# 6C.1 FORECAST TOOLS AND CONSIDERATIONS FOR FOUR RECENT FLASH FLOODS

Matthew Kelsch*
UCAR/COMET, Boulder Colorado

## 1. INTRODUCTION

Four flash floods from 2003 and 2004 will be briefly reviewed. The events are from the rural Kansas, the mountains of North Carolina, Las Vegas, Nevada, and Richmond, Virginia. Thus, they represent both urban and rural settings, and both humid and arid climate regions.

These cases illustrate the need to consider the variety of watershed responses in regions with different ground and vegetation characteristics. In particular, the impact of urban development is an increasingly important consideration for understanding the frequency and severity of flash flooding on small basins. This manuscript will review two flash floods in urban areas, and two in rural areas. However, even in one of the rural cases a human-engineered structure played an important role.

Other important forecast considerations include correctly analyzing and forecasting the intensity of the rainfall rates. Flash floods typically occur on small, fast-response basins. In these areas, rainfall rates may be more important than the total rainfall accumulation for triggering a flood.

Tools that help provide information about both rainfall rates and basin characteristics are vital to the flash flood forecast process. Weather radar provides rainfall information that is high resolution in both space and time. The Flash Flood Monitoring and Prediction System (FFMP) used by the National Weather Service (NWS) is an example of a tool that displays radar rainfall with information about the small basins.

## 2. FFMP AND URBANIZATION

FFMP has been implemented throughout the National Weather Service (NWS) and will continue to evolve as both researchers and forecasters gain experience with it (Davis, 2004b). FFMP enables forecasters to view rainfall information relative to Flash Flood Guidance (FFG) on a drainage basin background (Smith et al. 2000), with basins as small as 5.1 $km^2$ (2 $mi^2$). Thus, FFMP allows interrogation of a flash flood situation on the storm scale, the scale at which important runoff processes are occurring.

FFMP depends on accurate radar-derived rainfall information. It also depends on representative FFG values. Although efforts are underway to improve FFG, it currently is most sensitive to soil moisture. Thus, if the ground is dry then FFG is relatively high indicating it will take more rain to produce a flash flood. However, this is not an appropriate assumption for all drainage basins. In some areas, particularly in the semi arid and arid West, soil properties may prevent the absorption of high rainfall rates even when the soil is dry. In addition, throughout the country urbanized basins can result in rapid and efficient runoff even if the antecedent conditions are dry.

Urbanization affects both the amount of rainwater that runs off, as well as how quickly that runoff occurs (Chin and Gregory, 2001). Compaction of soils and impermeable surfaces can greatly increase the amount of runoff (Frazer, 2005). Thus, in urbanized basins flash floods can occur more frequently and at lower rainfall thresholds. Alterations to the stream channel, installation of storm drain systems, and the presences of a road grid can all result in a greater speed of runoff as well. In studies done within the urbanized basins of Baltimore, Maryland, the time lag from peak rainfall to peak discharge can be as little as 0.25 h (Smith, 2004). City streets become the path of least resistance for the excess runoff and can become deadly torrents of floodwater.

## 3. DISCUSSION

Four flash floods are reviewed here. Two are used to illustrate flooding in urbanized basins.

**Corresponding author address*: Matthew Kelsch, UCAR/COMET, P.O. Box 3000, Boulder, CO 80507-3000; email: kelsch@ucar.edu

Two are in more rural settings but illustrate the need to pay attention to small basins and radar precipitation products.

***3.1 Urbanization and FFG: 30 August 2004***

As Hurricane Gaston moved inland over Virginia on 30 August 2004, torrential rains struck the Richmond area. Figure 1 shows the rainfall in Virginia leading up to the time of the flooding. County boundaries are the dotted white lines. The City of Richmond appears on the county map as the small polygon in the middle of the yellow circle in Fig. 1. Note that the City of Richmond was receiving some of the greatest accumulations. Severe flash flooding closed many highways and caused considerable damage in the downtown area. A downtown drainage known as Shockoe Bottom had a peak discharge estimated at 227 cubic meters per second (8000 cubic feet per second) which is said to have a return period frequency of 500 years.

The period leading up Hurricane Gaston had been relatively dry in Virginia. Therefore, FFG values were rather high indicating that it would take substantial rainfall to trigger flash flooding. Values ranged as high as 83 mm (3.27 in) for 1 hour and 111 mm (4.38 in) for 3 hours. Indeed the storm system met these FFG thresholds in many areas. However in the urbanized basins within the city of Richmond, the flash flooding was particularly severe and started shortly after the intense rains commenced and before FFG was reached. This is not surprising since urban basins are more subject to enhanced runoff.

For flash flood forecasting it is important account for the additional risk in urbanized basins. Geographic Information Systems (GIS) and other mapping tools can be used to identify such basins. Within the NWS FFMP system, a forecaster now has the ability to alter FFG to values that are more appropriate for special-case basins like urban basins. For example, FFG in urban areas will be lower, sometimes much lower, than in surrounding rural areas.

In the Richmond case the FFG values were unrealistic for urban basins. FFG differences between urban and non-urban areas are greatest during dry periods. That is because in non-urban areas it often takes considerably more rainfall to trigger a flash flood during dry spells. Thus FFG is high. In urbanized areas, runoff is often driven more by ground surface properties than soil moisture. The greater coverage of impermeable surfaces and the presence of road and storm sewer networks result in flash floods from short intense rainfalls even when it is dry. Thus, FFG is always relatively low.

Using the forced FFG Graphical User Interface (GUI) an NWS forecaster can change the FFG for specific basins. For example, with that tool we lowered the 3-h FFG in Richmond to values more appropriate for the city (Figure 2). The purple shows FFG values for 3h of 41 mm (1.6 in) and the blue shows values of 76 mm (3.0 in). There was a greater reduction made to the 3-h FFG in the most heavily urbanized areas and a lesser reduction in other parts of the city. The basin rainfall is shown in Figure 3. Figure 3 is a zoom in on the City of Richmond with its small drainage basins in white. Note how some of the basins in Richmond have received over 127 mm (5 in) of rain. Figure 4 is an FFMP product showing the difference between the 3-h rainfall and the 3-h FFG, where positive values show rainfall exceeding FFG. The right side of Fig. 4 uses our altered 3-h FFG. Here we can see that the FFG values for urban Richmond have been exceeded by more than 102 mm (4 in). The left side of Fig. 4 shows the unaltered FFG value for comparison. Thus changing the FFG values for urbanized basins can assist forecasters with highlighting the increased flash flood risk in those areas.

Alteration to FFG can also be very useful other special-case basins such as fire burn areas.

***3.2 Urban flooding: 19 August 2003***

During the late afternoon of 19 August 2003, heavy thunderstorm activity deluged the city of Las Vegas, particularly the northwestern parts of the city and its northwestern suburbs. Many of the natural basins in this region are quite small and heavily urbanized resulting in a situation where the time lag from peak rainfall to peak discharge is very short. Figure 5 shows the topography of Clark County, Nevada. Las Vegas and its subdivisions are outlined in yellow, the drainage basin are in white and the bold white circle highlights the area impacted by the flash flooding. Note how many of the small basins are elongated as they drain from the higher terrain down into the city.

Fig. 6 shows a 1-h basin accumulation product from FFMP for the small basins in the Las Vegas vicinity. Note the high accumulations in some of the elongated basins draining toward the city. Some of the basins flowing into the northwest side of Las Vegas received at least 76 mm (3 in) of rainfall.
As these basins convey water into the northwest side of Las Vegas, many of the natural channels, washes, and flood plains are forced into culverts. When the culverts cannot handle the volume, water surges downstream along the road. Numerous rapid water rescues were performed in and just downstream of the basins highlighted by the FFMP accumulation field (black circle in Fig. 6).

### *3.3 Radar Z-R: 30 August 2003*

During the evening of 30 August 2003, a quasi-stationary convective complex drenched a small area of Lyon and Chase counties in Kansas along and just upstream of Interstate 35, the Kansas Turnpike. Flooding from Jacob Creek began to seriously impact the highway by 0130 UTC (8:30 PM CDT) causing a large traffic backup as vehicles stalled in the high waters. Water completely inundated the northbound lanes as it ponded against the concrete Jersey barriers that separated the northbound from the southbound lanes. Just before 0230 UTC (9:30 PM CDT), a section of the concrete barriers gave way under the force of the water causing the floodwaters, along with seven vehicles, to be swept downstream.

Figure 7 shows the three-hour radar-derived accumulation as of 0200 31 August 2003. This is 30 min before the flood surge across the highway, but floodwater was already impeding traffic. Zooming in on the area, Figure 8 shows the small basins along the Kansas Turnpike and their drainage areas. Jacob Creek flows from southeast to northwest and only drains about 2 square miles upstream of the turnpike. FFMP products highlighted this basin as seen in Kelsch (2004). The flood occurred where Jacob Creek intersects the turnpike and is labeled “flood” on Figs. 7 and 8.

The accumulation amounts indicated by the radar were not exceptional given the severity of the flooding. Ground observations indicated much higher accumulations occurred. Precipitation microphysics associated with the warm-rain process of this storm may have resulted in underestimated radar-derived rainfall rates. AWIPS products showed relatively warm cloud-top temperatures (warmer than −40°C), strong low-level echoes (50-55 dBZ), and no lightning strikes. This is consistent with low-centroid intense rainstorms where very efficient precipitation growth is taking place in the liquid (above freezing) portion of the cloud. Fig. 9 shows a cross section through the storm complex. Note that the intense echo area is in a region below 6000 m (20 Kft) AGL where temperatures are above freezing. The 0°C isotherm is shown with the white dashed line in Fig. 9. Strong and moist low level flow was feeding this storm complex and strong low-level frontogenesis led to very efficient precipitation production in the low levels, with the warm-rain process dominating.

The standard reflectivity-rainfall rate (Z-R) relationship used in Kansas, $Z= 300R^{1.4}$, assumes a certain drop size distribution (DSD). By comparison, in more tropical areas the DSD is often characterized by higher concentrations of smaller droplets than in Kansas. The tropical Z-R, $Z= 250R^{1.2}$, may be used in such areas. However, far inland from the warm ocean waters there are situations when the tropical Z-R may result in more representative rainfall rates (Davis, 2004a). Precipitation growth through collision coalescence of droplets in the above-freezing portion of the cloud was likely a primary mechanism in the Kansas Turnpike case. This is often called the warm rain process and is more typical of moist, tropical situations. Indeed the tropical Z-R seemed to provide more accurate rainfall rates and thus greater accumulations. The accumulation was considerably greater than the derived accumulation with the default Z-R as seen in Fig. 10. Caution should be taken when changing Z-R relationship because not all convective systems within a County Warning Area (CWA) may be experiencing the same precipitation growth process. Regardless of the Z-R used, a forecaster will still be required to make a judgment about the precipitation physics of a storm complex based on an array of available data including surface observations, radar, satellite, and lightning.

### *3.4 Radar coverage: 16 September 2004*

On 16 September 2004 intense rains triggered flash floods and debris flows in the Peeks Creek basin of rural Macon County in southwestern North Carolina (Lamb, 2004). The rains were part of a rain band associated with Hurricane Ivan as it moved inland from the Gulf of Mexico. Strong east and southeast winds to the northeast of the storm drew Atlantic moisture into the lower Appalachians.

Radar products never indicated any very serious rainfall rates during the 6 hours leading up to the flood. Upon closer examination, one can see a sharp linear discontinuity in the radar-derived storm accumulation (Fig 11). This discontinuity suggests that the radar beam from the Greer, South Carolina radar (KGSP) was blocked in the direction of the Peeks Creek basin. Upon reviewing the topography we can see that a higher terrain feature relatively close to the radar is probably the culprit (Fig 12).

It is important to identify areas of unreliable radar coverage, particularly when using a tool like FFMP. With FFMP, the display of accumulations on a basin or county background can smear out the telltale discontinuities one can see when using the precipitation information direct from the radar. Radar climatology studies can be very useful for developing a map of "good" radar coverage (Breidenbach, 1999).

## 4. SUMMARY

Both meteorological and geographic information are necessary for the accurate and timely diagnoses and forecasts of flash floods. In addition to the rain that falls, forecasters need to anticipate the runoff characteristics once the water is on the ground. Information about the basins is critical for forecasting the localized nature of the phenomenon.

In many areas, radars are vital for providing high-resolution rainfall information. Basin information is often from a variety of sources. GIS and mapping tools, such as those used in FFMP, can assist with displaying basin information with the rainfall information. To date, the NWS FFG values are not typically good at delineating special-case basins, such as urban areas and fire scars. The NWS forced flash flood guidance GUI can assist forecasters with changing FFG to more appropriate values in special-case basins.

Of the four cases mentioned in this manuscript, two demonstrated the importance of understanding radar-derived rainfall and recognizing its limitations. In the Kansas Turnpike case of 30 August 2003, unusually efficient warm-rain processes caused large underestimation of rainfall when using the default Z-R relationship. The tropical Z-R relationship provided more realistic rainfall rates for this storm. In the Peeks Creek, North Carolina case from 16 September 2004, the rain band from Hurricane Ivan was obscured by high terrain between the radar and the site of the flash flood. The underscores the need to have mapping tools reminding forecasters where radar beam blockage is likely to cause large underestimation of rainfall. In these areas alternate sources of precipitation data, such as rain gauges and satellite, need to be used.

Two other cases show the impact of urbanization on runoff. In the Las Vegas, Nevada case of 19 August 2003 a small area in the northwestern part of the city experienced rapid-onset flash flooding from a relatively short but intense rainstorm. In this case the road grid and stormwater systems helped convey water rapidly through the small basins. In the Richmond, Virginia case of 30 August 2004, some of the most heavily urbanized basins in the city were inundated by floodwater. This case illustrates how FFG can be quite inappropriate for urban basins unless it is adjusted to account for increase runoff efficiency in a city.

## 5. ACKNOWLEDGEMENTS

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## 6. REFERENCES


Breidenbach, J. P., D.J. Seo, P. Tilles and K. Roy, 1999: Accounting for radar beam blockage patterns in radar-derived precipitation mosaics for River Forecast Centers. *Preprints, 15th Int. Conferece on Interactive Information Processing Systems (IIPS) for Meteorology, Oceanography, and Hydrology,* AMS, 179-182.

Chin, A., and K. Gregory, 2001: Urbanization and adjustment of ephemeral stream channels. *Annals of the Association of American Geographers,* Assoc. of American Geographers, Malden, MA, pp. 595-608.

Davis, R., 2004a: The impact of tropical rainfall rates on flash flood detection. *Preprints, 22nd Conference on Severe Local Storms*, AMS, compact disk.

Davis, R., 2004b: Locally modifying flash flood guidance to improve the detection capability of the Flash Flood Monitoring and Prediction program. *Preprints, 18th Conference on Hydrology*, AMS, compact disk.

Frazer, L., 2005: Paving paradise: The peril of impervious surfaces. *Environmental Health Perspectives*, National Institute of Environmental Health Science, National Institutes of Health, Research Triangle Park, NC, pp. A456-A462.

Kelsch, M., and R. Koehler, 2004: Flash flood warning technology and metrics. *Proceedings, 22nd Conference on Severe Local Storms*, AMS, paper1.5.

Lamb, J. R, 2004: The deadly debris flow in Macon County NC during Hurricane Ivan. Web presentation: http://www.erh.noaa.gov/gsp/localdat/cases/PeeksCreek/PeeksCreek.htm.

Smith, J. A., 2004: Flash flood forecasting in urban drainage basins. *Preprints, 18th Conference on Hydrology,* AMS, compact disk.

Smith, S. B., M. Churma, J. Roe, and L. Xin, 2000.: Flash Flood Monitoring and Prediction in AWIPS build 5 and beyond. *Preprints, 15th Conference on hydrology,* AMS, 229-232

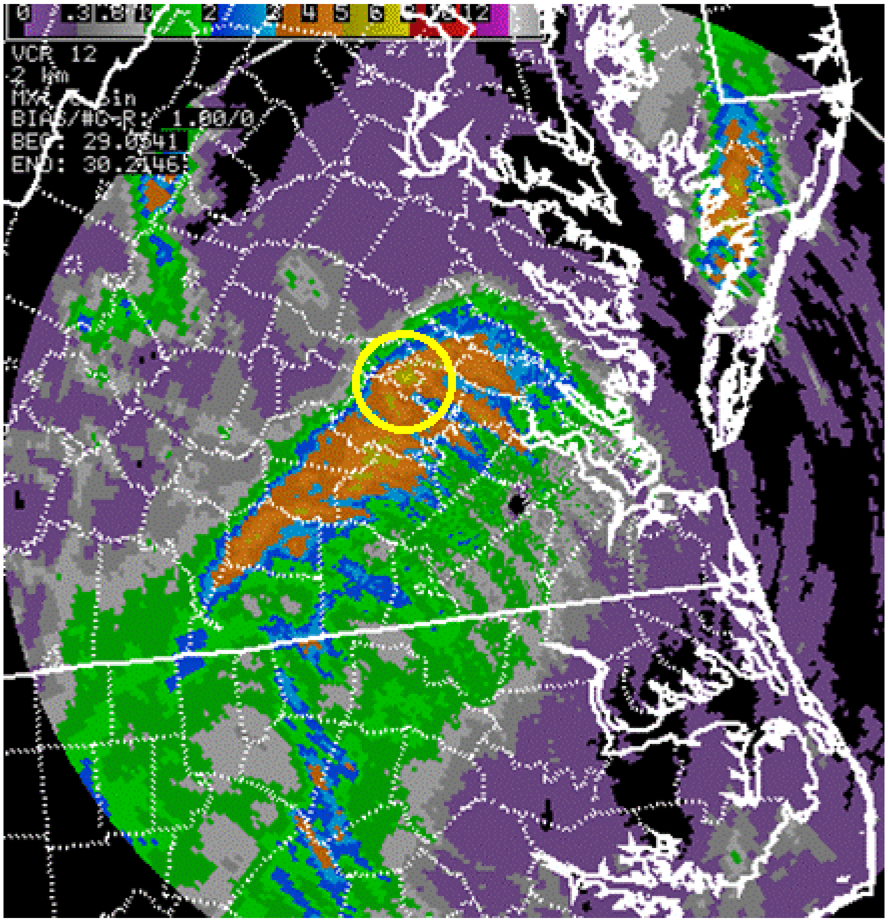


Figure 1: Radar-derived precipitation accumulation at 2146 UTC 30 August 2004. Colorbar units are inches of accumulation. Map background includes states (solid) and counties (dotted). Yellow circle locates the City of Richmond in the state of Virginia.

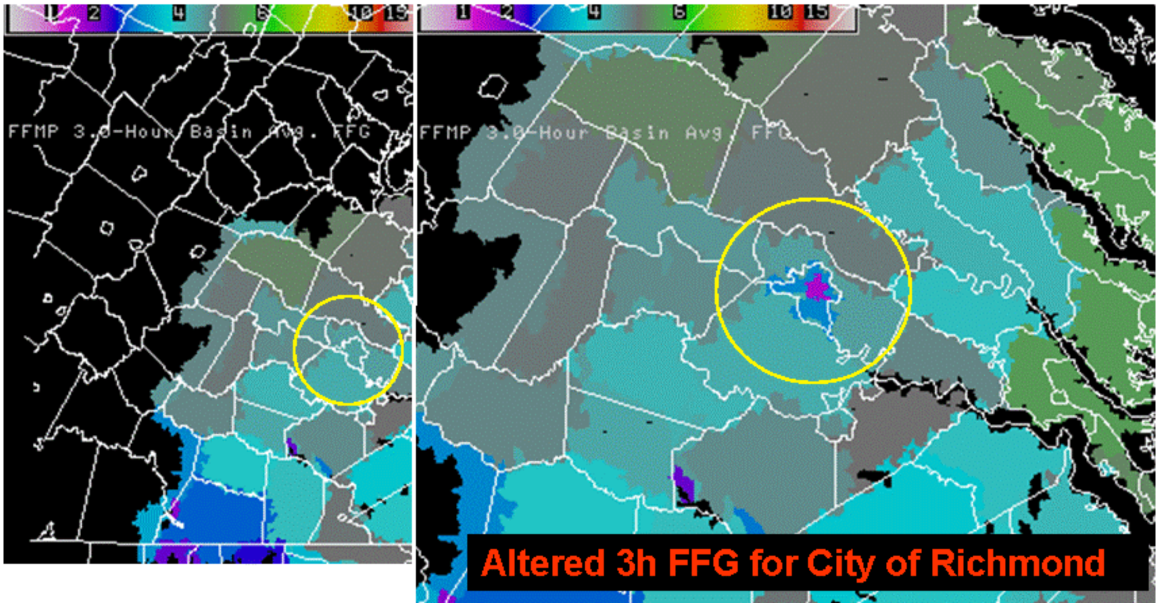


Figure 2: Three-hour Flash Flood Guidance (FFG) for 30 August 2004. Colorbar units are inches of accumulation over 3 hours. The City of Richmond is outlined in white in the middle of the yellow circle. The left side is the unaltered 3-h FFG at 4.38 inches (111 mm). The right side shows the altered 3-h FFG in the City of Richmond, with the purple at 1.6 inches (41 mm) and the blue at 3.0 inches (76 mm).

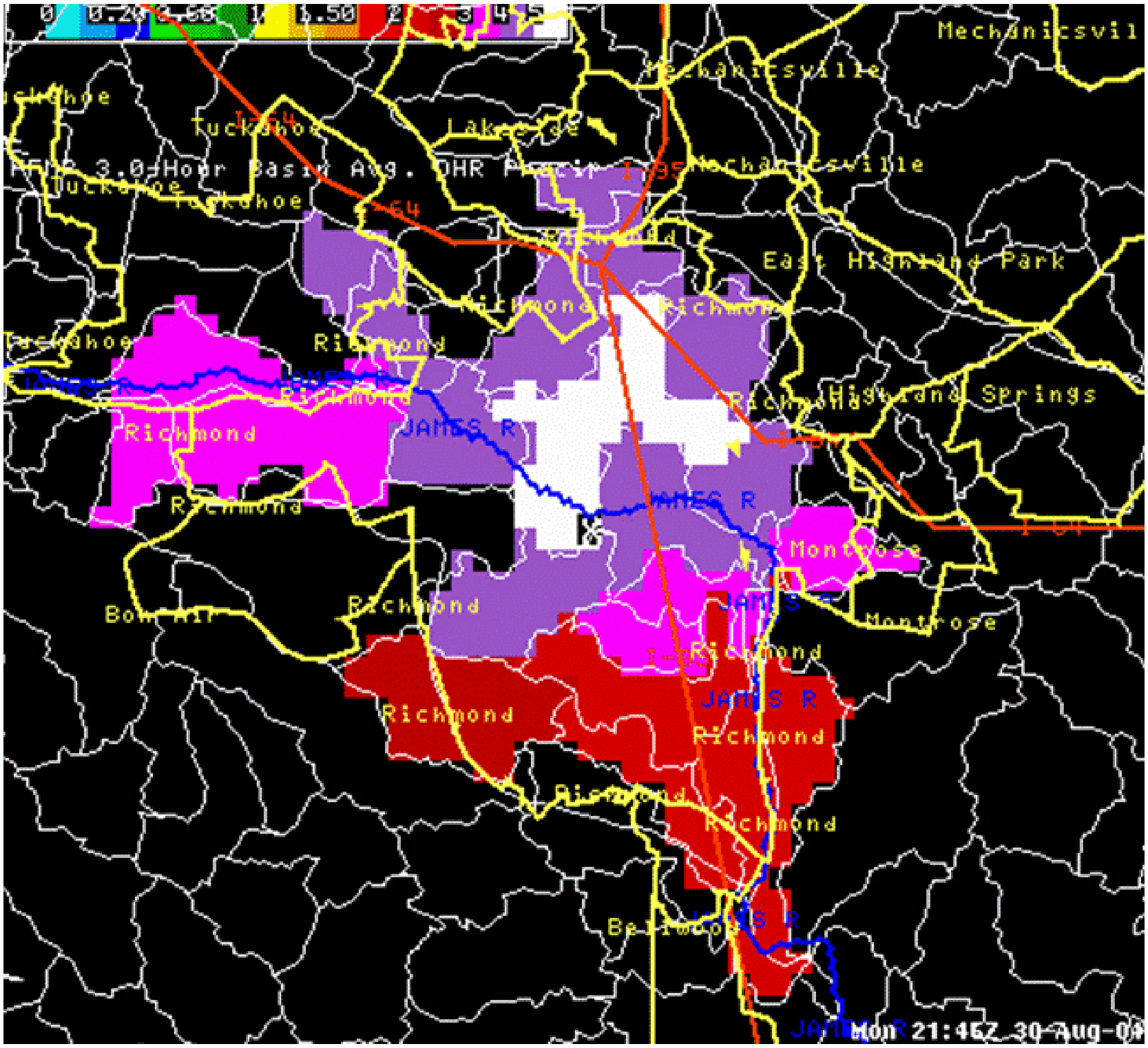


Figure 3: Three-hour basin accumulation as of 2146 UTC 30 August 2004 zoomed in on the City of Richmond. The White polygons are the drainage basins, the yellow outlines the city and its subdivisions, the red lines are interstate highways, and the blue line is the James River. Colorbar units are inches.

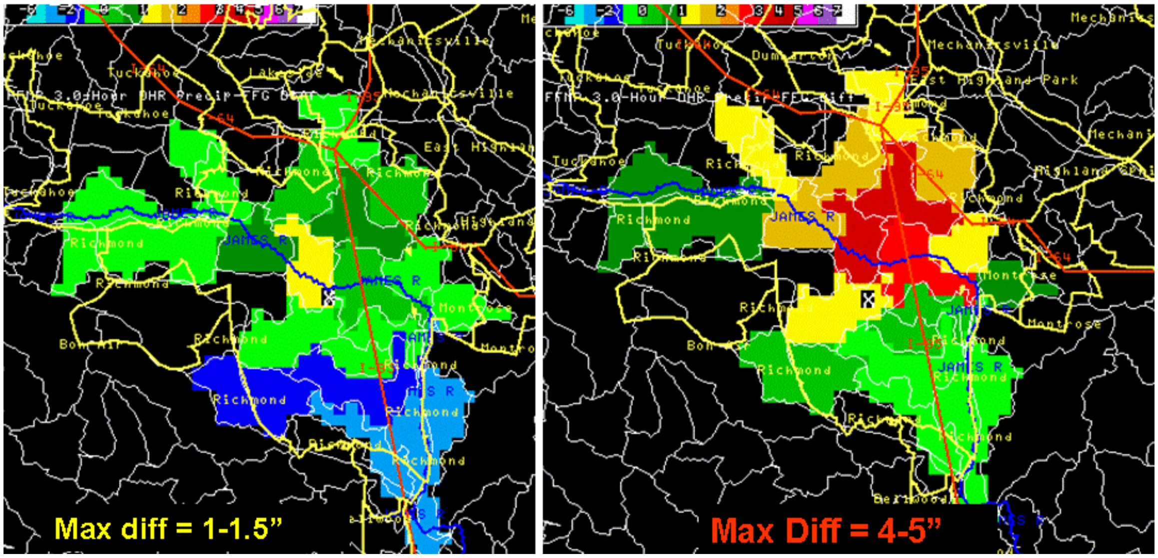


Figure 4: FFMP 3-h difference field both before (left) and after (right) the 3-h FFG was altered. Colorbar units are inches. Positive values indicate rainfall has exceeded FFG. The map background and date/time are the same as Figure 3.

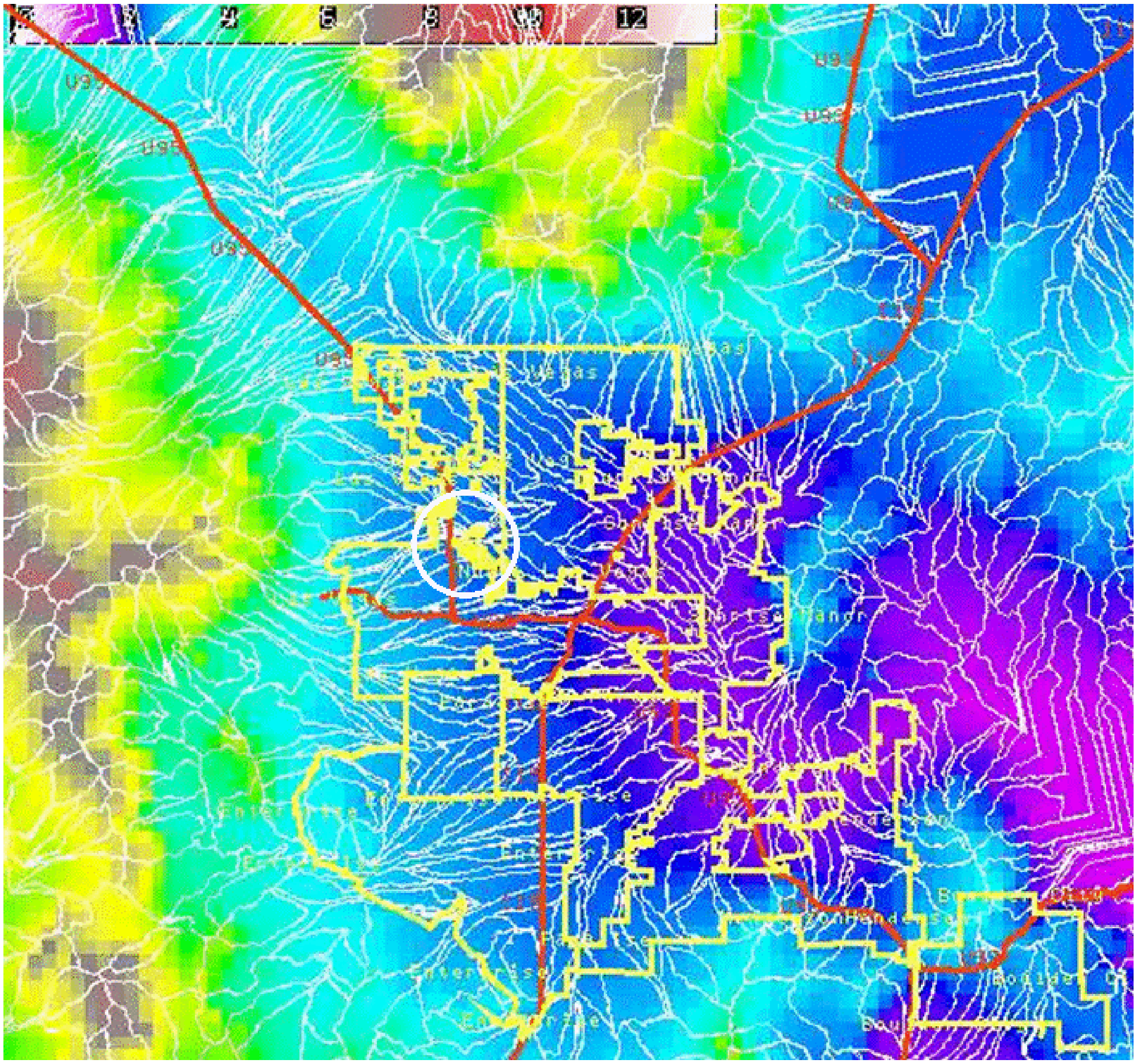


Figure 5: Topography image with basin background (white) for Clark County, Nevada. Las Vegas and its subdivisions are outlined in yellow. Major highways are in red. The white circle indicates where the worst flash flooding occurred. Colorbar units are thousand of feet.

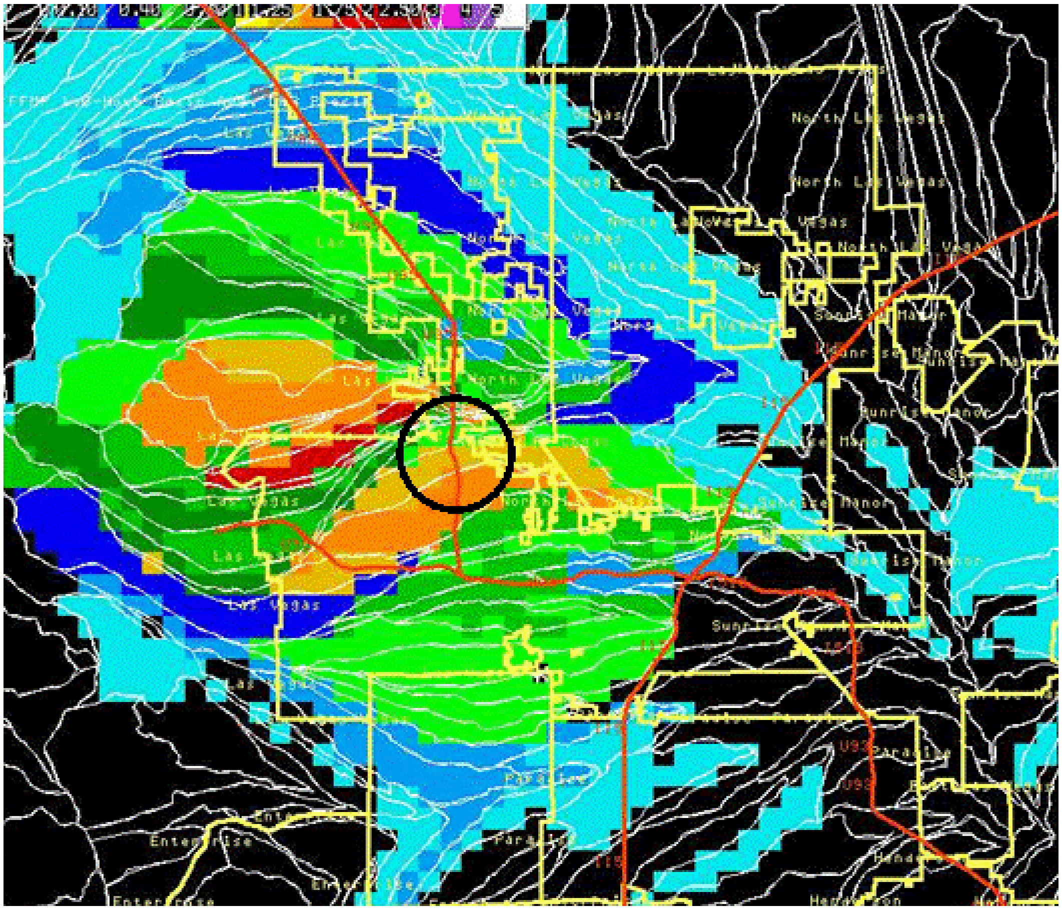


Figure 6: One-hour Las Vegas area basin accumulation (from FFMP) as of 0015 UTC 20 August 2003. Colorbar units are inches. White lines are the basin boundaries, yellow lines depict Las Vegas and its subdivisions, red lines are major highways, and the black circle is where the most severe flash flooding occurred.

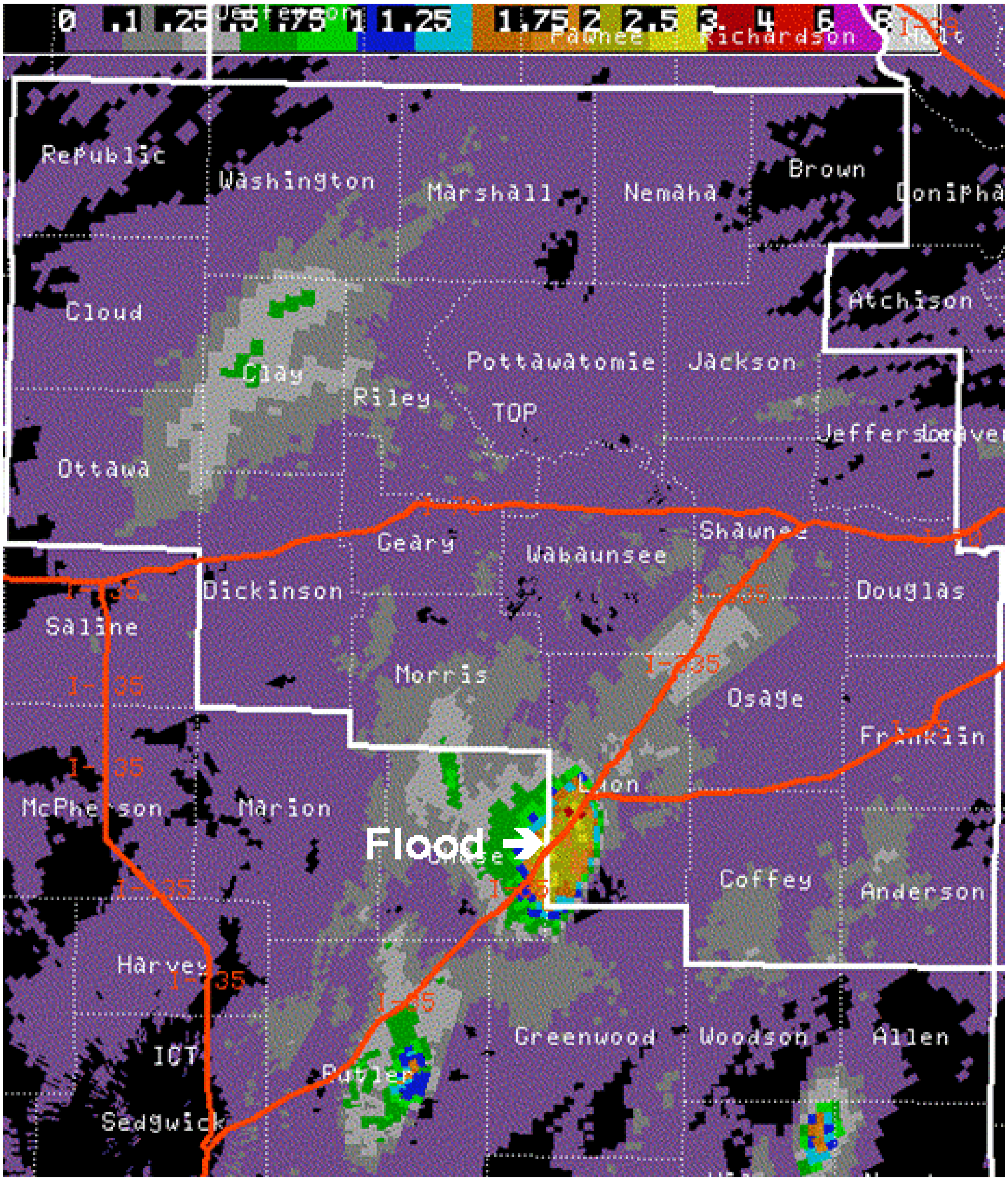


Figure 7: Radar-derived total accumulation as of 0200 UTC 31 August 2003 on county map of eastern Kansas. Colorbar units are inches. Red lines are interstate highways and the bold white line encloses County Warning Areas (CWAs) for various NWS offices.

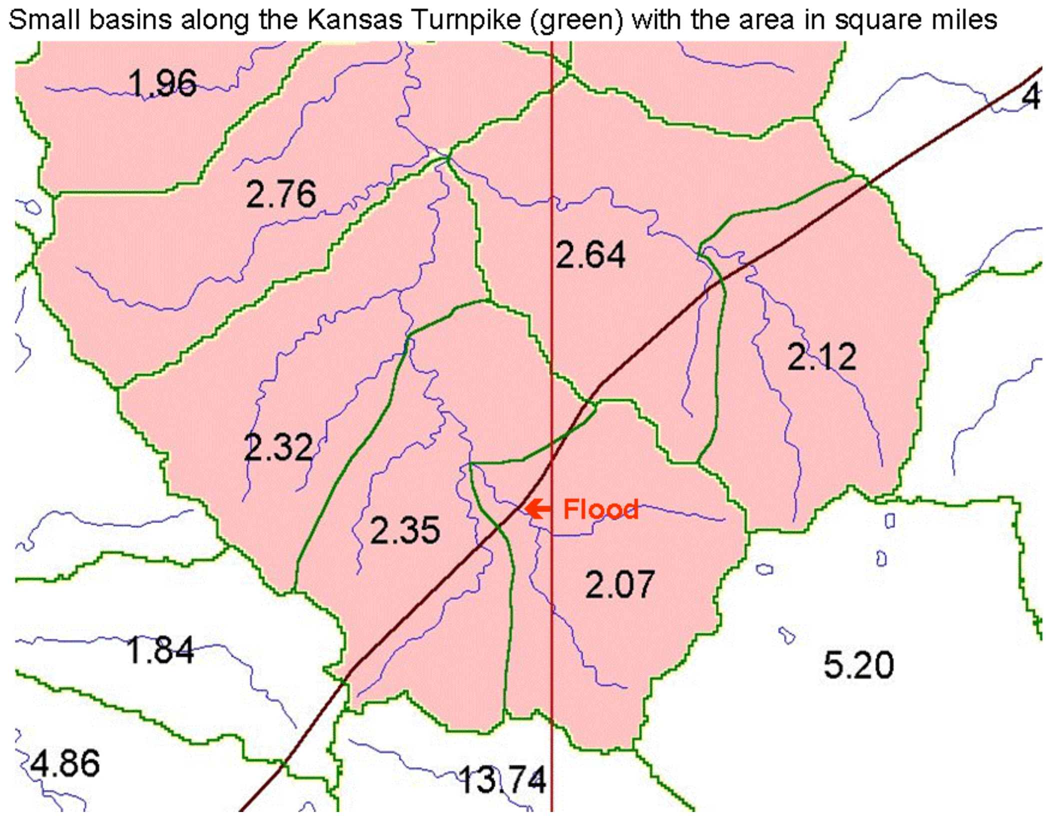


Figure 8: Basin boundaries (green) and areas (black numbers) in square miles. The rust color line is Interstate 35, or the Kansas Turnpike. The vertical red line is the boundary between Chase (left) and Lyon counties.

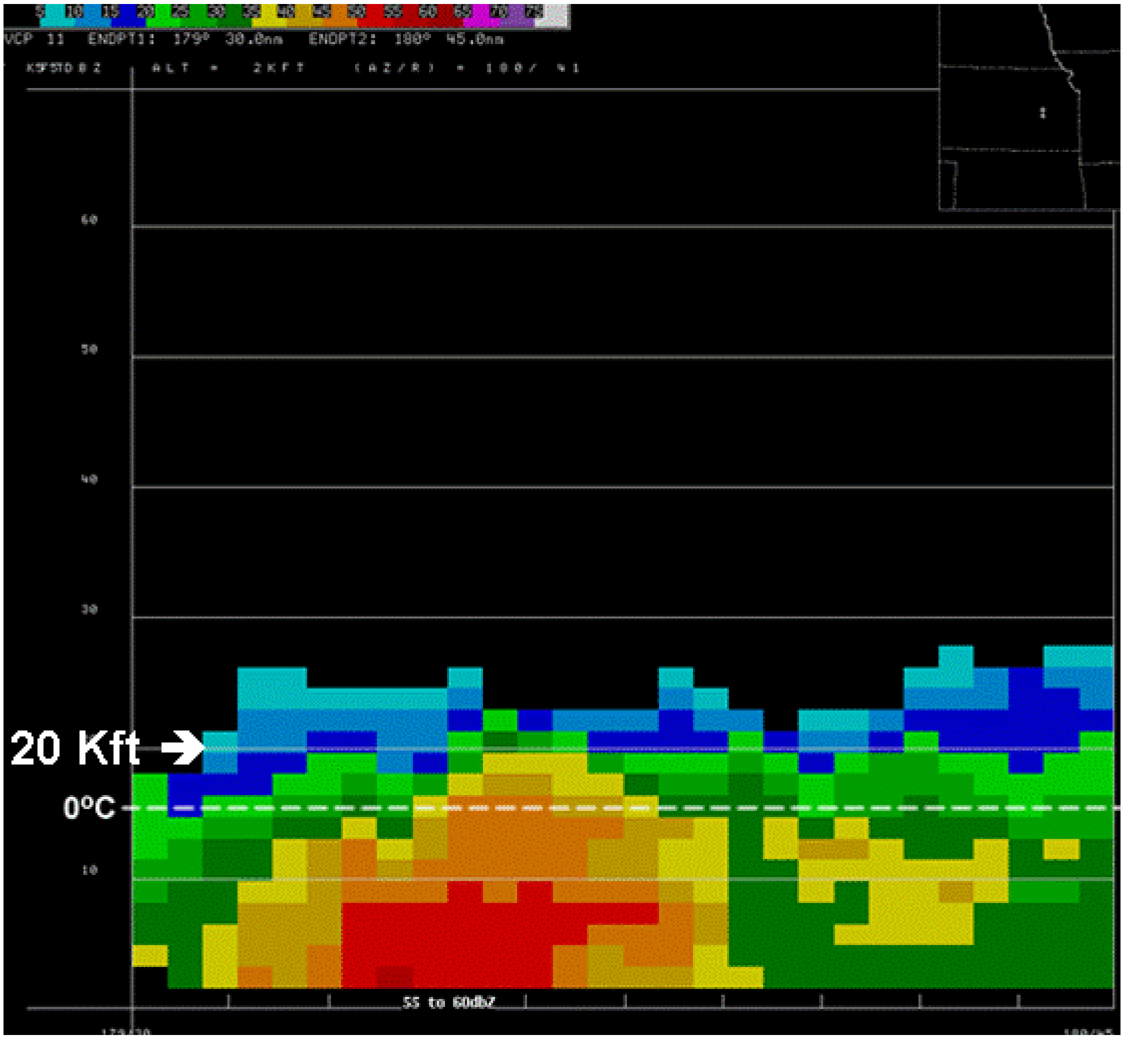


Figure 9: North-South cross section through the Kansas Turnpike Storm near the peak reflectivity time. Cross section is courtesy of Paul Schlatter at NOAA/CIMMS.

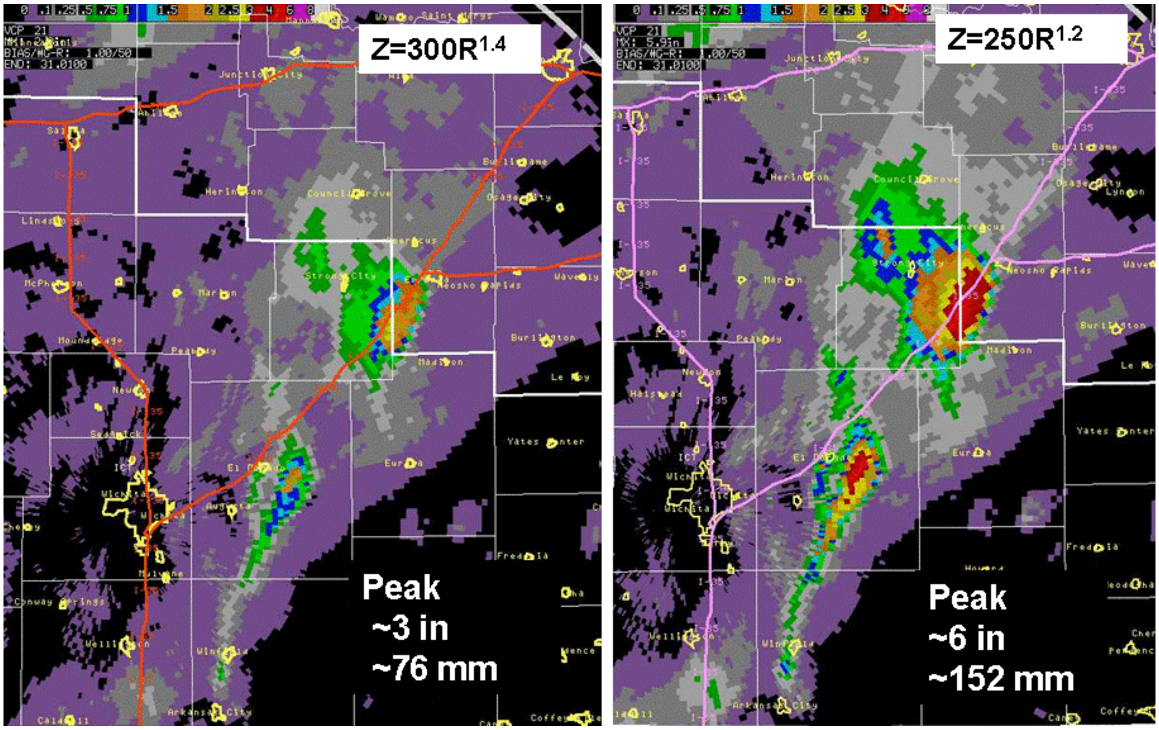


Figure 10: Comparison of radar-derived total accumulation as of 0200 UTC 31 August 2003 for the default Z-R (left) and the tropical Z-R (right). Colorbar units are inches.

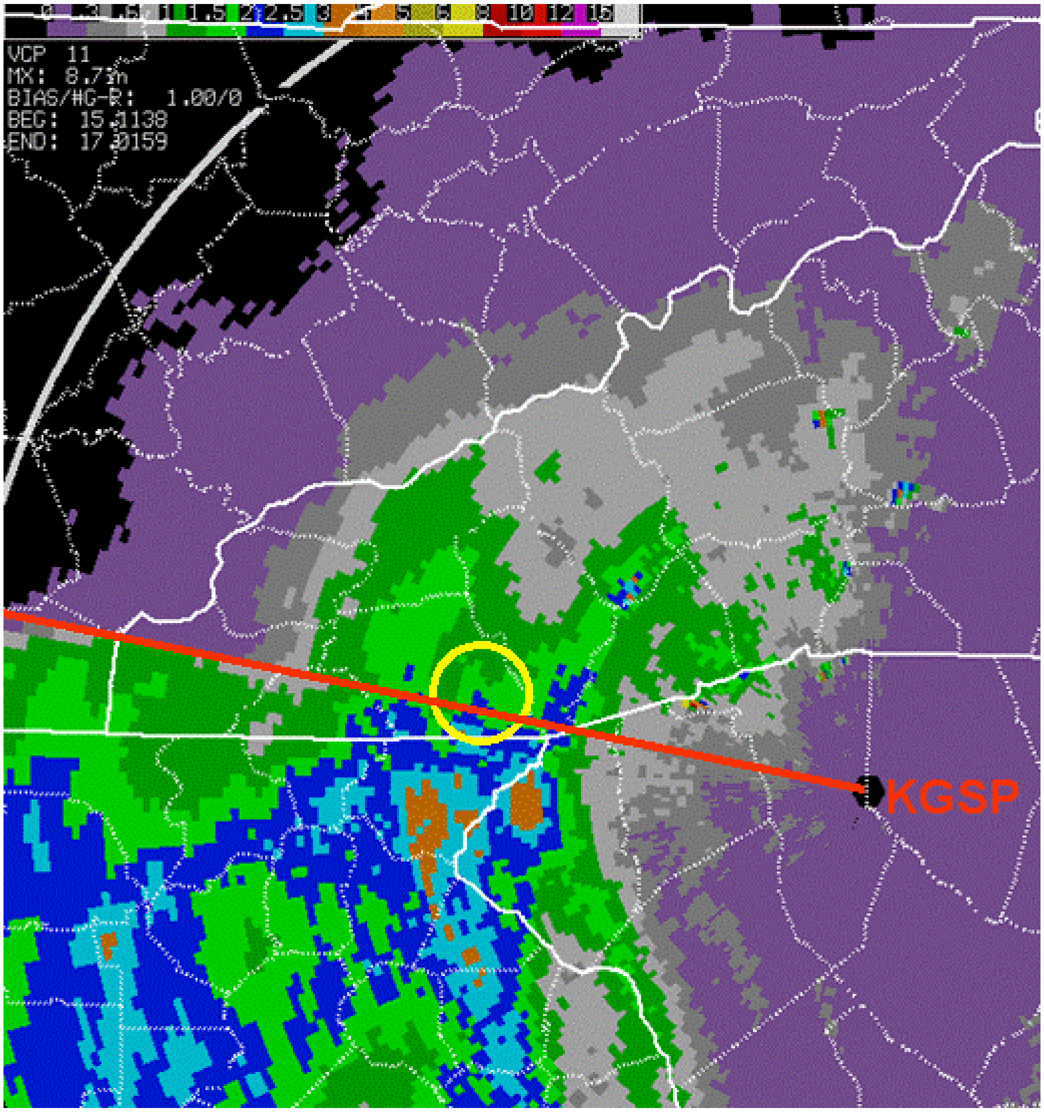


Figure 11: Radar-derived storm total accumulation as of 0159 UTC 17 September 2004 from the Greer, SC radar. Colorbar units are inches. State boundaries are bold white and county boundaries are dotted white. The Peeks Creek flood and debris flow was at the center of the yellow circle.

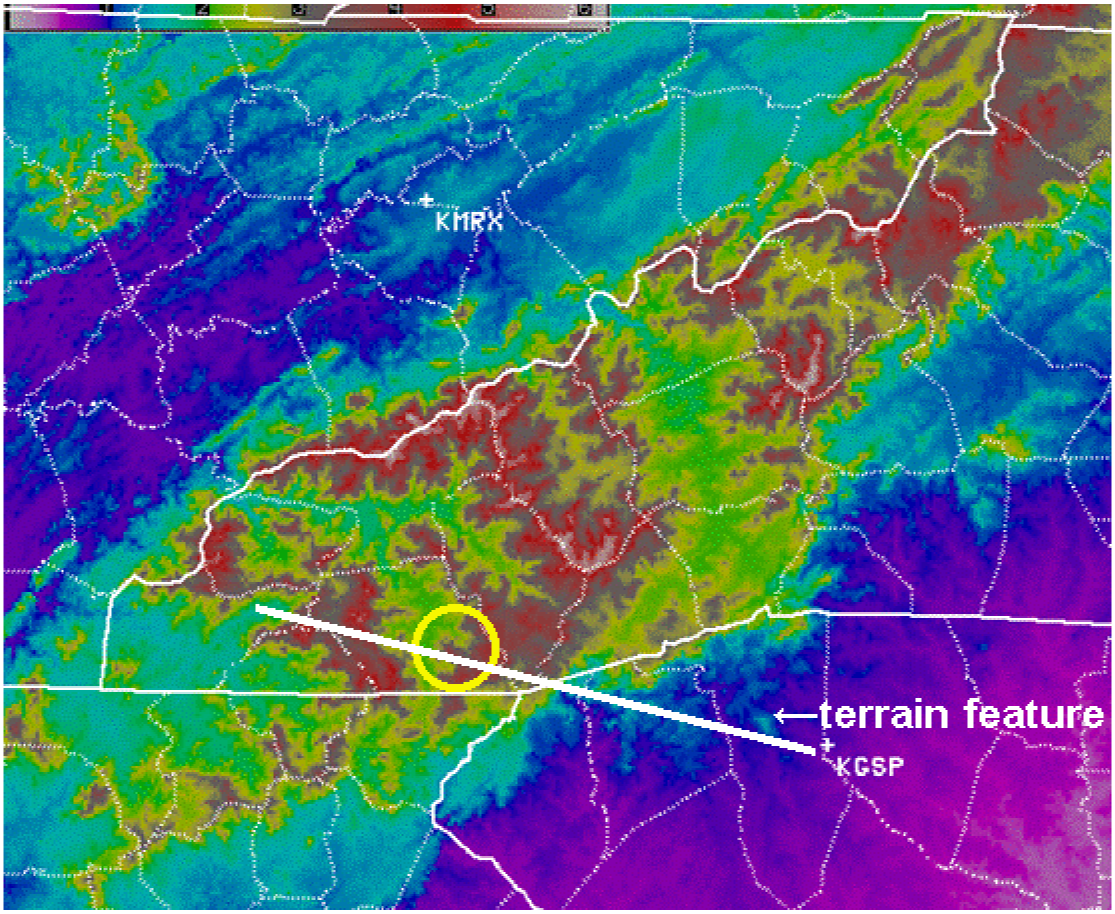


Figure 12: Topography image of western North Carolina and vicinity. Colorbar units are thousands of feet. The Peeks Creek flood and debris flow was at the center of the yellow circle.