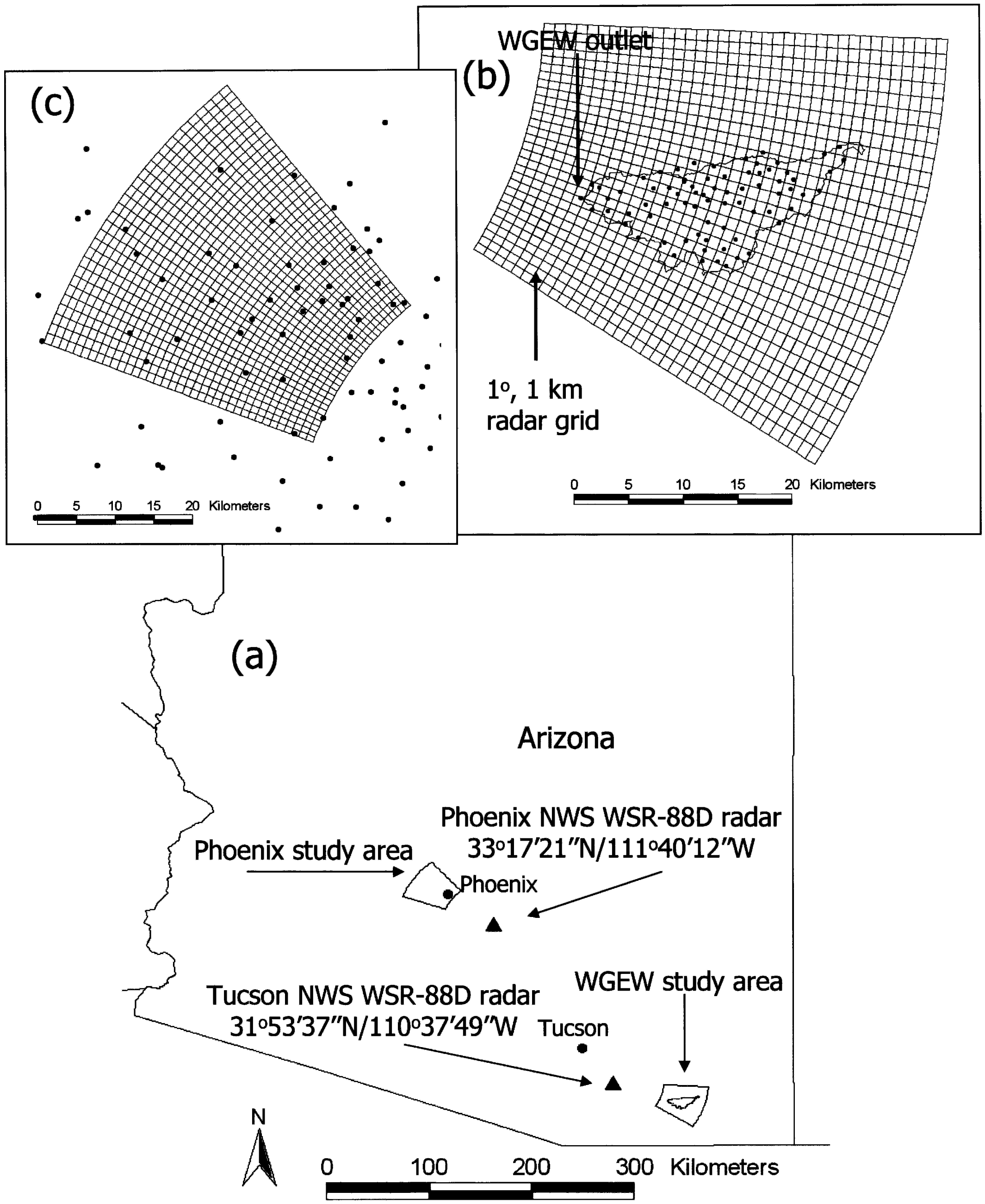

FIG. 1. (a) Location map of the two study areas and the radar stations. (b) The radar segment (azimuth, 93°–122°; range, 42–78 km relative to the Tucson radar) encompassing the 148-km^2 WGEW study area and the 74 gauges in the watershed. (c) The radar segment of the Phoenix study area (azimuth, 291°–320°; range, 42–78 km relative to the Phoenix radar) and the gauge network of the Flood Control District of Maricopa County. Radar polar grid resolution is of 1° × 1 km.

was adjusted based on comparison of gauge and radar storm depth data such that

$$\sum_{i=1}^{n} G_i = \sum_{i=1}^{n} R_i, \qquad (2)$$

where G_i is the gauge rainstorm depth and R_i is the radar rainstorm depth at the pixel above the gauge. The resulting Z–R relationship, based on analysis of radar and gauge data for the selected 13 storms over WGEW, is

$$Z = 655R^{1.4}. \qquad (3)$$

TABLE 1. Storm characteristics.

Storm	Study area	Local start time	Duration (h)	Areal storm depth[a] (mm)	Max 1 min[b] (mm h^{-1})	Max depth[c] (mm)
1	WGEW	1400 UTC 17 Jun 1999	3	2.1	150	26.7
2	WGEW	1800 UTC 6 Jul 1999	3	10.2	148	28.8
3	WGEW	1000 UTC 14 Jul 1999	14	43.9	260	89.0
4	WGEW	1700 UTC 25 Jul 1999	3	1.7	232	25.2
5	WGEW	1600 UTC 2 Aug 1999	6	10.0	152	28.8
6	WGEW	1400 UTC 18 Aug 1999	3	2.1	166	16.2
7	WGEW	1600 UTC 28 Aug 1999	5	19.7	230	37.7
8	WGEW	1500 UTC 31 Aug 1999	5	16.4	219	47.8
9	WGEW	1600 UTC 18 Jun 2000	3	3.1	129	23.7
10	WGEW	1100 UTC 29 Jun 2000	3	15.2	182	57.6
11	WGEW	1700 UTC 16 Jul 2000	6	7.1	113	29.5
12	WGEW	1800 UTC 6 Aug 2000	7	25.3	326	55.8
13	WGEW	1100 UTC 11 Aug 2000	4	24.0	391	90.4
14[d]	Phoenix	2000 UTC 14 Jul 2002	4	20.2	NA[e]	56.9

[a] Average of all gauge data available. For the WGEW study area all the gauges are located within the watershed.
[b] Maximum 1-min rainfall intensity recorded at a gauge.
[c] Maximum storm depth recorded at a gauge.
[d] Data for the Phoenix storm were obtained from rain gauges operated by the Flood Control District of Maricopa County.
[e] NA = data not available.

The upper threshold was set to 56 dB*Z* to match the NWS threshold in terms of maximum allowed rain rate.

The relatively high value of the multiplicative parameter is likely due to the process of evaporation that results in a greater loss of small-diameter drops than large-diameter ones in the drop size distribution (Rosenfeld and Ulbrich 2003). Similar behavior of the multiplicative parameter is indicated also by previous studies, which obtained *Z–R* relationships from measurements of drop size distributions in Arizona. For example, Foote (1966) presents the two *Z–R* relationships, $Z = 520R^{1.81}$ and $Z = 646R^{1.46}$, resulting from different selection of dependent and independent regression variables. Stout and Mueller (1968) list the $Z = 593R^{1.61}$ relationship and Smith and Krajewski (1993) derive the relation $Z = 653R^{1.49}$. The above studies derived the *Z–R* relationships from distrometer data at a point, while the current study presents analysis of radar and gauge data over an area of about 150 km^2. Discussion of the dependencies of the power law parameters on scale and on each other for the current dataset is presented in Morin et al. (2003).

Figure 2 presents a comparison of gauge and radar total storm depth for the WGEW-calibrated *Z–R* data. The NWS convective *Z–R* (Fig. 2a) relation seriously overestimates total storm rainfall for almost all gauges and all events. Due to calibration, an improved fit was obtained for the WGEW *Z–R* (Fig. 2b), although there does appear to be a tendency for higher (lower) radar amounts for lower (higher) gauge amounts. This occurs because the bias of the derived *Z–R* was forced to be 1.0.

Figure 3 presents the results for the single, independent Phoenix area case. For this case, estimates were made using the radar reflectivity data from each of the first three elevation tilts (0.5°, 1.5°, and 2.4°). Once again the total storm estimates derived from the NWS convective *Z–R* are almost universally too high, in comparison to the gauge measurements, although a few estimates for the third tilt are low. The WGEW *Z–R* performs much better, even though the Phoenix area is far removed from the WGEW. Data from the first and second tilts match the gauge data very well, and data from the third tilt underestimate the gauge amounts considerably for larger gauge amounts.

The fit between the gauge and radar-estimated rainstorm depths was evaluated using two criteria: bias and RMSD, defined as

$$\text{Bias} = \frac{\sum_{i=1}^{n} R_i}{\sum_{i=1}^{n} G_i}, \text{RMSD} = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(G_i - R_i)^2}. \quad (4)$$

The two criteria were applied to data for each of the 13 WGEW storms separately and as a single dataset and, in addition, to the Phoenix data. The results presented in Table 2 clearly indicate, for the selected statistics, that the WGEW *Z–R* in Eq. (3) developed here is superior to the standard convective NWS *Z–R*. The NWS convective *Z–R* results in overestimation of total storm rainfall (75% overestimation for the WGEW storms and about 60% for the Phoenix event). The mul-

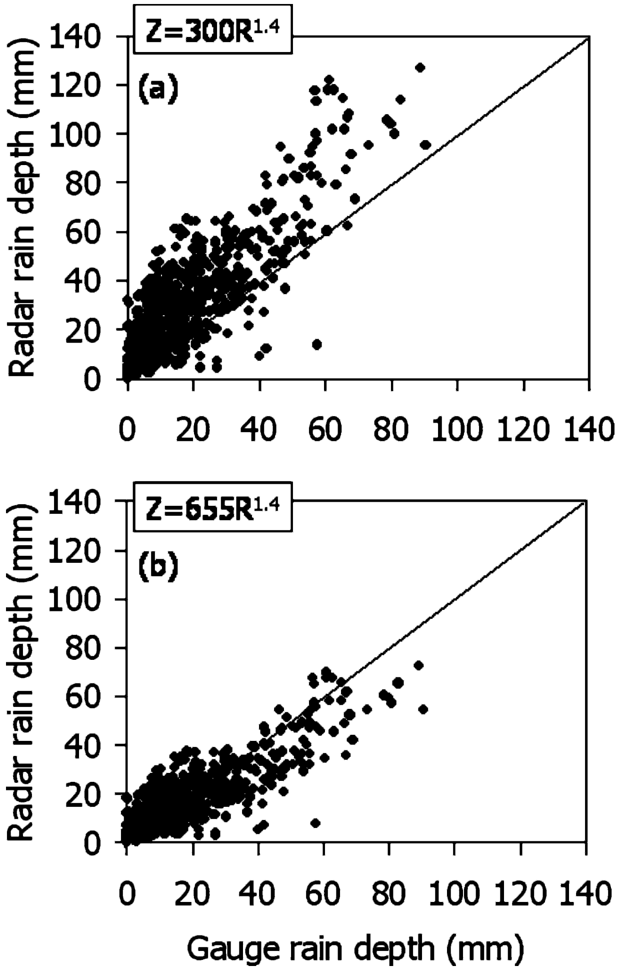

FIG. 2. Comparison of gauge and radar total storm depth for the WGEW-calibrated Z–R data (74 gauges, 13 storms), using (a) the NWS convective Z–R and (b) the determined WGEW Z–R.

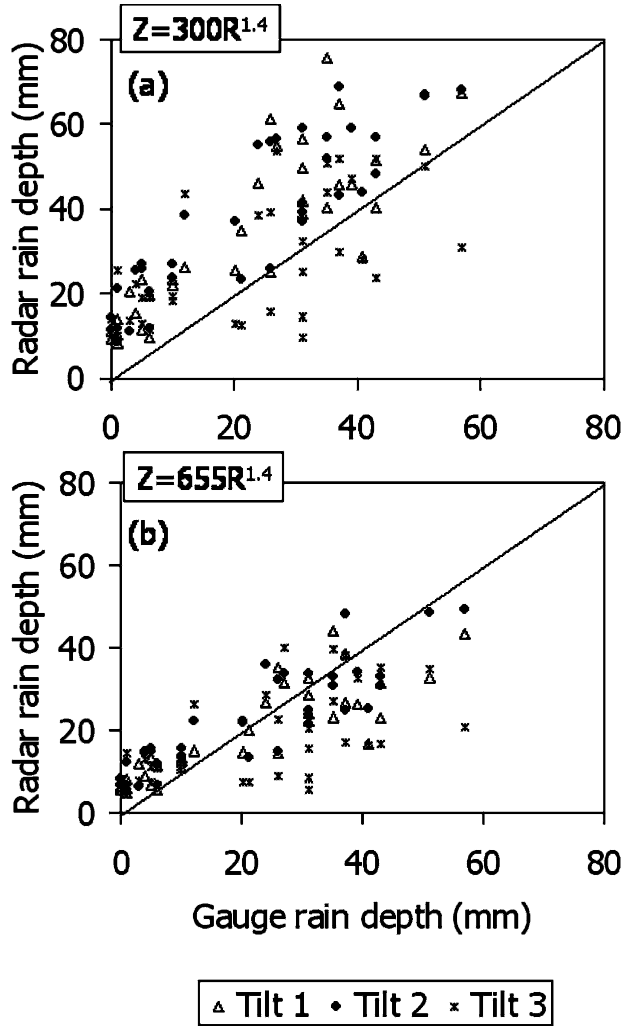

FIG. 3. Comparison of gauge and radar total storm depth for the independent Phoenix area case for the first three elevation tilts (0.5°, 1.5°, and 2.4°), using (a) the NWS convective Z–R and (b) the determined WGEW Z–R.

tiplicative parameter in (3) removes the overall bias for the 13 WGEW storms and, except for 1 storm, improves the Bias and RMSD. A very substantial improvement in terms of Bias and RMSD is indicated for the Phoenix validation storm. This is true for all three tilts, with the best results found for the second tilt.

4. Rainfall–runoff modeling

The radar rainfall estimations were used as input to a rainfall–runoff–erosion model. The model used is the Kinematic Erosion and Runoff Model (KINEROS2), a physically based, event-oriented, rainfall–runoff model (Woolhiser et al. 1990; Smith et al. 1995) developed by USDA/ARS scientists for watersheds in semiarid environments. The model represents the watershed as a cascade of overland flow planes and channels, thereby allowing rainfall, infiltration, runoff, and erosion parameters to vary spatially. Recently, the Automated Geospatial Watershed Assessment (AGWA) Geographic Information Systems (GIS) based tool was developed by the USDA/ARS (Miller et al. 2002) for delineating watersheds into hillslope contributing areas (abstracted into overland flow plane model elements) and channels and generating model parameter files, based on topography, soil, and land cover information. In this study, we used the KINEROS2 model with default parameters generated by AGWA for the WGEW (delineation of 53 planes—average area 2.8 km^2—and 21 channels). Small modifications were made in parameters related to channel loss for the downstream portion of the main channel based on previous simulation studies in the WGEW (Goodrich et al. 2004). We ana-

TABLE 2. Gauge–radar rainstorm depth comparisons using the two Z–R relationships.

		$Z = 300R^{1.4}$ (NWS)		$Z = 655R^{1.4}$ (WGEW calibrated)	
Storm	Study area	Bias	RMSD (mm)	Bias	RMSD (mm)
1	WGEW	2.60	6.0	1.49	2.5
2	WGEW	3.14	23.6	1.80	9.9
3	WGEW	1.61	30.6	0.92	10.2
4	WGEW	2.03	5.1	1.16	1.9
5	WGEW	1.99	12.3	1.14	4.8
6	WGEW	2.59	5.8	1.48	3.2
7	WGEW	1.27	11.0	0.73	9.1
8	WGEW	2.17	22.5	1.24	10.1
9	WGEW	2.03	6.0	1.16	3.6
10	WGEW	1.01	10.7	0.58	11.8
11	WGEW	2.58	15.1	1.48	6.5
12	WGEW	1.68	21.2	0.96	11.8
13	WGEW	1.49	14.9	0.85	10.5
All storms	WGEW	1.75	16.2	1.00	8.2
14 (tilt 1)	Phoenix	1.56	39.4	0.91	9.3
14 (tilt 2)	Phoenix	1.69	41.7	1.03	8.2
14 (tilt 3)	Phoenix	1.21	30.6	0.78	13.8

lyzed the rainfall–runoff event of 11 August 2000, which totaled a 25-mm watershed average rainfall depth with a maximum gauge depth of 91 mm and a recorded runoff peak discharge of 154 $m^3 s^{-1}$ at the watershed outlet.

Three rainfall inputs were analyzed using the hydrological model: (a) gauge-based input, (b) radar-based input using the NWS convective Z–R, and (c) radar-based input using WGEW Z–R developed in this study. Figure 4 and Table 3 present the three computed cases

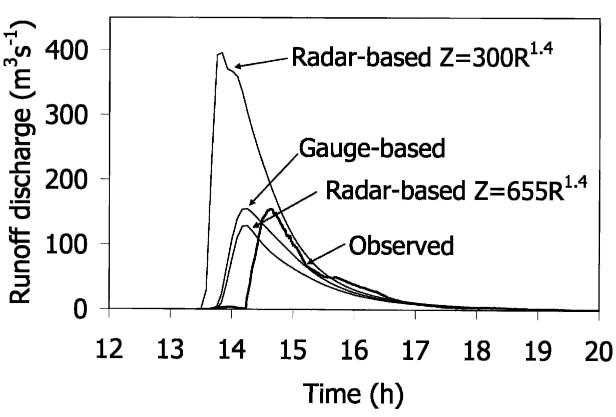

FIG. 4. Observed runoff and computed runoff hydrographs at the WGEW outlet using the KINEROS2 rainfall–runoff model for the 11 Aug 2000 storm with different inputs: gauge-based input, radar-based input using the NWS convective Z–R, and radar-based input using WGEW Z–R developed in this study.

TABLE 3. Observed and simulated runoff hydrograph characteristics for the 11 Aug 2000 event.

	Peak discharge ($m^3 s^{-1}$)	Runoff depth (mm)	Time of peak (UTC)
Observed runoff	154	4.4	1438
Gauge-based input	155	5.3	1415
Radar-based input $Z = 300R^{1.4}$	396	11.3	1350
Radar-based input $Z = 655R^{1.4}$	129	4.2	1415

and the observed runoff data at the watershed outlet (refer to Fig. 1b). The computed runoff using gauge input and radar input with the WGEW Z–R are reasonably close to the observed runoff in terms of peak discharge and runoff depth. The overestimation of rainfall from radar input using the NWS convective Z–R translates into proportionally higher overestimates of peak runoff rates (more than twice as high as the observed), as a result of the nonlinearity of the rainfall–runoff processes.

Comparison of computed and observed peak discharge rates and total runoff volume (expressed as depth of water over the watershed drainage area) at a range of subwatershed scales (4–148 km^2) is presented in Fig. 5. The results indicate the superiority of the WGEW Z–R relation over the convective NWS Z–R for the five subwatersheds in terms of peak discharge and runoff depth.

In terms of time to peak, the computed runoff is on average 25 min early relative to the observed runoff (not shown). This difference is equivalent to 16% error, which is reasonable considering the complexity of rainfall–runoff modeling in semiarid watersheds (Michaud and Sorooshian 1994).

5. Discussion

The WGEW-derived Z–R relationship may provide more accurate radar estimates for convective storms over the southwest United States than does the operational convective Z–R used by the NWS. This is an important, although preliminary, finding since radar data provide the most important real-time tool for monitoring the flood potential of convective storms. Rainfall data from the gauges and from the WGEW Z–R relation for a single relatively large event, when input into a hydrologic runoff model, are much closer to the observed runoff when compared to results from the simulated runoff using NWS radar–rainfall estimates. The NWS estimates lead to predicted peak discharge rates that are more than twice as large as the observed rates. Moreover, these significant overestimates were

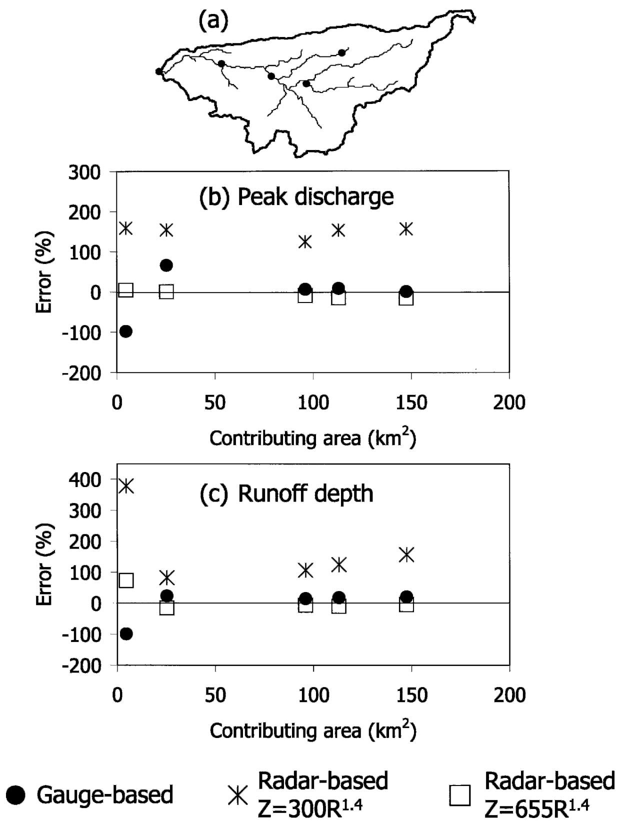

FIG. 5. (a) Watershed map with the five flumes for which comparisons were made between observed and computed runoff. Errors in computed runoff (difference between computed and observed values relative to the observed value) as a function of contributing area in terms of (b) peak discharge and (c) runoff depth.

found for a range of subwatershed areas, from 4 to 148 km^2 (an average 149% error in peak discharge). On the other hand, using the WGEW *Z–R* relation derived in this study yielded an average error of 7% in peak discharge. These preliminary results suggest that the generic NWS *Z–R* relation, used nationally for convective storms, may be substantially improved for regional application, especially over the southwestern United States where airmass thunderstorms are common.

Additional validation and assessment of the WGEW *Z–R* is being pursued for new, independent, rainfall events over the WGEW. We plan to run the hydrologic prediction model for more events of significance, and we plan to evaluate the WGEW *Z–R* for additional events over other well-instrumented areas of the western United States where convective precipitation is important.

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