Evaluation of the Areal Mean Basin Estimated Rainfall (AMBER) Flash Flood Algorithm at the Tulsa, OK and Sterling, VA NWSFOs

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EXECUTIVE SUMMARY

This project involves the evaluation of the Areal Mean Basin Estimated Rainfall (AMBER) flash flood algorithm, which was implemented as part of the National Severe Storms Laboratory's (NSSL) Warning Decision Support System (WDSS) in the Tulsa, OK and Sterling, VA National Weather Service Forecast Offices (NWSFOs) in 1998. The AMBER program accumulates rainfall on the basin level to alert forecasters to the potential for flash flooding. The purpose of this study was to conduct an objective evaluation of the AMBER algorithm and obtain quantitative feedback on its performance. AMBER output was analyzed for several case studies in the Tulsa and Sterling county warning areas (CWAs) to determine its utility as a tool to assist in flash flood warning decisions.

With guidance from the two NWSFOs, five case studies in the Tulsa CWA and four case studies in the Sterling CWA were identified. Pertinent data was obtained, including archived Level II data from the KINX and KLWX radars, archived county flash flood guidance (FFG) values from the Middle Atlantic and Arkansas-Red Basin River Forecast Centers, archived rain gage data from the Sterling NWSFO and the Arkansas-Red Basin River Forecast Center, and city/town population data from the Geographic Names Information System (GNIS). Storm event information and flash flood reports were taken from the *Storm Data and Unusual Weather Phenomena* publication.

For each case study, a description of the event and pre-existing hydrologic conditions is provided. The AMBER output is then analyzed, including a discussion of the accuracy of the precipitation estimates, the utility of using the average basin rainfall (ABR) rate and/or ratio of ABR accumulation to FFG value to determine flash flood potential, variation of results on different basin scales, and prediction errors.

Overall, the AMBER output provided good information about flash flood potential. However, it should be noted that AMBER output is only as good as the radar precipitation estimate input on which it is based. When a radar is overestimating or underestimating precipitation, flash flood guidance or other threshold guidance values become meaningless unless the forecaster has access to reliable ground truth and can adjust the precipitation estimates accordingly. In addition, in areas where there is beam blockage or incomplete radar coverage, AMBER is of little or no use.

In general, it is more beneficial to monitor ABR rate rather than the ratio or difference between ABR accumulation and FFG or other threshold guidance value. In each of the nine case studies, most or all of the reported flash floods occurred prior to the time ABR accumulation exceeded FFG. However, in most cases the ABR rate reached a significant value well before reported flash flooding. Therefore, it was concluded that ABR rate is the most important component of AMBER to produce timely warnings.

Basin size was examined to determine the utility of including various basin scales. It was concluded that basins delineated with a minimum drainage area threshold less than 10 mi^2 would better capture the high rainfall rates and accumulations in comparison to basins delineated with a minimum drainage area threshold of 10 mi^2 or greater. While accumulation and rate information in larger basins is useful to forecasters, basins smaller than 10 mi^2 are recommended for flash flood forecasting purposes.

Perhaps the most significant problem associated with the AMBER output was the number

of flash flood “false alarms”. However, there are several factors which may result in these false alarms. First, flash flood verification is a difficult if not impossible task. There is no guarantee that because a flash flood was not reported it did not occur. This is particularly true in rural areas where low population density increases the chance that a flash flood will not be observed. Second, this evaluation of the AMBER algorithm was strictly objective. Experienced forecasters who are familiar with the terrain, hydrologic conditions, and flash flood prone basins in their area would likely have eliminated many of the false alarms.

Ultimately, AMBER’s operational success will depend on three factors: 1) the quality of the basin delineation, 2) the accuracy of the precipitation estimates, and 3) the forecaster’s ability to interpret the output meaningfully. It is recommended that basins are delineated using a minimum drainage area threshold less than 10 mi^2, the ABR rate is used to identify flash flood potential, and NWSFO staff receives quality training in all aspects of the AMBER algorithm and its output.

Introduction

Objective

This project involves the evaluation of the Areal Mean Basin Estimated Rainfall (AMBER) flash flood algorithm, which was implemented as part of the National Severe Storms Laboratory's (NSSL) Warning Decision Support System (WDSS) in the Tulsa and Sterling National Weather Service Forecast Offices (NWSFOs) in 1998. The AMBER program accumulates rainfall on the individual basin level to alert forecasters to the potential for flash flooding. The rainfall accumulations are shown in a display containing a geographic view of the basins, tabular data, and time series information. Since the implementation of AMBER for real-time testing in Tulsa and Sterling, qualitative feedback has been provided on the utility of the algorithm and its display. The purpose of this evaluation is to obtain quantitative feedback on the performance of the algorithm. AMBER output is analyzed for several case studies in the Tulsa and Sterling county warning areas (CWAs) to determine its utility as a tool to assist in flash flood warning decisions.

Background

The AMBER program (Davis and Jendrowski, 1996) is a tool developed by Bob Davis (Pittsburgh NWSFO) and Paul Jendrowski (Honolulu NWSFO) to assist in flash flood warning decisions. Over a range of hydrologic and temporal scales, AMBER accumulates rainfall from estimates derived from the WSR-88D Digital Hybrid-Scan Reflectivity (DHR) product. The accumulations for each 1-degree by 1-km bin in a radar coverage area are used to calculate an area weighted average accumulation as well as an average rainfall rate for every basin delineated in each of the following categories:

1) Mean Areal Precipitation (MAP) Basins used by the River Forecast Centers (RFCs)
2) Major Basins (generally ≥200 square mile drainage areas)
3) Primary Basins (generally <200 square mile drainage areas)
4) Subdivisions of the Major and Primary Basins
5) Urban Areas

To determine flash flood potential in each basin, the average basin rainfall (ABR) accumulations are compared with flash flood guidance (FFG) or some other threshold guidance values, and ABR rates are monitored. Currently, the prototype AMBER output display developed at NSSL includes three components. The first is a geographic display consisting of maps of the first four basin categories listed above, color-coded according to flash flood potential. A yellow alert indicates an ABR value at least 80% of FFG, and a red alert indicates an ABR value greater than or equal to FFG. Streams, county lines, and state lines can also be overlaid in the geographic display. The second component of the AMBER display is a table containing the ratios of ABR to FFG for a range of time intervals. Information in the table is color coded with the same yellow and red scheme used in the geographic display to indicate flash flood potential for each basin. The third display component is a plot of the ABR rate and the cumulative ABR during the previous six hours.

During Spring 1998, basins were delineated and AMBER data files were created for the Sterling, VA and Tulsa, OK NWSFOs. Scripts developed by Paul Jendrowski at the Honolulu NWSFO were used to delineate basins in the ArcView Geographic Information System (GIS) with the Spatial Analyst Extension. Basins were delineated for the Major, Primary, and Subdivision categories, with a minimum drainage area of 10 mi^2 for the Subdivision headwater basins. MAP Basins were included based on latitude and longitude coordinates of the boundaries provided by the Middle Atlantic and Arkansas-Red Basin RFCs. Table 1 shows the number of basins included in each category at Sterling and Tulsa.

Table 1. Number of basins in each category included in the AMBER data files at Sterling and Tulsa.

Sterling, VA NWSFO (KLWX Radar)	
MAP Basins	**59**
Major Basins	**94**
Primary Basins	**441**
Subdivision Basins	**1885**
Tulsa, OK NWSFO (KINX Radar)	
MAP Basins	**114**
Major Basins	**133**
Primary Basins	**513**
Subdivision Basins	**2201**

Methodology

With the assistance of the Sterling and Tulsa NWSFOs, nine case events were identified. Storm event information and flash flood reports for these cases were taken from the *Storm Data and Unusual Weather Phenomena* publication. Archived Level II data from the KLWX and KINX radars were obtained from the National Climatic Data Center (NCDC). Using NSSL's WSR-88D Algorithm Testing and Display System (WATADS), the Level II reflectivity was used to create the DHR product which was then used to derive 1-kilometer by 1-degree precipitation estimates. The AMBER algorithm was run and ABR rates and accumulations were generated for each basin delineated. The AMBER output could then be displayed and analyzed using NSSL's AMBER display.

Archived county FFG values were obtained from the Middle Atlantic River Forecast Center and from the Arkansas-Red Basin River Forecast Center. Flash flood guidance is defined as the amount of rainfall necessary during a specified time period to initiate flooding on small streams (Sweeney and Baumgardner, 1999). It is derived from soil moisture state and threshold runoff, which is the runoff necessary to exceed bankfull stage based on the geographic and hydrologic features of the stream channel and basin. FFG may be computed for grids, zones, counties, or headwaters, and is generally issued twice a day with more frequent updates as a situation warrants. For each case study, the county FFG values were updated throughout the event as they would have been operationally.

Additional information pertinent to the analysis was obtained as needed and as available. Archived point precipitation measurements from rain gages were obtained from the Sterling NWSFO and from the Arkansas-Red Basin River Forecast Center. These were used to compare with the calculated ABR accumulations to determine the accuracy of the radar precipitation estimates for each event. In addition, the location and size of cities and towns within the county warning areas were obtained from the U.S. Geological Survey's Geographic Names Information

System (GNIS).

For each case study, a description of the event and pre-existing hydrologic conditions is provided, and the AMBER output is analyzed with regard to:

1) accuracy of the precipitation estimates
2) the utility of using the ratio of ABR accumulation to FFG value to determine flash flood potential
3) the utility of using ABR rate to determine flash flood potential
4) variation of results on different basin scales
5) prediction errors.

Tulsa CWA Case Studies

Case Study #1 - January 4, 1998

Supporting data and figures for this case study are included in Appendix A.

Description of Rainfall Event

According to *Storm Data*, a "strongly baroclinic, southwest-northeast oriented front" became stationary over eastern Oklahoma and northwest Arkansas on January 4. Heavy rains occurred across the region as a result of "a series of upper level disturbances in southwest flow aloft". Rain totals of two to six inches were common over ground already saturated by heavy rains the week before Christmas. Many creeks and rivers overflowed their banks, with several bridges becoming submerged.

The KINX 3-hour and storm total precipitation images for this event are shown in Figures A1 through A4, and a summary of the flash flooding reported is included in Table 2 below.

Table 2. Flash flooding associated with the January 4, 1998 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Adair OK	**Countywide**	**01/04 1530 01/04 1700**	**0 / 0**	**Not Reported**
Washington AR	**Countywide**	**01/04 1600 01/04 2000**	**0 / 0**	**$10,000**

Analysis of AMBER Output

Precipitation Estimates

Figure A5 shows the rain gage measurements from 1200 UTC on the 3rd to 1200 UTC on the 5th and the Subdivision Basin ABR values for the same 48-hour period. The same color-coding scheme was used for the rain gage totals and ABR values for easy comparison. It can be seen that the ABR accumulations are somewhat lower than the rain gage measurements. To a degree, this is expected because the ABR is an areal averaged precipitation estimate for the basin rather than a point measurement. However, because these values are consistently lower throughout the region, it is reasonable to conclude the radar was slightly underestimating precipitation during this event.

ABR/FFG

Figures A6 through A9 show all basins in the four basin categories where ABR accumulation equaled or exceeded FFG. In addition, a summary of the first basin(s) in each county where ABR accumulation exceeded FFG is shown in Table A1. This summary includes basins from each of the four basin categories (Subdivision, Primary, Major, and RFC) depending on which level ABR accumulation first exceeded FFG. The comparison of 1-hour, 3-hour, and 6-hour ABR values to the FFG values for the same time interval indicates flash flooding was likely in the two counties where it was reported in *Storm Data* (Table 2), as well as in five additional counties

(Pawnee, Muskogee, Sequoyah, Cherokee, and McIntosh) where flash flooding was not reported.

Although AMBER did indicate flash flooding in the two counties in which it was reported, monitoring the ABR/FFG ratios did not indicate this flash flooding until after it was reported. In this case study, ABR accumulation exceeded FFG an average of 25 minutes after flash flooding was reported in *Storm Data* in Adair and Washington Counties. This may indicate the FFG values were too high, or it may simply be a result of the fact that by the time the rainfall accumulation in a basin equals or exceeds FFG, flash flooding has likely commenced.

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 1.5 inches/hour is shown in Table A2. This analysis indicated the potential for flash flooding in the two counties where it was reported in *Storm Data* (Table 2), and also in seven counties where it was not reported (Muskogee, Sequoyah, Cherokee, McIntosh, Benton, Tulsa, and Washington, OK). Figure A10 shows all Subdivision Basins where ABR rate equaled or exceeded 1.5 inches/hour.

Similar to the ABR/FFG ratios, the ABR rates correctly indicated flash flooding in Adair and Washington Counties, but monitoring the ABR rates also indicated flash flood potential with significant lead time. In Adair and Washington Counties, ABR rate initially exceeded 1.5 inches/hour an average of 2 hours before flash flooding was reported in *Storm Data*.

Basin Size

Figures A6 through A9 show all basins in which ABR accumulation exceeded FFG during any time interval throughout the event, along with the total ABR values for each basin. The counties highlighted in bright yellow indicate counties in which flash flooding was both indicated by AMBER and reported in *Storm Data*. The counties highlighted in pale yellow indicate counties in which flash flooding was indicated by AMBER but not reported in *Storm Data*. Finally, the counties highlighted in red indicate counties in which flash flooding was reported in *Storm Data* but missed by AMBER.

For this event, monitoring ABR/FFG ratios in the Subdivision Basins alone (Figure A6) would indicate flash flooding in Adair and Washington Counties as reported in *Storm Data*, and also in the five additional counties mentioned previously. However, flash flooding would not have been detected in Washington County if the Primary, Major or RFC Basins were used alone (Figures A7 through A9). Similar results were observed when monitoring the ABR rates in the four basin categories. This emphasizes the need for small basins when using the AMBER program as a tool for flash flood warning decisions. In the Primary, Major, and RFC Basins, the higher precipitation values are averaged over larger areas than in the Subdivision Basins, resulting in lower average rainfall rates and lower ABR values which may not exceed FFG. Thus, larger basins require widespread high rainfall amounts to produce the same average rainfall rates and ABR values as smaller basins. Significant precipitation rates and accumulations in sub-basins may be overlooked if they are averaged over larger basin areas.

Prediction Errors

It is possible flash flooding may have occurred at some time but was not reported in portions of Pawnee, Muskogee, Sequoyah, Cherokee, McIntosh, Benton, Tulsa, and Washington, OK

Counties as indicated either by the ABR/FFG ratios or the ABR rates computed by AMBER. Figure A11 shows most of the towns in or near the "flooded" Subdivision Basins in these counties to be relatively small. The largest towns in these basins are Checotah (population 3499) and Vian (population 1351). In these sparsely populated areas, a flooded country road or a small creek overflowing its banks may not be observed. In addition, Checotah is located near a watershed divide and, thus, would not likely experience flash flooding to the same degree as a town located near a watershed outlet.

Case Study #2 - September 14, 1998

Supporting data and figures for this case study are included in Appendix B.

Description of Rainfall Event

According to *Storm Data*, on September 12, much-needed rainfall was delivered to eastern Oklahoma as a result of Tropical Storm "Frances" moving onshore in Texas and traveling northward. The rains on the 12th primarily affected southeast Oklahoma, infiltrating the soil quickly as a result of the drought central and southern Oklahoma had suffered during July and August.

Early on the 13th, "deep tropical moisture was established from the Gulf of Mexico right into eastern Oklahoma," producing 1-3 inches of rain over all of eastern Oklahoma. Once again, most of the rain infiltrated the soil, resulting in near saturation conditions by late evening.

Early on the 14th, "an approaching upper level disturbance combined with the fetch of rich moisture" to increase precipitation in the area from Eufaula to Miami. This brought overnight totals to 4-5 inches in this area with local reports of 7 inches or more. These totals, falling on soil that had been saturated by the rains of the previous two days, produced flash flooding in several counties. In addition, on the 15th and 16th, the Neosho River at Commerce rose above flood stage.

The KINX 3-hour precipitation images for this event are shown in Figures B1 through B4, and a summary of the flash flooding reported is included in Table 3 below.

Table 3. Flash flooding associated with the September 14, 1998 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Cherokee OK	**15 miles W of Tahlequah**	**09/14 0445 09/14 1000**	**0 / 0**	**Not Reported**
Muskogee OK	**Fort Gibson**	**09/14 0500 09/14 1300**	**0 / 0**	**Not Reported**
Adair OK	**Stilwell**	**09/14 0630 09/14 1200**	**0 / 0**	**Not Reported**
Cherokee OK	**Tahlequah**	**09/14 0630 09/14 1100**	**0 / 0**	**Not Reported**
Ottawa OK	**4 miles W of Miami**	**09/14 0830 09/14 1200**	**0 / 0**	**Not Reported**
Sequoyah OK	**3 miles N of Marble City**	**09/14 0900 09/14 1100**	**0 / 0**	**Not Reported**
Delaware OK	**Kansas**	**09/14 1015 09/14 1200**	**0 / 0**	**Not Reported**
Muskogee OK	**Muskogee**	**09/14 1030 09/14 1230**	**0 / 0**	**Not Reported**

Analysis of AMBER Output

Precipitation Estimates

Figure B5 shows the 24-hour rain gage totals from 1200 UTC on the 13th to 1200 UTC on the 14th, and the computed ABR values for the Subdivision Basins over the same 24-hour period. It can be seen that the rain gage totals in these six counties and in the surrounding counties are approximately twice the ABR accumulations. This consistent underestimation by the radar suggests the default Z-R relationship used in this analysis may have been inappropriate. Consultation with forecasters at the Tulsa NWSFO verified that a tropical Z-R relationship had been applied during operations to derive precipitation estimates for this event. Using the tropical Z-R in this case study would likely have produced better AMBER output.

ABR/FFG

Comparison of the 1-hour, 3-hour, and 6-hour ABR values to the FFG values for these same time intervals showed that ABR accumulation did not equal or exceed FFG in any of the basins. This is a direct result of the poor precipitation estimates derived using the default Z-R relationship as discussed above. In addition, some of the FFG values issued at 0100 and 0700 UTC on the 14th may have been unrealistically high given the saturated conditions produced by rains on the 12th and 13th. For example, 1-hour FFG values near three inches were issued at 0100 UTC and 1-hour values near two inches were issued at 0700 UTC for some eastern Oklahoma counties despite the one to three inches of rainfall over all of eastern Oklahoma on the 13th.

ABR Rate

Although the derived precipitation rates were lower than they should have been if a tropical Z-R had been used, the peak ABR rates were analyzed to determine where flash flood potential was highest. However, because the derived rates were lower than the actual rates, 1.0 inch/hour was used as the threshold rate rather than the 1.5 inches/hour used in the previous case study. A summary of the first basin(s) in each county where ABR rate equaled or exceeded 1.0 inch/hour is shown in Table B1. ABR rate equaled or exceeded 1.0 inch/hour in the six counties where flash flooding was reported in *Storm Data* (Table 3), and in one county where flash flooding was not reported (Craig). Figure B6 shows all Subdivision Basins where ABR rate equaled or exceeded 1.0 inch/hour. In the six counties where flash flooding was reported, ABR rate initially exceeded 1.0 inch/hour an average of 1 hour and 22 minutes before flash flooding was reported.

Prediction Errors

It is possible flash flooding may have occurred at some time but was not reported in portions of Craig County as indicated by the ABR rates computed by AMBER. Figure B7 shows the only town near the “flooded” Subdivision Basins in this county to be Big Cabin with a population of 266. Similar to the previous case study, flash flooding may have occurred in this sparsely populated area and simply was not observed or reported.

Case Study #3 - October 5-6, 1998

Supporting data and figures for this case study are included in Appendix C.

Description of Rainfall Event

According to *Storm Data*, on the evening of October 4, a “steady train of supercell thunderstorms” moved across northeast Oklahoma, producing Oklahoma’s worst October tornado outbreak in history. The supercells evolved into a line of thunderstorms which was quasi-stationary throughout the night and into the early morning of the 5th. Rainfall amounts of 5-7 inches were widespread over northeast Oklahoma, with some of the heaviest rain falling in the Tulsa area. A line of thunderstorms began to drift slowly southeastward after sunrise, producing 3-5 inches of rain over southeast and east-central Oklahoma.

The mainstem rivers that experienced flows above flood stage due to these storms included Bird Creek at Sperry and Owasso, the Verdigris River at Lenapah, the Neosho River at Commerce and Quapaw, the Poteau River at Panama, the Deep Fork River at Beggs, Black Bear Creek at Pawnee, and Polecat Creek at Sapulpa and Jenks.

These thunderstorms moved into Benton County, Arkansas during the early morning of the 5th. The slow-moving line of storms traveled from northwest Arkansas to south of Fort Smith during the day, and rainfall totals of 3-5 inches were widespread over this area. This produced flash flooding along small creeks and in urban areas, and the Arkansas River at Van Buren rose more than 2 feet above flood stage on the evening of the 6th.

The KINX 3-hour and storm total precipitation images for this event are shown in Figures C1 through C6, and a summary of the flash flooding reported is included in Table 4 below.

Table 4. Flash flooding associated with the October 5, 1998 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Washington* OK	**South Portion**	**10/05 0400 10/05 1100**	**0 / 0**	**Not Reported**
Osage* OK	**East Portion**	**10/05 0500 10/05 1100**	**0 / 0**	**Not Reported**
Pawnee* OK	**East Portion**	**10/05 0500 10/05 1100**	**0 / 0**	**$38,000**
Creek* OK	**Countywide**	**10/05 0530 10/05 1130**	**0 / 0**	**$120,000**
Craig* OK	**Countywide**	**10/05 0600 10/05 1200**	**0 / 0**	**Not Reported**
Rogers* OK	**Countywide**	**10/05 0600 10/05 1500**	**0 / 0**	**$11,000**
Wagoner* OK	**Countywide**	**10/05 0600 10/05 1100**	**0 / 0**	**$97,000**

Mayes* OK	**Countywide**	**10/05 0700 10/05 1300**	**0 / 0**	**$35,000**
Nowata* OK	**South Portion**	**10/05 0700**	**0 / 0**	**$5,000**
Okmulgee* OK	**Countywide**	**10/05 0700 10/05 1700**	**0 / 0**	**$193,000**
Tulsa* OK	**Countywide**	**10/05 0700 10/05 1300**	**0 / 0**	**$30,000**
McIntosh* OK	**Countywide**	**10/05 0800 10/05 1800**	**0 / 0**	**$51,000**
Ottawa* OK	**Countywide**	**10/05 0800 10/05 1400**	**0 / 0**	**$30,000**
Benton AR	**Countywide**	**10/05 1030 10/05 2100**	**0 / 0**	**Not Reported**
Cherokee OK	**Countywide**	**10/05 1100 10/05 1700**	**0 / 1**	**$149,000**
Delaware OK	**Countywide**	**10/05 1200 10/05 1800**	**0 / 0**	**$5,000**
Muskogee OK	**Countywide**	**10/05 1230 10/05 1600**	**0 / 0**	**$30,000**
Okfuskee OK	**Countywide**	**10/05 1400 10/05 2000**	**0 / 0**	**$118,000**
Haskell OK	**Countywide**	**10/05 1500 10/05 2200**	**0 / 0**	**Not Reported**
Washington AR	**Countywide**	**10/05 1500 10/05 2300**	**0 / 0**	**Not Reported**
Adair OK	**Countywide**	**10/05 1700 10/05 2300**	**0 / 0**	**$15,000**
Pittsburg OK	**Countywide**	**10/05 1700 10/06 0000**	**0 / 0**	**Not Reported**
Sequoyah OK	**Countywide**	**10/05 1800 10/06 0000**	**0 / 0**	**$30,000**
Sebastian AR	**Countywide**	**10/05 1900 10/06 0100**	**0 / 0**	**Not Reported**
Latimer OK	**Countywide**	**10/05 1900 10/06 0200**	**0 / 0**	**$10,000**
LeFlore OK	**Countywide**	**10/05 1900 10/06 0200**	**0 / 0**	**$10,000**

*** Not included in the analysis.**

Analysis of AMBER Output

Precipitation Estimates

Archived Level II data from the KINX radar was unavailable from 10/01/98 through part of 10/05/98. The first volume scan available on the 5th was at 0743 UTC, and, as a result, the AMBER analysis began partway through this event. Several counties experienced flash flooding prior to the time of the first available volume scan, and these were omitted from the study.

Figure C7 shows the 24-hour rain gage totals from 1200 UTC on the 5th to 1200 UTC on the 6th, and the computed ABR values for the Subdivision Basins over the same 24-hour period. The ABR accumulations generally agree with the rain gage totals and, thus, the radar precipitation estimates appear to be fairly accurate for this event.

ABR/FFG

Figures C8 through C11 show all basins in the four basin categories where ABR accumulation equaled or exceeded FFG. In addition, a summary of the first basin(s) in each county where ABR accumulation equaled or exceeded FFG is shown in Table C1. This summary includes basins from each of the four basin categories (Subdivision, Primary, Major, and RFC) depending on which level ABR accumulation first exceeded FFG. The comparison of 1-hour, 3-hour, and 6-hour ABR values to the FFG values for the same time interval indicates flash flooding was likely in ten of the thirteen counties where it was reported in *Storm Data* (Delaware, Cherokee, Sequoyah, Adair, Muskogee, Latimer, LeFlore, Pittsburg, Sebastian, and Haskell). However, flash flooding was not indicated in Okfuskee, Benton, and Washington, AR Counties.

Further examination of the data reveals possible reasons why flash flooding was missed in these three counties. Benton and Washington had relatively high FFG values, specifically 2.4 and 2.9 inches respectively for the 1-hour interval and 3.9 and 4.6 inches respectively for the 6-hour interval. In Okfuskee County, the bulk of the precipitation fell from 1100 to 1400 UTC as shown in Figure C2. The highest totals in Okfuskee during those three hours were about 1.3 inches, which was not enough to exceed the FFG value of 2.0 inches for the 3-hour interval or even 1.6 inches for the 1-hour interval. These FFG values were apparently high for this event.

Of the ten counties where flash flooding was indicated by AMBER and reported in *Storm Data*, only one had this information a reasonable lead time before flash flooding commenced. In the thirteen counties where flash flooding was observed, ABR accumulation exceeded FFG an average of 2 hours and 21 minutes after flash flooding was reported in *Storm Data*. This may indicate FFG values were too high for this event. FFG values over the area were generally 2 inches/hour for the 1-hour interval and 3 to 4 inches/hour for the 6-hour interval. Finally, as mentioned in the first case study, the inability to predict flash flooding in a timely manner using FFG may also be a result of the fact that by the time the rainfall accumulation in a basin equals or exceeds FFG, flash flooding has likely already begun.

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 1.5 inches/hour is shown in Table C2. This analysis indicated the potential for flash flooding in all thirteen counties where it was reported in *Storm Data* (Table 4) and in three additional counties where it was not reported (Crawford, Madison, and Carroll). Figure C12 shows all Subdivision Basins where ABR rate equaled or exceeded 1.5 inches/hour.

The ABR rates correctly indicated flash flooding an average of 1 hour and 16 minutes before it was reported in the thirteen counties in *Storm Data*. However, in Haskell, Washington, AR, and Sebastian Counties, flash flooding was not indicated until after the time it was reported. Further division of the Subdivision Basins would likely improve lead time in these counties. In larger basins, the higher rainfall rates tend to be lost when they are averaged with surrounding rates. Average rates in smaller basins provide a more accurate picture of the spatial variation in the precipitation field.

Basin Size

Figures C8 through C11 show all basins in which ABR exceeded FFG during any time interval throughout the event, along with the total ABR values for each basin. For this event, monitoring ABR/FFG ratios in the Subdivision Basins alone (Figure C8) would indicate flash flooding in eight of the thirteen counties where it was reported. Using the Primary Basins, flash flooding would be indicated in seven of the thirteen counties (Figure C9). Using the Major Basins or RFC Basins, flash flooding would be indicated in only six and four counties, respectively (Figures C10 and C11). Similar results were observed when monitoring the ABR rates in the four basin categories. This emphasizes the need for small basins when using the AMBER program as a tool for flash flood warning decisions. In the Primary, Major, and RFC Basins, the higher precipitation values are averaged over larger areas than in the Subdivision Basins, resulting in lower average rainfall rates and lower ABR values which may not exceed FFG. Thus, larger basins require widespread high rainfall amounts to produce the same average rainfall rates and ABR values as smaller basins. Significant precipitation rates and accumulations in sub-basins may be overlooked if they are averaged over larger basin areas.

Prediction Errors

It is possible flash flooding may have occurred at some time but was not reported in portions of Crawford, Madison, and Carroll Counties as indicated by the ABR rates computed by AMBER. Figure C13 shows towns in or near only three of the thirty “flooded” Subdivision Basins in these counties. The basins were generally in sparsely populated areas, with the populations of the three towns only 3624, 2469, and 175. Thus, it is again possible flash flooding may have occurred in portions of these counties and was not observed or reported.

Case Study #4 - April 25, 1999

Supporting data and figures for this case study are included in Appendix D.

Description of Rainfall Event

According to *Storm Data*, during the morning and early afternoon of the 25th, a "solid area of heavy rainfall lifted northeastward across northeast Oklahoma", producing 3-5 inches of rain over the area. Flash flooding was widespread, and many rivers flowed above flood stage. The heaviest rain remained stationary over the Tulsa metropolitan area for several hours, causing many roads and houses to experience flooding.

The KINX 3-hour and storm total precipitation images for this event are shown in Figures D1 through D4, and a summary of the flash flooding reported is included in Table 5 below.

Table 5. Flash flooding associated with the April 25, 1999 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Craig OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**$15,000**
Creek OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**Not Reported**
Mayes OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**$15,000**
Nowata OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**Not Reported**
Osage OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**$30,000**
Ottawa OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**$30,000**
Rogers OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**Not Reported**
Tulsa OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**$90,000**
Wagoner OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**$30,000**
Washington OK	**Countywide**	**04/25 1430 04/25 1930**	**0 / 0**	**Not Reported**

Analysis of AMBER Output

Precipitation Estimates

A comparison of the rain gage measurements from 1200 UTC on the 25th to 1200 UTC on the 26th and the Subdivision Basin ABR values for the same 24-hour period (Figure D5) shows the radar precipitation estimates to be fairly accurate for this event.

ABR/FFG

Figures D6 through D9 show all basins in the four basin categories where ABR accumulation equaled or exceeded FFG. In addition, a summary of the first basin(s) in each county where ABR accumulation equaled or exceeded FFG is shown in Table D1. This summary includes basins from each of the four basin categories (Subdivision, Primary, Major, and RFC) depending on which level ABR accumulation first exceeded FFG. The comparison of 1-hour, 3-hour, and 6-hour ABR values to the FFG values for the same time interval indicate flash flooding was likely in the ten counties where it was reported in *Storm Data* (Table 5), as well as in three additional counties (Pawnee, Okfuskee, and Okmulgee) where flash flooding was not reported.

Only four of the ten counties where flash flooding was indicated by AMBER and reported in *Storm Data* had this information a reasonable lead time before flash flooding commenced. ABR exceeded FFG an average of 1 hour and 29 minutes after flash flooding was reported in *Storm Data* for the ten counties. This may indicate FFG values were generally too high for this event, or it may be a result of the fact that by the time the rainfall accumulation in a basin equals or exceeds FFG, flash flooding has likely already begun.

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 1.5 inches/hour is shown in Table D2. This analysis indicated the potential for flash flooding in seven of the ten counties where it was reported in *Storm Data* (Creek, Osage, Tulsa, Mayes, Craig, Wagoner, and Rogers) and in three additional counties where it was not reported (Pawnee, Okmulgee, and Okfuskee). Figure D10 shows all Subdivision Basins where ABR rate equaled or exceeded 1.5 inches/hour.

Flash flooding was missed in Washington, OK, Nowata, and Ottawa Counties. The most likely explanation for this is the size of the basins in these three counties. Figure D10 shows many of the Subdivision Basins in these counties have relatively large drainage areas as compared to an average-sized Subdivision Basin. In larger basins, the higher rainfall rates tend to be lost when they are averaged with surrounding rates. Average rates in smaller basins provide a more accurate picture of the magnitude and location of high rain rates.

In the seven counties where ABR rates indicated flash flooding and it was reported in *Storm Data*, average lead time was 1 hour and 52 minutes. However, in Rogers and Wagoner Counties, flash flooding was not indicated until after the time it was reported. Again, it is likely further division of the Subdivision Basins would improve lead time in these counties.

Basin Size

Figures D6 through D9 show all basins in which ABR accumulation exceeded FFG during any time interval throughout the event, along with the total ABR values for each basin. For this event, monitoring the ABR/FFG ratios in the Subdivision Basins alone would indicate flash flooding in the ten counties reported in *Storm Data*, and also in the three additional counties mentioned previously. Using only the Primary Basins, flash flooding would likely be missed in Wagoner County. Using the RFC Basins alone, flash flooding would be missed in two of the ten counties where it was reported, and using the Major Basins alone, flash flooding would be missed in four of the ten counties. Similar results were observed when monitoring the ABR rates in the four basin categories. These results again emphasize the necessity of monitoring rainfall in relatively small basins to predict flash flooding.

Prediction Errors

It is possible flash flooding may have occurred in portions of Pawnee, Okfuskee, and Okmulgee Counties at some time as indicated by AMBER but was not reported. Figure D11 shows most of the towns in or near the "flooded" Subdivision Basins in these counties are relatively small. The largest towns in these basins are Beggs (population 1150), Okemah (population 2919), and Cleveland (population 3168). In addition, Beggs and Okemah are both located near watershed divides and, thus, would not likely experience flash flooding to the same degree as towns located near watershed outlets.

Case Study #5 - June 20, 1999

Supporting data and figures for this case study are included in Appendix E.

Description of Rainfall Event

As reported in *Storm Data*, a "cluster of thunderstorms developed during the early morning hours of June 20 on the nose of a nocturnal low-level jet." The deep-layer moisture combined with the fairly stationary character of these storms produced heavy rainfall. Mayes County received the heaviest rainfall, with radar precipitation estimates of 4-7 inches over much of the county. The flash flooding resulted in one fatality when a man was swept away in his car by floodwater flowing over a major highway.

The KINX 3-hour and storm total precipitation images for this event are shown in Figures E1 through E6, and a summary of the flash flooding reported is included in Table 6 below.

Table 6. Flash flooding associated with the June 20, 1999 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Cherokee OK	**Countywide**	**06/20 0945 06/20 1400**	**0 / 0**	**Not Reported**
Mayes OK	**Countywide**	**06/20 1045 06/20 1545**	**1 / 0**	**$150,000**
Craig OK	**Countywide**	**06/20 1300 06/20 1745**	**0 / 0**	**$100,000**
Rogers OK	**Countywide**	**06/20 1300 06/20 1745**	**0 / 0**	**Not Reported**
Nowata OK	**Countywide**	**06/20 1545 06/20 1645**	**0 / 0**	**Not Reported**

Analysis of AMBER Output

Precipitation Estimates

A comparison of the rain gage measurements for the 48-hour period from 1200 UTC on the 18th to 1200 UTC on the 20th and the Subdivision Basin ABR values for the same 48-hour period (Figure E7) shows the radar precipitation estimates to be fairly accurate for this event.

ABR/FFG

Figures E8 through E11 show all basins in the four basin categories where ABR accumulation equaled or exceeded FFG. In addition, a summary of the first basin(s) in each county where ABR accumulation equaled or exceeded FFG is shown in Table E1. This summary includes basins from each of the four basin categories depending on which level ABR accumulation first exceeded FFG. The comparison of 1-hour, 3-hour, and 6-hour ABR values to the FFG values for the same time interval indicate flash flooding was likely in the five counties where it was reported in *Storm Data* (Table 6), as well as in two additional counties (Osage and Muskogee) where flash flooding was not reported.

In the five counties where flash flooding was reported in *Storm Data*, ABR accumulation exceeded FFG an average of 39 minutes before flash flooding was reported. However, in Cherokee County, flash flooding was not indicated until after the time it was reported. This is most likely because Cherokee County's FFG values were significantly higher than those for the other four counties as shown in Table 7 below.

Table 7. FFG values issued at 0100 UTC on 06/20/99.

County	**1-hour FFG (inches)**	**3-hour FFG (inches)**	**6-hour FFG (inches)**
Cherokee	**2.1**	**2.5**	**3.1**
Mayes	**1.1**	**1.4**	**1.9**
Craig	**1.0**	**1.3**	**1.8**
Rogers	**1.1**	**1.4**	**1.9**
Nowata	**0.7**	**0.9**	**1.4**

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 1.5 inches/hour is shown in Table E2. This analysis indicated the potential for flash flooding in three of the five counties where it was reported in *Storm Data* (Mayes, Cherokee, and Rogers). Figure E12 shows all Subdivision Basins where ABR rate equaled or exceeded 1.5 inches/hour.

Flash flooding was missed in Nowata and Craig Counties. The most likely explanation for this is the size of the basins in these two counties. Figure E12 shows many of the Subdivision Basins in these counties have relatively large drainage areas, particularly along the countyline between the two where most of the high precipitation rates occurred during this event. It is likely smaller basins would have preserved the higher rainfall rates, allowing flash flooding to be indicated with reasonable lead time.

The ABR rates indicated flash flooding in the three counties where it was reported in *Storm Data* with an average lead time of 37 minutes. However, in Rogers County, flash flooding was not indicated until after the time it was reported. Again, it is likely further division of the Subdivision Basins would improve lead time.

Basin Size

Figures E8 through E11 show all basins in which ABR accumulation exceeded FFG during any time interval throughout the event, along with the total ABR values for each basin. For this event, monitoring the ABR/FFG ratios in the Subdivision Basins alone would indicate flash flooding in the five counties where it was reported in *Storm Data*, and also in the two additional counties mentioned previously. Using the Primary Basins alone, flash flooding would be detected in only two of the five counties in which it was reported. Using either the RFC Basins or Major Basins alone, flash flooding would be missed in one of the five counties where it was reported. Similar results were observed when monitoring the ABR rates in the four basin categories. This again emphasizes the need for small basins when using the AMBER program for flash flood warning decisions.

Prediction Errors

It is possible flash flooding may have occurred in portions of Osage and Muskogee counties as indicated by AMBER but was not reported. Figure E13 shows that no cities or towns are located in either of the two “flooded” basins in Osage County or in the one “flooded” basin in Muskogee County. The only town relatively close to (but still not in) any of these basins is Braggs (population 363). If flash flooding did occur in any of these basins, it would not likely have been observed or reported.

Sterling CWA Case Studies

Case Study #1 - June 27, 1995

Supporting data and figures for this case study are included in Appendix F.

Description of Rainfall Event

As reported in *Storm Data*, "the combination of a stalled front, strong (for the season) low-level upslope flow, deep tropical moisture, and an upper-level disturbance produced extremely heavy rainfall over the central and northern Shenandoah Valley" on June 27-28. Because the rain fell on soil that was nearly saturated from rains during previous days, catastrophic flooding and flash flooding occurred. The flooding resulted in three fatalities, 20 injuries, at least $50 million in property damage, and nearly $100 million in agricultural damage. Over 2000 homes were damaged, 132 were destroyed, and 800 people were evacuated from their homes. Madison, Greene, Albemarle, Culpeper, Augusta, Warren, Orange, and Rappahannock Counties were declared Federal Disaster Areas.

Madison County experienced the most severe flooding with rainfall exceeding 20 inches in a 12-hour period at higher elevations. One observer recorded 10 inches in two hours. During the day on the 27th, other severe flooding was reported in northern Greene, northwest Rappahannock, northwest Culpeper, Orange, and Warren Counties. Heavy rains redeveloped in eastern Augusta, western Albemarle, and Nelson Counties later that evening, producing additional flooding. River flooding along the Rapidan River near the Greene/Madison County line was considered to be a 500-year event, with the stage exceeding the previous record by almost 10 feet.

Landslides resulted in significant erosion and a restructuring of much of the central Shenandoah Valley, particularly in Madison, Albemarle, Augusta, and Greene Counties. Agricultural damage was also severe, particularly in Madison county where about half of the usable land was flooded and 600 livestock destroyed.

The KLWX 3-hour and storm total precipitation images for this event are shown in Figures F1 through F9, and a summary of the flash flooding reported is included in Table 7 below.

Table 7. Flash flooding associated with the June 27, 1995 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage Property / Crops
Orange VA		**06/27 1030 06/27 2000**	**0 / ?**	**$3.0M / $1.7M**
Madison VA		**06/27 1030 06/27 2100**	**1 / ?**	**$3.5M / $36M**
Fauquier VA	**Northern Portion**	**06/27 1230 06/27 1300**	**0 / 0**	**$25K / $25K**
Rappahannock VA		**06/27 1230 06/27 1900**	**1 / ?**	**$800K / $373K**
Warren VA		**06/27 1230 06/27 1900**	**1 / ?**	**$800K / $80K**

Culpeper VA		**06/27 1300 06/27 1900**	**0 / ?**	**$100K / $353K**
Frederick VA		**06/27 1330 06/27 1900**	**0 / 0**	**$35K / $25K**
Greene VA		**06/27 1430 06/27 2200**	**0 / ?**	**$1.9M / $250K**
Allegany MD	**Western Portion**	**06/27 1800 06/27 2000**	**0 / 0**	**$1.3M / $50K**
Mineral WV	**Piedmont-Keyser**	**06/27 1800 06/27 2000**	**0 / 0**	**$1.1M / $50K**
Shenandoah VA		**06/28 0100 06/28 0200**	**0 / 0**	**$50K / $50K**
Albemarle VA	**Sugar Hollow/ Near Moormans River**	**06/28 0300 06/28 0700**	**0 / ?**	**$250K / $1.0M**
Nelson VA		**06/28 0400 06/28 0600**	**0 / ?**	**$50K / $50K**

Analysis of AMBER Output

Precipitation Estimates

Figure F10 shows the rain gage measurements from 1200 UTC on the 27th to 1200 UTC on the 28th and the Subdivision Basin ABR values for the same 24-hour period. The same color-coding scheme was used for the rain gage totals and ABR values for easy comparison, and it can be seen that the ABR accumulations are somewhat lower than the rain gage measurements. To some degree, this is to be expected because the ABR is an areal averaged precipitation estimate for the basin. However, because these values are significantly lower in some areas of the region, it is reasonable to conclude the radar underestimated precipitation during this event. In addition, the ratio of ground truth to radar precipitation estimates was about 2:1 according to the report on “Flooding of Late June 1995" (Goldsmith, et al., 1995). Possible reasons for this discrepancy between ground truth and radar estimates are the beam not sampling that portion of the cloud where the heaviest precipitation was occurring and the tropical nature of the storms which likely warranted use of a different Z-R relationship. Mountain beam blockage also caused radar rainfall estimation problems in Mineral County, WV and Allegany County, MD.

ABR/FFG

Figure F11 shows all Subdivision Basins where ABR accumulation equaled or exceeded FFG. In addition, a summary of the first basin(s) in each county where ABR accumulation exceeded FFG is shown in Table F1. ABR accumulations were greater than FFG values only in Madison and Greene Counties and only on the Subdivision Basin level. Although it could possibly be argued that the FFG values were slightly high for this event, the most likely explanation for the failure to identify flash flooding is the underestimation of precipitation by the radar.

Although monitoring the ABR/FFG ratios did indicate flash flooding in two of the thirteen counties in which it was reported, ABR exceeded FFG an average of about 4   hours after flash flooding was reported in *Storm Data* in Madison and Greene Counties. This is probably a result of the fact that by the time the rainfall accumulation in a basin equals or exceeds FFG, flash flooding has likely already commenced.

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 0.6 inch/hour is shown in Table F2. Because the radar precipitation estimates for this event were low, a relatively low threshold rate was used for the ABR rate analysis. This analysis indicated the potential for flash flooding in ten of the thirteen counties where it was reported in *Storm Data* (Orange, Madison, Fauquier, Rappahannock, Warren, Culpeper, Frederick, VA, Greene, Albemarle, and Nelson), and also in three counties where it was not reported (Loudoun, Berkeley, and Clarke). Figure F12 shows all Subdivision Basins where ABR rate equaled or exceeded 0.6 inch/hour.

Flash flooding was not indicated in three of the counties (Allegany, Mineral, and Shenandoah) where it was reported in *Storm Data*. As mentioned previously, mountain beam blockage caused difficulties with radar rainfall estimation in Allegany and Mineral Counties. In addition, many of the basins in these counties and in Shenandoah County are relatively large as shown in Figure F12. Larger basins have a greater likelihood of their high rain rates being averaged out.

In each of the ten counties where ABR rates indicated flash flooding and it was verified in *Storm Data*, flash flood potential was identified with plenty of lead time. In these ten counties, ABR rate initially exceeded 0.6 inch/hour an average of 3 hours and 54 minutes before flash flooding was reported in *Storm Data*.

Basin Size

Similar to the results in the Tulsa case studies, ABR rate exceeded 0.6 inch/hour primarily in the Subdivision Basins rather than in the Primary, Major, or MAP Basins. As mentioned previously, in the counties or portions of counties where flash flooding was reported in *Storm Data* but was not indicated by AMBER, many of the Subdivision Basins were relatively large. Larger basins require widespread high rainfall amounts to produce the same average rainfall rates and ABR accumulations as smaller basins. Significant precipitation rates and accumulations in smaller sub-basins may be overlooked if they are averaged over larger basin areas. This emphasizes the need for small basins when using the AMBER program as a tool for flash flood warning decisions.

Prediction Errors

It is possible flash flooding may have occurred at some time but was not reported in portions of Berkeley, Clarke, and Loudoun Counties as indicated either by the ABR/FFG ratios or ABR rates computed by AMBER. Figure F13 shows no towns in or near the "flooded" Subdivision Basins in these counties. In these sparsely populated areas, flash flood verification is even more difficult than usual.

Case Study #2 - October 20-21, 1995

Supporting data and figures for this case study are included in Appendix G.

Description of Rainfall Event

As reported in *Storm Data*, during the late evening of the 20th, upslope flow of deep tropical moisture produced heavy rains over the northern Shenandoah Valley. Rainfall totals over central and northern portions of the valley ranged from four to six inches, producing flash flooding in several counties.

The KLWX 3-hour and storm total precipitation images for this event are shown in Figures G1 through G4, and a summary of the flash flooding reported is included in Table 8 below.

Table 8. Flash flooding associated with the October 20-21, 1995 event as reported by the Sterling WFO.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Nelson VA		**10/21 0145 10/21 0300**	**0 / 0**	**$5,000**
Rockingham VA	**Eastern Portion**	**10/21 0200 10/21 0300**	**0 / 0**	**0**
Augusta VA	**Eastern Portion**	**10/21 0230 10/21 0330**	**0 / 0**	**$10,000**
Warren VA		**10/21 0330 10/21 0430**	**0 / 0**	**0**
Page VA		**10/21 0330 10/21 0430**	**0 / 0**	**0**
Madison VA		**10/21 0430 10/21 0530**	**0 / 0**	**$25,000**
Shenandoah VA		**10/21 0430 10/21 0630**	**0 / 0**	**$1,000**

Analysis of AMBER Output

Precipitation Estimates

According to *Storm Data*, notable rainfall totals for this storm event included 6.98 inches in Nelson County and 6.14 to 6.23 inches in Page County, with unconfirmed reports of 8- and 9-inch isolated totals. Rainfall totals over the central and northern Shenandoah Valley ranged from 4 to 6 inches. However, the highest accumulations shown in the storm total precipitation image in Figure G4 are approximately 2 inches. Because these totals are significantly lower than the ground truth, it is reasonable to conclude the radar precipitation estimates were low during this event.

ABR/FFG

ABR accumulations were not greater than or equal to FFG values in any of the counties where flash flooding was reported. While the FFG values might be considered slightly high for this event (generally 2 inches or greater for the 1-hour time interval), the most likely explanation for the failure to identify flash flooding is the underestimation of precipitation by the radar.

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 0.6 inch/hour is shown in Table G1. Because the radar precipitation estimates for this event were low, a relatively low threshold rate was again used for the ABR rate analysis. This analysis indicated the potential for flash flooding in six of the seven counties where it was reported in *Storm Data* (Nelson, Rockingham, Warren, Page, Madison, and Shenandoah), and also in 23 counties where it was not reported. Figure G5 shows all Subdivision Basins where ABR rate equaled or exceeded 0.6 inch/hour.

Flash flooding was not indicated in one of the counties (Augusta County, specifically the eastern portion) where it was reported in *Storm Data*. Figure G5 shows many of the basins in eastern Augusta County to be relatively large, resulting in a greater likelihood of high rain rates being averaged out. Further division of these basins would likely have indicated areas of high rain rates and greater flash flood potential.

In each of the six counties where ABR rates indicated flash flooding and it was verified in *Storm Data*, flash flood potential was identified with a reasonable amount of lead time. In these six counties, ABR rate initially exceeded 0.6 inch/hour an average of 1 hour and 34 minutes before flash flooding was reported in *Storm Data*.

Basin Size

ABR rate exceeded 0.6 inch/hour primarily in the Subdivision Basins rather than in the Primary, Major, or MAP Basins. As mentioned previously, in eastern Augusta County where flash flooding was reported in *Storm Data* but was not indicated by AMBER, many of the Subdivision Basins were relatively large. Larger basins require widespread high rainfall amounts to produce the same average rainfall rates and ABR accumulations as smaller basins. Significant precipitation rates and accumulations in smaller sub-basins may be overlooked if they are averaged over larger basin areas. This emphasizes the need for small basins when using the AMBER program as a tool for flash flood warning decisions.

Prediction Errors

Because flash flooding was indicated by AMBER in 23 counties where it was not reported, further examination of this event is necessary to determine the reason for such large prediction errors. Figure G6 shows the cities and towns in or near the Subdivision Basins where flash flooding was indicated by AMBER. While several of these basins do not have a city or town located in or near them, many others do include a significant population center. This eliminates the possibility of the prediction errors being a result of lack of verification.

One possible explanation is that the ABR rate of 0.6 inch/hour used as a flash flooding indicator was too low for this event. To test this theory, additional analyses were conducted using thresholds of 0.7, 0.8, and 0.9 inch/hour. With each increment, flash flooding was indicated in fewer counties. These counties included not only those where flash flooding had not been reported in *Storm Data*, but also some where it had been reported. The results using the 0.9 inch/hour threshold rate are shown in Figure G7. It can be seen that the 0.9 inch/hour threshold did not indicate flash flooding in Nelson, Augusta, or Rockingham County, all three of which had reports of flash flooding in *Storm Data*. In addition, there were still 11 counties where AMBER indicated flash flooding but it was not reported in *Storm Data*. Thus, it does not appear a higher threshold rate would completely resolve the prediction errors.

The total precipitation image in Figure G4 shows that rainfall was fairly uniform over most of the CWA. Thus, there must have been another factor to distinguish the seven counties where flash flooding was reported from the many additional counties where AMBER indicated flash flooding. Perhaps the most obvious factor is terrain. The seven counties where flash flooding was reported generally lie along the Blue Ridge. It is possible the rainfall amounts and rates associated with this event were adequate to produce flash flooding in steeper terrain, but not sufficient to induce flooding in the flatter coastal regions. Perhaps it is necessary to use different threshold rates depending on the terrain. Case studies like this indicate the need for information in addition to that which AMBER provides. A flash flood index that attempts to quantify the effects of terrain, infiltration parameters, and antecedent moisture conditions would provide valuable guidance and improve the forecaster’s interpretation of AMBER output.

Case Study #3 - January 19, 1996

Supporting data and figures for this case study are included in Appendix H.

Description of Rainfall Event

According to *Storm Data*, a blizzard on January 6th and 7th dropped two to three feet of snow across the Sterling CWA, followed by more snow on the 9th, 10th, and 12th. One week later, snowcover ranged from a few inches in southern Maryland to three feet in western Maryland and eastern West Virginia. High dew point temperatures on the night of the 18th and early on the morning of the 19th caused most of the snow to melt within 12 hours, averaging two- to three-inch water equivalents. In addition, a storm system moved in, dropping one to three inches of rain over the area. This combination of snowmelt and rain produced the worst flooding in over 10 years across the Mid-Atlantic Region. Flash flooding occurred along the headwaters of the Potomac, Shenandoah, and Rappahannock River basins on the 19th, followed by river flooding which continued through the 23rd.

The KLWX 3-hour and storm total precipitation images for this event are shown in Figures H1 through H4, and a summary of the flash flooding reported is included in Table 9 below.

Table 9. Flash flooding associated with the January 19, 1996 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Rockingham VA	**Countywide**	**01/19 0630 01/19 1700**	**0 / 0**	**$7M**
Augusta VA	**Countywide**	**01/19 0630 01/19 1700**	**0 / 0**	**$900K**
Nelson VA	**Countywide**	**01/19 0630 01/19 1700**	**0 / 0**	**Not Reported**
Albemarle VA	**Countywide**	**01/19 0630 01/19 1700**	**1 / 0**	**Not Reported**
Greene VA	**Countywide**	**01/19 0630 01/19 1700**	**0 / 0**	**$1,000**
Madison VA	**Countywide**	**01/19 0630 01/19 1700**	**0 / 0**	**Not Reported**
Page VA	**Countywide**	**01/19 0630 01/19 1700**	**0 / 0**	**$700K**
Rappahannock VA	**Countywide**	**01/19 0630 01/19 1700**	**0 / 0**	**Not Reported**
Allegany MD	**Countywide**	**01/19 0800 01/19 1700**	**0 / 0**	**$7M**
Mineral WV	**Countywide**	**01/19 0800 01/19 1700**	**0 / 0**	**Not Reported**

Grant WV	**Countywide**	**01/19 0800 01/19 1700**	**0 / 0**	**Not Reported**
Pendleton WV	**Countywide**	**01/19 0900 01/19 1700**	**0 / 0**	**$10M**
Hardy WV	**Countywide**	**01/19 0900 01/19 1700**	**0 / 0**	**$9.5M**
Hampshire WV	**Countywide**	**01/19 0900 01/19 1700**	**0 / 0**	**Not Reported**
Highland VA	**Countywide**	**01/19 0900 01/19 1700**	**0 / 0**	**Not Reported**
Washington MD	**Countywide**	**01/19 1000 01/19 1700**	**0 / 0**	**$1M**
Morgan WV	**Countywide**	**01/19 1000 01/19 1700**	**1 / 0**	**$500K**
Shenandoah VA	**Countywide**	**01/19 1000 01/19 1800**	**0 / 0**	**$27M**
Frederick VA	**Countywide**	**01/19 1000 01/19 1800**	**0 / 0**	**$2M**
Berkeley WV	**Countywide**	**01/19 1100 01/19 1700**	**0 / 0**	**Not Reported**
Jefferson WV	**Countywide**	**01/19 1100 01/19 1700**	**0 / 0**	**Not Reported**
Warren VA	**Countywide**	**01/19 1100 01/19 1800**	**0 / 0**	**$2M**
Clarke VA	**Countywide**	**01/19 1100 01/19 1800**	**0 / 0**	**$600K**
Loudoun VA	**Countywide**	**01/19 1200 01/19 1800**	**0 / 0**	**$1M**
Fauquier VA	**Countywide**	**01/19 1200 01/19 1800**	**0 / 0**	**$200K**
Frederick MD	**Countywide**	**01/19 1200 01/19 1800**	**0 / 0**	**$500K**
Carroll MD	**Countywide**	**01/19 1200 01/19 1800**	**0 / 0**	**$300K**
Culpeper VA	**Countywide**	**01/19 1300 01/19 1800**	**0 / 0**	**Not Reported**
Orange VA	**Countywide**	**01/19 1300 01/19 1800**	**0 / 0**	**Not Reported**
Fairfax VA	**Countywide**	**01/19 1400 01/19 1800**	**0 / 0**	**Not Reported**
Prince William VA	**Countywide**	**01/19 1400 01/19 1800**	**0 / 0**	**$10,000**

Montgomery MD	**Countywide**	**01/19 1400 01/19 1800**	**0 / 1**	**Not Reported**
Howard MD	**Countywide**	**01/19 1400 01/19 1800**	**0 / 0**	**$5,000**
Baltimore MD	**Countywide**	**01/19 1400 01/19 1800**	**0 / 0**	**Not Reported**
Harford MD	**Countywide**	**01/19 1400 01/19 2000**	**0 / 0**	**$5,000**
Prince George's MD	**Countywide**	**01/19 1500 01/19 1900**	**0 / 0**	**Not Reported**
Stafford VA	**Countywide**	**01/19 1500 01/19 1900**	**0 / 0**	**$5,000**
Spotsylvania VA	**Countywide**	**01/19 1500 01/19 1900**	**0 / 0**	**$3,000**
District of Columbia	**Countywide**	**01/19 1600 01/19 1800**	**0 / 0**	**Not Reported**
Arlington VA	**Countywide**	**01/19 1600 01/19 1900**	**0 / 0**	**$3,000**
Anne Arundel MD	**Countywide**	**01/19 1600 01/19 2000**	**0 / 0**	**$5,000**
Baltimore City MD	**Countywide**	**01/19 1600 01/19 2000**	**0 / 0**	**Not Reported**

Analysis of AMBER Output

Precipitation Estimates

As stated in the January "Monthly Report of River and Flood Conditions" (Hall, 1996) produced by the Sterling NWSFO, the radar underestimated precipitation for this event by at least 50%, and beam blockage occurred across some of the areas of higher rainfall. The Virginia IFLOWS and LARC tipping bucket rain gages were filled with snow from the preceding blizzard, rendering any precipitation measurements for the event of the 19th inaccurate.

ABR/FFG

ABR accumulations were not greater than or equal to FFG values in any of the counties where flash flooding was reported, and the FFG values were generally reasonable for this event (generally 1.5 to 2 inches for the 1-hour time interval). Thus, the most likely explanation for the failure to identify flash flooding is the significant volume of runoff contributed by snowmelt as well as the underestimation of precipitation by the radar.

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 0.5 inch/hour is shown in Table H1. Because the radar precipitation estimates for this event were low and because radar-derived rates of even 0.6 inch/hour were rare, a lower threshold rate than the 0.6 inch/hour used for the previous two case studies was used for this ABR rate analysis. The analysis indicated the potential for flash flooding in 38 of the 40 counties where it was reported in *Storm Data*, and also in four counties where it was not reported (Charles, Calvert, King George, and St Mary's). Figure H5 shows all Subdivision Basins where ABR rate equaled or exceeded 0.5 inch/hour.

Flash flooding was not indicated in two of the counties (Greene and Highland) where it was reported in *Storm Data*. As shown in Figure H5, several of the basins in these counties are relatively large and somewhat elongated. Larger basins have a greater likelihood of high rain rates being averaged out. Similarly, elongated basins have a greater chance of experiencing heavy rainfall in one area of the basin and little or no rainfall in the rest of the basin. This also serves to average out high rain rates.

In 34 of the 38 counties where ABR rates indicated flash flooding and it was verified in *Storm Data*, flash flood potential was identified by AMBER after the time it was reported. In the 38 counties where flash flooding was reported, ABR rate initially exceeded 0.5 inch/hour an average of 2 hours and 31 minutes after flash flooding was reported in *Storm Data*. This is because flash flooding was primarily induced by the rapid snowmelt. In most areas, flash flooding probably began as soon as the first raindrops fell on the melting snowpack, and, in many areas, flash flooding likely began prior to the rainfall.

Basin Size

ABR rate exceeded 0.5 inch/hour primarily in the Subdivision Basins rather than in the Primary, Major, or MAP Basins. As mentioned previously, in the two counties where flash flooding was reported in *Storm Data* but was not indicated by AMBER, many of the Subdivision Basins were relatively large and elongated. Larger basins require widespread high rainfall amounts to produce the same average rainfall rates and ABR accumulations as smaller basins. Significant precipitation rates and accumulations in smaller sub-basins may be overlooked if they are averaged over larger basin areas. This emphasizes the need for small basins when using the AMBER program as a tool for flash flood warning decisions.

Prediction Errors

As mentioned above, AMBER indicated flash flooding in four counties where it was not reported in *Storm Data*. These counties may have had less snow cover than the other counties in the CWA, and thus the rapid snowmelt would not have produced the large runoff volumes necessary to induce flash flooding. In addition, because these four counties are located on the coast, it is possible the flat terrain and soil types in these areas were more conducive to slower runoff, allowing greater infiltration of the snowmelt and precipitation.

Case Study #4 - July 1-2, 1997

Supporting data and figures for this case study are included in Appendix I.

Description of Rainfall Event

As reported in *Storm Data*, on the evening of July 1st, "back-building, nearly stationary showers and thunderstorms developed over a portion of the central Shenandoah Valley". These storms contained significant tropical moisture and persisted through the early morning hours of the 2nd. Rain gages reported up to 8 inches along the Rapidan River between Greene and Madison Counties, and general totals over the area ranged from 4 to 5 inches.

The dry antecedent conditions allowed more infiltration than normal to occur, and thus flash flooding was not as severe as it could have been. In Greene County and western Orange County, several creeks overspilled their banks and several roads were closed. Brief rises in creeks also caused a few roads to be closed in southern Madison County.

The KLWX 3-hour and storm total precipitation images for this event are shown in Figures I1 through I4, and a summary of the flash flooding reported is included in Table 10 below.

Table 10. Flash flooding associated with the July 1-2, 1997 event as reported in *Storm Data*.

County	Location	Date / Time (UTC)	Fatalities / Injuries	Estimated Damage
Greene VA	Countywide	07/02 0200 07/02 0530	0 / 0	$5,000
Madison VA	Southern Portion	07/02 0200 07/02 0530	0 / 0	Not Reported
Orange VA	Western Portion	07/02 0300 07/02 0700	0 / 0	$5,000

Analysis of AMBER Output

Precipitation Estimates

As stated in *Storm Data*, rain totals of up to 12 inches were reported with this event. General totals between 4 and 5 inches were reported by spotters, and one rain gage along the Rapidan River between Madison and Greene Counties reported 8 inches. The highest accumulations shown in the storm total precipitation image in Figure I4 occur in a thin strip along the Madison/Greene countyline. The surrounding totals are 2 inches or less, which is considerably lower than the 4- and 5 -inchgeneral totals reported by spotters. Thus, it is reasonable to conclude the radar precipitation estimates were low during this event.

ABR/FFG

FFG values were not available for this event.

ABR Rate

Based on the AMBER output, a summary of the first basin(s) in each county where ABR rate equaled or exceeded 0.6 inch/hour is shown in Table I1. Because the radar precipitation estimates for this event were low, a relatively low threshold rate was again used for the ABR rate analysis. This analysis indicated the potential for flash flooding in all three counties where it was reported in *Storm Data* (Table 10), and also in four counties where it was not reported (Fauquier, Stafford, Spotsylvania, and St. Mary's). Figure I5 shows all Subdivision Basins where ABR rate equaled or exceeded 0.6 inch/hour.

In two of the three counties where ABR rates indicated flash flooding and it was verified in *Storm Data*, flash flood potential was identified with a reasonable amount of lead time. ABR rate initially exceeded 0.6 inch/hour an average of 40 minutes before flash flooding was reported in the three counties as cited in *Storm Data*.

Basin Size

ABR rate exceeded 0.6 inch/hour primarily in the Subdivision Basins rather than in the Primary, Major, or MAP Basins. Larger basins require widespread high rainfall amounts to produce the same average rainfall rates and ABR accumulations as smaller basins. Significant precipitation rates and accumulations in smaller sub-basins may be overlooked if they are averaged over larger basin areas. This emphasizes the need for small basins when using the AMBER program as a tool for flash flood warning decisions.

Prediction Errors

Flash flooding was indicated by AMBER in four counties where it was not reported. Figure I6 shows Warrenton and Leonardtown are the only towns located in or near the "flooded" basins in these counties, and both are relatively small. In addition, both are located near watershed divides, which means the likelihood of flash flooding occurring in Warrenton and Leonardtown is less than in the lower-lying areas of these basins. Therefore, it is possible flash flooding may have occurred in portions of the "flooded" basins in these four counties and was simply not observed or reported.

Another possible cause for the false alarms in these four counties was the dry weather preceding the storm. This dry spell allowed the ground to absorb more water than usual, thus lessening the impact of flooding. Under normal conditions, AMBER's indication of flash flooding in the four additional counties may have been accurate, but flash flood potential was apparently diminished by the antecedent moisture conditions. Again, this illustrates the need for knowledge of other hydrologic factors when using output from AMBER.

Results and Discussion

A summary of the flash flood prediction for each of the nine case studies is shown in Table 11 below. Both the predictions based on ABR rate and those based on ABR accumulation versus FFG value are included. The number of hits in column (d) indicate those counties where flash flooding was predicted by AMBER before the time at which it was reported in *Storm Data*. If flash flooding was predicted after the time at which it was reported in *Storm Data*, it was counted as a miss in column (c). The false alarms in column (b) indicate counties where AMBER predicted flash flooding but it was not verified in *Storm Data*. It is important to be aware of the difficulties in flash flood verification and to acknowledge that the accuracy of flash flood report times can vary from event to event. In addition, flash floods often occur in areas where no one is there to report it. It is important to remember these limitations when interpreting the case study results.

Table 11. Summary of flash flood prediction (by county) based on AMBER output for each of the nine case studies.

Storm Event	**(a) null predicted as null**	**(b) null predicted as event (false alarm)**	**(c) event not predicted (miss)**	**(d) event predicted (hit)**
Tulsa (ABR Rate)				
01/04/98	**20**	**7**	**0**	**2**
09/14/98	**22**	**1**	**1**	**5**
10/05/98	**13**	**3**	**3**	**10**
04/25/99	**16**	**3**	**5**	**5**
06/20/99	**24**	**0**	**3**	**2**
Sterling (ABR Rate)				
06/27/95	**28**	**3**	**3**	**10**
10/21/95	**15**	**22**	**1**	**6**
01/19/96	**0**	**4**	**36**	**4**
07/02/97	**37**	**4**	**1**	**2**
Tulsa (ABR ≥ FFG)				
01/04/98	**22**	**5**	**2**	**0**
10/05/98	**16**	**0**	**11**	**2**
04/25/99	**16**	**3**	**7**	**3**
06/20/99	**22**	**2**	**1**	**4**
Sterling (ABR ≥ FFG)				
06/27/95	**31**	**0**	**13**	**0**

For each of the nine case studies in this evaluation, the probability of detection (POD), false alarm ratio (FAR), and critical skill index (CSI) were calculated from AMBER results based on both ABR rate (Table 12) and ABR accumulation versus FFG value (Table 13). These values were calculated from the values in Table 11 as shown below:

$$\mathbf{POD} = \frac{\mathbf{hits}}{\mathbf{misses + hits}} = \frac{\mathbf{d}}{\mathbf{c + d}}$$

$$\mathbf{FAR} = \frac{\mathbf{false\ alarms}}{\mathbf{false\ alarms + hits}} = \frac{\mathbf{b}}{\mathbf{b + d}}$$

$$\mathbf{CSI} = \frac{\mathbf{hits}}{\mathbf{false\ alarms + misses + hits}} = \frac{\mathbf{d}}{\mathbf{b + c + d}}$$

Table 12. Probability of detection, false alarm ratio, and critical success index based on ABR rate.

Storm Event	**POD**	**FAR**	**CSI**	**Time in hours from occurrence of first significant ABR rate to flash flooding as reported in *Storm Data***
Tulsa (ABR Rate)				
01/04/98	**1.00**	**0.78**	**0.22**	**2.50**
09/14/98	**0.83**	**0.17**	**0.71**	**1.36**
10/05/98	**0.77**	**0.23**	**0.63**	**1.27**
04/25/99	**0.50**	**0.38**	**0.38**	**1.87**
06/20/99	**0.40**	**0.00**	**0.40**	**0.61**
Average	**0.70**	**0.31**	**0.47**	**1.52**
Sterling (ABR Rate)				
06/27/95	**0.77**	**0.23**	**0.63**	**3.90**
10/21/95	**0.86**	**0.79**	**0.21**	**1.57**
01/19/96	**0.10**	**0.50**	**0.09**	**-2.51**
07/02/97	**0.67**	**0.67**	**0.29**	**0.67**
Average	**0.60**	**0.55**	**0.31**	**0.91**
Average (excluding 01/19/96)	**0.77**	**0.56**	**0.38**	**2.05**

The average statistics shown above for the Tulsa and Sterling CWAs based on ABR rate alone are reasonable considering the completely objective nature of this evaluation. These numbers would likely be improved upon in an operational setting with forecasters who are familiar with the specific flash flood problems of these CWAs and the limitations of the radar-derived precipitation estimates.

It is interesting to note the two Tulsa events with the lowest PODs based on ABR rate were those occurring in the spring and summer. Overall, the lowest POD based on ABR rate was associated with the Sterling event of 01/19/96. This is also the only event where the average time from the occurrence of the first significant ABR rate to flash flooding as reported in Storm Data is negative. As mentioned in the case study, this flash flood event was primarily a result of snowmelt and, therefore, could not be predicted in a timely manner by AMBER output alone. Omitting this event from the calculation of average statistics, the POD and CSI for the Sterling case studies are closer to those for the Tulsa case studies.

Table 13. Probability of detection, false alarm ratio, and critical success index based on ABR accumulation versus FFG value.

Storm Event	**POD**	**FAR**	**CSI**	**Time in hours from the point at which ABR accumulation ≥ FFG value to flash flooding as reported in *Storm Data***
Tulsa (ABR ≥ FFG)				
01/04/98	**0.00**	**1.00**	**0.00**	**-0.42**
10/05/98	**0.15**	**0.00**	**0.15**	**-2.35**
04/25/99	**0.30**	**0.50**	**0.23**	**-1.48**
06/20/99	**0.80**	**0.33**	**0.57**	**0.65**
Average	**0.31**	**0.46**	**0.24**	**-0.90**
Sterling (ABR ≥ FFG)				
06/27/95	**0.00**	**0.00**	**0.00**	**-4.56**

Because a tropical Z-R relationship should have been used for the Tulsa event of 09/14/98, AMBER output did not yield any results when comparing ABR accumulation to FFG value. Thus, statistics for this case study were not computed. In addition, because the KLWX precipitation estimates were generally low for each of the Sterling case studies, AMBER output did not yield results for three of the four events. Statistics for these three Sterling cases were not computed.

The average POD and CSI for the Tulsa storm events were low, and the only event with reasonable statistics and a positive lead time was that of 06/20/99. The average lead time for the Tulsa events and the lead time for the one Sterling event in which ABR accumulation exceeded FFG value were negative. This indicates the comparison of ABR accumulation to FFG value is not always a reliable way to determine flash flood potential. In particular, it does not provide a timely assessment of the situation. By the time ABR accumulation exceeds FFG value, flash flooding has likely already commenced.

Conclusions and Recommendations

Conclusions

Precipitation Estimates

AMBER output is only as reliable as the radar precipitation estimates upon which it is based. The forecasters in each office are aware of the limitations of their radar-derived precipitation estimates, and it is important to understand these limitations translate into limitations in AMBER output.

ABR/FFG

The comparison of ABR accumulations to FFG values almost invariably resulted in fewer "hits" than when ABR rates were used as the determining criteria. Although occasionally they might have been considered slightly high, in general FFG values were reasonable for both the Tulsa and Sterling CWAs. However, underestimation of precipitation by the KLWX radar rendered the comparison of ABR accumulations to FFG useless in the Sterling CWA. In the Tulsa CWA, the comparison of ABR accumulations to FFG was generally useful in determining where flash flooding was occurring, but was not useful in determining this information with adequate lead time to produce warnings.

The applicability of county FFG values to any flash flood basin within that county is debatable given varying basin sizes and characteristics. The work currently underway at the Office of Hydrology to improve threshold runoff values for both local and accumulated basin areas will in turn improve the FFG products issued. Theoretically, FFG values computed individually for each of the flash flood basins in AMBER would provide the best guidance to the forecaster. However, it is still uncertain whether using such a basin-centric FFG product in AMBER for ABR/FFG comparisons would provide adequate lead time to produce timely warnings.

ABR Rate

Comparing ABR rate to a threshold rate generally resulted in identification of the areas where flash flood potential was greatest during the nine storm events. Significant ABR rates generally occur prior to significant accumulations, which means using rate as the determining criteria generally provides information on flash flood potential with adequate lead time to produce warnings. In addition, in cases where the radar-derived precipitation estimates are too low or too high, it is difficult to make comparisons of ABR accumulations to FFG, but it is always possible to examine the relative ABR rates among basins to determine the areas of highest flash flood potential.

It is important to note the threshold rate will vary according to basin size, terrain, location, radar performance, type of storm event, antecedent moisture conditions, and the time of year. The ABR rate necessary to produce flash flooding in a 2-mi^2 basin will generally be greater than the rate necessary to produce flash flooding in a 10-mi^2 basin. Generally, a higher ABR rate will be needed to produce flash flooding in a flat basin where the rainfall has more time to infiltrate than in a basin with steep terrain where most of the rainfall becomes runoff before it has a chance to infiltrate. These and many other hydrologic factors affect the threshold rates, and additional information on basin terrain, infiltration properties, and moisture conditions would help to establish more meaningful threshold rates. The staff at each office will develop improved threshold rates as they become more familiar with the AMBER algorithm and as more basin information is available.

Basin Size

In each of the nine case studies, AMBER output was the most reliable and timely when computed for the Subdivision Basins. In several cases, it was suspected that further division of the Subdivision Basins would have significantly improved the results. While computation of ABR accumulations and rates for the Primary, Major, and MAP Basins may provide useful information for some applications, they provide little or no benefit to flash flood forecasting.

Prediction Errors

One of the most frequent problems encountered using the AMBER algorithm was over-prediction. Many of the false alarms would likely have been eliminated by forecasters from the Tulsa and Sterling offices who are more familiar with the terrain, specific flash flooding problems, and limitations of the radar precipitation estimates. However, it is impossible to eliminate entirely the false alarms associated with flash flooding. Flash flood verification is a difficult task which becomes nearly impossible in sparsely populated areas. These difficulties in verification make false alarms an inevitable part of flash flood forecasting.

Recommendations

Based on the results of this evaluation, the following are recommended:

1) It is essential to be able to examine not only the ABR accumulations over time, but also the ABR rates over time. ABR rates are actually more indicative of flash flood potential in a timely manner than are ABR accumulations.

2) The accuracy of FFG values varies from office to office, as does the accuracy of radar-derived precipitation estimates. The staff at each office is aware of these limitations, but they must be sure to acknowledge these will translate into limitations in the AMBER output. These factors reiterate the need for a time series of ABR rate for each basin as stated in the first recommendation.

3) Basins should at least be delineated to a similar level as the current Subdivision Basins in Sterling and Tulsa, and smaller basins are recommended. The current NWS mandate for basins delineated using a minimum drainage area threshold of 2 mi^2 will more than satisfy this need.

4) The determination of meaningful threshold accumulations and rates and, in turn, the reliability of forecasts based on AMBER output could be significantly improved with additional hydrologic information such as basin terrain, infiltration characteristics, and antecedent moisture conditions.

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