Evaluation of the Accuracy of Radar-based Precipitation for Use in Flow Forecasting for the Fox Chain of Lakes

by

Nancy E. Westcott and H. Vernon Knapp

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Illinois State Water Survey
Center for Atmospheric Science
Center for Watershed Science
Champaign, Illinois

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FINAL REPORT

To

Illinois Department of Natural Resources
Office of Water Resources

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Abstract

This study evaluated the use of radar-derived daily precipitation values for estimating watershed precipitation in the Fox River watershed in northeastern Illinois and southeastern Wisconsin, and for the potential use in preparing real-time streamflow forecasts for the Fox River. Two types of radar-derived precipitation estimates based on data from the National Weather Service (NWS) WSR-88D radar network were evaluated. These estimates were developed using a 4-km grid resolution and computed using: 1) radar data alone and 2) composite or multi-sensor precipitation estimate based on radar data and real-time hourly precipitation gage observations. These gridded precipitation estimates were obtained from the National Center for Environmental Prediction (NCEP) and were compared to point measurements of daily precipitation from precipitation gages in the vicinity of the Fox River watershed for the period February 2002–September 2004. Multi-sensor precipitation estimates were found to be a considerable improvement over the gridded radar estimates during all seasons. In comparison to the daily gage data, however, the multi-sensor precipitation estimates were on average 25 percent lower throughout the year.

Multi-sensor daily precipitation estimates from four storm periods were input to the Fox River Forecast Model to evaluate their potential application in hydrologic forecasting. Only one storm event produced flooding conditions on the Fox River in the period for which radar data was available. The remaining three storm events analyzed in this report produced only moderately high flows. Simulated flow forecasts using the multi-sensor precipitation values were less accurate than companion forecasts using observed data from precipitation gages. Based on the limited number and size of storm events available for simulation, this study was unable to conclude whether or not the multi-sensor precipitation values would be useful for forecasting floods. Until more comparisons can be conducted using data from future major flood events, flow forecasts for the Fox River should continue to be developed using near real-time data from precipitation gages. The present tendency of the multi-sensor precipitation data to underestimate rainfall amounts also makes their use generally inappropriate for longer term hydrologic simulations.

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Background

The Fox River Forecast Model (FRFM) and Stratton Dam operations database were developed by the Illinois State Water Survey (ISWS) for use by the Office of Water Resources (OWR) as a tool to assist in operation of Stratton Dam (Knapp, 1998). The dam is located on the Fox River in northeastern Illinois and partially controls the outflow from the Fox Chain of Lakes. Both the FRFM and the Stratton Dam database are maintained on ISWS computers and are accessible to OWR over the Web, with the FRFM automated to run on a daily basis. Climatic inputs needed to run the forecast model and other information necessary for operations support at Stratton Dam currently are obtained automatically from various Web sites and loaded into the Stratton Dam database.

Precipitation gages traditionally have been used to estimate watershed precipitation for flow forecasting and other types of hydrologic simulations. These gages are relatively easy and inexpensive to maintain, and well-maintained gages are generally very reliable. But point measurements of precipitation may not adequately represent precipitation over a wide area such as a watershed, depending on gage density and distribution. Real-time gage data also may not be available for all gages when the FRFM is run, and the closest gage available for input may be many kilometers away from the gage with missing data.

With the advent of the National Weather Service (NWS) WSR-88D radar network in the late 1990s, areawide radar and multi-sensor (radar + gage) precipitation estimates with 4-km grid resolution became available in near real time. By 2002, many issues related to radar calibration and data processing procedures were resolved for the operation of the WSR-88D radar network (Westcott and Kunkel, 2002). Radar estimates (RDR), while providing information related to the spatial coverage of precipitation, still provide inaccurate precipitation estimates due to properties inherent to the measurement system and to the physical properties of precipitation (Fulton et al., 1998; Klazura et al., 1999). Thus, the National Center for Environmental Prediction (NCEP) and the NWS Office of Hydrology developed a multi-sensor precipitation estimate (MPE) that incorporated both real-time hourly gage data and radar information (Seo and Breidenbach, 2002). Both types of gridded estimates are available in near real time from NCEP but have an approximate 7-hour lag following the end of each available time step. If the spatial pattern of precipitation is well represented by MPE estimates, and the magnitude of MPE values are related in a regular way to that of quality controlled gages, real-time MPE data may be a great improvement over real-time gage data for input into models.

The objective of this study was to evaluate the use of daily radar-derived precipitation values for improving near real-time estimates of watershed precipitation in the Fox River watershed in northeastern Illinois and southeastern Wisconsin. The most direct evaluation of the accuracy and possible bias of radar-derived precipitation estimates was to compare them to point measurements of precipitation at precipitation gages. A second, indirect level of evaluation of

radar-derived data used these data as input in hydrologic simulations, with comparison of observed streamflows and simulated values.

Methodology and Tasks

Gridded Precipitation Fields

Gridded RDR and MPE values have been obtained in near real time from the NCEP since March 1997. The MPE values are based upon a composite of data from the WSR-88D radars and hourly gage observations from the Hydrometeorological Automated Data System (HADS) and the Automated Surface Observing System (ASOS). Currently, 6 HADS and 6 ASOS sites are located within or near the Fox River watershed (Figure 1). Some of these HADS and ASOS sites currently are used as input to the FRFM. Details on techniques used in processing these data are available in Fulton et al. (1998) and Seo (1998). During the winter of 2002, the NWS Office of Hydrology, in conjunction with the NWS River Forecast Centers, implemented a new Stage III/IV MPE algorithm that includes provisions for quality-controlling gage data (NWS Office of Hydrologic Development, 2005) and incorporates a new method of bias-correction computation (Seo and Breidenbach, 2002). Since February 2002, the 6-hour and 24-hour (valid at 0600 Central Standard Time, CST) Stage III/IV MPE gridded data have been downloaded daily. The 4-km gridpoints from Stage II RDR and Stage III/IV MPE data fields (Figure 2) were compared with the closest gage on a daily basis.

Precipitation Gages

Some real-time gages used as input to the FRFM also are used to adjust the MPE data. Further, sometimes gages have not reported by the time the FRFM is run each day. To avoid problems comparing data that are not entirely independent and to avoid problems with missing data, quality-controlled daily cooperative (QC_coop) gage data obtained from the National Oceanic and Atmospheric Administration were used as the reference standard and compared to the gridded RDR and MPE data. Only gages that reported between 0500 and 0900 CST were used because they best correspond with the daily gridded data valid at 0600 CST. A list of the 20 QC_coop gages in the vicinity of the Fox River watershed is presented in Table 1, and their locations are shown in Figures 1 and 2. Because the QC_coop data are only available 3-5 months after data collection, this is a retrospective study. County-averaged monthly sums based upon the preliminary Stage II MPE data were found to be of comparable quality to QC_coop estimates in predicting county level corn yields over the Midwest (Westcott et al., 2005).

This study compared daily area-averaged watershed precipitation estimates computed using the average of all available QC_coop gages with the averages of the RDR and MPE gridpoint value nearest each gage. This study also compared point precipitation amounts from the QC_coop gages with the nearest RDR and MPE grid point value for the 32-month period February 1, 2002–September 30, 2004. Accuracy and bias of both types of gridded estimates were examined.
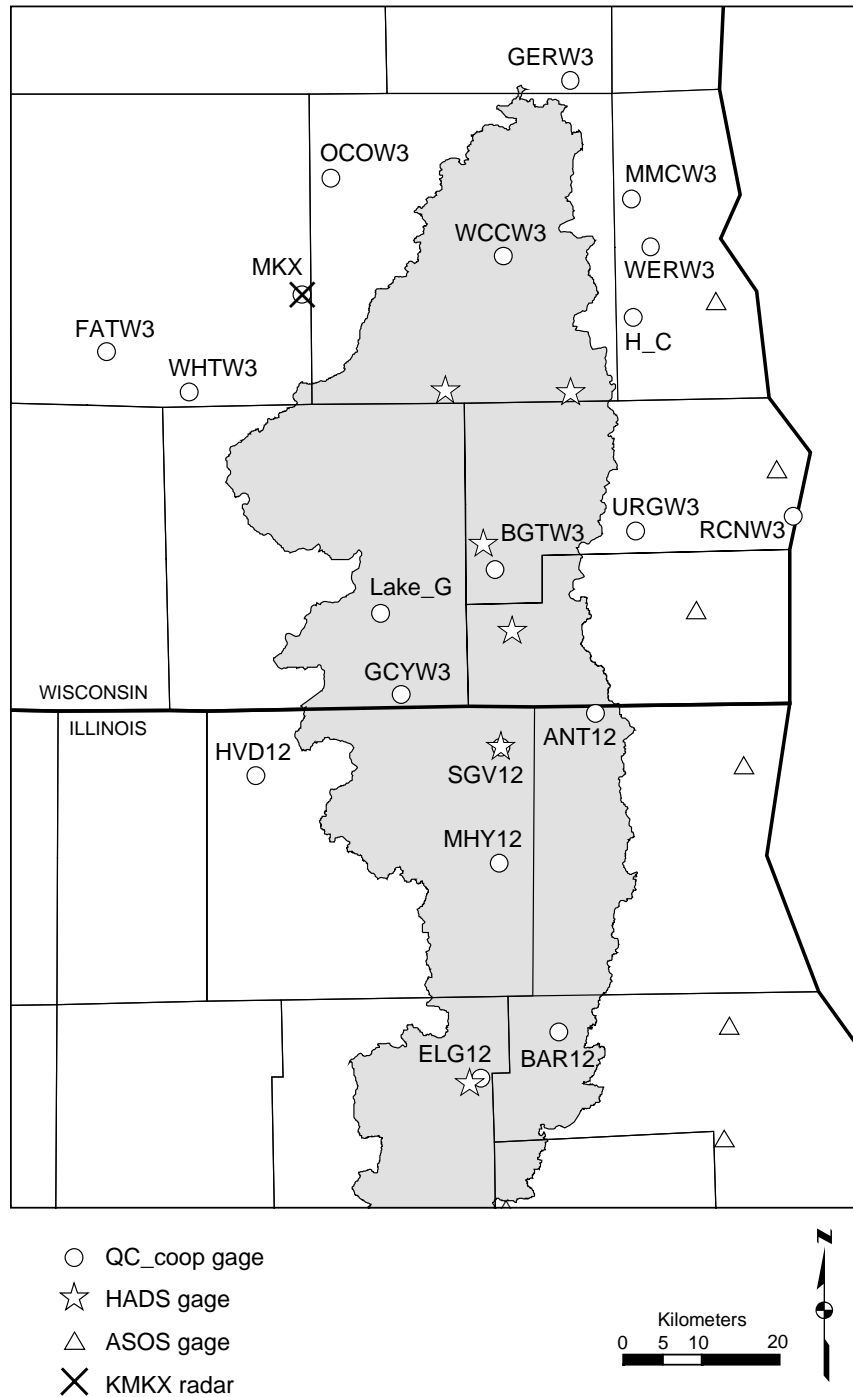
Figure 1. Locations in the Fox River watershed of the Milwaukee Radar (KMKX) and precipitation gages for the Hydrometeorological Automated Data System (HADS), Automated Surface Observing System (ASOS), and the quality-controlled daily cooperative data (QC_coop).
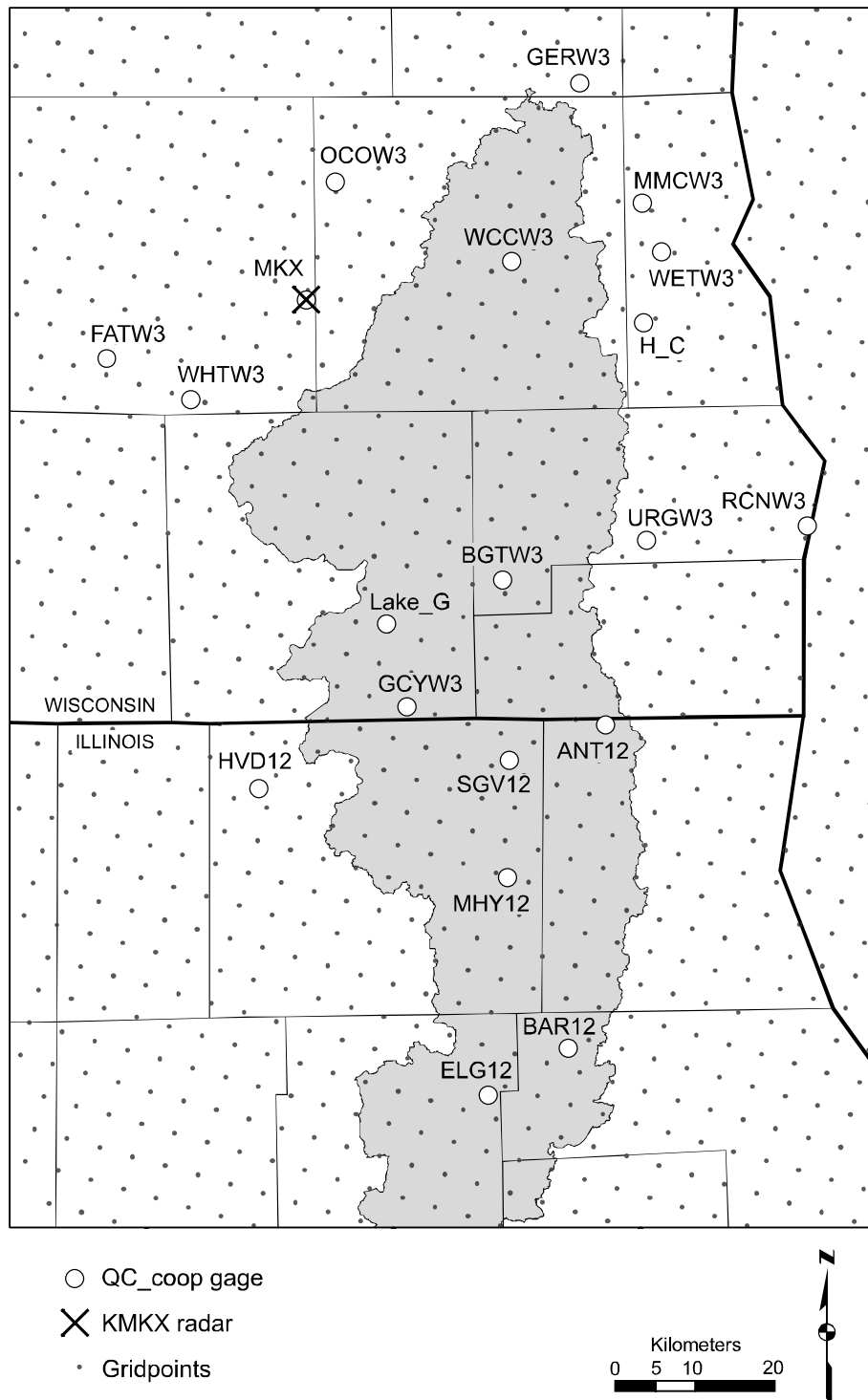
Figure 2. Locations in the Fox River watershed of the Milwaukee Radar (KMKX),
the quality controlled daily cooperative data (QC_coop), and gridpoints
for the radar and multi-sensor precipitation estimates.

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Table 1. Stations Employed in the Precipitation Gage Analysis

COOP ID	Station ID	State	County	Coop Name	Latitude	Longitude
110203	ANTi2	IL	Lake	Antioch	42.4811	-88.0994
110442	BARi2	IL	Cook	Barrington 3 SW	42.1153	-88.1639
112736	ELGi2	IL	Kane	Elgin	42.0628	-88.2861
113902	HVDi2	IL	McHenry	Harvard	42.4147	-88.6308
115493	MHYi2	IL	McHenry	McHenry WG Stratton L&D	42.3103	-88.2525
118192	SGVi2	IL	McHenry	Spring Grove	42.4678	-88.2372
471205	BGTw3	WI	Racine	Burlington	42.6506	-88.2544
472869	FATw3	WI	Jefferson	Fort Atkinson	42.9050	-88.8589
473040	GCYw3	WI	Walworth	Genoa City	42.5058	-88.4036
473058	GERw3	WI	Washington	Germantown	43.2097	-88.1233
474457	Lake_G	WI	Walworth	Lake Geneva	42.6000	-88.4333
473391	H_C	WI	Milwaukee	Hales Corner / Whitnall	42.9369	-88.0300
475474	MMCw3	WI	Milwaukee	Milwaukee Mt Mary Col	43.0719	-88.0294
476200	OCOw3	WI	Waukesha	Oconomowoc	43.1003	-88.5036
476922	RCNw3	WI	Racine	Racine	42.7022	-87.7861
478316	MKX	WI	Jefferson	Sullivan 3 SE / Milwaukee WSFO Dousman	42.9675	-88.5497
478723	UGRw3	WI	Racine	Union Grove	42.6903	-88.0336
478937	WCCw3	WI	Waukesha	Waukesha	43.0064	-88.2492
479046	WETw3	WI	Milwaukee	West Allis	43.0175	-88.0017
479190	WHTw3	WI	Jefferson	Whitewater	42.8508	-88.7247

Hydrologic Simulations Using the Fox River Forecast Model

The preliminary step for this analysis was to develop an interface to compute an area-average precipitation estimate for each subwatershed in the FRFM using precipitation estimates (RDR or MPE) from the 4-km grid. These subwatersheds are illustrated (Figure 3). Radar-based subwatershed estimates of daily rainfall were used as the precipitation input into the FRFM to simulate the streamflow at the two primary inflow points to the Fox Chain of Lakes: the Fox River near New Munster and Nippersink Creek near Spring Grove. The values of physical variables (such as antecedent soil moisture, stream, and lake levels) used to define initial conditions for each simulation were established by running the FRFM using gage precipitation data leading up to the start of the period for which radar-derived precipitation estimates were to be applied. Subwatershed precipitation estimates using gage precipitation data were based on a nearest-neighbor approach, i.e., the average daily precipitation for any subwatershed is set equal to the daily precipitation amount recorded at the gage nearest to the watershed for which real-time data were available. For details on the algorithms, physical variables, hydrologic parameters, and data used with the FRFM, the reader is referred to Knapp et al. (1991).

Flow simulations were performed to compare the flood forecasts based on MPE values versus traditional flow forecasts using reporting precipitation gages. Both types of flow forecasts then were compared to observed flows at two U.S. Geological Survey streamflow gages (Fox River gage near New Munster and Nippersink Creek gage near Spring Grove) to evaluate the potential accuracy of both forecasting approaches. Four runoff events during the February 2002–June 2005 period were selected for the simulations: May 13–June 10, 2004; February 11–24, 2005; June 1–15, 2002; and March 1–16, 2004. These events represent four of the five largest runoff events over the three-year period for which the Stage III/IV MPE values are available, and were selected for that specific attribute.
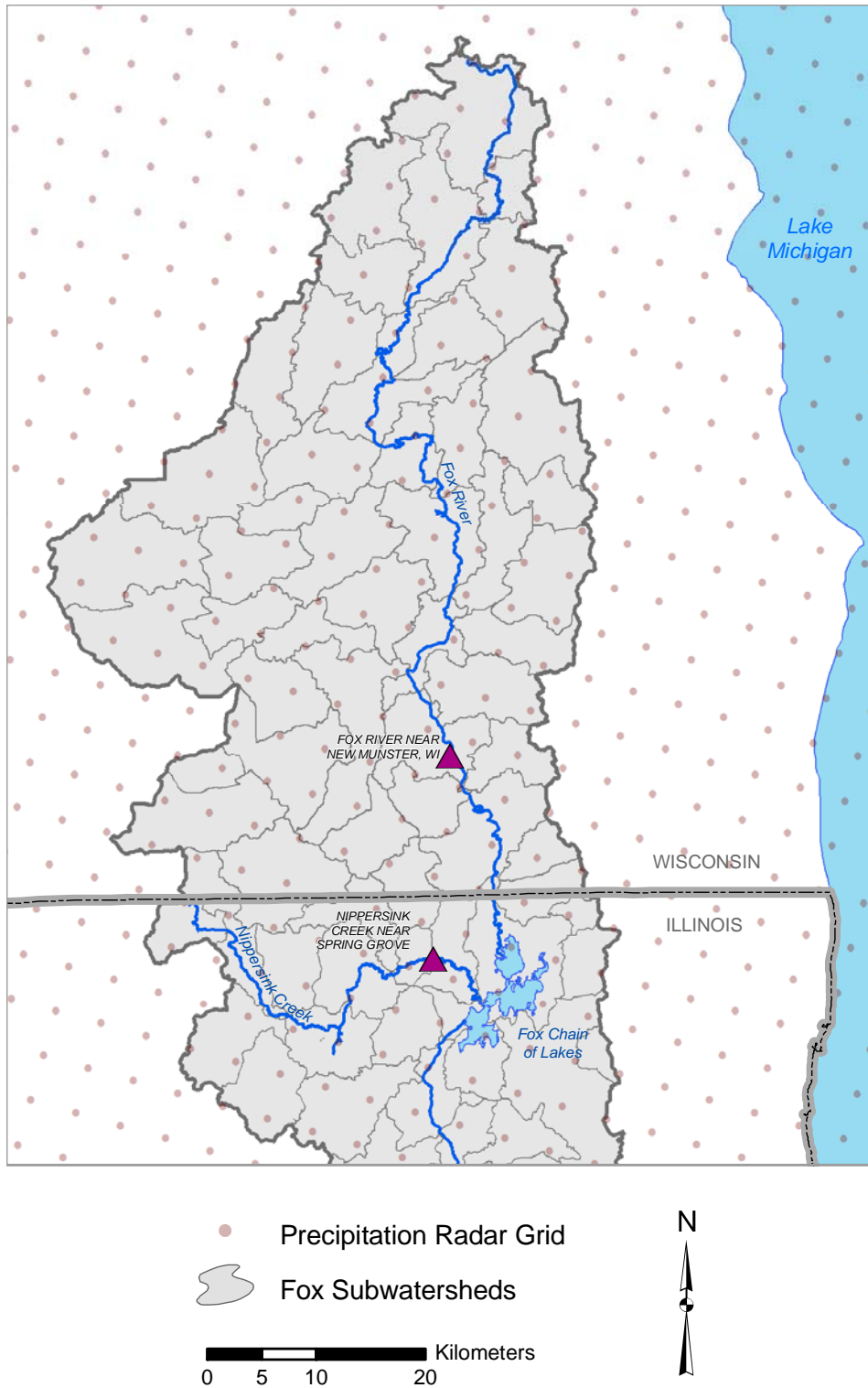
Figure 3. Locations of subwatersheds in the Fox River watershed, radar gridpoints, and the USGS streamgages on the Fox River near New Munster and Nippersink Creek near Spring Grove.

Results

Comparison of Area-Averaged Daily Values

The 20 precipitation gages within the Fox River watershed were averaged to form a "network" daily average. The closest gridpoint to each gage also was averaged for the RDR and MPE data. The daily-averaged RDR values and the QC_coop average values generally were centered about the 1:1 line, but with large positive and negative deviations (Figure 4a).

In contrast, differences between the MPE and QC_coop averages were smaller (Figure 4b), and there was a tendency for the MPE values also to be smaller than the QC_coop values. The MPE values fell more frequently within 25 percent of the QC_coop daily-averaged values, but were most often less than the QC_coop averages. The linear correlation coefficient R between gage and gridded daily-averaged pairs was 0.89 for RDR and 0.96 for MPE data, respectively. Linear regression slopes were 0.94 and 0.79 for RDR and MPE averages, respectively.

Daily data were stratified by year to determine if the relationship between gage and RDR, and gage and MPE changed during the period. During 2003, there appeared to be more scatter in the QC_coop versus RDR values (Figure 5a). During 2002, there appeared to be some missing MPE data (Figure 5b). There appeared to be no real difference in the QC_coop versus MPE relationship during the three years of observations.

Data were examined for seasonal differences. For the Fox River Network, during winter months (November–February), the nearest gridded RDR average daily values were typically smaller than gage values. During summer months (June–August), the nearest RDR average daily precipitation values were often larger, but could be smaller than the gage values (Figure 6a). If one assumes that winter precipitation is from low-reflectivity horizontal gradient events and that summer precipitation is from high-reflectivity horizontal gradient events, these results are similar to those of Klazura et al. (1999).

The MPE algorithm reduced differences between the gage and gridded precipitation estimates (Figure 6b). The relationship between gage and gridded MPE daily averages was similar for both wintertime and summertime days.
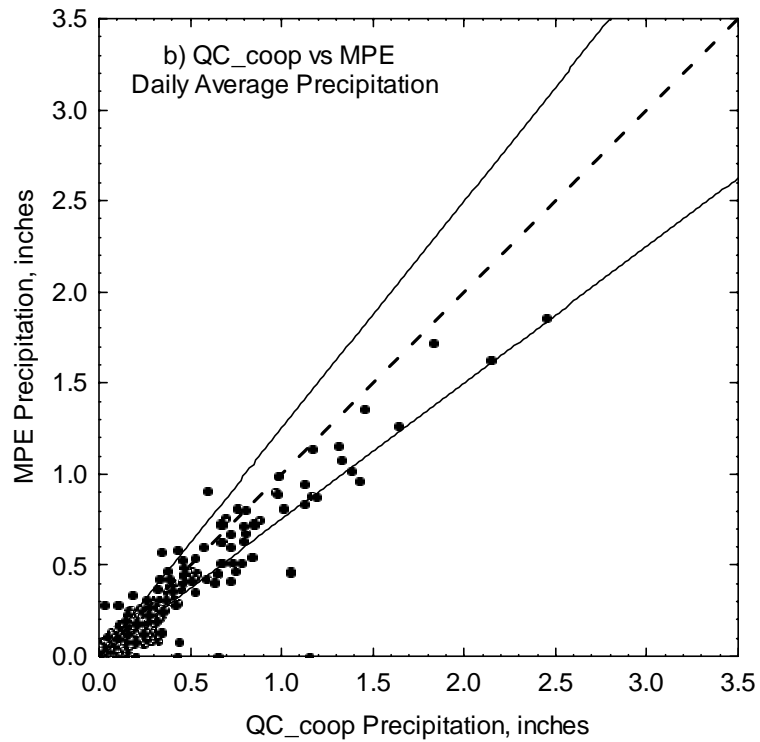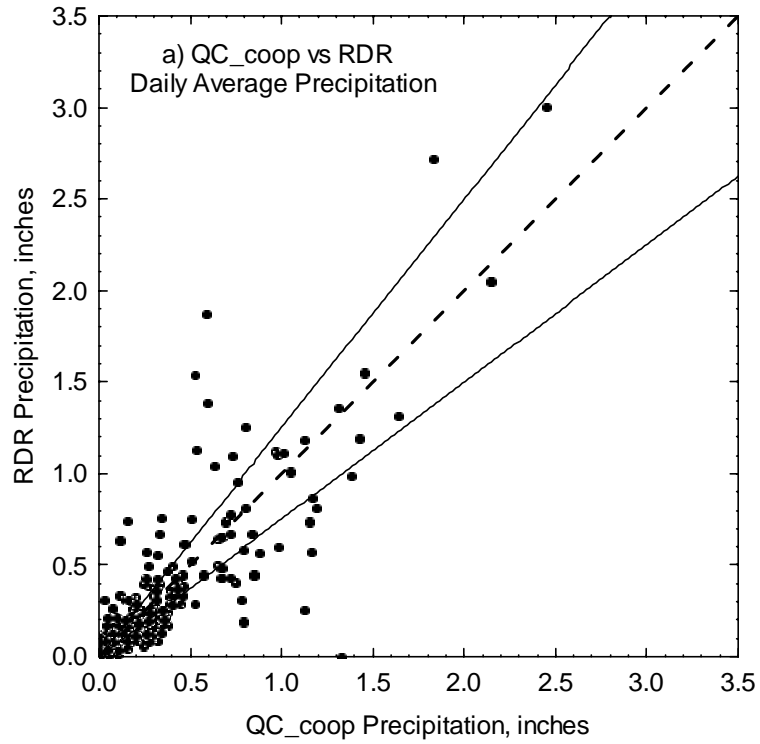
Figure 4. Daily "network" average precipitation February 2002–September 2004, based on QC_coop gages and on corresponding nearest neighbor gridpoints for a) RDR and b) MPE values. The dashed line indicates a 1:1 slope and the solid lines ±25 percent of the QC_coop value.
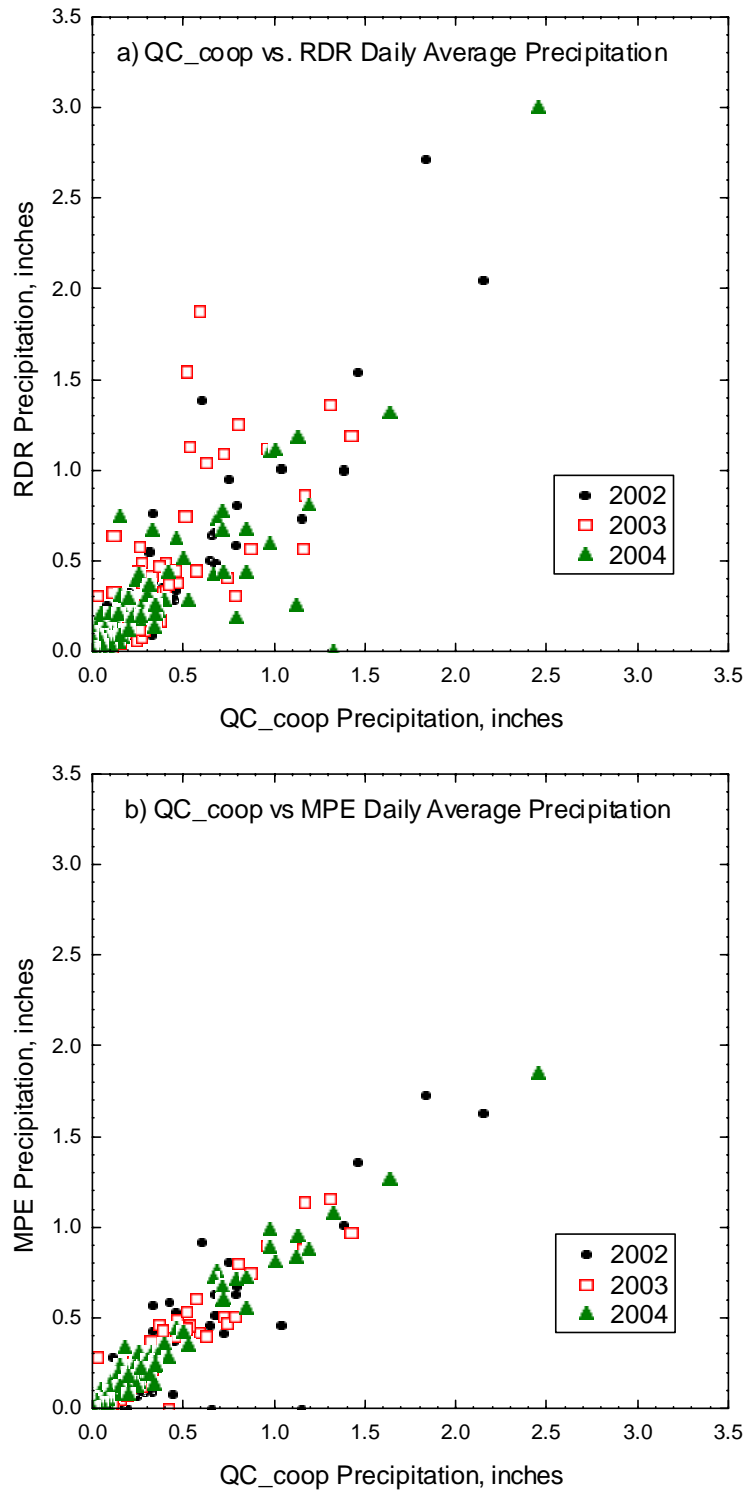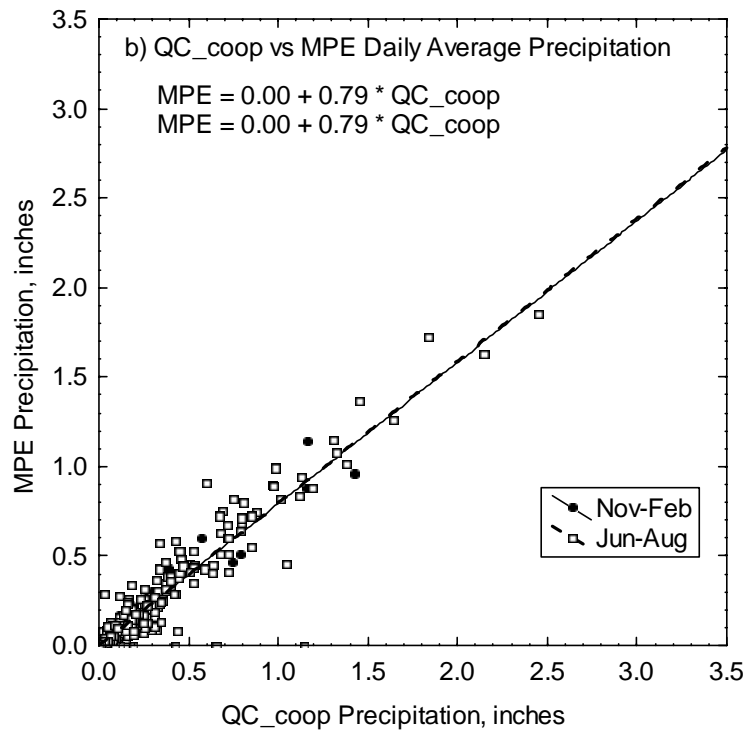
Figure 5. Daily "network" average precipitation February 2002–September 2004, based on QC_coop gages and on corresponding nearest neighbor gridpoints for a) RDR and b) MPE values by year.
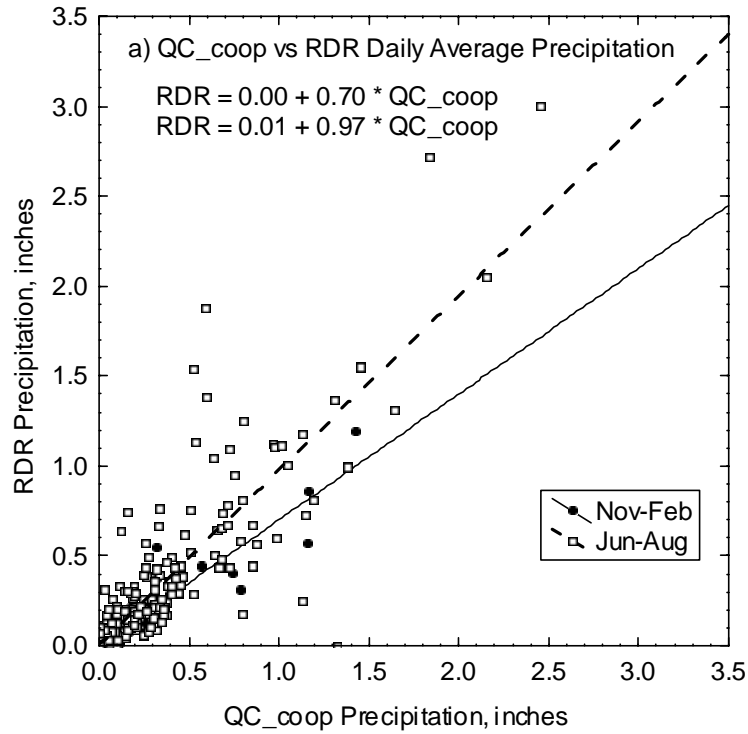
Figure 6. Daily "network" average precipitation February 2002–September 2004, based on QC_coop gages and on corresponding nearest neighbor gridpoints for a) RDR and b) MPE values by season.

Comparison of Daily Point Values

Individual QC_coop gages were compared with the nearest gridpoint to determine how well each performed on a daily basis for all precipitation amounts and for larger precipitation amounts ($\geq$ 1 inch). It was found that the median percent difference [(QC_coop-MPE) / (QC_coop) *100] was about 30 percent for the Fox QC_coop gages for all precipitation amounts and for larger amounts. Figure 7a shows percent difference values for each Illinois QC_coop gage for precipitation amounts greater than one inch, and Figure 6b for all QC_coop precipitation amounts. For the gage at McHenry (MHYi2), there were 259 days with precipitation during February 2002–September 2004, of which on 18 days precipitation exceeded one inch. Frequencies were similar at the other gages. Because large percent differences can occur at precipitation amounts of less than 0.1 inch, the scale was truncated for the graph in Figure 6b. Fifteen outliers from days with precipitation less than 0.1 inch, and one outlier for daily precipitation amount of less than 0.2 inch were not shown in Figure 7b.

Figure 8 shows percent difference values for each Wisconsin QC_coop gage for precipitation amounts exceeding one inch and for all precipitation amounts. As with the Illinois gages, the median percent difference was about 30 percent, and for precipitation values over one inch, at least 50 percent of all MPE precipitation amounts were within zero to +50 percent of the QC_coop gage amount.

The median difference between the gage and corresponding gridpoint closest to the Sullivan, Wisconsin (KMKE) radar (<1 km, Figure 2), however, was on the order of 50 percent, much greater than the median difference for all other gages, except the gage at Lake Geneva. Annual precipitation maps for 2002, 2003, 2004, and many monthly maps (not shown), indicate a minimum in precipitation, near but offset from the KMKE radar. Gage-MPE differences did not appear dependent on distance from the radar in any other way for the Fox QC_coop gages. The Lake Geneva gage stopped reported precipitation on June 15, 2003. Further, from the scatter plot of QC_coop versus RDR (not shown), it appears that at least some of the Lake Geneva reports were at midnight rather than near 0700 CST, as there were many values along both axes indicating that the date of precipitation may have been offset.

In summary, although the MPE data correlated better with the QC_coop data than the RDR precipitation estimates, the MPE values were generally lower than the QC_coop precipitation estimates. For the area as a whole, the underestimate was approximately 20 percent. When considering individual gage precipitation amounts over one inch, the underestimate was approximately 30 percent.
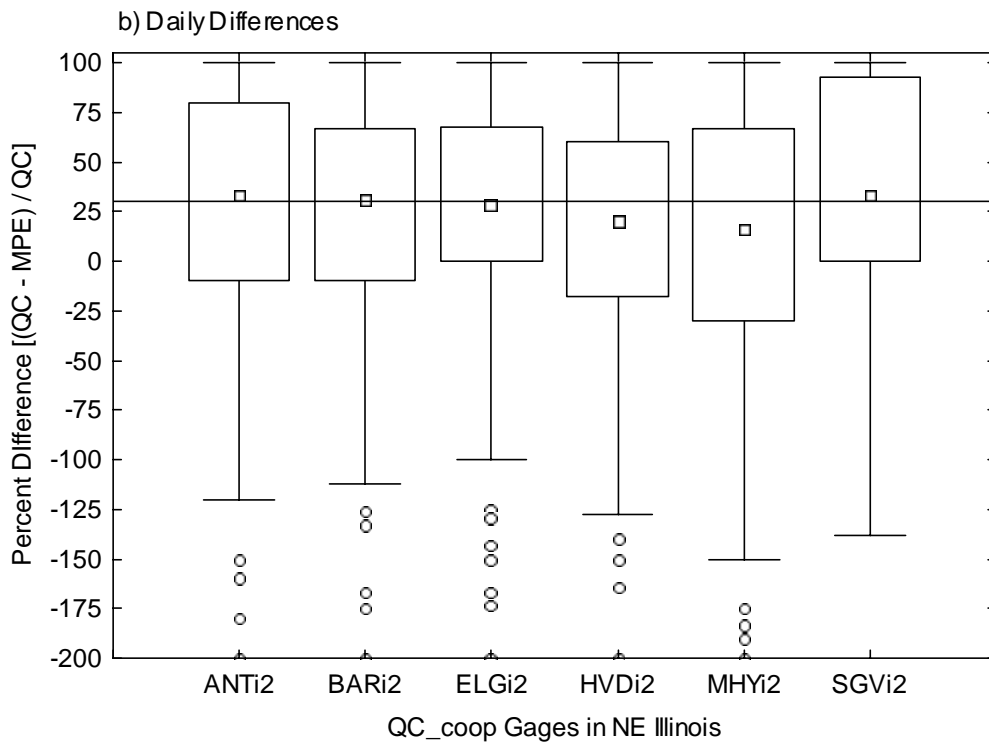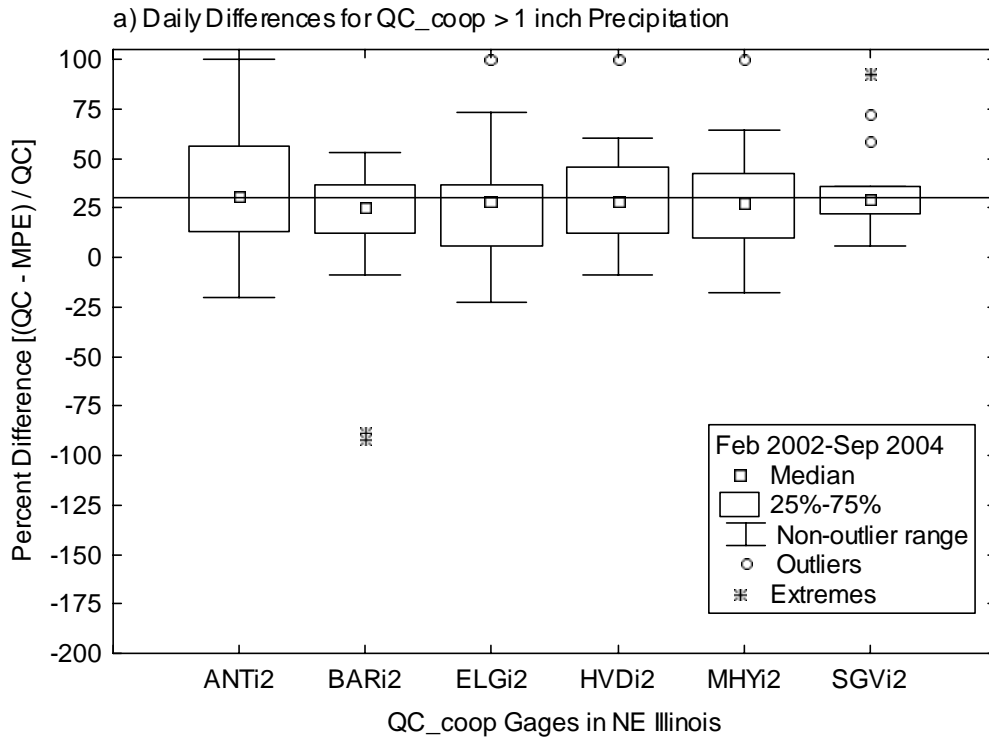
Figure 7. Percent difference in daily precipitation February 2002-September 2004, based on QC_coop gages and corresponding nearest neighbor gridpoints for Illinois for a) QC_coop precipitation amount greater than 1 inch and b) all precipitation amounts. Solid line indicates a 30 percent difference.
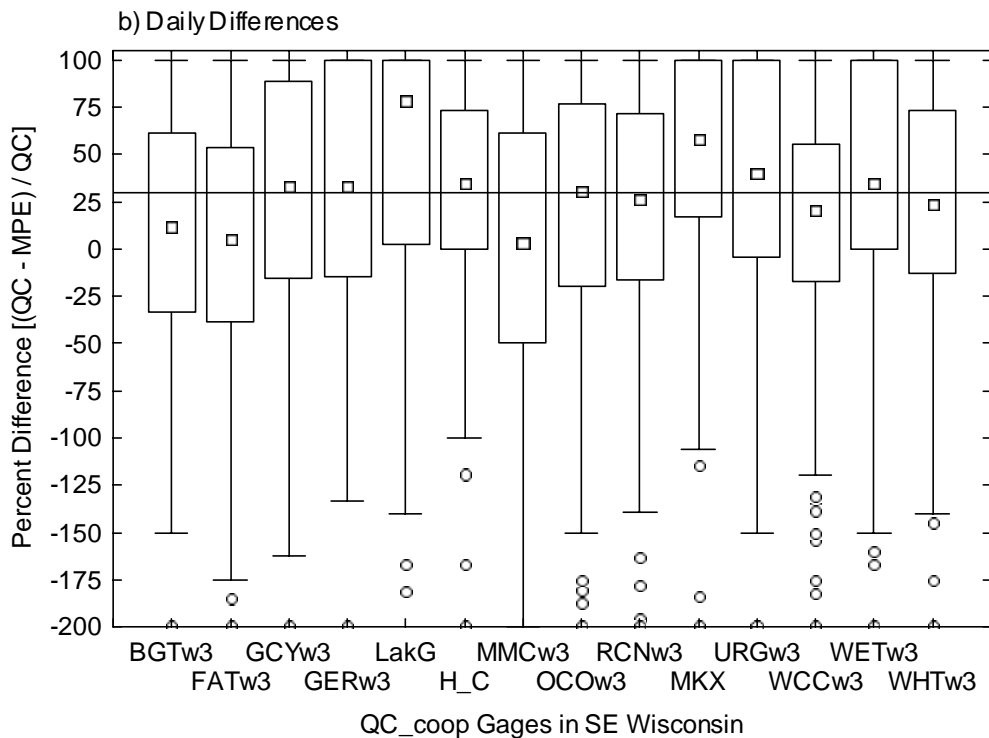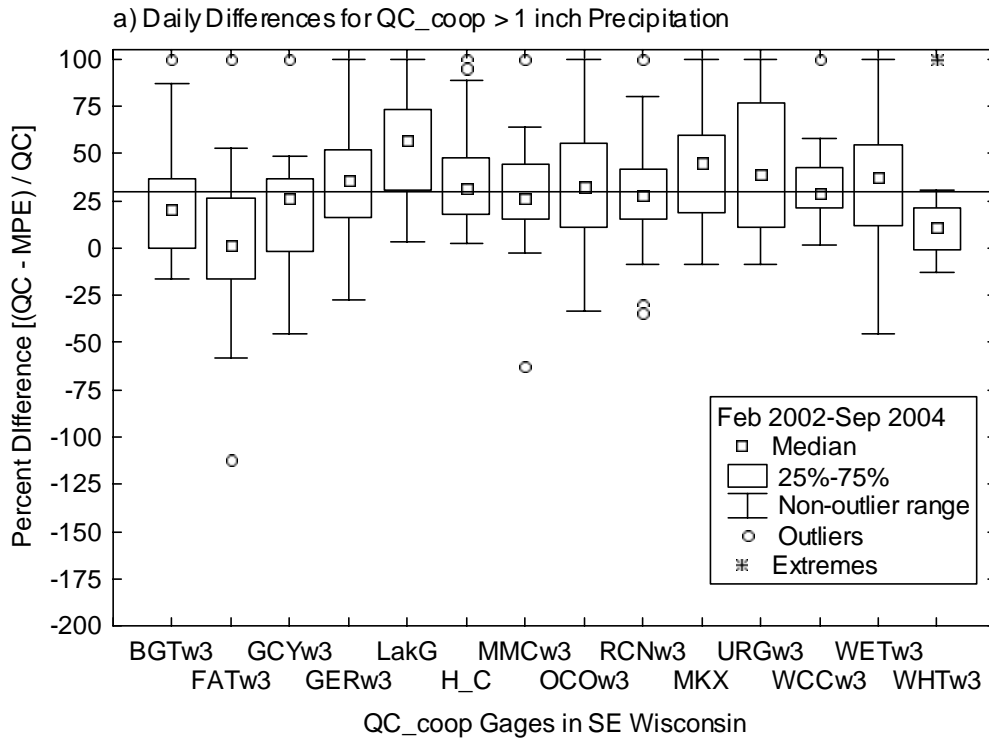
Figure 8. Percent difference in daily precipitation February 2002–September 2004, based on QC_coop gages and corresponding nearest neighbor gridpoints for Wisconsin for a) QC_coop precipitation amount greater than 1 inch and b) all precipitation amounts. Solid line indicates a 30 percent difference.

Hydrologic Simulations Using the Fox River Forecast Model

Figures 9–12 compare the simulated streamflows using the FRFM and the observed flows for the Fox River and Nippersink Creek for four runoff events (May 13–June 10, 2004; February 11–24, 2005; June 1–15, 2002; and March 1–16, 2004, respectively). Flow values are presented as the average daily flow rate in cubic feet per second (cfs). For each event, the precipitation gage record leading up to the event was used as input into the FRFM to establish the initial conditions for the comparison. The FRFM then was used to simulate flow during each of the four specified runoff events, alternately using as input into the model: 1) daily precipitation from reporting gages and 2) daily MPE values. Thus, each figure compares the two simulated flow hydrographs using the gage precipitation and the MPE values to the observed flow record.

Of these four runoff events, only the May 13–June 10, 2004 event was a major flood event that reached flood stage on the Chain of Lakes. Because the most important use of the FRFM is to assist in decisionmaking during major flood events, the model performance for this major event (Figure 9) was considered of greater importance than for any of the other three events. Because only one major runoff event was available for this comparison, the flow simulations may not provide a sufficient sample from which to determine conclusively the adequacy of MPE data for use in flood forecasts.

For all simulations there was a consistent one-day lag between observed and simulated amounts. This lag may be related to changes in the daily precipitation gages used for simulation and differences in the actual time of day that the new gages record. There also may be a need to adjust parameters in the channel routing process. These problems should be correctable through model recoding, model calibration, or both; however, such modifications were not made as part of the current study (nor has the model been fully recalibrated since it originally was developed in 1989). If the model were to be recalibrated, it likely would affect the simulated peak flows but not change the overall runoff volume. For evaluation of the comparative performance of the radar-derived precipitation estimates versus gage data, it was necessary to ignore the differences in hydrograph timing and concentrate instead on runoff volume and peak flow.

Tables 2 and 3 compare the differences in the runoff volume between the observed and simulated hydrographs at the New Munster and Spring Grove gages for each of the four events simulated. Runoff volume is computed as the summation of average daily flow values (cfs) over the specified storm period. For the New Munster gage, there was a slight tendency for gage precipitation simulations to overestimate runoff volume, and a somewhat greater tendency for MPE simulations to underestimate runoff volume. Simulated peak flows using precipitation gage data were greater than the observed peak flows for two events (Figures 9 and 12) and less than observed peak flows for the other two events (Figures 10 and 11). In contrast, simulated peak flows using MPE values were less than observed peak flows for the first three events (Figures 9–11) and similar to observed peak flow for the fourth event (Figure 12). For the Spring Grove gage, there was no clear tendency for either overestimation or underestimation of the simulated runoff volumes (Table 3) or peak flows (Figures 9–12). Also, simulated runoff volumes and peak flows using gage precipitation versus MPE values were very similar for all events except the May–June 2004 major event.
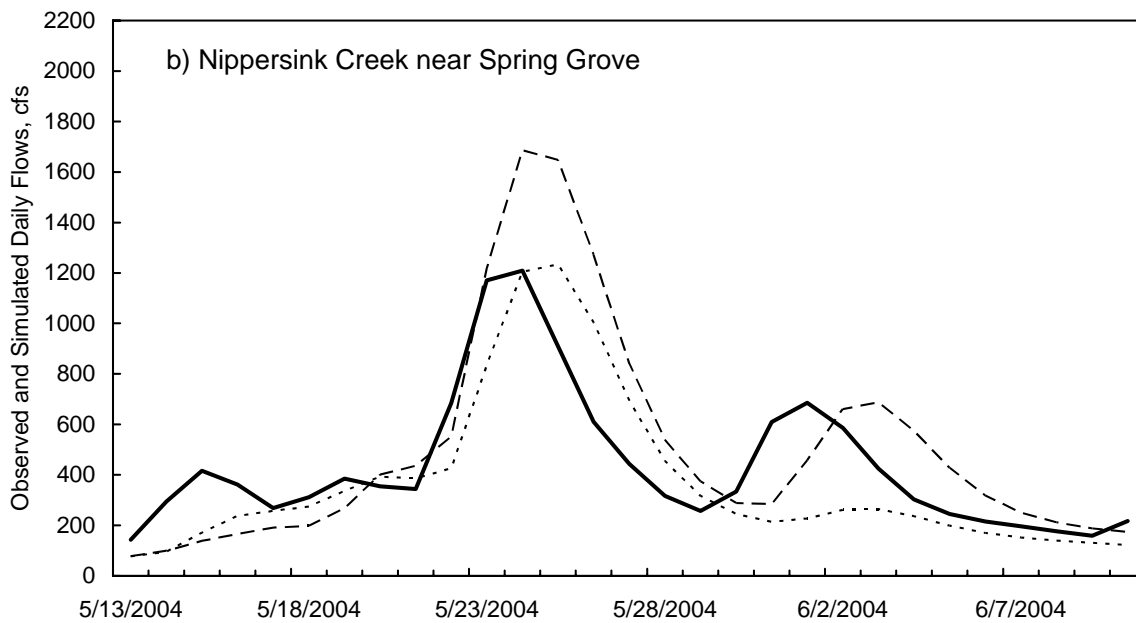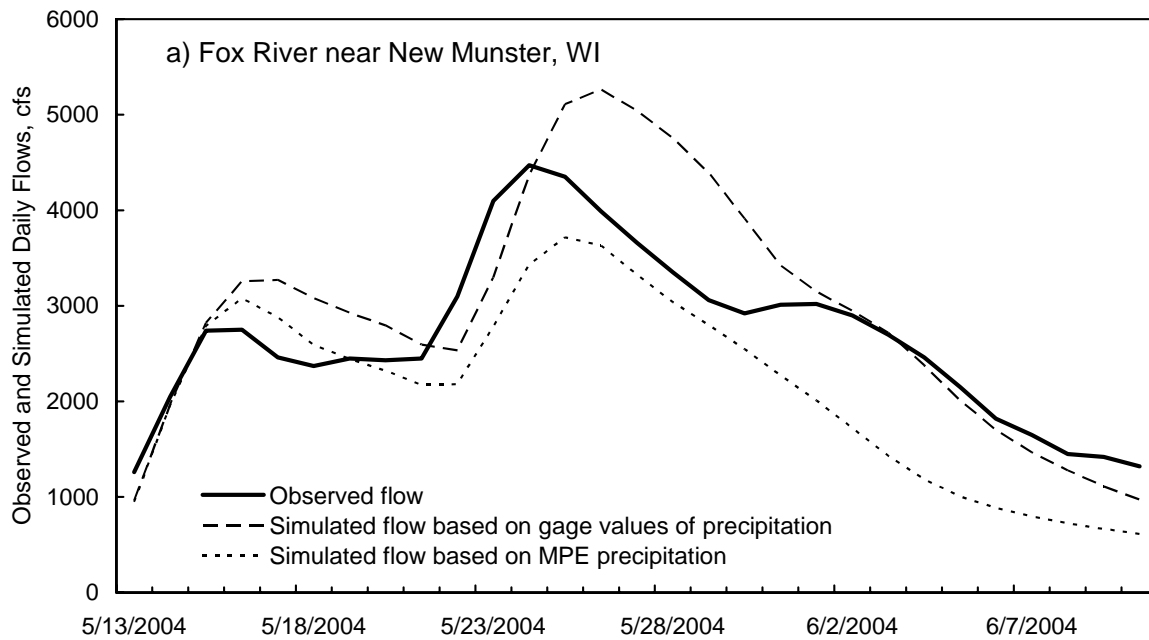
Figure 9. Comparison of simulated flows using gage precipitation and MPE values with observed flow for the May 13–June 10, 2004, runoff event: a) Fox River near New Munster, and b) Nippersink Creek near Spring Grove.
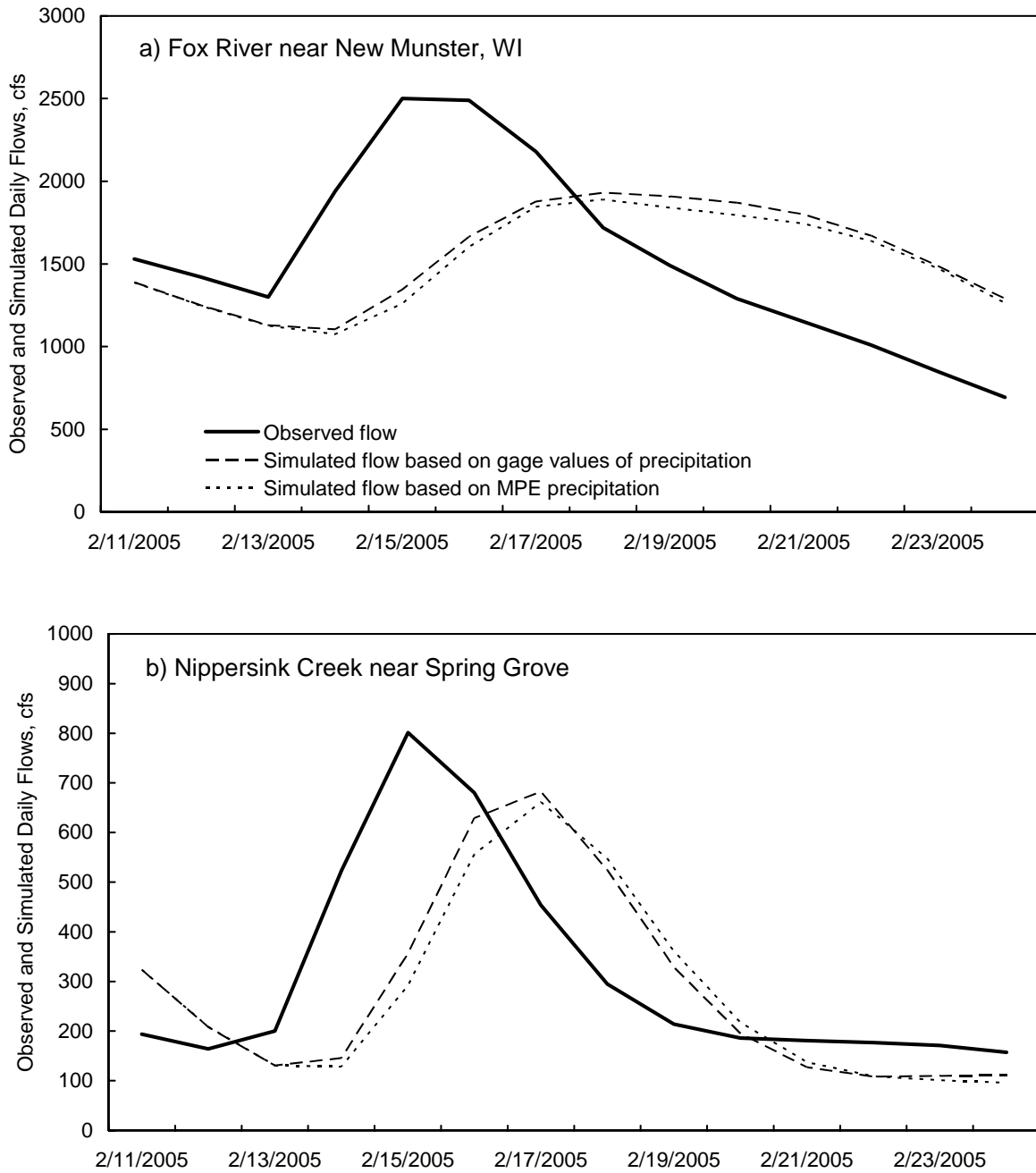
Figure 10. Comparison of simulated flows using gage precipitation and MPE data with observed flow for the February 11–24, 2005, runoff event: a) Fox River near New Munster, and b) Nippersink Creek near Spring Grove.
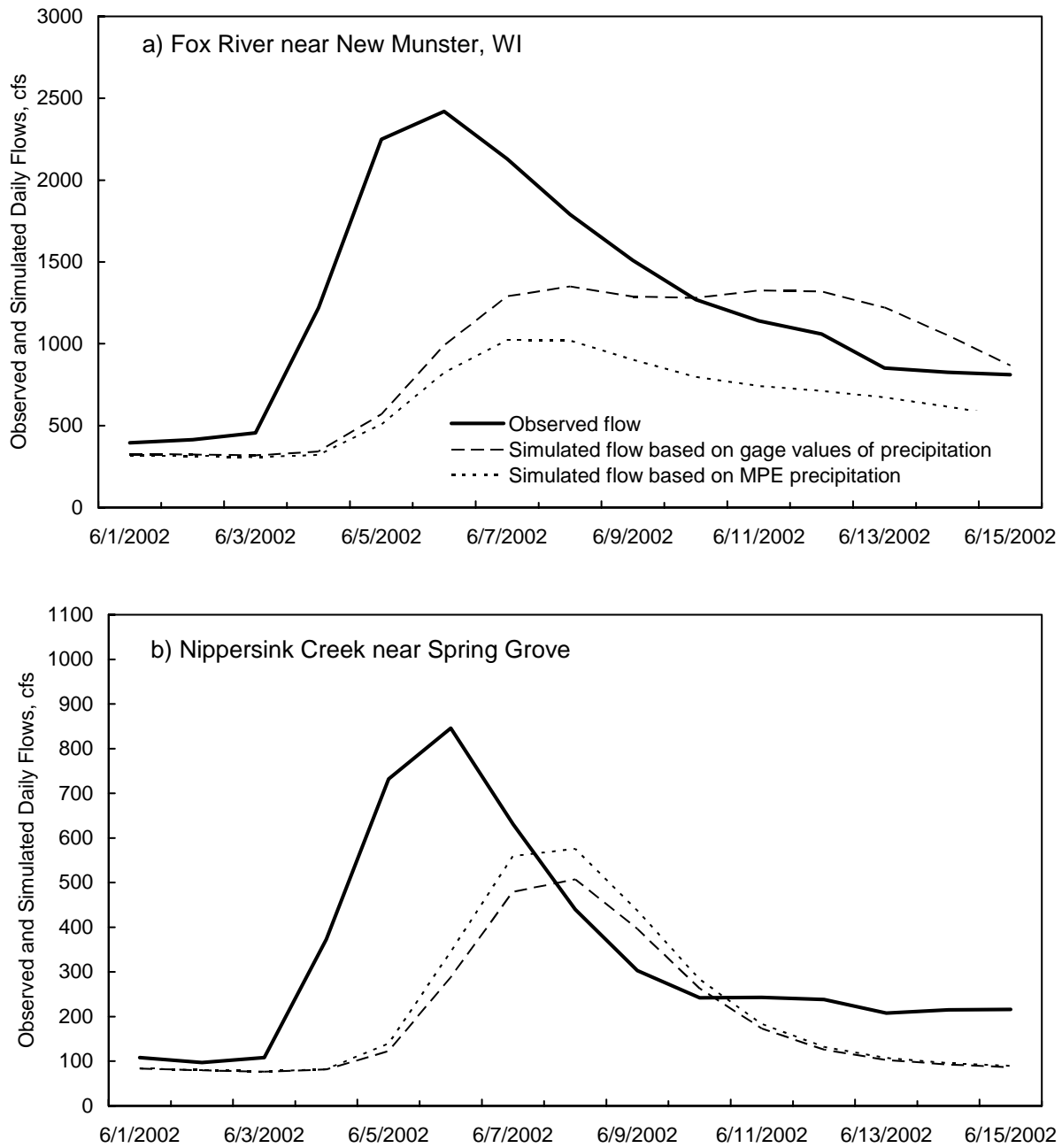
Figure 11. Comparison of simulated flows using gage precipitation and MPE data with observed
flow for the June 1–15, 2002, runoff event: a) Fox River near New Munster, and
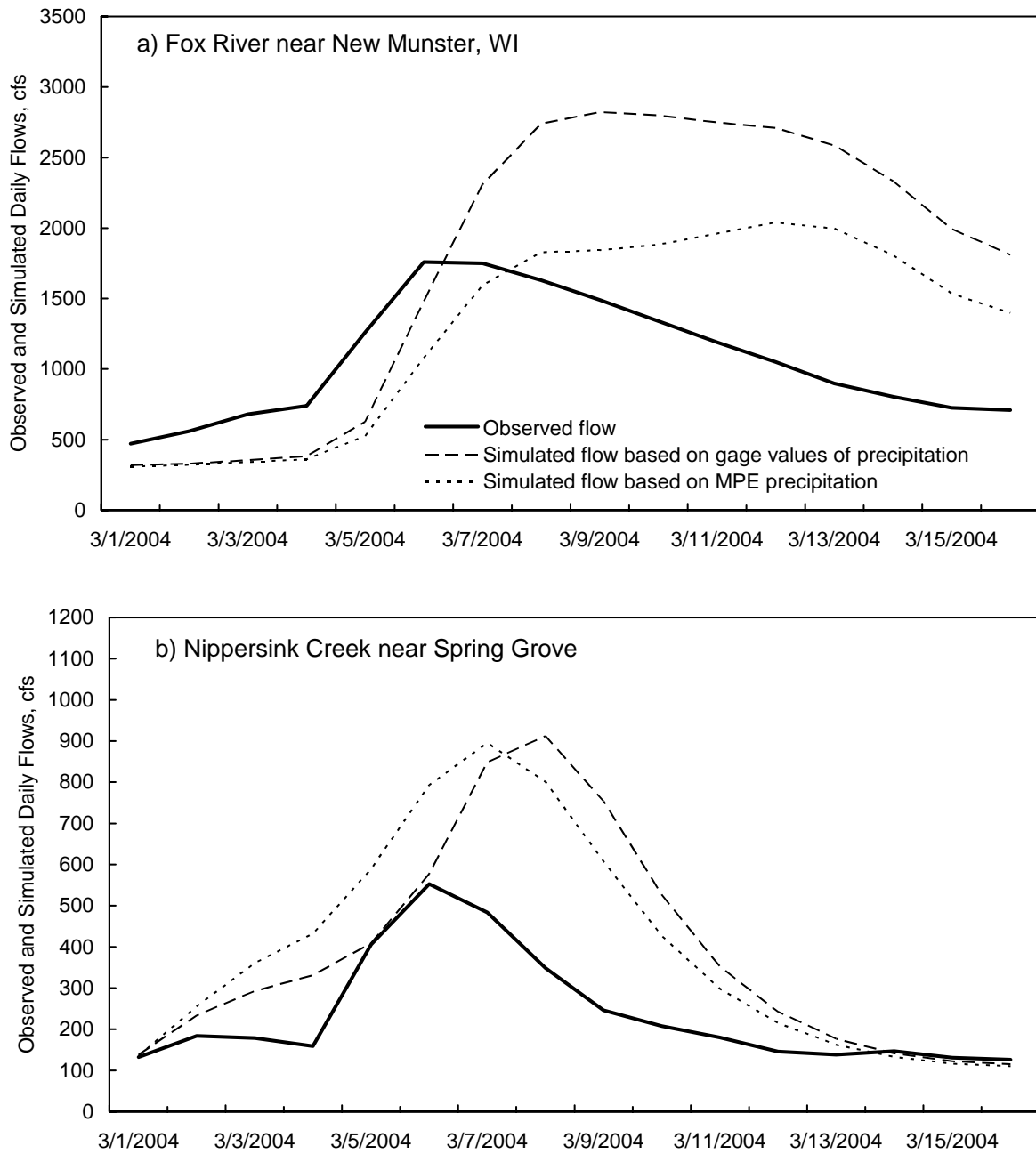b) Nippersink Creek near Spring Grove.

Figure 12. Comparison of simulated flows using gage precipitation and MPE data with observed
flow for the March 1–16, 2004, runoff event: a) Fox River near New Munster, and
b) Nippersink Creek near Spring Grove

Table 2. Runoff Volumes (cfs x day) for Observed and Simulated Hydrographs, Fox River near New Munster

Event Period	Observed Hydrograph	Precipitation Gage Data Simulated Hydrograph	MPE Precipitation Data Simulated Hydrograph
May 13-June 10, 2004	77860	85490 (+10)	61933 (-20)
February 11-24, 2005	21562	21717 (+ 1)	21189 (- 2)
June 1-15, 2002	18543	13866 (-25)	9632 (-48)
March 1-16, 2004	17059	28343 (+66)	20820 (+22)

Table 3. Runoff Volumes (cfs x day) for Observed and Simulated Hydrographs, Nippersink Creek near Spring Grove

Event Period	Observed Hydrograph	Precipitation Gage Data Simulated Hydrograph	MPE Precipitation Data Simulated Hydrograph
May 13-June 10, 2004	12634	14631 (+16)	10758 (-15)
February 11-24, 2005	4397	3979 (-10)	3869 (-22)
June 1-15, 2002	5000	2957 (-41)	3268 (-35)
March 1-16, 2004	3642	6056 (+66)	6220 (+71)

Note:
Numbers in parentheses represent percent difference from the observed volume
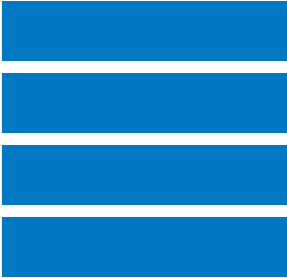
Conclusion and Recommendation

For the Fox River watershed in southeastern Wisconsin, MPE values were found to be a considerable improvement over RDR precipitation estimates during all seasons of the year. In comparison to the QC_coop gage data, however, MPE data on average were lower by about 25 percent throughout the year. Although there was not much change in the bias of the MPE values in the vicinity of the Fox River watershed in recent years, it appears that the annual bias for the broader Midwest region may be getting smaller over time as the NWS now is actively using and disseminating MPE data. If this is the case, then it is likely that the MPE bias for the Fox River watershed could lessen in upcoming years. Alternatively, because the bias in the MPE data appears to be consistent, it may be possible to adjust the data for the Fox River watershed to correct much of the bias.

The tendency of the MPE data to underestimate rainfall amounts makes its use inappropriate for long-term hydrologic simulation. It is possible, however, that there may be value in basing flow forecasts on MPE data for individual storm events, even with the existing bias of the MPE data. With the limited number of storm events available for this study, the authors cannot conclude whether the MPE-generated flow forecasts will or will not be consistently useful. Thus, the authors recommend additional comparisons of the MPE-generated hydrographs and gage-generated hydrographs as data from future major runoff events become available (using the MPE data and FRFM model interface developed in this study). Until shown differently, flow forecasts generated using gage precipitation values should be considered the primary information source for making decisions concerning Stratton Dam operation.

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