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An AMBER Playback of the Tennessee Flash Flood of May 2010: Contributions of Tropical Rain

Robert S. Davis, Pittsburgh NWS, NOAA

1.0 INTRODUCTION

The robust playback mode of the Areal Mean Basin Estimated Rainfall (AMBER) program, (Davis and Jendrowski 1996) was used to replay the devastating flash floods in Greater Nashville on May 1-2, 2010. The purpose of the playback is to determine if tropical rainfall rates contributed to the extreme rainfall accumulations of 18 to 20 inches that caused the flash flooding. If tropical rainfall rates occur, the flash flood detection capability of the Flash Flood Monitoring and Prediction (FFMP) can be critically impacted, unless tropical ZR is manually selected on the WSR-88D radar (Davis 2004a). The FFMP software, used by all National Weather Service offices for flash flood detection, is based on the AMBER software originated and used operationally at the Pittsburgh NWS office from 1990 to present (Davis and Drzal 1991).

The playback was accomplished for both the Convective ZR ($Z = 300R^{1.4}$) and the Tropical ZR ($Z = 250R^{1.2}$), the two primary Convective ZR relationships used by the WSR-88D precipitation algorithms. The occurrence of Tropical ZR was determined by comparing radar/gage pairs in or near watersheds impacted by the severe flooding in Greater Nashville. FFMP Average Basin Rainfall (ABR) displays for those Nashville watersheds were used to demonstrate the flash flood detection capability of FFMP for both Tropical ZR and Convective ZR.

2.0 ANTICIPATING TROPICAL RAINFALL

Upper air sounding analysis is critical to determining if tropical rainfall rates may occur (Davis 2001). The two best indicators are high values of precipitable water (PW) and a deep warm rain coalescence layer. The NWS service assessment (National Weather Service 2011) shows that the PW values (Fig.1) were at near seasonal record levels for both May 1st and May 2nd, 2010.

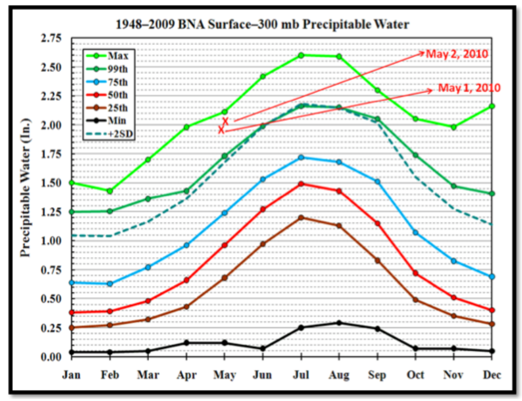


Fig.1. Seasonal precipitable water climatology for Nashville, TN. Any value over 1.70 inches is in the 99th percentile for the first two days of May, 2010.

Figures 2-6 show the series of soundings for Nashville from the evening before the heavy rainfall began (00 UTC on May 1, 2010 through the end of the heavy rainfall (00 UTC on May 3, 2010). Tropical rainfall rates can be easily anticipated within the confines of a tropical storm. However, if no tropical storms are present, the observed or forecast soundings are the most valuable tool available to determine the potential occurrence of tropical rainfall processes. In the initial sounding (Fig. 2) the PW has climbed above one inch, but the sounding

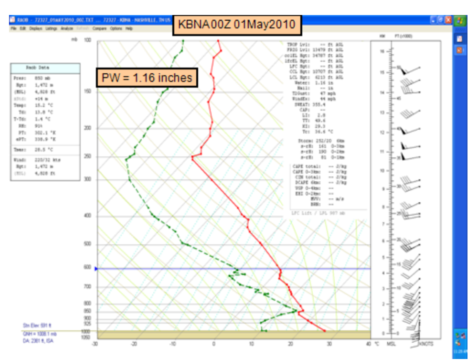


Fig. 2. Nashville, TN sounding for 00 UTC on May 1, 2010.

Corresponding author address: Robert S. Davis, NOAA/National Weather Service 192 Shafer Road, Moon Twp, PA 15108, Email: Robert.Davis@noaa.gov

had not become saturated though a deep layer. Looking at the sounding twelve hours later (Fig. 3) the air column had saturated through 600 mb, PWs have risen to nearly two inches, and with a narrow cape profile the sounding suggests that tropical ZR rates associated with warm rain coalescence is a real possibility.

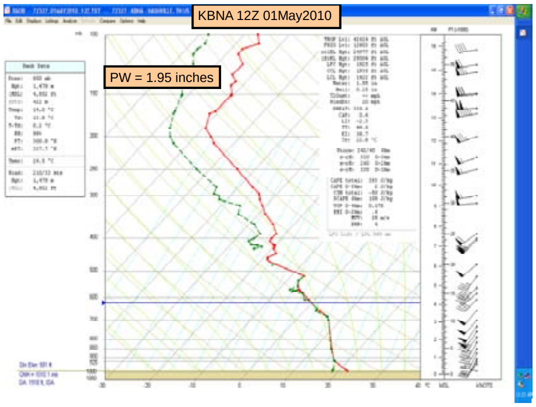


Fig. 3. Nashville, TN sounding for 12 UTC on May 1, 2010.

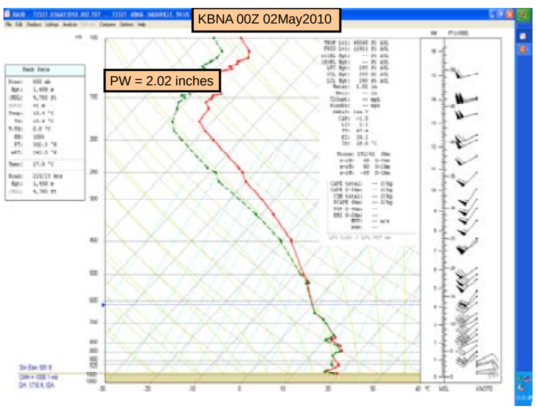


Fig. 4. Nashville, TN sounding for 00 UTC on May 2, 2010.

Twelve hours later the sounding at 00 UTC on May 2, 2010 (Fig. 4) the PWs have topped two inches and with a continued narrow cape profile persisting, making warm rain processes a good possibility. One unusual aspect of these soundings, not usually associated with flash flooding, is the strong winds and the resulting high cell training speeds. Strong winds aloft and a significant shear structure are more often associated with severe thunderstorms or tornadoes, than with flash flooding. High cell training speeds do not rule out flash flooding. The occurrence of tropical rainfall rates along with high cell training speeds persisting over the same watersheds can result in heavy rainfall spread over a relatively large area. This can lead to flash flooding on large watersheds (100 to 500 mi^2 in area) and may even lead to severe river flooding as occurred in Johnstown, PA in 1977, and in the Redbank Creek near Saint Charles, PA in 1996 (Davis 2001 and Davis 2004). The occurrence of Tropical ZR results in higher ABR over larger areas than with Convective ZR rates (Davis 2001).

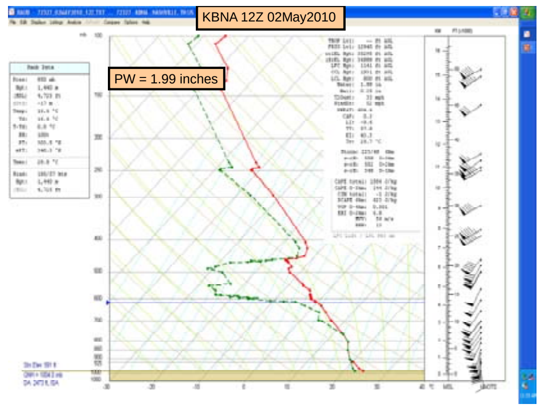


Fig. 5. Nashville, TN sounding for 12 UTC on May 2, 2010.

The soundings for May 2-3, 2010 of the Nashville flash flood event (Figs. 5-6) show continued support for tropical rainfall rates. Both soundings show high PWs, narrow cape profiles through the warm rain coalescence layer, and saturated moisture profiles through 600 mb.

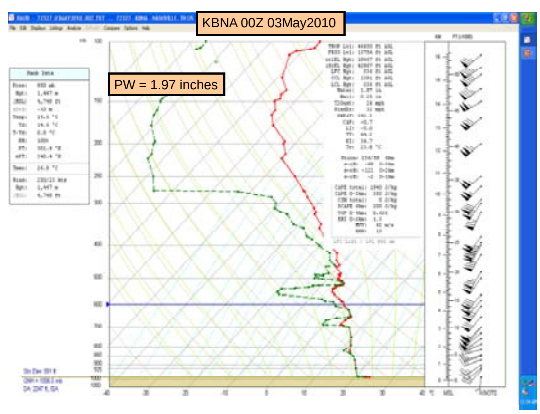


Fig. 6. Nashville, TN sounding for 00 UTC on May 3, 2010.

The only reliable way to verify Tropical ZR occurrence in real time is to do radar/gage comparisons, when real time gage data is available.

3.0 STORM TOTAL RAINFALL ESTIMATE

"How much rain fell?" is usually the first question asked when putting together a flash flood case study. And the second question is, "What was the time duration of the heavy rainfall?" On page 8 of the Nashville service assessment (National Weather Service 2011), maps of the multi-sensor precipitation estimate (MPE) were used to represent the storm total for the Nashville event. MPE makes a nice composite picture of rainfall from multiple

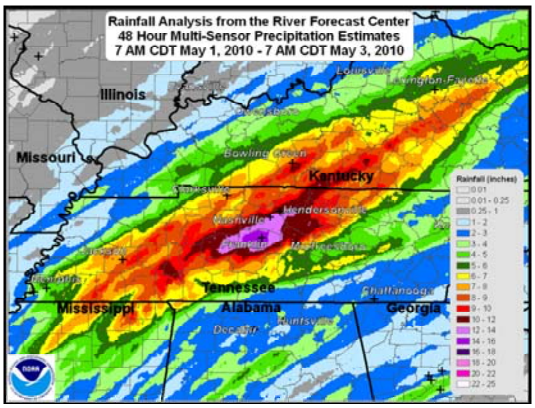


Fig. 7. MPE rainfall (in.) estimate for the Nashville Flood event.

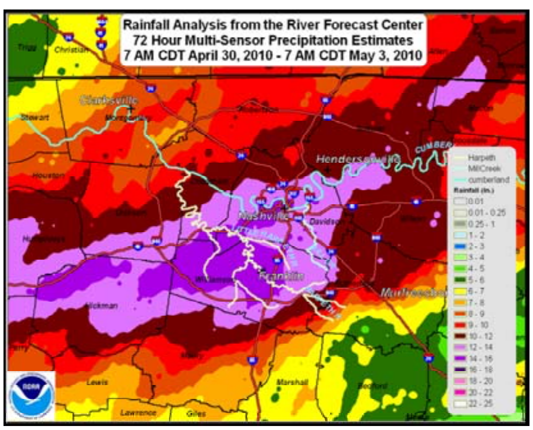


Fig. 8. MPE rainfall (in.) estimate for the Greater Nashville area.

radars, but the 4km grid of the MPE data is too coarse for most flash flood applications (Davis and Drzal 1991). For this reason, FFMP does not use MPE as input, but uses the more detailed Digital Hybrid Scan Reflectivity product to compute rainfall each volume scan in small watersheds. FFMP can use either Tropical and Standard ZR, depending on which adaptable parameter is manually selected on the WSR-88D.

Figure 9 shows the AMBER/FFMP basins for the NWS Nashville, TN county warning area using Convective ZR.

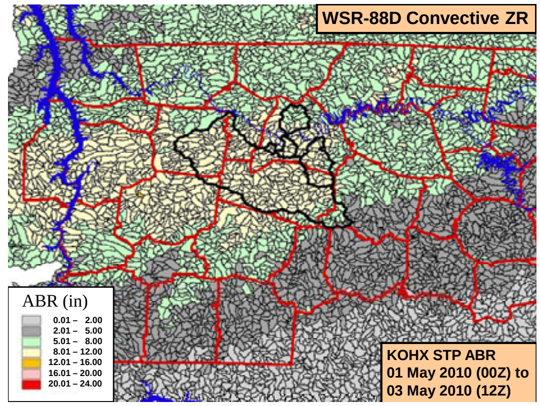


Fig. 9. AMBER ABR for the Nashville Flood event using Convective ZR.
Heavy black lines show the five watersheds where fatalities occurred near Nashville.

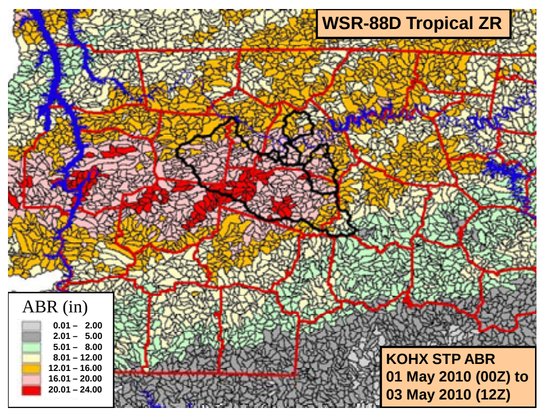


Fig. 10. AMBER ABR for the Nashville Flood event using Tropical ZR.
Heavy black lines show the five watersheds where fatalities occurred near Nashville.

The AMBER/FFMP displays of Figs 9-10 show Average Basin Rainfall (ABR) in each of the small FFMP basins with the thin black line boundaries. FFMP uses these small watersheds to detect flash floods on basins down to 2 mi^2 in area. Notice the white stream channels in Fig. 8 show the Harpeth River, while the largest watershed with the heavy black lines in Figs. 9-10 shows the ridge-line boundary of the same Harpeth River watershed. Is Fig. 9 or Fig. 10 closer to the actual rainfall that fell near Nashville?

Prior to the WSR-88D radar rainfall era, service assessment storm total rainfall was almost exclusively generated from a rain gage rainfall extrapolation. Figure 11 shows the rain gage analysis for the Nashville event and is available on line at: http://www.srh.noaa.gov/news/display_cmsstory.php?wfo=ohx&storyid=51806&source=0

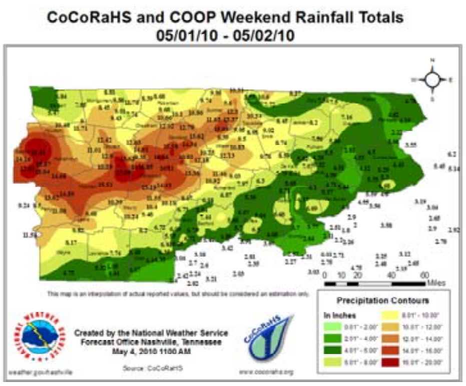


Fig. 11. Rain gage analysis for the County Warning Area of the Nashville NWSFO for May 1-2, 2010.

A rain gage only analysis will seldom catch the rainfall maxima that occur in any heavy rain event. FFMP computes radar rainfall estimates at the location of every rain gage location contained in the hydrology data base of each NWS forecast office. The FFMP gage/radar comparison can be invaluable in determining if tropical ZR is occurring in real time. Later in the paper radar/gage comparisons are shown for specific basins near the city of Nashville.

4.0 AVERAGE BASIN RAINFALL (ABR)

By definition, the time scale of flash floods must occur in a six hour time duration or less, from the start of the heavy rainfall surge to the initiation of flooding. Looking at shorter time durations, Figures 12-20 show the ABR in discrete six hour time intervals from 00 UTC on May 1, 2010 to 06 UTC on May 3, 2010.

The series of figures reveals that two surges of heavy rainfall occurred during the flash flood event. The first surge of rainfall started on May 1, 2010 before daybreak (Fig. 13) and spread from the western portion of the county warning area east into the Mill Creek watershed south of Nashville by afternoon (Fig. 14). The pattern of the rainfall in Figs. 13-14 suggests the heavy rain spread from west to east along an east-west boundary with strong southwest winds overrunning the boundary. Some of the heaviest rain near Nashville fell from 18 UTC to 00 UTC, just south of the city in the headwaters of the Mill Creek basin (Fig. 15). The second bout of heavy rain occurred on May 2, 2010 as a frontal boundary oriented from northeast to southwest moved from west to east across the county warning area (Fig. 16-19). The bold red lines in Figs. 12-19 show the county warning area (CWA) of Nashville NWS. The thin red lines are counties outside of the Nashville NWS CWA.

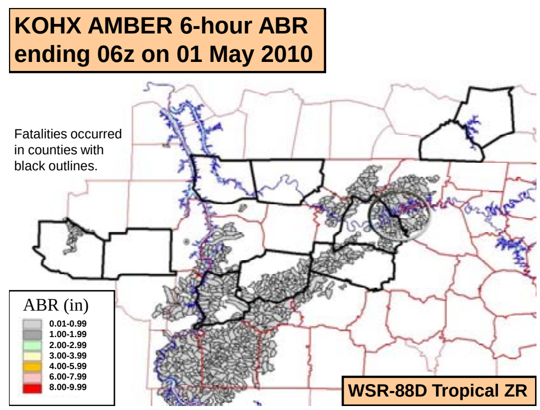


Fig. 12. AMBER 6-hour ABR ending at 06 UTC on May 1, 2010. Gray circle is the 20km range ring from the KOHX WSR-88D.

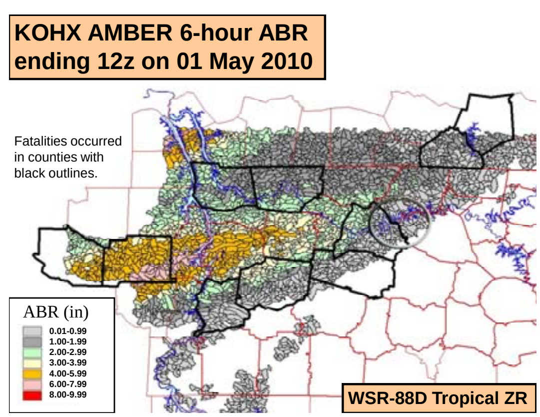


Fig. 13. AMBER 6-hour ABR ending at 12 UTC on May 1, 2010.

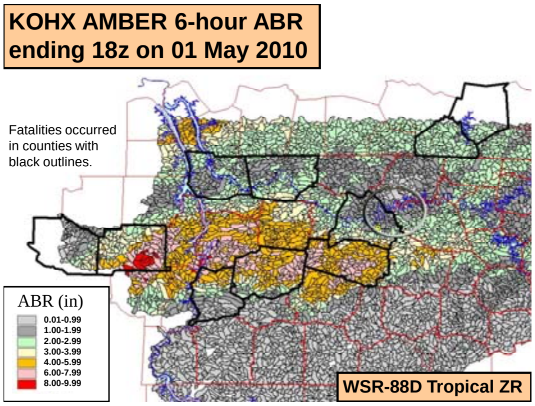


Fig. 14. AMBER 6-hour ABR ending at 18 UTC on May 1, 2010.

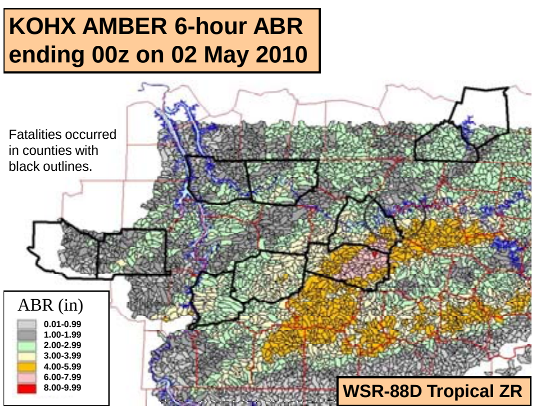


Fig. 15. AMBER 6-hour ABR ending at 00 UTC on May 2, 2010.

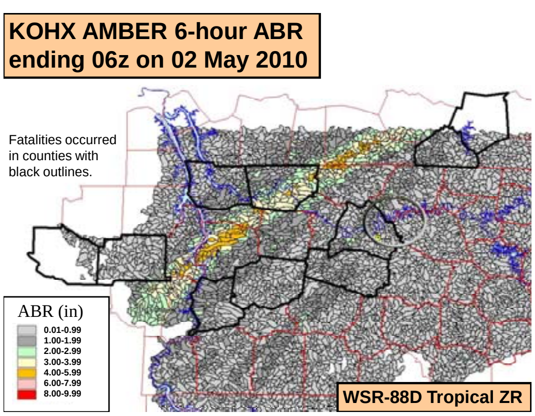


Fig. 16. AMBER 6-hour ABR ending at 06 UTC on May 2, 2010.

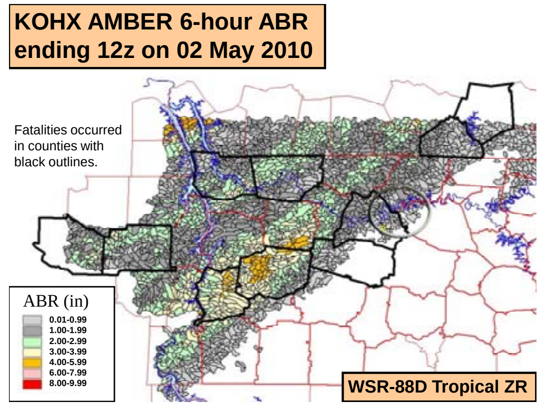


Fig. 17. AMBER 6-hour ABR ending at 12 UTC on May 2, 2010.

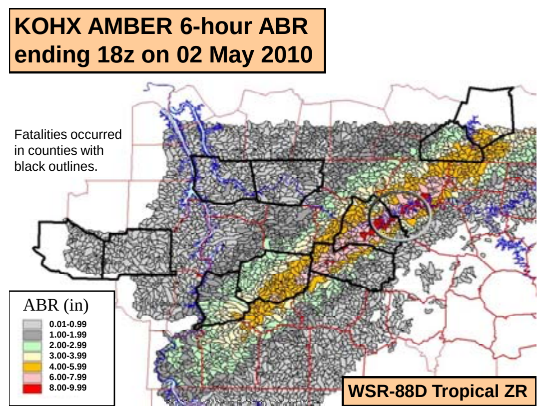


Fig. 18. AMBER 6-hour ABR ending at 18 UTC on May 2, 2010.

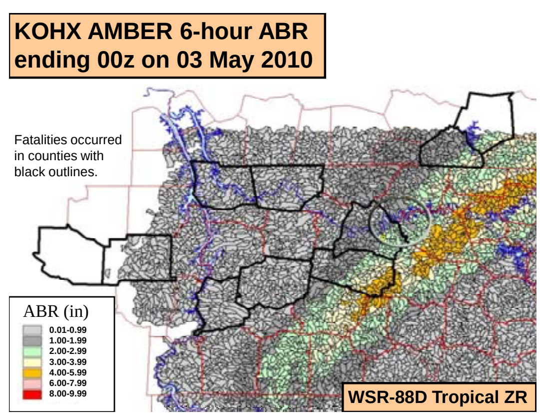


Fig. 19. AMBER 6-hour ABR ending at 00 UTC on May 3, 2010.

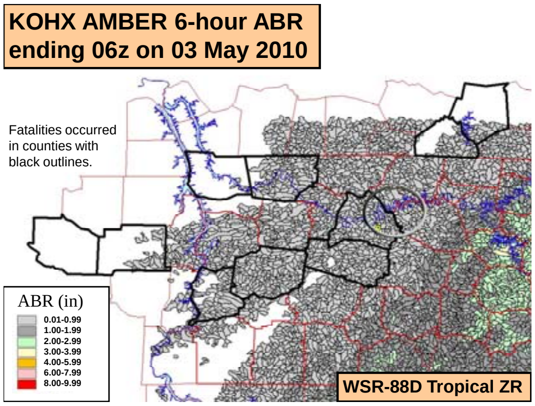


Fig. 20. AMBER 6-hour ABR ending at 06 UTC on May 3, 2010. Gray circle is the 20km range ring from the KOHX WSR-88D.

On May 2, 2010 the six hours of rainfall with the greatest impact on the Nashville watersheds was from 12 UTC to 18 UTC (Fig. 18). By 00 UTC on May 3, 2010 , the heavy rainfall event on was over and had pushed east of Nashville (Fig. 20).

5.0 Location of Fatalities

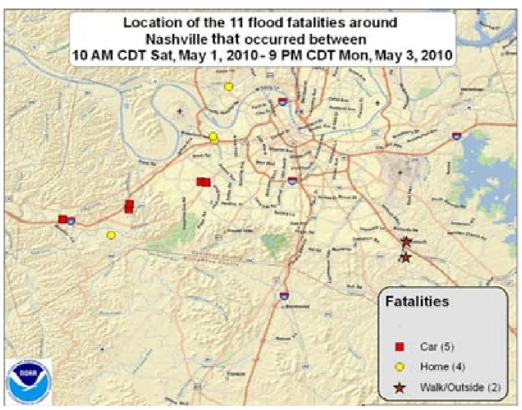


Fig. 21. Location of Nashville fatalities from the Service Assessment, National Weather Service (2011).

The first step in any flash flood case study is to identify the specific location of the flooding. The map in Fig. 21 from the service assessment, National Weather Service (2011), shows the location of each fatality. The table in the service assessment associated with the above map is show in Fig. 22. The red numbers have been added to the table as a reference, and information relating the fatalities to the AMBER/FFMP watersheds has been added above the table in Fig. 22. The watershed information includes the stream name, AMBER_ID of the stream segment, upstream area that contributed runoff to the flooding, and closest rain gages with an impact on each watershed.

Watersheds for the Flash Flood Fatalities near Nashville

Fatality#	AMBER_ID	Steam Name	Upstream area in mi^2	Rain Gages
1	15048	Mill Creek	53.0	20032, 21007, 21009
2	14980	Harpeth River	428.1	20032, 20316, 20110
3	13919	Richland Creek	13.4	21004, 21010
4	13919	Richland Creek	13.4	21004, 21010
5	14163	Overall Creek	1.1	20316
6	14163	Overall Creek	1.1	20316
7	13922	Whites Creek	53.3	20116
8	16704	Mill Creek	62.2	20032, 21007, 21009
9	16696	Harpeth River	421.1	20032, 20316, 20110
10	13919	Richland Creek	28.3	21004, 21010
11	13919	Richland Creek	28.3	21004, 21010

Flood Fatalities

Date and Time	Location	Sex	Age	Activity
5/01 200 p.m. #1	Blue Hole Rd @ Bell Rd	M	21	In flood water
5/01 1000 p.m. #2	Harpeth River	M	39	Vehicle
5/02 930 a.m. #3	Near Richland Ck @ Harding	M	70	Fleeing vehicle
5/02 930 a.m. #4	Near Richland Ck @ Harding	F	65	Fleeing Vehicle
5/02 930 a.m. #5	Sawyer Brown Rd	M	88	Vehicle
5/02 930 a.m. #6	Sawyer Brown Rd	F	78	Vehicle
5/02 1000 a.m. #7	West Hamilton Ave.	M	75	yard at home
5/02 1000 a.m. #8	Mill Creek	M	18	Tubing
5/02 1030 a.m. #9	Sawyer Brown Rd	M	86	In home
5/02 1100 a.m. #10	Delray Rd.	M	78	In home
5/02 1100 a.m. #11	Delray Rd.	F	80	In home

Fig. 22. Table from the service assessment with location of Nashville fatalities (National Weather Service 2011). Red numbers added to the table will be used to locate fatalities on watershed maps. Additional AMBER information relating the location of the fatalities to the small stream network is shown above the original table.

To see the details of the flash flooding that occurred near Greater Nashville, we must move downscale in both space and time. Figure 23 shows the five watersheds with fatalities near Nashville. ABR in each of these watersheds will be examined in detail.

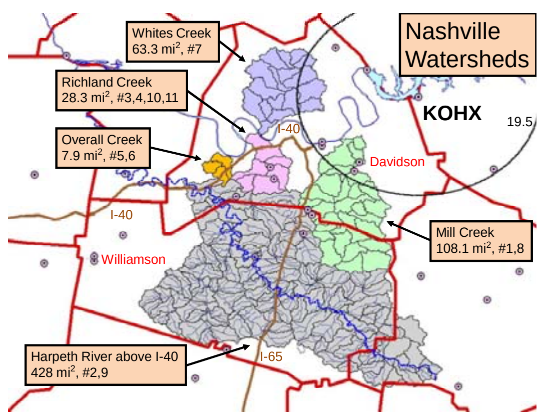


Fig. 23. Nashville watersheds where fatalities occurred on May 1-2, 2010. Gray circle is the 20km range ring from the KOHX WSR-88D.

6.0 SUMMARY OF MAY 1, 2010 RAINFALL

Did tropical rainfall rates occur during the May 1, 2010 rainfall events? Figure 24 shows the graphicast issued by the NWS office in Nashville at 1023 PM (0330 UTC) on the evening of May 1, 2010.

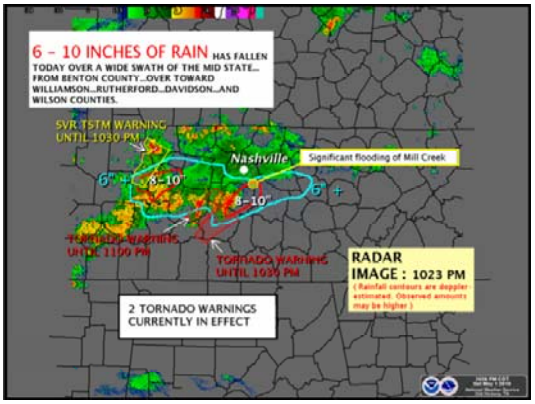


Fig. 24. Graphicast issued by the NWS office in Nashville at 0330 UTC on May 2, 2010. Blue line shows the radar rainfall estimate for the KOHX WSR-88D.

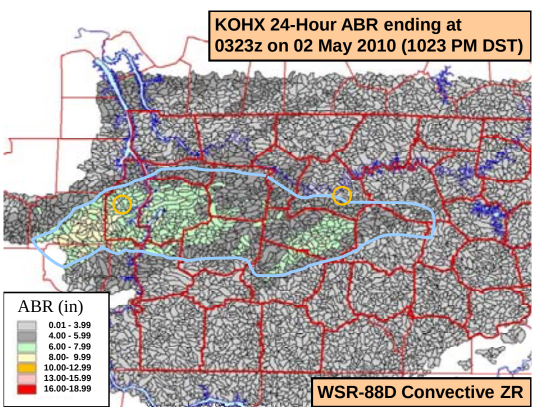


Fig. 25. AMBER ABR for 24 hours ending at 0323 UTC (1023PM) using Standard ZR. Blue line shows the 6 inch isopleths from Fig. 24. Small orange circles locate the Camden Coop rain gage to the west and the Nashville Airport rain gage to the east.

Compare Fig. 24 with Fig. 25. Note that the light green color in Fig 25 is the 6 to 8 inch radar rainfall estimate and corresponds well with the 6 inch isohyet in Fig. 24. The yellow shaded area of 8 to 10 inches is in good agreement with the 8-10 inch red isohyets.

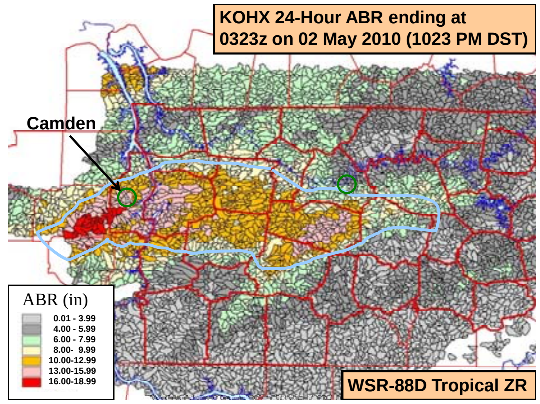


Fig. 26. AMBER ABR for 24 hours ending at 0323 UTC (1023PM) using Tropical ZR. Blue line shows the 6 inch isopleths from Fig. 24. Green circle at the black arrow shows the location of the Camden cooperative observer.

In Fig. 26 the Tropical ZR estimates show a widespread area of 10 inches or more of rain, in line with the blue isohyet of Fig. 25. It appears for May 1, 2010 that the KOHX WSR-88D was operating in Standard ZR as indicated by the 6- inch rainfall area of Fig. 24**.** The Operational ZR of the WSR-88D is a user selectable parameter of the radar. The rainfall products of the WSR-88D and the rainfall computations of FFMP are determined by which ZR is selected on the WSR-88D. If Convective ZR is selected, the FFMP display will appear like the rainfall in Fig. 25. If Tropical ZR is selected on the WSR-88D, then the rainfall display will appear like the rainfall in Fig. 26. Changing from Convective ZR to Tropical ZR in the middle of an event, say at 18 UTC on May 1, 2010, does not allow FFMP to go back and compute Tropical ZR prior to 18 UTC. Tropical ZR computation would only occur from 18 UTC and forward in time.

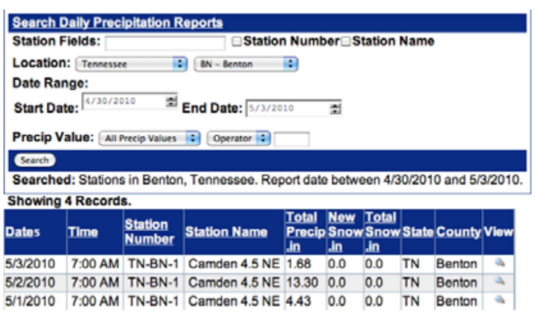
The NWS offices will routinely switch to Tropical ZR when a tropical storm impacts their forecast area. The occurrence of Tropical ZR outside of tropical storms occurs infrequently north of the Gulf Coast states and is difficult to determine in real time. However, when Tropical ZR does occur, serious flash flooding can result (Davis 2004).

There are several possible solutions to this problem with FFMP. One solution is to maintain two parallel databases of ABR, one with Tropical ZR and the second with Convective ZR with both datasets available at all times. A second solution is to determine ZR on the fly using a more refined radar rainfall analysis with Dual-polarization techniques: www.wdtb.noaa.gov/courses/dualpol/outreach/ or the vertical reflectivity structure analysis of the NMQ Q2 project: http://www.nssl.noaa.gov/projects/q2/.

Both of these new rainfall computation methods should be compared to the legacy Convective and Tropical ZR procedures to determine their operational utility for real-time flash flood events.

The rainfall estimates for Figs. 24 - 26 are all radar estimates with no rain gage comparisons. To see if Tropical ZR is occurring, the rainfall estimates should be compared with real time rain gages.

Fig. 27 shows the gage measurement by the Camden, TN observer available from: http://cocorahs.org/ViewData/ListDailyPrecipReports.aspx.



Search Daily Precipitation Reports

Station Fields: ☐Station Number ☐Station Name

Location: Tennessee | BN – Benton

Date Range:

Start Date: 4/30/2010 End Date: 5/3/2010

Precip Value: All Precip Values | Operator

Search

Searched: Stations in Benton, Tennessee. Report date between 4/30/2010 and 5/3/2010.

Showing 4 Records.

Dates	Time	Station Number	Station Name	Total Precip .in	New Snow .in	Total Snow .in	State	County	View
5/3/2010	7:00 AM	TN-BN-1	Camden 4.5 NE	1.68	0.0	0.0	TN	Benton	
5/2/2010	7:00 AM	TN-BN-1	Camden 4.5 NE	13.30	0.0	0.0	TN	Benton	
5/1/2010	7:00 AM	TN-BN-1	Camden 4.5 NE	4.43	0.0	0.0	TN	Benton	

Fig. 27. Camden Cocorahs observations for May 1-3, 2010.

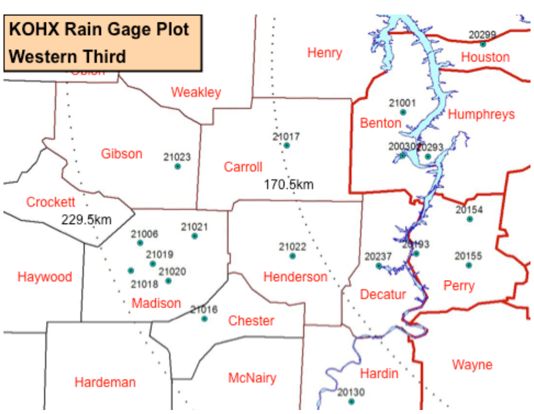


Fig. 28. Rain gage locations west of KOHX. Radar range rings for 170.5 and 229.5 km.

Fig. 25 shows the location of rain gages in Tennessee Counties west of the KOHX radar. Radar rainfall estimates can be relied on to locate the heavy rainfall in space and to accurately define the time duration of the rain. The absolute value of the rainfall estimate can be impacted by many variables. One of the biggest impacts on accurate radar rainfall estimates is radar range. A hydrologic range of about 150 km is where a reduction in rainfall estimates due to lack of beam filling occurs. If tropical ZR is occurring the hydrologic range may be reduced to 120 km as the higher reflectivity tends to be concentrated in the lower layers.

Looking at the radar estimates for Camden in Fig. 29, the gage total of 19.41 inches for the event compares to the tropical ZR amount of 15.59 inches compared to the Standard ZR amount of 8.37 inches. The Tropical ZR estimate for 12 UTC on May 1st of 5.33 inches compares to the gage report of 4.43 inches. This measurement will be very sensitive to the exact time the rain was measured as heavy rain was occurring at between 6AM and 7AM. The rainfall depicted at 1023 PM (0337 UTC on May 2nd) in Fig. 24, the estimated rain gage reading for that time (using 80 percent of the total) would be 15.53 inches, while the radar estimate was 12.58 inches (which was 80 percent of the Tropical ZR storm total). This gage comparison is a pretty strong indicator that warm rain processes that support Tropical ZR were occurring. Was Tropical ZR occurring further east near Nashville?

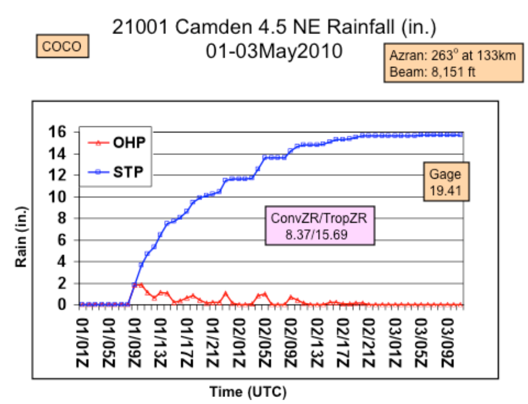


Fig. 29. Tropical ZR rainfall estimate for the Camden Cooperative observer. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP).

7.0 MAY 1, 2010 WATERSHEDS

The following sections will look at the individual watersheds where fatalities occurred on May 1, 2010 and then on May 2, 2010. ABR of Tropical ZR and Convective ZR will be compared to rain gages in or near those watersheds.

7.1 Mill Creek Watershed

The first fatality on May 1, 2010 occurred in the Mill Creek watershed shown in Fig. 23. While then entire Mill Creek watershed is over 100 mi^2, the fatality was upstream of Interstate 24 in FFMP basin 15048. Using

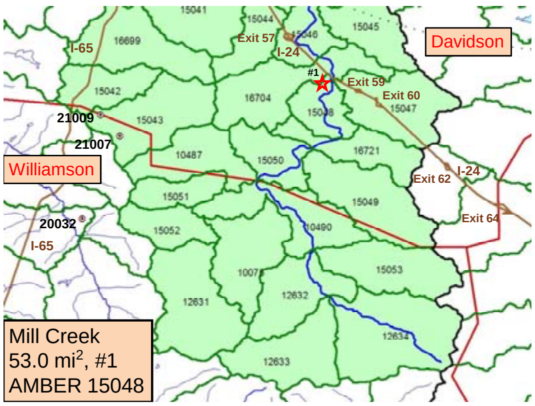


Fig. 30. FFMP watershed segments of Mill Creek upstream of Interstate 24.

the upstream tool in FFMP and clicking on basin 15048, the upstream area that contributed to the flooding is highlighted in yellow in Fig. 31. While the upstream area

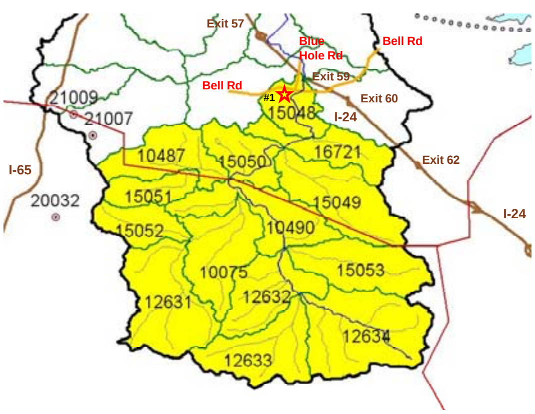


Fig. 31. FFMP basins upstream of basin 15048. The orange lines show the intersection of Bell Rd and Blue Hole Rd.

Fig. 32. Enhanced view of Bell and Blue Hole Roads near Interstate 24. The two roads are highlighted as solid red lines, with the dotted blue line showing the location of the Mill Creek stream channel.

is used to determine the flash flood threat along the stream channel in basin 15048. The red star in both Figs 30 and 31, shows the location of fatality #1 from the table in Fig. 22. Note that in Fig. 30 the mouth of basin 15048 directly crosses Interstate 24. Programs like Mapquest (Fig. 32) and Google Earth can be used to make impact statements of road crossings for FFMP watershed segments. The severity of the flooding where Mill Creek crosses I-24 is show in Fig. 33.

Fig. 33. View of the flooding at I-24 at Blue Hole Road from NWS (2011).

Fatality #1 occurred at 2PM (19 UTC) near the intersection of Blue Hole Road and Bell Road. Figs. 34 – 35 show the 6-hour FFMP ABR at 1700 UTC as the rain began in Mill Creek around 1100 UTC.

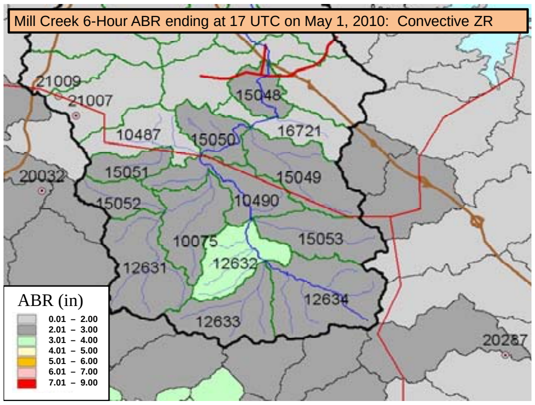


Fig. 34. AMBER/FFMP 6-hour ABR ending at 17 UTC on May 1, 2010 using Convective ZR.

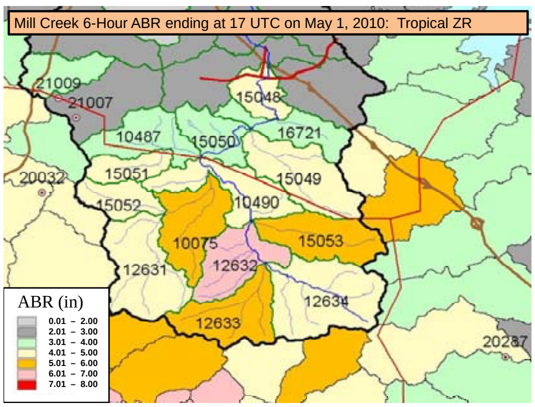


Fig. 35. AMBER/FFMP 6-hour ABR ending at 17 UTC on May 1, 2010 using Tropical ZR.

The importance of Tropical ZR vs. Convective ZR is clearly demonstrated by the two figures above. If Convective ZR is occurring, Fig 34 shows a general 2 to 4 inches of rain in the past 6 hours in Mill Creek above Interstate 24. If warm rain processes are occurring, Fig. 35 shows a general 4 to 6 inches of rain has fallen.

Figures 36 – 38 show the radar rainfall estimates for three rain gages (20287, 21007, and 21009 in Fig. 35). Both 21007 and 21009 are in the Mill Creek basin, but downstream of Blue Hole Road. Gage 20187 was included due to its proximity of the headwaters of Mill Creek where the maximum rainfall occurred.

All three gages clearly show, based on radar/raingage comparisons in Figs. 36 to 38, that tropical rainfall rates were indeed

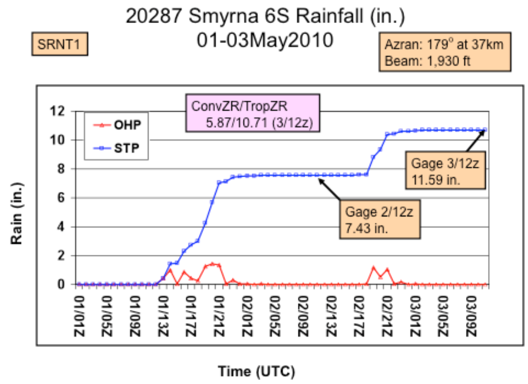


Fig. 36. Tropical ZR rainfall estimate for the Smyrna 6S observer. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP).

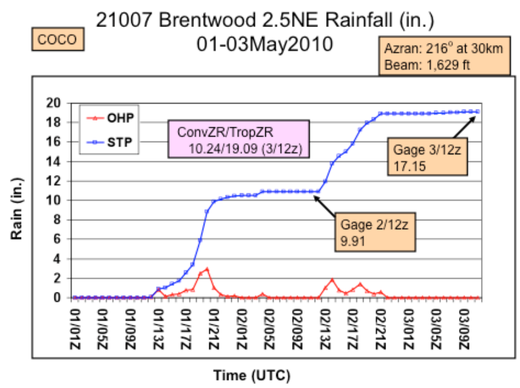


Fig. 37. Tropical ZR rainfall estimate for the Brentwood 2.5 NE observer. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP)

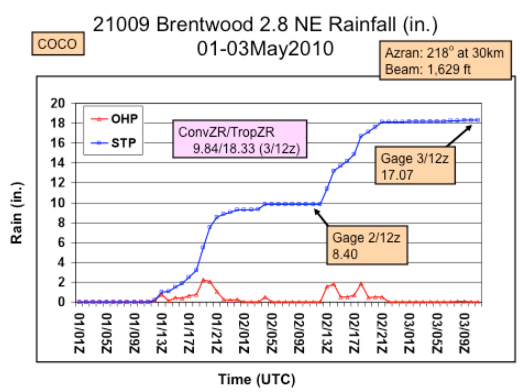


Fig. 38. Tropical ZR rainfall estimate for the Brentwood 2.8 NE observer. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP)

occurring. Unfortunately these gages would not be available in real time, as these coop observers report once a day at 7AM (12 UTC). Real time determination of Tropical ZR is only possible if the rain gage data is available in near real time, preferably in time increments of one hour or less.

The data in Fig. 35 for 17 UTC sets the table for the flash flooding that will caused a fatality at 19 UTC. Figs. 39 and 40 show the one hour ABR for each of the next two hours. While less than a half inch of rain fell

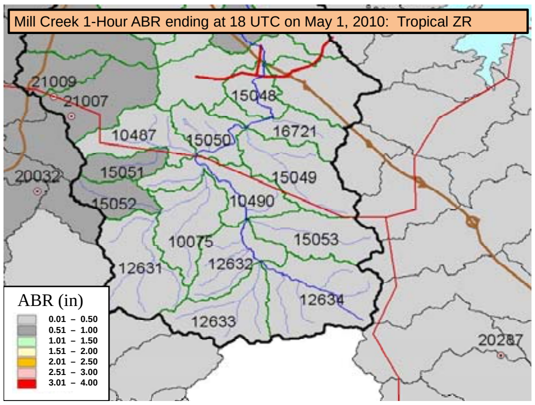


Fig. 39. AMBER/FFMP 1-hour ABR ending at 18 UTC on May 1, 2010 using Tropical ZR.

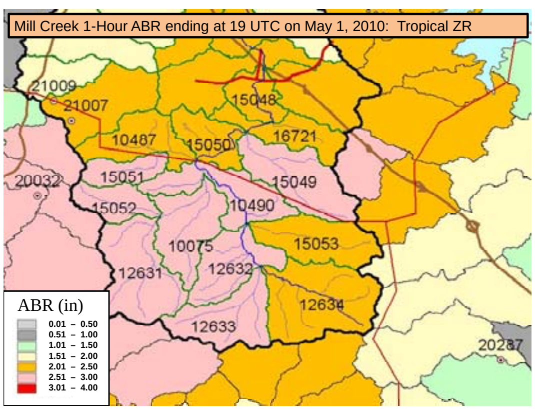


Fig. 40. AMBER/FFMP 1-hour ABR ending at 19 UTC on May 1, 2010 using Tropical ZR.

in the hour ending at 18 UTC (Fig. 39) The deluge that produced the flash flooding resumed in earnest in the hour ending at 19 UTC with 2-3 inches of rain. With the soil in the Mill Creek basin already saturated from the previous 7 hours of rain, this additional rainfall would go directly into runoff and cause a rapid rise on Mill Creek. The heavy rainfall continued through the next hour with another general 2-3 inches ending at 20 UTC (Fig. 41.) The storm total through 9 hours shows 8-12 inches of rain in the headwaters of Mill Creek (Fig. 42).

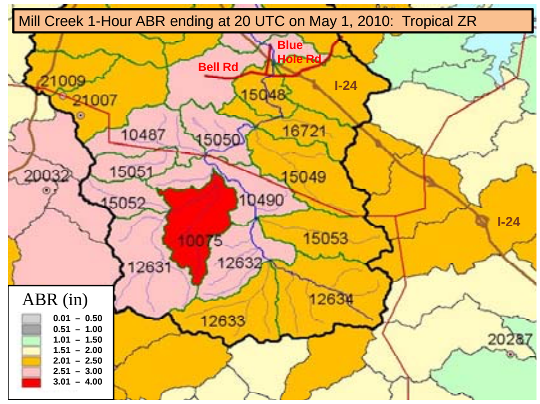


Fig. 41. AMBER/FFMP 1-hour ABR ending at 20 UTC on May 1, 2010 using Tropical ZR.

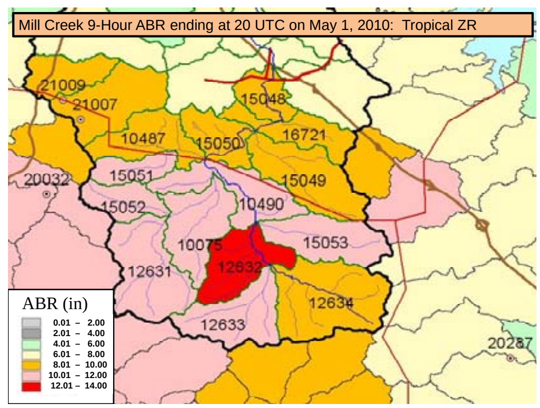


Fig. 42. AMBER/FFMP 9-hour ABR ending at 20 UTC on May 1, 2010 using Tropical ZR.

FFMP is limited in finding flash flood threat in larger watersheds (over 25 mi^2 in area). One way to help in determining risk in large watersheds like Mill Creek is to create map backgrounds for use in FFMP like the heavy black line shown in Fig. 42 for the boundary of Mill Creek. The aggregated layers in FFMP do computations in these larger watersheds, but the data is difficult to find operationally. FFMP does not provide shapefiles for these aggregated basins. If shapefiles were provided for the aggregated basins layers, these shapefiles could be used to make map backgrounds for FFMP.

7.2 Harpeth River Watershed

The Harpeth River watershed (Fig. 43) is over 800 mi^2 in area and too big to be considered a flash flood watershed. The individual tributaries such as Jones Creek or the Little Harpeth River are watersheds small enough to support flash flooding. The Harpeth River upstream of Interstate 40 (near the Bellevue river gage) could support flash flooding as well, with watersheds less than 500 mi^2 considered the upper limit for flash flooding (Davis 2004).

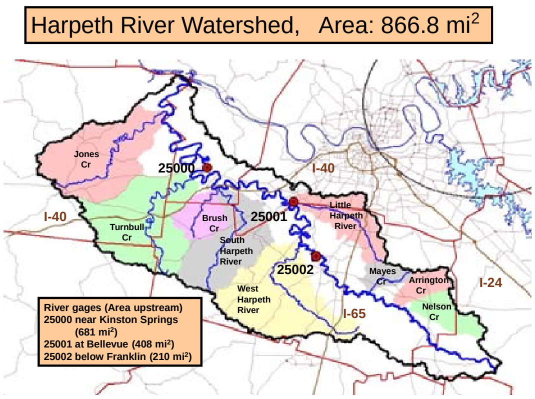


Fig. 43. The Harpeth River watershed, with primary tributaries shaded in a variety of colors. The red circles are river gages. The heavy blue line is the main stem of the Harpeth River.

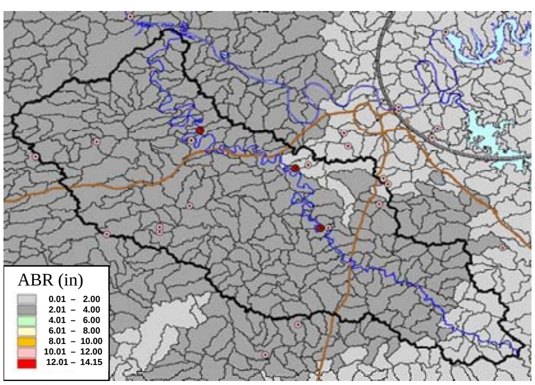


Fig. 44. AMBER/FFMP 8-hour ABR ending at 17 UTC on May 1, 2010 using Convective ZR. Pink dots are rain gages.

Figs 44 and 45 show the Convective ZR and Tropical ZR FFMP ABR display in the Harpeth River watershed for the 8 hours of rain ending at 17 UTC. Again the ability of FFMP to determine flood risk is dramatically impacted if Tropical ZR is occurring and is not selected on the WSR-88D.

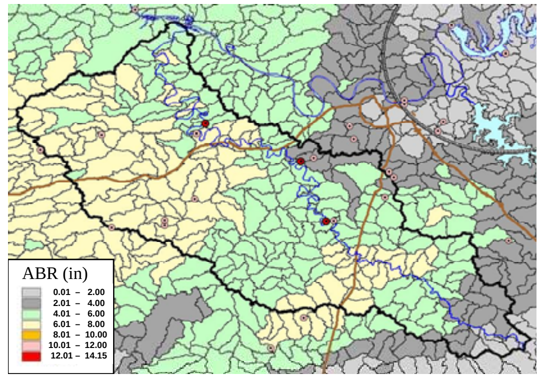


Fig. 45. AMBER/FFMP 8-hour ABR ending at 17 UTC on May 1, 2010 using Tropical ZR.

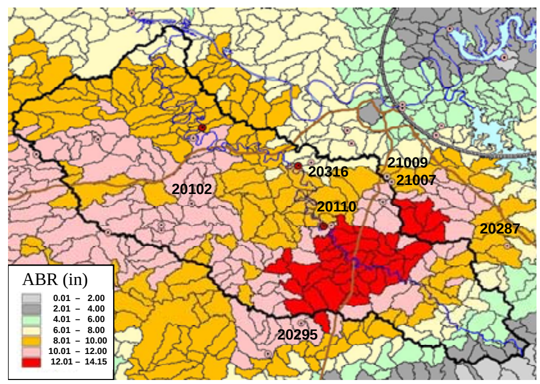


Fig. 46. AMBER/FFMP 12-hour ABR ending at 21 UTC on May 1, 2010 using Tropical ZR.

By 21 UTC the twelve hour rainfall total in the Harpeth River watershed (Fig. 46) showed a large area of 12 to 14 inches upstream of Interstate 40. Most of the entire watershed received 8 inches or more of rain.

A common occurrence of radar/rain gage comparisons is that the maximum radar rainfall falls equidistant between all rain gages. Notice in Fig. 46 that no rain gages are in the red, 12-14 inch area, but the rain gages ring the perimeter of heavy rain near the 10 inch isohyet. After 20 years of doing these radar/rain gage comparisons at the Pittsburgh NWS office, we refer to this phenomena as the “Law of rain gages”. Of the five gages surrounding the heavy rain, 20287, 21007, and 21009 were previously examined for Mill Creek (Figs. 36 – 38) and all clearly indicated tropical rainfall rates.

Looking more closely at the rainfall maximum upstream of I-40 in Williamson County (Fig. 47), the heaviest rain fell between gages 20295 and 20110. Notice that gage 20110 is in a very tight gradient of rainfall with the dark gray basin having an ABR value of 11.96 inches while the adjacent light yellow basin to the east has an ABR of 13.75 inch. The variations from observed in Fig. 48 may be due to this tight gradient. Ideally the gage/radar comparison should be made near the maximum rainfall values (in the pink areas of Fig. 47) where the rainfall gradient is not so steep.

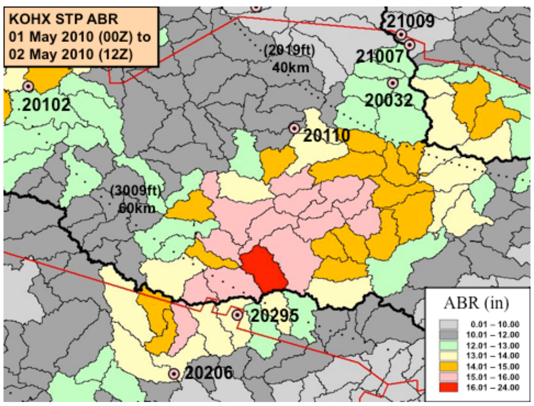


Fig. 47. FFMP/AMBER Storm Total ABR from 00 UTC on May 1, 2010 to 12 UTC on May 2, 2010. Dotted lines are radar range rings. **(3009ft)** entries are beam center sampling elevations in MSL for each range ring. Pink dots are rain gage locations.

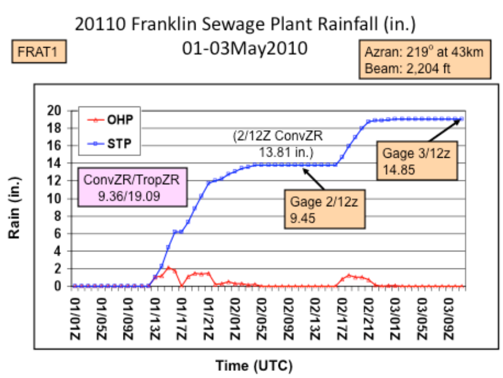


Fig. 48. Tropical ZR rainfall estimate for the Franklin Sewage Plant. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP)

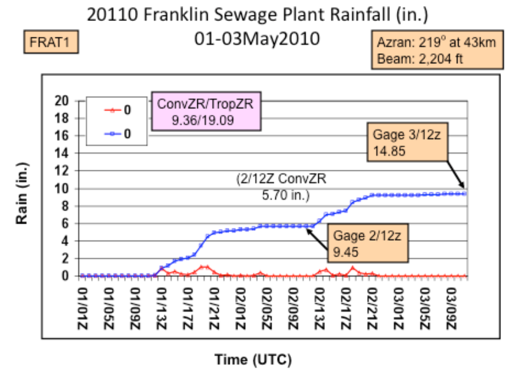


Fig. 49. Convective ZR rainfall estimate for the Franklin Sewage Plant. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP)

Looking at the Convective ZR radar estimates (5.70 in.) for Franklin in Fig. 49, the gage readings (9.45 in.) are well above the convective estimates again indicating that Tropical Rainfall rates are occurring.

The gage on the southern border of Williamson County (20295), while three inches higher than the Convective ZR estimate for the gage, is considerably below the Tropical ZR estimate (Fig. 50). Again the gage is located (Fig. 51) in an area of relatively tight rainfall gradient. The FFMP basin segment containing the gage is shaded yellow and has an ABR of 13.57 inches, while the pink basin to the north is 15.09 inches and the gray basis to the south has an ABR of 10.37 inches. That is an ABR variation of 4.7 inches in a distance of 4.5 km or about a one inch change of ABR per kilometer.

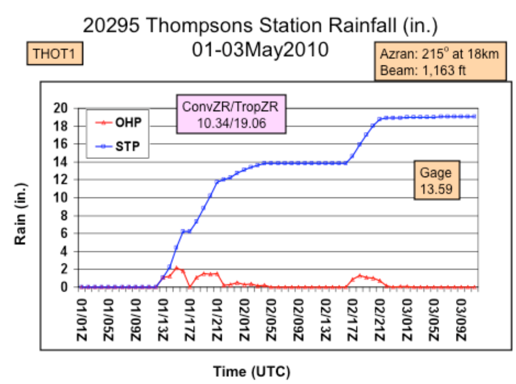


Fig. 50. Tropical ZR rainfall estimate for Thompsons Station. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP)

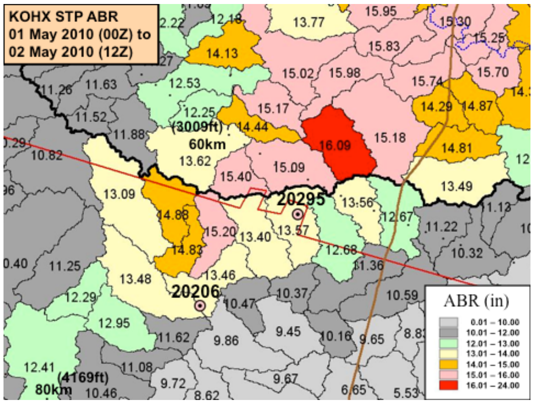


Fig. 51. FFMP/AMBER Storm Total ABR from 00 UTC on May 1, 2010 to 12 UTC on May 2, 2010. Dotted lines are radar range rings. **(3009ft)** entries are beam center sampling elevations in MSL for each range ring. Pink dots are rain gage locations.

The reason for the tight gradient of ABR to the south can be gleaned from the mesoscale forcing initiating the convection. Looking at Fig. 13 showing the ABR from 06 UTC to 12 UTC on May 1, 2010, the rainfall maximum is oriented west to east and no rainfall has yet fallen in the eastern half of Williamson County south of Nashville. A west to east (warm frontal-like) boundary is set up south of this rainfall maximum and strong overrunning southwest winds are feeding moisture over the boundary and initiating the strong convection. In the next six hours (Fig. 14), from 12 UTC to 18 UTC, the rainfall maximum spreads east and puts heavy rain across all of Williamson county. As a result much less rain is falling south of the boundary with much heavier rainfall falling to the north of the boundary. In the next six hours (Fig. 15), the mesoscale forcing changes to a boundary oriented from the northeast to the southwest more similar to a pre-cold frontal boundary. In the hours from 18 UTC to 24 UTC the rainfall maximum orientation has clearly changed, and heavy rainfall is now occurring well south of the previous east west boundary.

The storm total depicted in Fig. 51 shows much less ABR to the south of the old boundary (south of Williamson County). The local maximum south of Williamson county, from gage 20295 to gage 20206 resulted from the very heavy rain that fell from 20 UTC to 22 UTC with convection training much further south along the newly formed northeast to southwest boundary. The impact of gage 20295 sitting very close to the old east-west boundary and at a range just beyond 60 km from the radar and a beam centerline sampling elevation of about 3100 feet MSL, the heavy rain indicated by the radar at that location may be transported several km to the northeast by the strong transport winds out of the southwest in the strong gradient of ABR. This may be a contributing factor as to why the Tropical ZR estimates are considerably higher than the observed gage values. The higher the sampling elevation of the radar, the greater this problem becomes, especially in areas where ABR gradient may reach one inch per kilometer.

If Tropical ZR is indeed occurring in the Harpeth River basin, then the magnitude of ABR shown in Fig. 46 should result in unprecedented flooding. Fig. 52 shows road crossings of Interstate 40 with the Harpeth River from near Exit 192 to Exit 188.

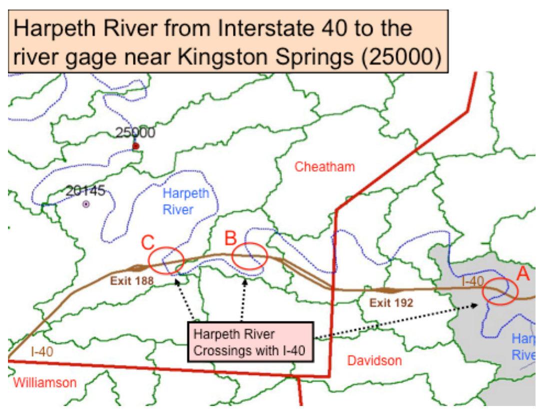


Fig. 52. Harpeth River road crossings with Interstate 40. The large red circles, A, B and C show the Interstate 40 crossings with the Harpeth River. The dark red circle is the location of the Kingston Springs river gage (25000) on the Harpeth River.

The only other fatality (#2 in Fig. 22) on May 1, 2010 occurred at 10 PM (03 UTC on May 2, 2010) at the road crossing of the Harpeth River (Fig. 52) with I-40 at “A”. The service assessment indicated that many miles of I-40 were closed due to flooding. The maximum rain fell in the headwaters of the Harpeth River between 18 UTC and 21 UTC on May 1, 2010, the travel time to cover the 71 miles from the headwaters to the I-40 “A” crossing along the river channel accounts for the time difference between the end of the heavy rain around 21 UTC and the time of the fatality about 6 hours later.

The importance of stream crossing with highways should not be understated in the flash flood warning process. A great percentage of flash flood deaths occur in automobiles. Using map references like Mapquest (Fig. 53) and Google Earth (Fig. 54), impact statements for FFMP stream segments can be created and used during real-time flash flood operations.

Fig. 53. Enhanced display showing Interstate 40 road crossing "A" with the Harpeth River. Red star shows location of fatality #2. Blue line is the river channel.

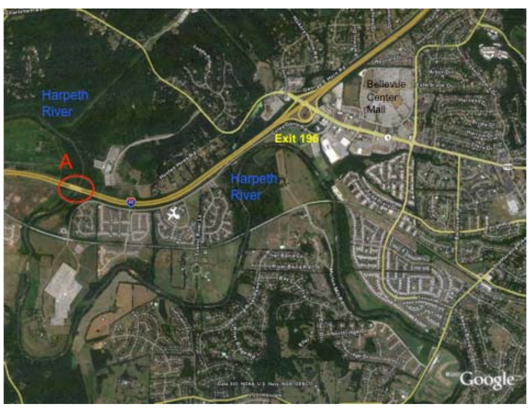


Fig. 54. Enhanced Google Earth display showing Interstate 40 road crossing "A" with the Harpeth River.

When Tropical ZR occurs along with high cell training speeds, heavy rainfall can be spread over large watersheds if the rainfall persists. When a large area is inundated with rain, widespread stream flooding often leads to record river flooding.

If the Tropical ZR storm totals in the Harpeth River (Fig. 46) are close to reality, an unprecedented hydrologic response should occur along the Harpeth River channel. Most flash flood watersheds do not have stream gages, but most large scale rivers do have gaged river forecast points. See Fig. 55 for the United States Geological Survey (USGS) gage on the Harpeth River near Kingston Springs (gage 25000 in Fig. 52).

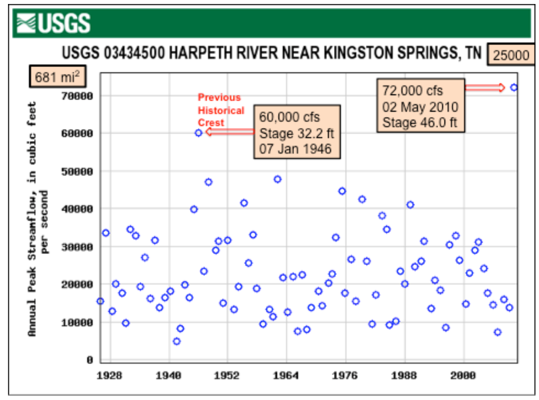


Fig. 55. Graph showing Annual Peak Flow for the Harpeth River Near Kingston Springs, TN. Stage readings with date have been appended for the top two flow readings.

The extreme observed peak flow of May 2, 2010 adds further support for the occurrence of Tropical ZR rates during the extreme flash flooding observed in Nashville, TN on May 1, 2010. The next section will look at the rainfall and location of the fatalities that followed on May 2, 2010.

8.0 MAY 2, 2010 WATERSHEDS

The following section will look at the individual watersheds where fatalities occurred on May 2, 2010. Radar rainfall estimates of Tropical and Convective ZR will be compared to rain gages readings in or near those watersheds. FFMP Average Basin Rainfall (ABR) displays will be shown for each watershed where fatalities occurred.

8.1 Harpeth River

Fatality #9 in Fig. 22 occurred along Sawyer Brown Road near the Harpeth River at 1530 UTC, about 12 hours after Fatality

#2 at the I-40 road crossing. Recall that the record crest along the Harpeth River occurred on May 2, 2010. The upstream area of the Harpeth River watersheds above Sawyer Brown Road is about 421 mi^2. ABR and rain gage plots for this fatality can be seen in Section 7.2.

Fig. 55. Enhanced display of the Interstate 40 road crossings with the Harpeth River. Red star shows location of fatality #9. Blue line shows river channel of the Harpeth River. Red line shows Sawyer Brown Road.

8.2 Mill Creek

While Mill Creek was still at elevated stream levels from the heavy rain on May 1,

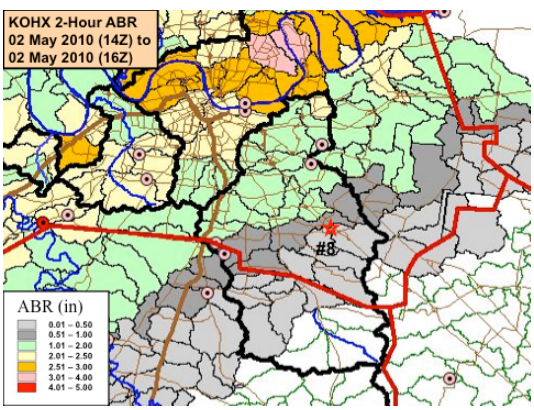


Fig. 56. AMBER/FFMP 2-hour ABR ending at 16 UTC on May 2, 2010 using Tropical ZR. Red star show fatality location.

2010 (See section 7.1), when fatality #8 occurred at 15 UTC on May 2, 2010 no rain had fallen overnight in the headwaters of Mill Creek. The two hour ABR (Fig. 56) shows that less than one half inch of rain had fallen in the headwaters of Mill Creek from 14 UTC to 16 UTC as the heavy rain resumed. The upstream contributing watershed area for this portion of Mill Creek is 62.2 mi^2. This type of fatality can only be avoided by educating the general public on the dangers of tubing, or canoeing in high flow scenarios.

Fig. 57. Enhanced display of the Mill Creek area near Blue Hole Road. Red star shows location of fatality #8. Dotted blue line shows stream channel of the Mill Creek.

8.3 Whites Creek

The final three watersheds (Whites Creek, Richland Creek, and Overall Creek) are clustered around the city of Nashville. The following figures (Figs. 58 – 61) will be used to show the AMBER/FFMP ABR for all three watersheds. Whites Creek is the largest watershed of the three with an upstream contributing area of at 53.3 mi^2.

All seven fatalities in these three watersheds occurred from 1430 UTC to 16 UTC. After heavy rain fell during the afternoon and evening hours on May 1, 2010, no heavy rain resumed in these basins until after 10 UTC on May 2, 2010.

The six hour rainfall from 10 UTC to 16 UTC (Fig. 58) produced the severe flash flooding observed in these basins. Looking at shorter time durations during this six hour time period gives significant insight into the heavy downpours that caused the flash flooding (Figs. 59-61).

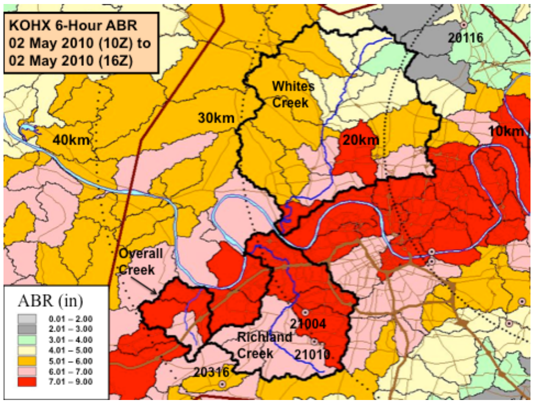


Fig. 58. AMBER/FFMP 6-hour ABR ending at 16 UTC on May 2, 2010 using Tropical ZR.

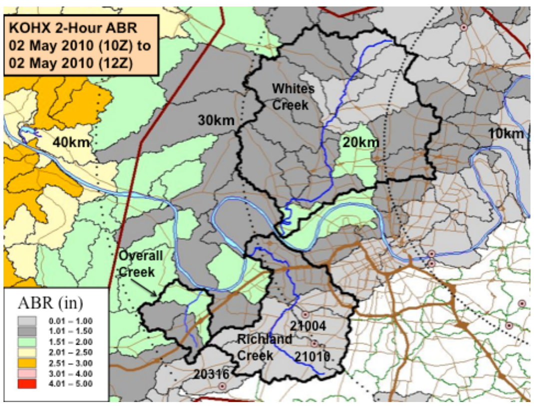


Fig. 59. AMBER/FFMP 2-hour ABR ending at 12 UTC on May 2, 2010 using Tropical ZR.

The fatality in Whites Creek occurred around 15 UTC. The rainfall total for Whites Creek for the 6 hours ranged from 4 to 7 inches (Fig. 58), with 2 to 4 inches of that total falling in the two hours from 12 UTC to 14 UTC (Fig. 60). An additional 1.5 to 2.5 inches fell in the two hours from 14 to 16 UTC (Fig. 61), adding to the flood wave down Whites Creek. Peak flow at the stream gage (25003) near Bordeaux reach 21,600 cfs, with a record stage of 25.59 feet.

There are no rain gages in the Whites Creek watershed, but gage 20116 (Fig. 58) east of the watershed, had rain gage totals that surpassed the Tropical ZR rainfall estimates for the gage location (Fig. 63).

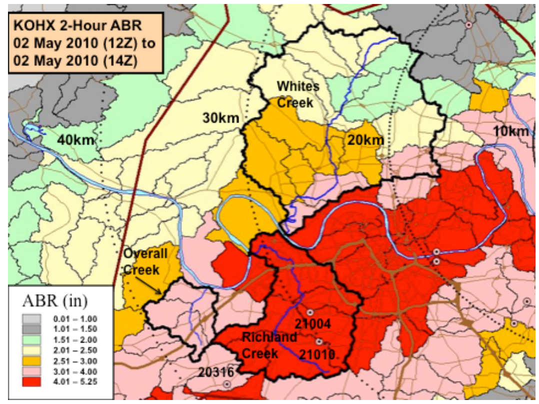


Fig. 60. AMBER/FFMP 2-hour ABR ending at 14 UTC on May 2, 2010 using Tropical ZR.

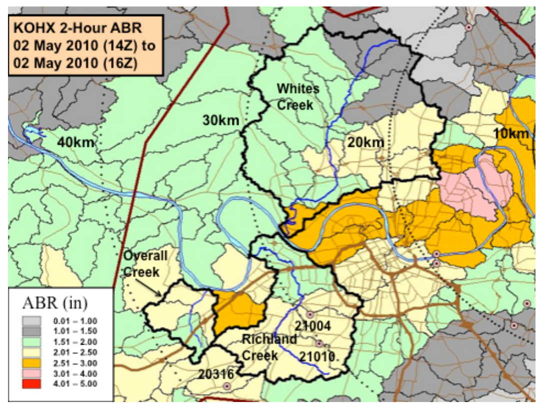


Fig. 61. AMBER/FFMP 2-hour ABR ending at 16 UTC on May 2, 2010 using Tropical ZR.

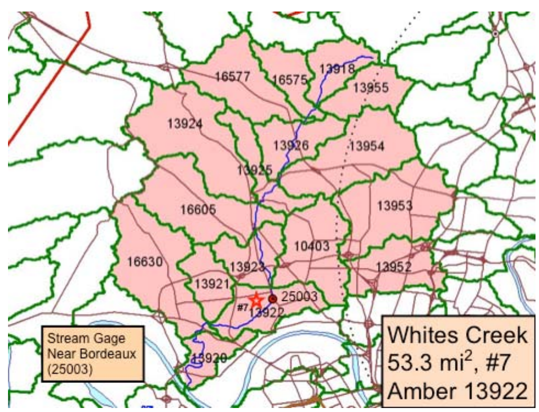


Fig. 62. Whites Creek watershed shaded in pink. Red star shows the location of fatality #7. Black numbers are FFMP Basin Identifiers. Brown lines are roads.

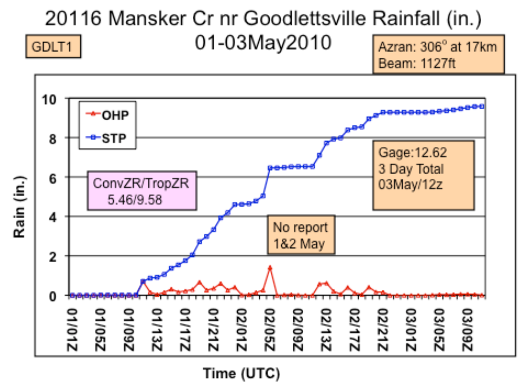


Fig. 63. Tropical ZR rainfall estimate for Goodlettsville. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP).

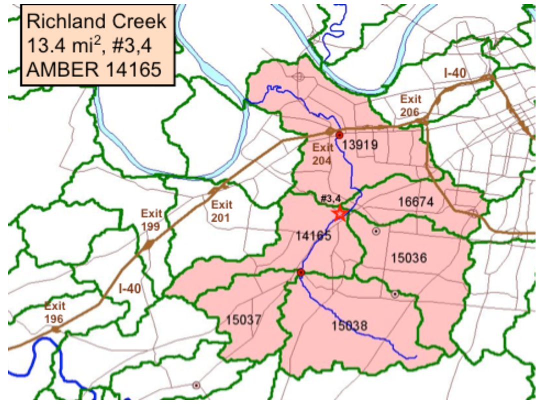


Fig. 65. Richland Creek watershed shaded in pink. Red star shows the location of fatalities #3, #4. Black numbers are FFMP Basin IDs.

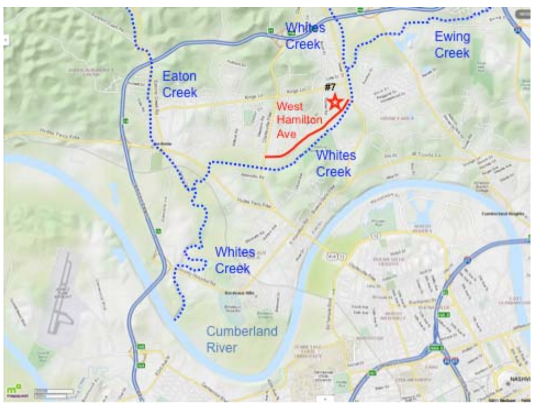


Fig. 64. Enhanced Mapquest display showing the Whites Creek near West Hamilton Avenue. Red star shows location of fatality #7. Dotted bue line shows stream channel of Whites Creek plus tributaries.

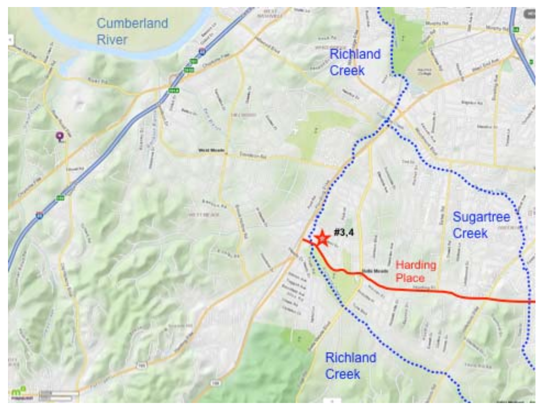


Fig. 66. Enhanced display of Richland Creek near Harding Place. Red star shows location of fatalities #3,#4. Dotted bue line shows stream channels.

8.4 Richland Creek

Richland Creek contained 4 of the 11 fatalities near the city of Nashville. Two of the four fatalities (#3 and #4) occurred around 1430 UTC in FFMP basin segment 14165 (Fig. 65) The upstream contributing area for basin 14165 is 13.4 mi^2. Less than 1 inch of rain fell in this upstream area from 10 to 12 UTC (Fig 59). But from 12 to 14 UTC, 4 to 5 inches fell (Fig. 60) producing the flood wave that caused the flash flooding. Another 2 inches of rain fell in the headwaters of Richland Creek from 14 to 16 UTC (Fig. 61), resulting in two additional fatalities (#10 and #11) further downstream (Fig. 67) around 1600 UTC. The upstream

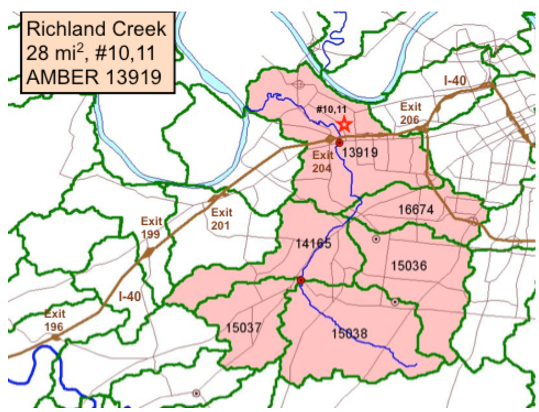


Fig. 67. Richland Creek watershed shaded in pink. Red star shows the location of fatalities #10, #11. Black number are FFMP Basin Identifiers. Brown lines are roads.

contributing area at the location of the two additional fatalities was 28 mi^2.

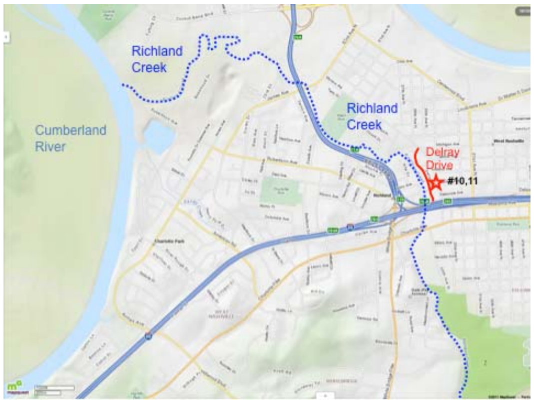


Fig. 68. Enhanced display of Richland Creek near Delray Drive. Red star shows location of fatalities #10,#11. Dotted bue line shows stream channel of Richland Creek.

Two rain gages reside in the Richland Creek watershed (21004 and 21010). For gage 21004 (Fig. 69), the radar estimate from 12UTC May 2, 2010 to 12UTC May 3, 2010 is 11.13 inches. The rain gage reading for the same time period is 10.35 inches.

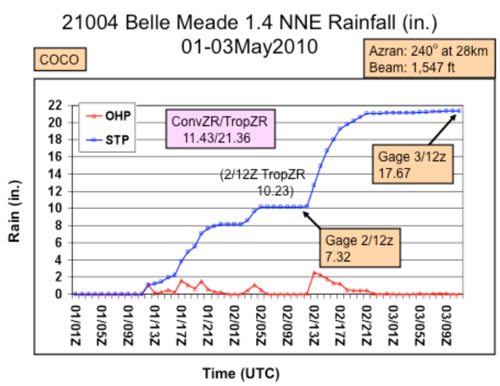


Fig. 69. Tropical ZR rainfall estimate for Belle Meade 1.4 NNE. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP).

For the same time period from 12UTC on May 2, 2010 to 12 UTC on May 3, 2010 for gage 21010 (Fig. 70), the radar estimate is 9.48 inches, while the rain gage total is 9.58 inches. These gage/radar comparisons show clearly that Tropical ZR was occurring for the heavy rainfall from 10 UTC to 16 UTC in Richland Creek.

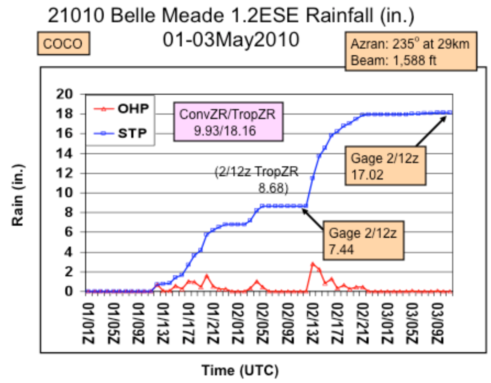


Fig. 70. Tropical ZR rainfall estimate for Belle Meade 1.2 ESE. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP).

8.5 Overall Creek

Overall Creek is the smallest of the watersheds (7.9 mi^2 in area) near Nashville that had fatalities (Fig. 71). Because fatalities #5, #6 occurred well into the headwaters of the creek, the upstream contributing area was very small.

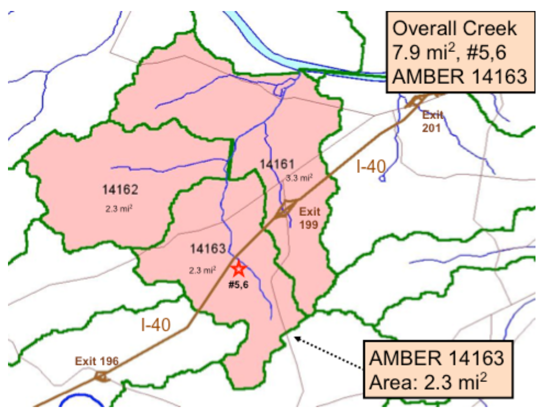


Fig. 70. Overall Creek watershed shaded in pink. Red star shows the location of fatalities #5, #6. Black number are FFMP Basin Identifiers. Brown lines are roads.

FFMP allows each local office to customize the small stream data base that was produced by the (NBD) National Basin Delineation Project with more information at: http://www.nssl.noaa.gov/projects/basins/ The NBD delineated all flash flood watersheds for the entire continental United States down to 1.78 mi^2 in area. The watersheds were sent to each forecast office on compact disk and allowed all NWS Offices to run the AMBER program as FFMP. Without the NBD project, AMBER would still be just a local application at the Pittsburgh, PA NWS office. Look at Fig. 71 to see how the basins in Overall Creek might be locally customized. Note that the

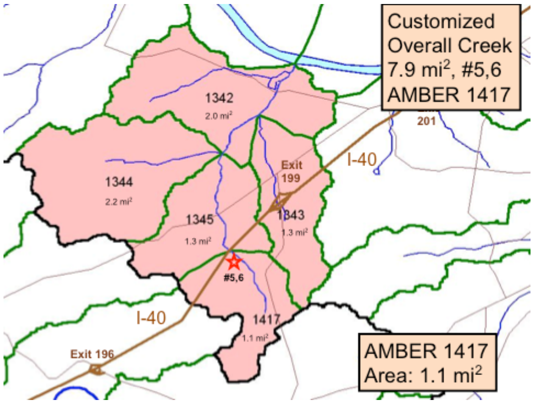


Fig. 71. Customized AMBER watersheds for the Overall Creek watershed shaded in pink. Red star shows the location of fatalities #5, #6. Black number are AMBER Basin Identifiers. Brown lines are roads.

three watershed segments in Fig. 70 now become five watershed segments in Fig. 71. Old basin 14163 is divided into two basins at the road intersection with Interstate 40. The mouth of basin 1417 is near the site of fatalities #5,#6 with an upstream area of only 1.1 mi^2. Customizing basins for intersections with highways can be a very valuable tool in improving flash flood detection capabilities in FFMP. Basin segment 1343 was not analyzed as a separate basin segment by NBD because the area of the basin (1.3 mi^2) was less than the minimum basin area default (1.78 mi^2) used in the National NBD analysis. FFMP will easily handle customized basin segments down to 0.5 mi^2.

No rain gages are contained in the Overall Creek watersheds, but since this small watershed is immediately adjacent to Richland Creek watershed, Tropical ZR is likely occurring in Overall Creek as well.

Fig. 72. Enhanced display of Overall Creek near Sawyer Brown Road. Red star shows location of fatalities #5,#6. Dotted blue line shows stream channel of Richland Creek.

The fatalities on Overall Creek occurred around 1430 UTC in FFMP basin 14163. The basin received 1.30 inches from 10 UTC to 12 UTC (Fig. 59) and an additional 3.22 inches from 12 UTC to 14 UTC (Fig. 60). Considering the existing hydrologic conditions of the basin from the heavy rain the previous afternoon, almost all of this rain went as direct runoff into the stream channel, causing the serious flash flooding observed in Overall Creek.

While there is no rain gage in the Overall Creek watershed, gage 20316 is several kilometers south of the basin (Fig. 61).

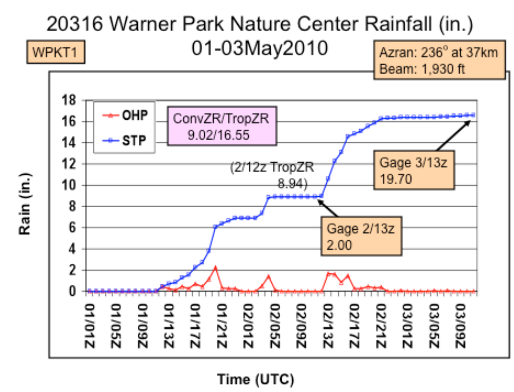


Fig. 73. Tropical ZR rainfall estimate for Belle Meade 1.4 NNE. Blue line is Storm Total Precipitation (STP) and the red line is One Hour Precipitation (OHP).

Looking at the gage reports for Warner Park Nature Center, something looks amiss with the time periods of the reported rainfall. While the gage total for the event of 19.70 inches is in line with the radar estimate of

16.55 inches, the gage report of just 2 inches for 13 UTC on May 2, 2010 seems to be in error. The radar estimate at 12 UTC is 8.94 inches or 54 percent of the radar rainfall total. Computing 54 percent of the rain gage total would give at least 10.64 inches in the rain gage at 12 UTC on May 2, 2010. The Warner Park Nature Center rain gage total does further support the occurrence of Tropical ZR.

9.0 CONCLUSIONS

A large body of evidence has been presented to show that Tropical ZR rates were occurring during the heavy rainfall events that caused flash flooding near Nashville, TN for the first rainfall surge on May 1, 2010 and again with the second rainfall surge on May 2, 2010.

The occurrence of Tropical ZR can have a great impact on the effectiveness of FFMP to detect both the occurrence and severity of flash flooding. Providing both Tropical ZR and Convective ZR ABR databases would help flash flood detection in FFMP.

New sophisticated radar algorithms such as the Dual Polarization upgrade to the WSR-88D and the NMQ Q2 algorithm that uses vertical structure of the radar echoes to determine ZR on the fly for each radar grid may provide some help in the Tropical ZR vs. Convective ZR problem. These new methods must be compared to the existing WSR-88D Convective ZR and Tropical ZR computations and rain gage data to determine their utility for flash flood applications.

Support for FFMP flash flood detection in larger watersheds needs to be improved and become more efficient. At a minimum, shapefiles should be provided for the aggregated basin layers of FFMP, so large watershed boundary maps could be more easily created for use in FFMP. A more robust solution would be to include the Basin Upstream Rainfall (BUR) computation proposed by Davis (2008), allowing for the elimination of the FFMP aggregated layers and greatly simplifying the FFMP display. Upstream contributing area is an essential element in determining flash flood risk in large watersheds.

Impact statements developed for the small FFMP watershed database could be of great value in the flash flood warning program. An updated national warngen program would have to be created to define the required format for the impact statements and allow their automatic insertion into flash flood warnings. The detail of the Mapquest and Google Earth displays shows the capability of creating impact statements to the flash flood scale is possible and potentially very valuable.

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