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Comparisons between NEXRAD Radar and Tipping-Bucket Gage Rainfall Data: A Case Study for DuPage County, Illinois

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Abstract

The ability to use radar-based rainfall estimates either alone or as a supplement to rain-gage data in real-time or historical rainfall-runoff simulations or other hydrologic applications would be valuable because of the relative sparseness of available gaged rainfall data. To investigate this ability, a comparison study between rainfall estimates from the National Weather Service (NWS) Next Generation Weather Radar (NEXRAD) and the recorded measurements collected from a network of 27 tipping-bucket rain gages located in or near DuPage County in northeastern Illinois over the period from July 1997 through September 2005 was carried out at the daily time scale. The NEXRAD data used in this comparison consist of Stage III (1997-2001) and Multisensor Precipitation Estimate (MPE) (2002-2005) gridded hourly products. These NEXRAD products were corrected using rain-gage data, but data from the DuPage County gage network were not used for this purpose. Periods of missing or frozen precipitation were excluded from the comparisons. Results show that early in the study period, NEXRAD data first under-estimated and then over-estimated the gage measurements on a spatial average basis, while since 2001, the long-term spatial averages were similar. For most of the study period, the differences between gage and NEXRAD estimated daily totals decreased with distance from the nearest radar site. An analysis of the distribution of daily rainfall values shows that over most of the period, the radar data has more small values and fewer large values than the gage data, which is consistent with the radar sampling a larger area. Overall, these findings indicate that, at least in this region, while total NEXRAD precipitation estimates have become more comparable to the rainfall recorded by the gage network over the period of the study, spatially-variable biases may remain, and extreme values may have a different distribution. As a result, caution should be employed when using NEXRAD Stage III and MPE data for hydrologic modeling.

Introduction

For small basins, the sparseness of available rain-gage data is a severe hindrance to accurate hydrologic modeling for purposes such as flood forecasting, flood simulation in support of flood-plain management, and hydrologic model testing and development. Urban areas have particularly high rain-gage data requirements due to the larger runoff rates and rapid response times of urban basins. Since the deployment of the first Next Generation Weather Radar (NEXRAD) systems in the earlier 1990's, it has been hoped that radar-based rainfall estimates could provide important complementary rainfall information where gage data is lacking. However, because of the complex nature of the radar-rainfall measurement process, the procedures for estimation of rainfall rates from the NEXRAD system remained under development for several years after the deployment of the radars, and accuracy of radar-based rainfall estimates is still under evaluation. The first gage-corrected, mosaicked NEXRAD rainfall estimate, Stage III, was produced at National Weather Service (NWS) river forecasting centers (RFC's) for their in-house in large-basin flood forecasting. Stage III was under continuous development until it was replaced, in 2002 in the North Central RFC domain, which includes the study area, by an updated and improved estimation product, the Multisensor Precipitation Estimate (MPE). A network of 27 tipping-bucket rain gages has been operated by the US Geological Survey, Illinois Water Science Center (IWSC), in cooperation with the DuPage County Stormwater Management Division (SMD) since July 1997 in and near DuPage County, Illinois, for use in real-time streamflow simulation and flood-plain management. The interest of DuPage County SMD in supplementing the gage network with NEXRAD data led to the present study, which is being carried out by the IWSC in cooperation with DuPage County SMD. The large DuPage County gage network, which has been operated over most of the period of the availability of NEXRAD data and includes overlap with both Stage III and MPE products, provides an opportunity to examine, by means of a local case study, the changes in, and current status of, the accuracy of NEXRAD-based radar rainfall estimates.

Previous Studies

Several previous studies have presented comparisons of Stage III NEXRAD data and co-located rain-gage data (for example, Pereira Fo et al., 1998; Johnson et al., 1999; Wang et al., 2000; Young et al., 2000; Stellman et al., 2001; Jayakrishnan et al., 2004; Xie et al., 2006; Westcott and Knapp, 2006). However, four of these eight studies utilized Stage III data only through 1996 when either the study period ended or another gage-correction and mosaicking algorithm (the "P1" algorithm) was implemented in the study area. Only Westcott and Knapp (2006) utilized MPE data. As the present study commences with data from July 1997, because of modifications to the Stage III algorithms during 1996, including removal of bi-scan maximization during mosaicking (Young et al. 2000), results from these older studies may not be applicable to later Stage III or MPE data. Nevertheless, we note that these studies, including the older ones, indicate that Stage III NEXRAD data was observed to usually under-estimate precipitation at co-located gages, sometimes severely, except in the study of Xie et al. (2006). This study, which is the only study listed above from an arid region, noted over-estimation during the summer monsoon in central New Mexico but severe under-estimation during the winter season. Jayakrishnan et al. (2004) observed overall under-estimation over the period from 1995-99 but over-estimation during 1998-99, similar to what is observed in the present study. Westcott and Knapp (2006) found the NEXRAD MPE data also, like most of the studies that examined Stage III data, under-estimated the rain-gage values by about 20% in their study in northeastern Illinois and southeastern Wisconsin (just north of the present study location).

Data and Processing

The NEXRAD radar system scans radially at multiple elevation angles, and the raw data it returns are so-called radar-reflectivity values usually denoted by Z. Obtaining gridded estimates of rainfall from this reflectivity data is a multi-step process that includes: (1) combination of different elevation angles into the "best" single scan; (2) removal of non-precipitation returns; (3) converting reflectivity to rain rate by use of a Z-R power law relation, $Z = aR^b$, where R denotes rain rate; (4) correcting for hail returns; (5) correcting for range bias; and (6) conversion from radial coordinates to the Hydrologic Rainfall Analysis Project (HRAP) grid (hereafter referred to as NEXRAD grid), whose pixels are approximately 4 by 4 km in size. Execution of these steps, among others, constitutes the Stage I processing, which occurs in the precipitation processing subsystem (PPS) at the individual radar (see Fulton et al. (1998) for further details). The Stage I gridded rainfall product is then sent to the applicable river forecasting center (RFC) for further processing. Stages II and III consist of bias corrections using available gage data (Stage II) and mosaicking the radar fields together to cover the RFC's domain (Stage III). MPE processing is an update of the Stage II and III algorithms to provide better gage-correction and mosaicking, and to provide the possibility of the use of satellite-derived precipitation estimates (National Weather Service, 2002).

Final processing of the Stage III and MPE NEXRAD radar data used in this study was performed at the North Central River Forecasting Center (NCRFC) of the NWS; however, the data used in this study were obtained from the archive at http://dipper.nws.noaa.gov/hdsb/data/nexrad/nexrad.html. The archive contains Stage III data from the NCRFC through April 2002 and MPE data from the NCRFC from February 2002 through September 2005. For this study, the Stage III data through October 2001 were analyzed. The period of MPE data analyzed begins with the beginning of the archive data in February, 2002. Therefore, no data from November 2001 through January 2002 were analyzed. The Stage III data were downloaded in 2003. MPE data downloads continued into 2006.

The rain-gage data used in this study are from a network of 27 radio-telemetered tipping-bucket rain gages operated by the USGS IWSC in cooperation with the DuPage County SMD for the purposes of flood-plain management and real-time streamflow simulation in the Salt Creek watershed (Ishii et al., 1998). The location and layout of the gages are shown in figure 1. The gages are regularly checked, cleaned, and calibrated and record the time of the tip for each 0.01 inch of rainfall. Each gage has a back-up datalogger to record data when problems occur with the radio-telemetry system. The data are published in the annual data report of the IWSC (LaTour et al., 2005), which may be obtained on-line at http://il.water.usgs.gov/annual_report/start.htm.

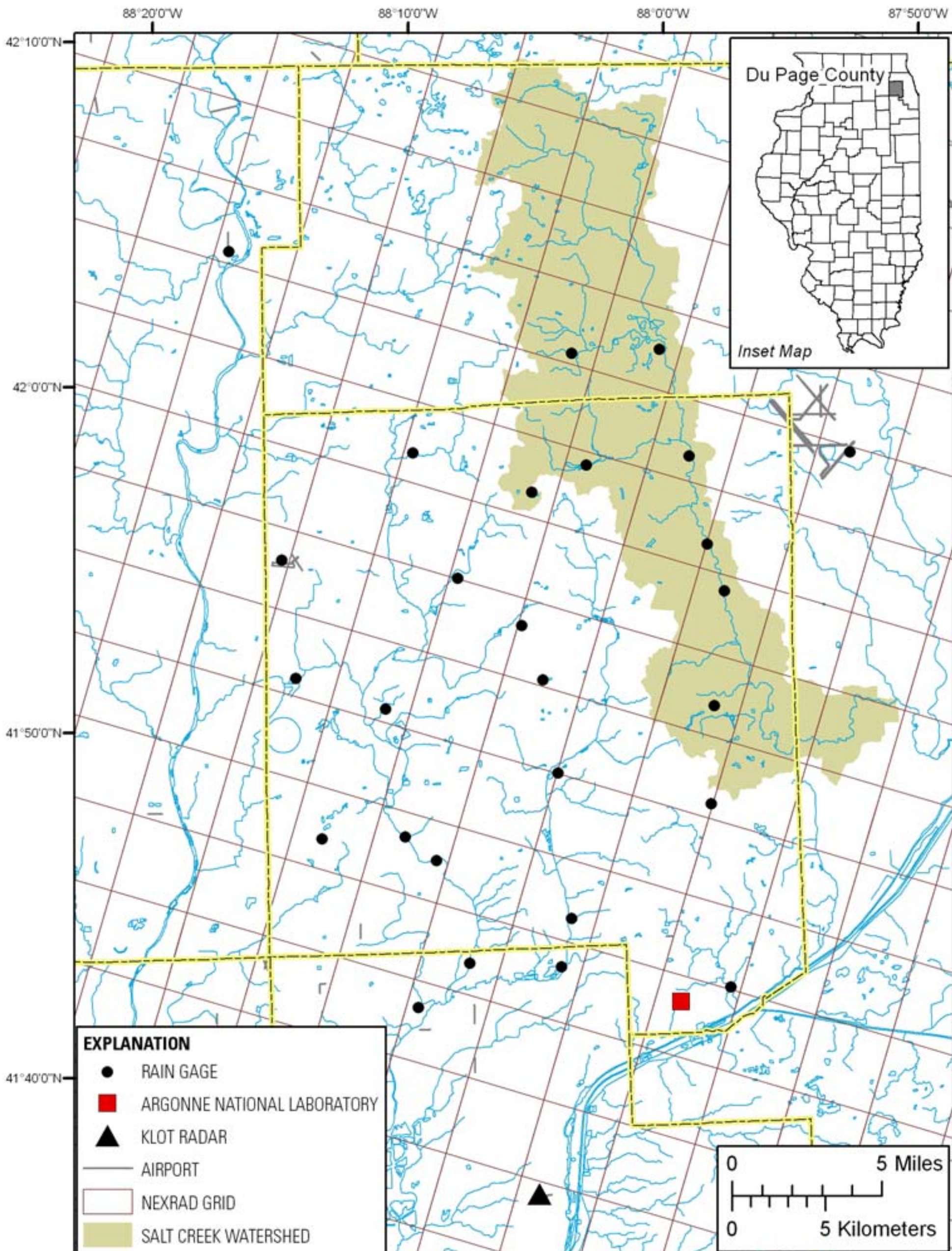


Figure 1. DuPage County in Illinois with rain gages used in this analysis and NEXRAD grid.

Because local urban flooding in the midwestern United States generally occurs during warm-season events and because estimation of frozen precipitation adds another layer of complexity for the measurement of precipitation by both radar and gages, days on which freezing conditions occurred were removed from the study period. A day was removed as affected by freezing if the temperatures measured at the Argonne National Laboratory (fig. 1) weather station (http://www.atmos.anl.gov/ANLMET/) had nine or more hours with temperatures below 34 degrees Fahrenheit or if the day had an average temperature below 38 degrees Fahrenheit. In order to be able to compute consistent spatial statistics, gages with significant amounts of missing data during a particular analysis period were removed, as were days during which one or more of the remaining gages had missing values. All statistics reported here are based on pairs of co-located rain gages and the NEXRAD pixel in which the gage lies. While Stage III / MPE data is hourly, and the basic gage data consists of tips of 0.01 inches, only results from analysis of daily values are reported here.

Results

The total rainfall observed by the two systems as a function of time can be observed from a spatially-averaged double-mass curve, as presented in figure 2. This figure shows significant under-estimation by the radar observations of the gage rainfall from the beginning of the study in July 1997 until summer or early autumn of 1999, followed by about a year of approximate equality, and then a period, from autumn 2000 to spring 2001, when the radar over-estimated the gage rainfall. Since spring 2001, the two systems have recorded approximately equal total average rainfall. Recall that the last Stage III data analyzed here is from October 2001 and the first MPE data is from February 2002. Based on the results of this double-mass analysis, much of the analysis that follows will be divided into the three periods: (1) July 1997 through September 1999; (2) October 1999 through October 2001; and (3) February, 2002 through September 2005. Table 1 shows that on average NEXRAD under-estimated the rain-gage rainfall by about 25% during period 1, over-estimated the gage rainfall by about 9% during period 2, under-estimated the gage rainfall by about 3% during period 3, and under-estimated the gage rainfall by about 7% during the entire study period.

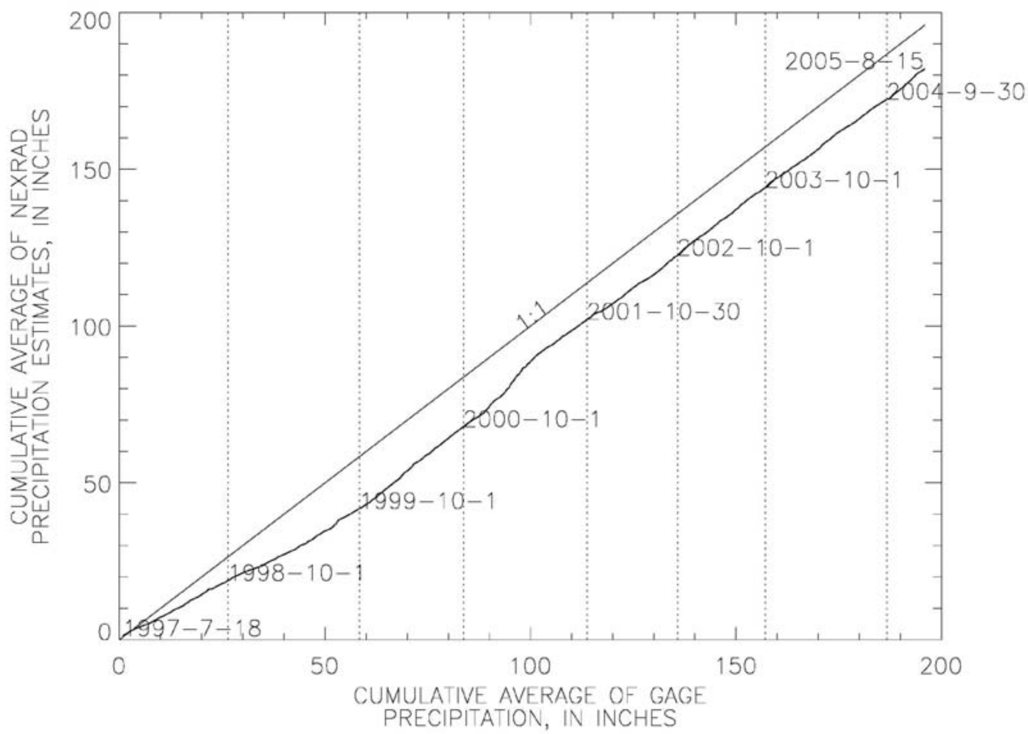


Figure 2. Comparison of cumulative average NEXRAD precipitation estimates and cumulative average gage precipitation from July 1997 through September 2005 for all non-removed days.

The spatially-averaged double-mass analysis masks significant spatial variability in the gage-radar errors. Figures 3a-c show error statistics for gage-radar pixel pairs for the three periods defined above compared to the distance ("range") from the KLOT radar located at the Chicago Weather Forecast Office in Romeoville, Illinois. The values plotted in figures 3a-c, averaged together, form the average differences (or "errors") listed in the last two columns of table 1. As observed in other studies using both Stage III and non-gage-corrected NEXRAD data (for example, Young et al., 1999; Young et al., 2000), NEXRAD tends to under-estimate the rainfall within 40 km of the radar. This apparent range effect is not so clear during the second period but re-appears during the third period. Note that the detection of range effects in Stage III / MPE data may be complicated by occasional radar outages and the mosaicking of multiple radars.

Table 1. Spatial average gage rainfall and radar-gage differences.

Period	Number of Gages Used	Number of Days Included in Analysis	Average Gage Total Rainfall (inches)	Radar - Gage Average Difference (inches)	Radar - Gage Average Difference (% of Gage Total)
Jul. 1997 - Sep. 1999	23	576	69.0	-17.1	-24.8%
Oct. 1999 - Oct. 2001	27	449	55.2	5.1	9.3%
Feb. 2002 - Sep. 2005	22	804	79.9	-2.3	-2.9%
Jul. 1997 - Sep. 2005	20	1819	195.9	-13.3	-6.8%

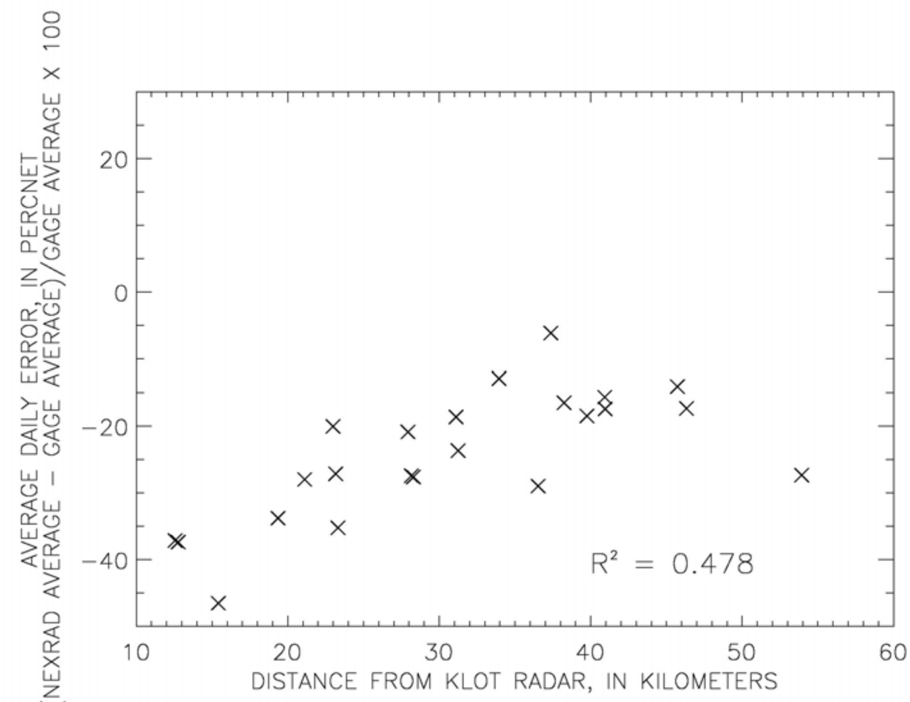


Figure 3a. Average radar-gage error compared to distance from the KLOT radar for the period from July 1997 through September 1999.

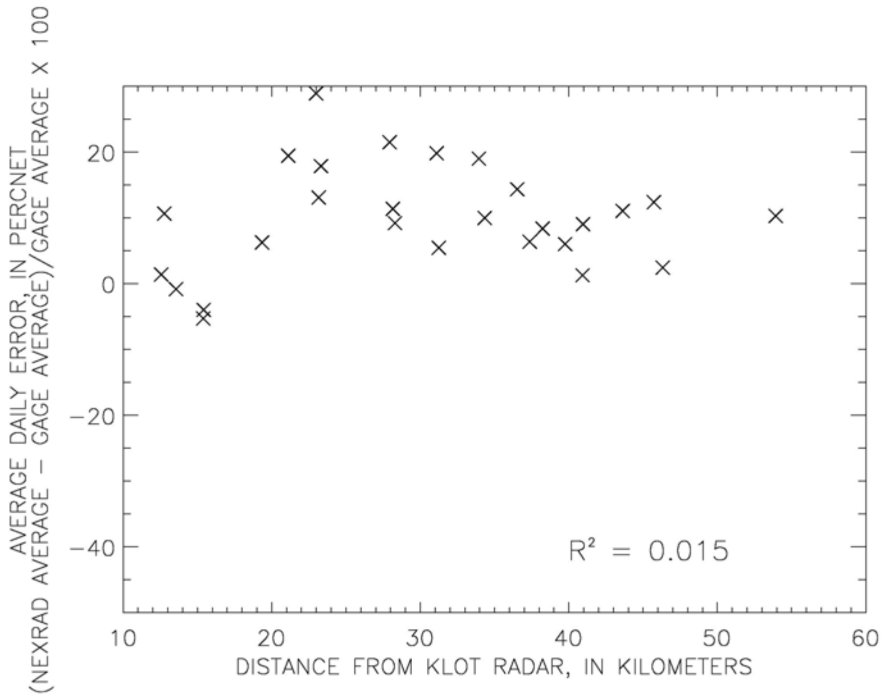


Figure 3b. Average radar-gage error compared to distance from the KLOT radar for the period from October 1999 through October 2001.

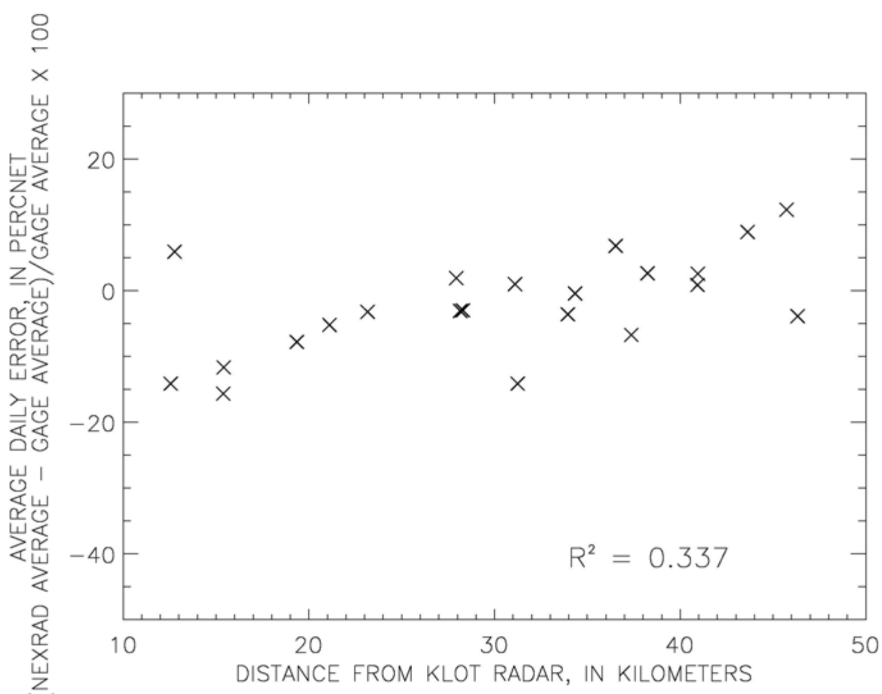
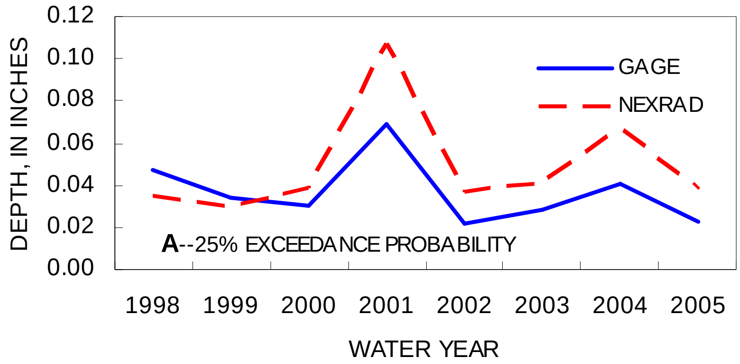
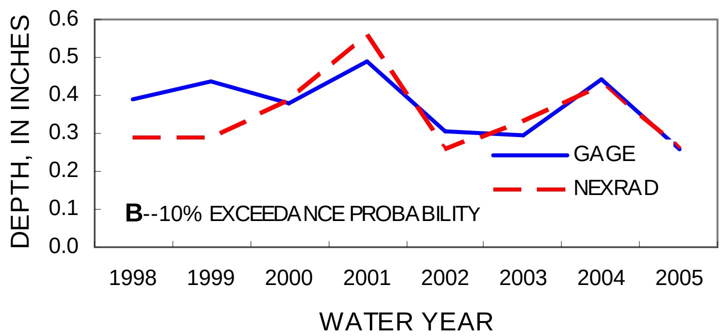
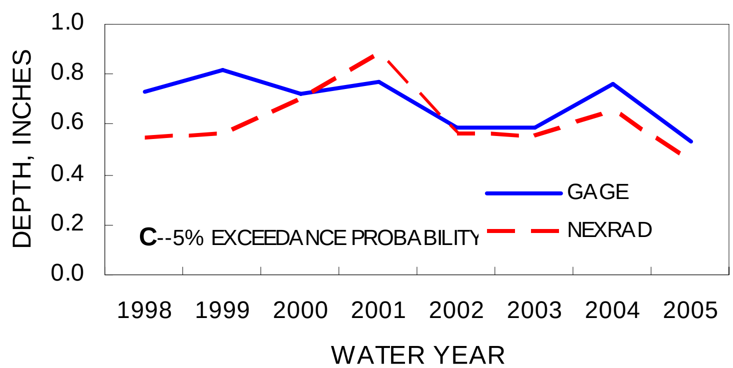


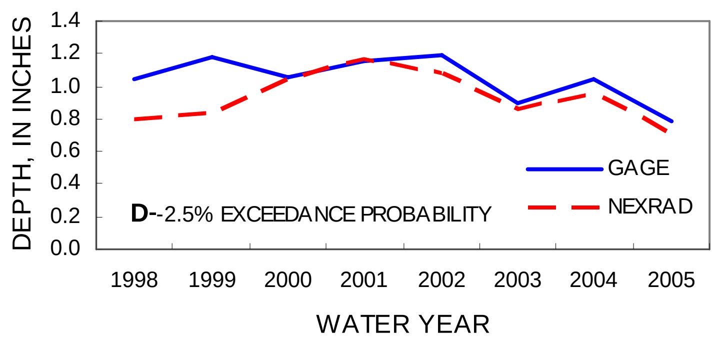
Figure 3c. Average radar-gage error compared to distance from the KLOT radar for the period from February 2001 through September 2005.

Evaluation of the suitability of NEXRAD data for local urban flood simulation requires more than an assessment of long-term biases; it requires analysis of the distribution of the values in order to determine if the extremes are accurately estimated. A complete assessment would require analysis of the data at a sub-daily temporal resolution (hourly or better), but a preliminary assessment can be obtained from the present daily data. The results of such an analysis are presented here as quantiles for various exceedance probabilities (figures 4a-e). The quantile analysis shows the radar data under-estimated the rain-gage values for all quantiles during 1997-1999 and then matched or exceeded the rain-gage values during 1999-2001. These results would be as expected from the double-mass analysis discussed above, because these two periods correspond to the periods of significant under-estimation and over-estimation observed in figure 2, respectively. However, from 2002-2005, when the double-mass analysis indicates approximately equal average rainfall estimates, the smallest quantile presented, the 25% exceedance probability quantile q_{25}, is over-estimated by NEXRAD, while the q_{10}'s are approximately equal, and the higher quantiles (q_5 through q_1) are under-estimated by NEXRAD. This general behavior, that is, more rain observed by the radar at lower rain rates as compared to the gages and less at heavier rain rates, is consistent with the sampling properties of the two systems, because an 8-inch rain gage samples an area of about 0.35 ft^2 while the NEXRAD samples an area of about 16 km^2, a difference of more than eight orders of magnitude. This “representativeness” error (so-called because the gage is being used to represent the larger radar pixel) depends on the spatial correlation of the rainfall at the sub-pixel scale, and it decreases with the temporal averaging interval as the spatial correlation increases (Habib et al., 2004). Methods to estimate this error have been presented in the literature (for example, Kitchen and Blackall, 1992; Ciach and Krajewski, 1999; Habib et al., 2004), but application of these methods to the present data is beyond the scope of the current study.


0.12
0.10
0.08
0.06
0.04
0.02
0.00
DEPTH, IN INCHES
GAGE
NEXRAD
A--25% EXCEEDANCE PROBABILITY
1998
1999
2000
2001
2002
2003
2004
2005
WATER YEAR


0.6
0.5
0.4
0.3
0.2
0.1
0.0
DEPTH, IN INCHES
GAGE
NEXRAD
B--10% EXCEEDANCE PROBABILITY
1998
1999
2000
2001
2002
2003
2004
2005
WATER YEAR


1.0
0.8
0.6
0.4
0.2
0.0
DEPTH, INCHES
GAGE
NEXRAD
C--5% EXCEEDANCE PROBABILITY
1998
1999
2000
2001
2002
2003
2004
2005
WATER YEAR


1.4
1.2
1.0
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0.6
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0.2
0.0
DEPTH, IN INCHES
GAGE
NEXRAD
D--2.5% EXCEEDANCE PROBABILITY
1998
1999
2000
2001
2002
2003
2004
2005
WATER YEAR

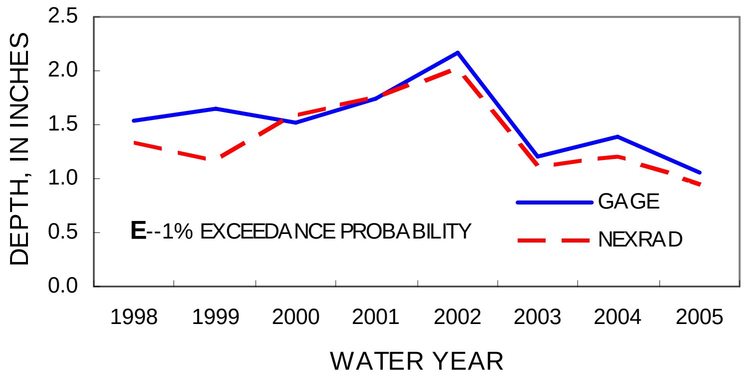

Figure 4. Average exceedance probability quantiles of gage and NEXRAD estimated daily rainfall averaged over all non-removed days and gages computed on a Water Year basis for (A) 25-percent exceedance probability; (B) 10-percent exceedance probability; (C) 5-percent exceedance probability; (D) 2.5-percent exceedance probability; and (E) 1-percent exceedance probability. Data from July through September 1997 were included in Water Year 1998, and data from October 2001 were included in Water Year 2001. The data for Water Year 2002 used in this figure includes only February through September 2002.

Conclusions

The statistics reported here, based on co-located rain gage-NEXRAD radar pixel pairs in the northeastern Illinois USGS rain-gage network, indicate that important differences in daily rainfall estimates between the NEXRAD Stage III product and rainfall gage are present from 1997 until some time in 2001, including overall under-estimation of rainfall and a strong spatial gradient in gage-radar errors (apparently an effect of range from the nearest radar). Since 2001, these differences have been greatly reduced. Total rainfall at NEXRAD pixels co-located with gages was about 3% less than the gage catch during the MPE period, February 2002 through September 2005. Analysis of the daily rainfall depth distribution during the MPE period shows lower extremes in the radar data, consistent with the sampling properties of the two systems. The spatial gradient errors still appear to be present but have been reduced. The improvement in the gage-radar match is encouraging; however, hydrologic modelers should be aware of remaining differences.

References

Ciach, G.J., and Krajewski, W.F. (1999). "On the estimation of radar rainfall error variance." *Adv. Water Resour.*, 22(6), 585-595.

Fulton, R. A., Breidenbach, J. P., Seo, D.-J., Miller, D. A., and O'Bannon, T. (1998). "The WSR-88D rainfall algorithm." *Wea. Forecasting*, 13, 377-395.

Habib, E., Ciach, G.J., and Krajewski, W.F. (2004). "A method for filtering out raingauge representativeness errors from the verification distributions of radar and raingauge rainfall." *Adv. Water Resour.*, 27, 967–980.

Ishii, A.L., Charlton, T.J., Ortel, T.W., and Vonnahme, C.C. (1998). "Modeling system for near real-time flood simulation for Salt Creek in Du Page County, Illinois." *Proceedings of the First Federal Interagency Hydrologic Modeling Conference*, Las Vegas, NV, 8.51-8.58.

Jayakrishnan, R., Srinivasan, R., and Arnold, J.G. (2004). "Comparison of raingage and WSR-88D Stage III precipitation data over the Texas-Gulf basin." *J. Hydrology*, 292, 135-152.

Johnson, D., Smith, M., Koren, V., and Finnerty, B. (1999). "Comparing mean areal precipitation estimates from NEXRAD and rain gauge networks." *J. Hydrol. Engrg*., ASCE, 4(2), 117-124.

Kitchen, M., and Blackall, R.M. (1992). "Representativeness errors in comparisons between radar and gauge measurements of rainfall." *J. Hydrology*, 134, 13-33.

LaTour, J.K., Weldon, E.A., Dupre, D.H., Halfar, T.M. (2005). *Water Resources Data – Illinois, Water Year 2005*. U.S. Geological Survey, Illinois Water Science Center, Urbana, Illinois.

National Weather Service (2002). "About the Stage III data." http://www.nws.noaa.gov/oh/hrl/dmip/stageiii_info.htm. Accessed 11 January 2007.

Pereira Fo, A.J., Crawford, K.G., and Hartzell, C.L. (1998). "Improving WSR-88D hourly rainfall estimates." *Wea. Forecasting*, 13(12), 1016-1028.

Stellman, K.M., Fuelberg, H.E., Garza, R., and Mullusky, M. (2001). "An examination of radar and rain gauge-derived mean area precipitation over Georgia watersheds." *Wea. Forecasting*, 16(2), 133-144.

Wang, D., Smith, M.B., Zhang, Z., Reed, S., and Koren, V.I. (2000). "Statistical comparison of mean areal precipitation estimates from WSR-88D, operational and historical gage networks." Paper 2.17, 15th Conference on Hydrology, American Meteorological Society, Jan. 9-14, 2000, Long Beach, CA.

Westcott, N. E., and Knapp, H. V. (2006). *Evaluation of the Accuracy of Radar-based Precipitation for Use in Flow Forecasting for the Fox Chain of Lakes*, Illinois State Water Survey, Champaign, Illinois.

Xie, H., Zhou, X., Hendrickx, J.M.H., Vivoni, E.R., Guan, H., Tian, Y.Q., Small, E.E. (2006). "Evaluation of NEXRAD Stage III precipitation data over a semiarid region." *J. Am. Water Resour. Assoc*., 42(1), 237-256.

Young, C.B., Nelson, B.R., Bradley, A.A., Smith, J.A., Peters-Lidard, C.D., Kruger, A., and Baeck, M.L. (1999). "An evaluation of NEXRAD precipitation estimates in complex terrain." *J. Geophys. Res*., 104(D16), 19,691-19,703.

Young, C.B., Bradley, A.A., Krajewski, W.F., Kruger, A., and Morrissey, M.L. (2000). "Evaluating NEXRAD multisensor precipitation estimates for operational hydrologic forecasting." *J. Hydrometeorol*., 1(3), 241-254.