Multi-Watershed Evaluation of WSR-88D (NEXRAD) Radar-Precipitation Products

Stuart Hardegree, Steven Van Vactor, Kathleen Healy, Carlos Alonso, James Bonta, David Bosch, Dwight Fisher, Dave Goodrich, Daren Harmel, Jean Steiner, Michael Van Liew

Abstract

The National Weather Service (NWS) operates a network of Doppler-radar stations (NEXRAD, WSR-88D) that produce hourly-rainfall estimates, at approximately 4-km^2 resolution, with nominal coverage of 96% of the conterminous US. Utilization of these data by the NWS is primarily for the detection and modeling of extreme-weather events. Radar-precipitation estimates were compared with gauge estimates at six ARS watershed-research locations in Idaho, Arizona, Oklahoma, Georgia and Mississippi to evaluate the utility of these data for hydrologic and natural resources modeling applications. Radar precipitation estimates underestimated gauge readings for all locations except Tucson. In all cases, the total number of hours with measured-radar precipitation was much less than hours containing gauge-precipitation estimates. Additional modification of NWS precipitation processing procedures will be necessary to improve accessibility and utility of these data for hydrologic and natural-resource modeling applications.

Keywords: NEXRAD, radar, gauge, precipitation, watershed, calibration

Introduction

The National Weather Service (NWS) operates approximately 160 WSR-88D Doppler-radar stations as part of a Next Generation Radar (NEXRAD) program that began implementation in 1992. These radar stations provide spatial rainfall estimates, at approximately 4-km^2 resolution, with nominal coverage of 96% of the conterminous United States (Crum et al. 1998). This network was originally designed to support Departments of Defense, Transportation and Commerce objectives for detection and mitigation of severe weather events (Crum and Alberty 1993, Baeck and Smith 1998, Crum et al. 1998, Whiton et al. 1998, Winchell et al. 1998, Witt et al. 1998a, Witt et al. 1998b, Anagnostou and Krajewski 1999, Fulton 1999, Warner et al. 2000). The primary hydrologic applications have been modeling of river flow and flood forecasting by thirteen NWS River Forecast Centers (RFC). Data processing and quality control of NEXRAD precipitation products is optimized for a relatively large spatial domain (>100,000 km^2) (Anagnostou and Krajewski 1998, Seo et al. 1999).

Utilization of NEXRAD data in agricultural and natural-resource management applications has been slow to develop (Brandes et al. 1991, Nelson et al. 1996). Studies that evaluate NEXRAD datasets for input into non-NWS hydrologic models focus on parameter sensitivity and variability rather than spatial accuracy of the data (Winchell et al. 1998, Koren et al. 1999, Carpenter et al. 2001). NWS-RFC applications

Hardegree is a Plant Physiologist/Research Leader, Northwest Watershed Research Unit, Boise, ID 83712. E-mail: shardegr@nwrc.ars.udsa.gov. All authors are with the U.S. Department of Agriculture, Agricultural Research Service. Van Vactor is a Hydrologist and Healy is an Information Technology Specialist, also at NWRC in Boise. Alonso is a Hydraulic Engineer/Research Leader, National Sedimentation Laboratory, Oxford, MS 38655. Bonta is a Hydraulic Engineer, North Appalachian Experimental Watershed, Coshocton, OH 43812. Bosch is a Hydrologist, Southeast Watershed Research Unit, Tifton, GA 31793. Fisher is a Rangeland Scientist, J. Phil Campbell. Sr., Natural Resource Conservation Center, Watkinsville, GA 30677. Goodrich is a Research Hydraulic Engineer, Southwest Watershed Research Center, Tucson, AZ 85719. Harmel is an Agricultural Engineer, Natural Resources Systems Research Unit, Temple, TX 76502. Steiner is a Soil Scientist/Research Keader and Van Liew is a Hydrologist, both at the Great Plains Agroclimate and Natural Resources Research Unit, El Reno, OK 73036.

for NEXRAD data occur in real-time within a custom software system that is inaccessible to most external users (Anagnostou and Krajewski 1998). Digital, distributed-precipitation radar products can be downloaded directly from the NWS but hourly precipitation files are stored in binary-coded format. Georeferencing tools for comparing NEXRAD and ground-based measurements are relatively difficult to obtain and must be adapted for use outside of the NWS-RFC application domain. The ARS Northwest Watershed Research Center has developed software tools to decode, process and evaluate NEXRAD precipitation products. The purpose of this study was to use data from the ARS-watershed gauge network to evaluate the utility of NEXRAD Stage-1, Level-3 spatial-precipitation data for agricultural and natural-resource management applications.

Methods

NEXRAD precipitation-processing protocols consists of three processing Stages (Anagnostou and Krajewski 1998, Fulton et al. 1998). We are concerned with Stage-1 processing which produces spatial rainfall estimates for a single radar domain. Within Stage-1 processing there are three processing levels. Level 1 consists of the raw analog output from the radar scanning process. Level-2 processing produces reflectivity estimates for every radial scan (5-10 minutes), in a polar grid of 82,800 bins representing 1° of arc and 1-km distance out to a radius of 230 km. Reflectivity is measured at multiple beam angles between 0.5 and 20° for each bin (Young et al. 1999). The processing program selects an appropriate beam angle for every bin based on a map of potential beam blockage for a given site location (Fulton et al. 1998).

The Level-2 processing program conducts a number of error checking procedures, and estimates precipitation within each bin using an algorithm that relates reflectivity (Z) to precipitation (R). The default equation relating Z and R is the power function, $R = aZ^b$, where a = 0.017 and b = 0.714. Z-R coefficients have been shown to vary as a function of many factors and previous studies have shown that it is not possible to derive a single equation that is accurate at every point in a given radar domain, and for every storm-type and storm intensity (Austin 1987, Hunter 1996, Glitto and Choy 1997, Anagnostou and Krajewski 1999, Ciach and Krajewski 1999, Ulbrich and Lee 1999). Level-2 processing also involves selection of a precipitation detection function (pdf) which establishes a threshold reflectivity, below which radar-rainfall estimates are set to zero (Anagnostou and Krajewski 1998, Fulton 1999, Kingsmill and Huggins 1999).

Level 3 processing aggregates and re-maps Level-2 precipitation estimates into hourly values within the Hydrologic Rainfall Analysis Project (HRAP) grid (Reed and Maidment 1999). The HRAP grid is a polar stereographic projection that covers the 48 contiguous states in the continental United States (Reed and Maidment 1999). HRAP cells are approximately 4 km x 4 km in size and have a row (1-861) and column (1-1121) designation relative to a reference cell (1,1) located just west of Baja California (Fulton 1998). Reformatting the data to fit the HRAP grid facilitates utilization of data for locations with overlapping radar coverage. Files from individual radar locations, however, are georeferenced relative to a local HRAP grid that contains only a 131-row x 131-column (17,161 cell) subdomain of the national-HRAP grid.

Figure 1. Radar (circle) and watershed (square) locations.

Hourly Level-3 radar data were obtained for the closest radar location to each of the ARS-watershed locations listed in Table 1 (Figure 1). Individual hourly-precipitation files were decoded using a computer program (decode.pl) which we modified from the original source code obtained from the NWS Hydrologic Research Laboratory in Silver Springs MD. This program converts binary-coded files into ASCII-formatted files that contain a precipitation estimate, in mm, for every row and column within the 17,161-cell local-HRAP grid domain. We also developed a computer program (gauges_lh.exe) using code from existing NWS algorithms to geo-reference radar and gauge data relative to both the local and national-HRAP grids. We encountered 3 versions of level-3 files that differ significantly in structure. The most current files are labeled DPA (for Digital Precipitation Array) and have a different structure than older files that are labeled HDP (for Hourly Digital Precipitation).

A transition period also occurred when files with the HDP format were labeled as DPA files. The program "decode.pl" decodes older, newer, and transition files by calling specific subroutines depending upon the nature of the file that it is tasked to decode. If no precipitation is detected during a given hour, DPA and HDP-file headers contain a flag indicating that all of the precipitation values are zero.

Precipitation-gauges within each ARS watershed were georeferenced relative to the local-radar HRAP grid. A single mean-precipitation estimate was calculated for all gauge measurements that fell within a single HRAP-grid cell in a given hour. Significant periods in which NEXRAD data were not available were excluded from the analysis. Comparative statistics concerning radar and gauge estimates were averaged across all instrumented-grid cells.

Results

NEXRAD radar-precipitation records obtained from the NWS contain significant gaps in which no data are available. For the periods in which the radar data were evaluated, the NEXRAD system underestimated gauge precipitation for all location except Tucson (Table 1). The estimate improved somewhat when the period of consideration was limited to those hours in which the radar data were both present and flagged as operational. The ratio of radar to gauge data changed significantly when a comparison was made only for those hours in which radar data showed positive precipitation (Table 1). For hours with positive radar-precipitation estimates, the radar overestimated rainfall for 4 locations and underestimated at both Georgia locations, relative to gauge readings (Table 1). In all cases, the number of hours showing positive radar-precipitation estimates was very much less than the number of hours showing positive gauge-precipitation estimates (Table 1).

Discussion

Radar-data products are subject to three types of error that affect the accuracy of precipitation estimates: mean-field systematic bias, range dependent systematic error, and random error (Hunter 1996, Seed et al. 1996, Smith et al. 1996, Anagnostou and Krajewski 1998, Anagnostou et al. 1998, Anagnostou and Krajewski 1999, Ciach and Krajewski 1999, Steiner et al. 1999, Young et al. 1999, Young et al. 2000). Range dependent error in this study should be similar among gauges within a given location as the watersheds in question are all an order of magnitude smaller than the individual radar domain. Error detection and optimization or radar-precipitation products is almost always conducted by comparing radar-precipitation estimates with ground-truth gauge data (Smith et al. 1996, Anagnostou and Krajewski 1998, 1999, Seo 1998, Anagnostou et al. 1998, Anagnostou et al. 1999, Fulton 1999, Seo et al. 1999, Steiner et al. 1999, Seo et al. 2000a). Gauge data can be used to improve the accuracy of WSR-88D radar-precipitation estimates in two ways: development of more accurate Z-R relationships and pdf values for Level-2 data processing; and in post-estimate bias correction of Level-3 DPA data (Glitto and Choy 1997, Anagnostou and Krajewski 1998, Anagnostou et al. 1998, Seo 1998, Ciach and Krajewski 1999, Seo et al. 1999, Steiner et al. 1999, Ulbrich and Lee 1999, Ciach et al. 2000, Seo et al., 2000a).

Additional analysis of the Boise data indicated that the majority of gauge-precipitation, during hours where the radar reported zero precipitation, occurred at a rate below the precipitation detection function for NEXRAD. Post-processing bias adjustment with gauge data may be inappropriate for the Boise-radar data as the procedure assumes that all precipitation occurs at a rate that is higher than the precipitation detection function. Errors associated with low-rainfall rates may be under-represented in the literature as most radar-gauge comparisons focus on storm totals for higher intensity events or specifically ignore lower intensity events that occur during the test periods (Austin 1987, Anagnostou and Krajewski 1998, Baeck and Smith 1998, Brandes et al. 1999, Fulton 1999, Steiner et al. 1999, Ulbrich and Lee 1999, Seo et al. 2000a). Recently detected programming errors in the WSR-88D precipitation processing system have also been

Table 1. NEXRAD and gauge information by watershed location. Numbers in parentheses represent 1 standard error of the mean across all HRAP grid cells. Values for total precipitation are in mm. POR = period of record.

ARS location **Radar location**	**Boise, ID** **Boise (CBX)**	**Tucson, AZ** **Tucson (EMX)**	**El Reno, OK** **OK City (TLX)**	**Oxford, MS** **Memphis (NQA)**	**Tifton, GA** **Tallahassee (TLH)**	**Watkinsville, GA** **Atlanta (FFC)**
Start date	1-1-98	9-21-99	2-1-98	1-1-99	1-1-98	7-17-98
End date	12-31-00	12-31-00	12-31-00	12-31-00	11-28-00	3-30-01
HRAP cells	4	12	34	7	18	3
# gauges	4	50	34	28	28	5
Total hours in POR	26304	11232	25559	17548	25517	23690
Non-zero hours (NEXRAD)	207 (18)	154 (11)	386 (12)	483 (19)	442 (17)	491 (8)
Non-zero hours (Gauge)	845 (100)	248 (34)	719 (21)	1065 (296)	1116 (172)	1516 (215)
Precipitation (mm):						
Mean radar total (POR)	233 (41)	502 (67)	1326 (96)	1673 (43)	1242 (101)	1303 (62)
Mean gauge total (POR)	728 (114)	435 (51)	2315 (395)	2071 (122)	3158 (183)	2511 (83)
Mean gauge total (NEXRAD functional)	593 (95)	424 (54)	1933 (392)	1899 (121)	2618 (165)	2166 (68)
NEXRAD/gauge (mm/mm):						
N/G (POR)	33 (8)	116 (9)	58 (7)	81 (6)	39 (3)	52 (1)
N/G (NEXRAD functional)	40 (9)	119 (10)	70 (9)	89 (6)	44 (3)	60 (2)
N/G (NEXRAD Non-Zero)	123 (21)	165 (21)	128 (14)	116 (6)	59 (4)	94 (2)

determined to cause truncation errors that may systematically lower cumulative radar-precipitation estimates (Seo et al. 2000b). There were significantly fewer hours of NEXRAD-precipitation detection relative to gauge-precipitation detection for every radar evaluated in this study (Table 1). This indicates that the various radar locations were not detecting many events and their data would, therefore, also be unsuitable for bias adjustment with gauge data.

Our analysis indicates that NEXRAD radar data may not be suitable for long-term water balance and natural-resource modeling applications that require estimates of total annual rainfall. The utility of the data for modeling extreme-event flooding, runoff and erosion requires more detailed analysis of radar and gauge data for individual storms within a given watershed location. These data should also be evaluated for potential errors associated with beam blockage (Andrieu et al. 1997, Creutin et al. 1997, Maddox et al. 2002). Furthermore, additional research should be conducted to compare radar and gauge estimates in watershed locations with multiple, overlapping radar coverage.

References

Anagnostou, E.N., and W.F. Krajewski. 1998. Calibration of the WSR-88D precipitation processing subsystem. Weather and Forecasting 13:396-406.

Anagnostou, E.N., and W.F. Krajewski. 1999. Real-time radar rainfall estimation. Part I: Algorithm formulation. Journal of Atmospheric and Oceanic Technology 16:189-197.

Anagnostou, E.N., W.F. Krajewski, D.-J. Seo, and E.R. Johnson. 1998. Mean-field radar rainfall bias studies for WSR-88D. ASCE Journal of Engineering Hydrology 3:149-159.

Anagnostou, E.N., W.F. Krajewski, and J. Smith. 1999. Uncertainty quantification of mean-areal radar-rainfall estimates. Journal of Atmospheric and Oceanic Technology 16:206-215.

Andrieu, H., J.D. Creutin, G. Delrieu, and D. Faure. 1997. Use of a weather radar for the hydrology of a mountainous area. 1. Radar measurement interpretation. Journal of Hydrology 193:1-25.

Austin, P.M. 1987. Relation between measured radar reflectivity and surface rainfall. Monthly Weather Review 115:1053-1070.

Baeck, M.L., and J.A. Smith. 1998. Rainfall estimation by the WSR-88D for heavy rainfall events. Weather and Forecasting 13:416-436.

Brandes, E.A., D.S. Zrnic, G.E. Klazura, C.F. Suprenant, and D. Sirmans. 1991. The next generation weather radar (WSR-88D) as an applied research tool. In Proceedings of the 25th International Conference on

Radar Meteorology, pp. 47-50. American Meteorological Society, Boston.

Brandes, E.A., J. Vivekanandan, and J.W. Wilson. 1999. A comparison of radar reflectivity estimates of rainfall from collocated radars. Journal of Atmospheric and Oceanic Technology 16:1264-1272.

Carpenter, T.M., K.P. Georgakakos, and J.A. Sperfslagea. 2001. On the parametric and NEXRAD-radar sensitivities of a distributed hydrologic model suitable for operational use. Journal of Hydrology 253:169-193.

Ciach, G.J., and W.F. Krajewski. 1999. Radar-rain gauge comparisons under observational uncertainties. Journal of Applied Meteorology 38:1519-1525.

Ciach, G.J., M.L. Morrissey, and W.F. Krajewski. 2000. Conditional Bias in Radar Rainfall Estimation. Journal of Applied Meteorology 39:1941-1946.

Creutin, J.D., H. Andrieu, and D. Faure. 1997. Use of a weather radar for the hydrology of a mountainous area. 2. Radar measurement validation. Journal of Hydrology 193:26-44.

Crum, T.D., and R.L. Alberty. 1993. The WSR-88D and the WSR-88D operational support facility. Bulletin of the American Meteorological Society 74:1669-1687.

Crum, T.D., R.E. Saffle, and J.W. Wilson. 1998. An update on the NEXRAD program and future WSR-88D support to operations. Weather and Forecasting 13:253-262.

Fulton, R.A. 1998. WSR-88D Polar-to-HRAP mapping. National Weather Service, Hydrologic Research Laboratory, Technical Memorandum, pp. 1-34. www.nws.noaa.gov/oh/hrl/papers/wsr88d/hrapmap.pdf.

Fulton, R.A. 1999. Sensitivity of WSR-88D rainfall estimates to the rain-rate threshold and rain gauge adjustment: a flash flood case study. Weather and Forecasting 14:604-624.

Fulton, R.A., J.P. Breidenbach, D.-J. Seo, D.A. Miller, and T. O'Bannon. 1998. The WSR-88D rainfall algorithm. Weather and Forecasting 13:377-395.

Glitto, P., and B. Choy. 1997. A comparison of WSR-88D storm total precipitation performance during two tropical systems following changes to the multiplicative bias and upper reflectivity threshold. Weather and Forecasting 12:459-471.

Hunter, S.M. 1996. WSR-88D radar rainfall estimation: Capabilities, limitations and potential improvements. National Weather Digest 20:26-38.

Kingsmill, D.E., and A.W. Huggins. 1999. Quantitative precipitation estimates from a mountain-top WSR-88D: The 1997 new year's flood. In Proceedings of the 29th International Conference on Radar Meteorology, pp. 713-716. American Meteorological Society, Boston.

Koren, V.I., B.D. Finnerty, J.C. Schaake, M.B. Smith, D.-J. Seo, and Q.Y. Duan. 1999. Scale dependencies of hydrologic models to spatial variability of precipitation. Journal of Hydrology 217:285-302.

Maddox, R.A., J. Zhang, J.J. Gourley, and K.W. Howard. 2002. Weather radar coverage over the contiguous United States. Weather and Forecasting 17:927-934.

Nelson, J.A., J.A. Jackman, M.I. Biggerstaff, and D. Austin. 1996. Agricultural applications of the hourly digital precipitation array (HDP) from the WSR-88D (NEXRAD) doppler radars. In Proceedings of the 22nd Conference on Agricultural and Forest Meteorology, pp. 339-340. American Meteorological society, Boston.

Reed, S.M., and D.R. Maidment. 1999. Coordinate transformations for using NEXRAD data in GIS-based hydrologic modeling. Journal of Hydrologic Engineering 4:174-182.

Seed, A.W., J. Nicol, G.L. Austin, C.D. Stow, and S.G. Bradley. 1996. The impact of radar and raingauge sampling errors when calibrating a weather radar. Meteorological Applications 3:43-52.

Seo, D.-J. 1998. Real-time estimation of rainfall fields using radar rainfall and rain gage data. Journal of Hydrology 208:37-52.

Seo, D.-J., J.P. Breidenbach, and E.R. Johnson. 1999. Real-time estimation of mean field bias in radar rainfall data. Journal of Hydrology 223:131-147.

Seo, D.-J., J. Breidenbach, R. Fulton, D. Miller, and T. O'Bannon. 2000a. Real-time adjustment of range-dependent biases in WSR-88D rainfall estimates due to nonuniform vertical profile of reflectivity. Journal of Hydrometeorology 1:222-240.

Seo, D.-J., J.P. Breidenbach, R. Fulton, D. Miller, B. Vignal, and W. Krajewski. 2000b. Final Report, Interagency Memorandum of Understanding among the NEXRAD Program, the WSR-88D Operational Support Facility, and the National Weather Service Office of Hydrology.

Smith, J.A., D.-J. Seo, M.L. Baeck, and M.D. Hudlow. 1996. An intercomparison study of NEXRAD precipitation estimates. Water Resources Research 32:2035-2045.

Steiner, M., J.A. Smith, S.J. Burges, C.V. Alonso, and R.W. Darden. 1999. Effect of bias adjustment and rain gauge data quality control on radar rainfall estimation. Water Resources Research 35:2487-2503.

Ulbrich, C.W., and L.G. Lee. 1999. Rainfall measurement error by WSR-88D radars due to variations in Z-R law parameters and the radar constant. Journal of Atmospheric and Oceanic Technology 16:1017-1024.

Warner, T.T., E.A. Brandes, J.Z. Sun, D.N. Yates, and C.K. Mueller. 2000. Prediction of a flash flood in complex terrain. Part I: a comparison of rainfall estimates from radar, and very short range rainfall simulations from a dynamic model and an automated algorithmic system. Journal of Applied Meteorology 39:797-814.

Whiton, R.C., P.L. Smith, S.G. Bigler, K.E. Wilk, and A.C. Harbuck. 1998. History of operational use of weather radar by US weather services. Part II: Development of operational Doppler weather radars. Weather and Forecasting 13:244-252.

Winchell, M., H.V. Gupta, and S. Sorooshian. 1998. On the simulation of infiltration- and saturation-excess runoff using radar-based rainfall estimates: Effects of algorithm uncertainty and pixel aggregation. Water Resources Research 34:2655-2670.

Witt, A., M.D. Eilts, G.J. Stumpf, J.T. Johnson, E.D. Mitchell, and K.W. Thomas. 1998a. An enhanced hail detection algorithm for the WSR-88D. Weather and Forecasting 13:286-303.

Witt, A., M.D. Eilts, G.J. Stumpf., E.D. Mitchell, J.T. Johnson, and K.W. Thomas. 1998b. Evaluating the performance of WSR-88D severe storm algorithms. Weather and Forecasting 13:513-518.

Young, C.B., B.R. Nelson, A.A. Bradley, J.A. Smith, C.D. Peters-Lidard, A. Kruger, and M.L. Baeck. 1999. An evaluation of NEXRAD precipitation estimates in complex terrain. Journal of Geophysical Research-Atmospheres 104:19691-19703.

Young, C.B., A.A. Bradley, W.F. Krajewski, A. Kruger, and M.L. Morrissey. 2000. Evaluating NEXRAD multisensor precipitation estimates for operational hydrologic forecasting. Journal of Hydrometeorology 1:241-254.