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THE HISTORIC NORTH MISSISSIPPI FLASH FLOODS OF JUNE 2021: A FLASH ANALYSIS

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1. INTRODUCTION

Very heavy rainfall affected much of north Mississippi and east-central Arkansas over a 3-day period in early June 2021, leading to historic flash flooding over a large footprint. This flooding resulted in catastrophic agricultural losses, especially across the low-lying delta region of northwest Mississippi and southeast Arkansas. Homes and public infrastructure suffered widespread flood damage across the region. This significant flash flooding mainly affected portions of the County Warning Areas (CWA) for National Weather Service (NWS) Weather Forecast Offices (WFO) in Little Rock, Arkansas (LZK), Jackson, Mississippi (JAN), and Memphis, Tennessee (MEG). The analysis in this study will be confined to the MEG CWA (Fig. 1) which includes most of north Mississippi but also a small portion of east-central Arkansas.

Over a 72-hr period, a bulls-eye of 400-500 mm (16-20 in) of rain fell over portions of north Mississippi (Fig. 2). Meteorologists at WFO MEG issued 24 Flash Flood Warnings (FFW) across portions of east-central Arkansas and north Mississippi for excessive rainfall, with an additional FFW for a potential dam failure. Catastrophic, life-threatening flash flooding resulted in three of these warnings being classified as Flash Flood Emergencies (FFE). Numerous roads were washed out, dozens of homes were inundated, and more than 1 million acres of cropland were damaged or destroyed by floodwaters. Water rescues were performed in several communities across north Mississippi. Fortunately, injuries were minimal and there was no loss of life within the CWA during this prolonged flooding event.

The Flooded Locations and Simulated Hydrographs (FLASH) project (Gourley et al. 2017) has been a tremendous benefit to NWS meteorologists in assessing the likelihood of flash flooding. Previous studies have examined the utility of the FLASH model output in the warning processes on a national scale and provided rough thresholds to assist NWS meteorologists. The first objective of this study is to compare how well these national recommendations translate to the local scale. Verification of these potential thresholds can enhance forecaster confidence when issuing FFWs during convective operations. Some of the FLASH parameters can also assist in assessing the severity of flash flooding, offering more context than traditional metrics like quantitative precipitation estimation (QPE) and flash flood guidance (FFG). This FLASH model data can also provide guidance for determining when to upgrade a base FFW to a considerable event or an emergency.

The second objective is to provide a brief case study for this historic event, analyzing both the synoptic and mesoscale environments that led to prolonged, widespread heavy rainfall. The impacts from this flash flooding event were felt across a very large area and resulted in some of the most extreme flooding conditions the affected area has experienced in many years.

Fig.1. The County Warning Area for the National Weather Service Office in Memphis, Tennessee.

2. DATA AND METHODS

Unlike measurable quantities such as rainfall amounts or hail size, the onset of flash flooding remains a subjective determination. This subjectivity and the areal nature of flash flooding impacts can lead to uncertainty in determining precisely when and where flash flooding began. With that uncertainty in mind, it was decided to use quality-controlled flash flooding narratives from the NOAA Storm Data Publication (SD) to determine the time and location of the onset of flash flooding. Care was taken to ensure that flash flooding points reports used in

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the study were separated by at least 32 km (20 mi) and/or 90 minutes to limit oversampling of specific locations or events. A few points were removed where ongoing, significant areal flooding was exacerbated by additional heavy rainfall. This resulted in 20 unique flash flooding events to be analyzed in this study.

Once flash flood points were identified and mapped, several fields were collected from the FLASH data set using the website hosted by the National Severe Storms Laboratory (NSSL). The specific FLASH parameters analyzed were:

1) Coupled Routing and Excess Storage (CREST) maximum unit streamflow
2) Maximum precipitation average recurrence interval (ARI)
3) Maximum QPE to FFG (QPE/FFG) ratio.

The maximum ARI and QPE/FFG ratio fields are composites of the greatest values for each pixel over periods of 30-min, 1-hr, 3-hr, and 6-hr.

These data are available on a 2 km x 2 km grid, consistent with the Multi-Radar Multi-Sensor (MRMS) system that is used as the QPE input for the FLASH model. Values for the grid box identified as the location for the flash flood report from SD were put into Microsoft Excel for analysis. Values were computed for the 10th, 25th, 50th, 75th, and 90th percentiles, as well as the mean and median. These data fields were placed in a box and whiskers chart to highlight the mean, the inner quartiles, and the outliers.

There are a few caveats to consider with this analysis. First, the sample size is small and may not be sufficient to provide a broad recommendation. The authors plan to build on the current data set to increase sample points to a statistically significant number. Second, much of this flooding occurred in very rural areas and/or during the early morning hours. Timely flash flooding reports in these scenarios can often be difficult to obtain. Finally, the subjective nature of what constitutes the onset or severity of flash flooding can vary from individual to individual.

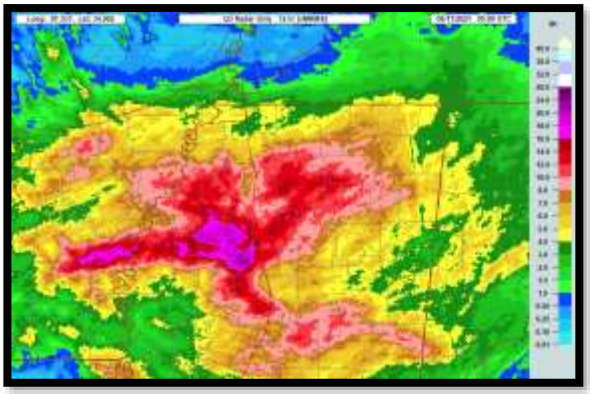


Fig. 2. MRMS v12 72-hr radar-only QPE (Q3).

3. FINDINGS

CREST maximum unit streamflow at the onset of observed flash flooding in our dataset ranged from 1.1-6.5 $m^3s^{-1}km^{-2}$ (90-600 $ft^3s^{-1}mi^{-2}$). The 25th percentile value of 2.0 $m^3s^{-1}km^{-2}$ (180 $ft^3s^{-1}mi^{-2}$) is suggested as a good lower bound estimate for FFW issuance. This finding is similar to that proposed by Gourley and Vergara (2021). Using the 25th percentile is a good compromise between a high probability of detection (POD) and a low false alarm rate (FAR). This threshold assumes zero lead time, so we do not recommend waiting until these values are reached. Instead, the forecaster must anticipate CREST maximum unit streamflow values reaching the threshold based on mesoanalysis and radar trends and issue the warning in advance.

While a few studies have looked at ARIs for specific time intervals, this study examined the maximum ARI. The maximum ARI is essentially a composite of the highest 30-min, 1-hr, 3-hr, or 6-hr value for each grid box in the domain. The maximum ARIs for this study ranged from 2 years to a maximum of 200 years. Lincoln and Thomason (2018) found that a 3-hr ARI of 2-yrs captured 90 percent of flash flooding reports. Herman and Schumacher (2018) found that ARIs outperformed both fixed thresholds and flash flood guidance, with the 1-hr ARI being the most skillful, varying between 1 and 5 years, depending on the region. Our study, using the maximum ARI, found that a threshold of 4.3 years covered 75 percent of flash flood reports with 2.7 years capturing 90 percent of reports. Thus, the values defined in this study are generally consistent with those noted above.

The QPE/FFG ratio is a simple ratio of the MRMS radar-only rainfall estimates to the FFG provided by a River Forecast Center (RFC). Traditional methods would expect flash flooding to commence when this ratio nears 100 percent, but analysis from this study indicates a slightly higher threshold is warranted. The 25th percentile is near 120 percent while the mean value is just over 150 percent. We suggest FFW consideration when QPE/FFG ratio exceeds 120 percent. It must also be noted that the issuance of new FFG (routinely updated every 6 hrs) from the RFC during the middle of a rainfall event can result in rapid maximization of this ratio so it must be used with the proper context and temporal window. These findings are shown in the box and whiskers plot in Fig. 3.

4. EVENT SUMMARY AND IMPACTS

A complex of showers and thunderstorms moved into the Mid-South during the early morning hours on 8 Jun 2021, laying down a weak outflow boundary extending from central Arkansas across north Mississippi. Deep moisture was in place across the region with precipitable water near or greater than 51 mm (2.0 in) to the south and west

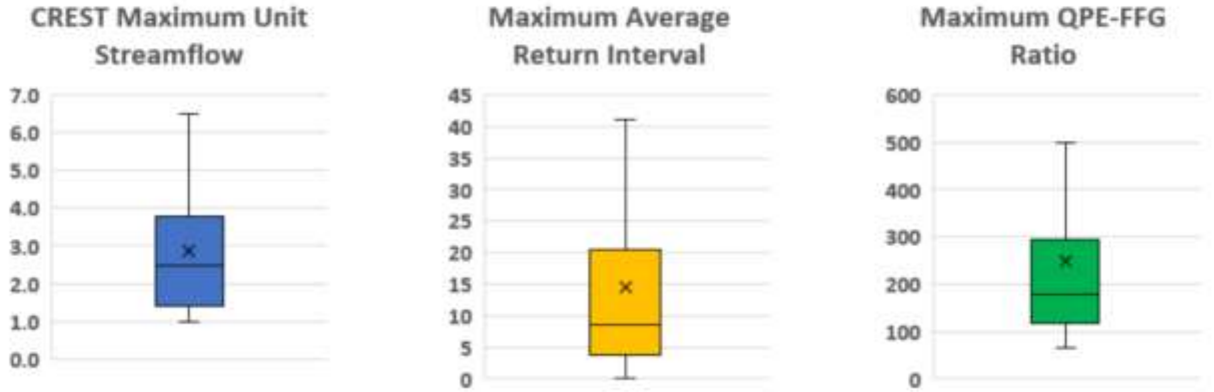


Fig. 3. Box and whiskers diagram showing the results of this study. The boxes indicate the inner quartiles (25th and 75th percentiles) with the whiskers capturing the outer quartiles.

of Memphis, Tennessee, (Fig. 4) and with surface dewpoints in the low to middle 70s. These precipitable water values were on the higher end of climatology, ranging from the 90th to the 97th percentile of the 1979-2009 Climate Forecast System Reanalysis (CFSR) climatology. Forcing for ascent was provided by differential positive vorticity advection associated with a broad trough over the middle Mississippi River Valley, enhanced by a prominent mesoscale convective vortex (MCV) over Arkansas. This MCV resulted from persistent convection associated with a mesoscale convective system (MCS) moving across the Arklatex region during the overnight hours. A modest low-level jet (LLJ) of 13 m/s (25 kts) provided anomalous poleward transport of warm and moist air, aiding in the destabilizing of the near-storm environment.

Backbuilding and training convection was anticipated using the methods described by Corfidi (1996) within a regime similar to the mesohigh archetype (Fig. 5) from Maddox et al. (1979). This pattern favors nocturnal events with a general peak during the summer months across the Southeast United States and may also be accompanied by severe weather. This persistent, backbuilding convection continued through the morning hours, gradually decreasing in coverage after 1900 UTC. This precipitation was highlighted by efficient warm rain processes and a melting level above 4,100 m (13,500 ft) AGL and presented persistent rainfall rates of 25-75 mm/hr (1-3 in/hr). Significant flash flooding was observed across north Mississippi during this period with widespread rainfall amounts of 100-200 mm (4-8 in), necessitating 8 FFWs between 1000-2000 UTC. The first FFE was issued for western Tallahatchie County where MRMS radar-only QPE indicated a rainfall maximum near 240 mm (9.5 in) over a period of 6-8 hrs. In this area, several homes were inundated with flood waters and evacuations were taking place in the community of Tutwiler, Mississippi.

Convection persisted through the afternoon and evening hours, even spawning damaging wind and a tornado just to the south and west of Tupelo, Mississippi. There was a brief downward trend in convection during the early evening, but showers and thunderstorms began to redevelop along residual outflow boundaries by 0400 UTC as the LLJ intensified. The LLJ was somewhat weaker at 10 m/s (20 kts) and more veered than the previous night, but remained sufficient to support organized convection. This convection was focused to the north and east of the previous day's heavy rainfall axis, affecting the Oxford and Tupelo areas in north Mississippi. While synoptic scale forcing for ascent was weaker, very high, persistent rainfall rates and slow-moving storms provided ample rainfall across already saturated areas. Veered winds aloft resulted in storm motion vectors that allowed storms to move south of the CWA by 2100 UTC, resulting in a bit of an afternoon and evening lull. The 24-hr MRMS radar-only QPE ending at 0000 UTC 10 Jun 2021 showed another 75-150 mm (3-6 in) of rain from Oxford to Tupelo, with localized amounts near 200 mm (8 in). While no FFEs were issued on 9 Jun 2021, several homes were flooded and numerous roads were closed or washed out.

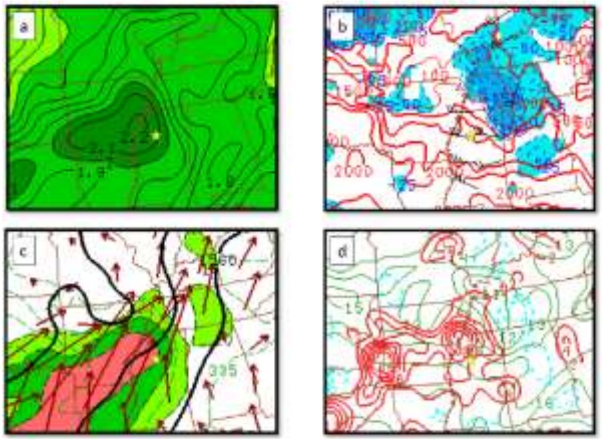
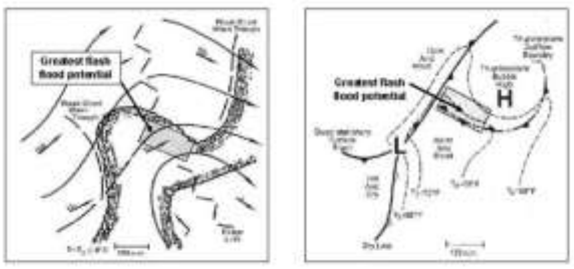


Fig. 4. 1200 UTC data from the Storm Prediction Center's mesoanalysis page. a) Precipitable water, b) Most Unstable Convective Available Potential Energy (MUCAPE), c) 850 hPa moisture transport vectors, and d) deep-layer moisture convergence and 100 hPa mean mixing ratio.



Midlevel Schematic **Surface Schematic**

Fig. 5. The mesohigh archetype from Maddox et al. (1979) is a common pattern favorable for heavy rainfall in the warm season.

Nocturnal convection ramped up again during the overnight period on 10 Jun 2021 along a remnant outflow boundary extending from east-central Arkansas into northwest Mississippi. This convection became anchored along a corridor from St. Francis County in Arkansas through Tallahatchie County in Mississippi, producing heavy rainfall across some of the same areas affected just 2 days prior. Antecedent conditions were primed for flash flooding with CREST soil saturation generally between 50-60 percent. A slow-moving, backbuilding complex of thunderstorms with significant rainfall rates of 50-100 mm/hr (2-4 in/hr) affected these areas for several hours, primarily between 0600-1500 UTC. MRMS 6-hr radar-only QPE ranged from 125-250 mm (5-10 in) by 1100 UTC in southern Quitman County and much of central and eastern Tallahatchie County. The FLASH model data during this event was very impressive with CREST maximum unit streamflow increasing to more than 12 $m^3s^{-1}km^{-2}$ (1,100 $ft^3s^{-1}mi^{-2}$), suggesting significant runoff was occurring across an already saturated area. Multiple FFEs were issued during the early morning hours as water began infiltrating homes, submerging roads, and threatening to breach flood-control levees. In fact, a few of these levees failed, resulting in widespread flooding of significant crop acreage. This third wave of heavy rainfall produced additional amounts of 200-300 mm (8-12 in).

The cumulative 3-day rainfall totals were devastating across north Mississippi. A significant portion of north Mississippi received 150-300 mm (6-12 in) of rainfall with locally higher totals. Tallahatchie and Quitman Counties were the epicenter of the event with 3-day totals up to 500 mm (20 inches). Fortunately, there were no deaths or significant injuries attributed to this flash flooding event. However, widespread impacts were felt across north Mississippi and portions of east-central Arkansas. At least 95 homes and 8 businesses were damaged by flood waters in the CWA for WFO MEG alone. More than 200 roads were closed (or washed out) and the impacts to local agriculture were catastrophic. The Mississippi State University Extension Service estimated agricultural losses from this flooding event will exceed $839 million with more than 1.5 million crop acres damaged or destroyed (Mills, 2021).

5. CONCLUSIONS AND FUTURE WORK

The suite of FLASH products available to NWS forecasters has become an invaluable tool in the flash flood warning decision-making process (Martinaitis et. al. 2017). Traditional methods for flash flooding detection primarily relied on static thresholds based on rainfall estimates with some local knowledge of land use or topography. These new tools can offer a much broader context as to what is happening to this rainfall after it reaches the surface. The capability to model runoff in near real-time with streamflow and unit streamflow products is a significant benefit. This study attempted to calibrate nationally recommended thresholds for the onset of flash flooding by analyzing FLASH model data during a multi-day flash flooding event across north Mississippi and east-central Arkansas. We looked specifically at CREST maximum unit streamflow, maximum precipitation ARI, and maximum QPE/FFG ratio.

We chose the 25th percentile of FLASH model fields to determine local threshold recommendations for the onset of flash flooding. The CREST maximum unit streamflow analysis matches well with that of Gourley and Vergara (2021), indicating that an adequate threshold for the onset of flash flooding was 2.0 $m^3s^{-1}km^{-2}$ (180 $ft^3s^{-1}mi^{-2}$) or greater. A maximum QPE/FFG ratio of 120 percent or greater is recommended for FFW issuance. We also examined the maximum ARI and found that a value of 4.3 years captured 75 percent of the flash flooding reports while 2.7 years included 90 percent. (See Table 1).

We would like to add a note of caution when using ARIs to assess the likelihood of flash flooding. ARIs are determined based on rainfall frequency values from NOAA Atlas 14 and are not correlated with past flash flooding events. ARIs also have no relation to antecedent conditions or FFG in general. With that in mind, it is the authors recommendation to rely on ARIs to assess the rarity of rainfall estimates compared to climatology to add context to the event.

FFEs were issued for catastrophic flash flooding that constituted a significant threat to life and property. These emergencies were typically included in subsequent warnings and statements where ongoing flash flooding was exacerbated by additional heavy rainfall. CREST maximum unit streamflow values with these FFEs generally exceeded 10.9 $m^3s^{-1}km^{-2}$ (1,000 $ft^3s^{-1}mi^{-2}$) with maximum QPE/FFG ratios near 300 percent and maximum ARIs of well over 100 years.

There are a few caveats to consider. As stated previously, these thresholds are based on the onset of observed flash flooding and would offer little to no lead time as a prognostic tool. It is imperative to anticipate these thresholds being met in advance based on proper mesoanalysis, rainfall trends, and antecedent conditions. Future work should include expanding this study to cover all of WFO MEG's area of responsibility over a period of a few years. This should be sufficient to ensure the sample size is large enough to provide valid results that can be used in warning operations. We also did not examine the impact of rainfall rates in this study. It is well understood that extreme rainfall rates can overwhelm drainage systems rapidly and lead to flash flooding on shorter time scales, especially in urban settings in in flashy topography.

FLASH Parameter	Recommended FFW Thresholds
CREST maximum unit streamflow	**> 2.0 $m^3s^{-1}km^{-2}$ (> 180 $ft^3s^{-1}km^{-2}$)[†]**
Maximum ARI	**4.3 years[‡]**
Maximum QPE/FFG ratio	**> 120 %**

Table 1. Recommended FLASH thresholds for the onset of flash flooding. Waiting for these values to be reached will limit or preclude lead time, so forecasters must anticipate these thresholds being met.

Other FLASH model fields of importance that were not specifically addressed in this study were CREST maximum streamflow, CREST soil saturation, and the streamflow and soil saturation products from the Sacramento Soil Moisture Accounting Model (SAC-SMA), a counterpart of the CREST model. Future studies may consider examining these fields. Antecedent conditions are a significant contributing factor in flash flooding events and should always be considered before and during heavy rainfall. In addition, augmentation of the unit streamflow field with streamflow can assist in showing which direction surface water is moving. This can help forecasters more readily determine potential downstream or down basin impacts where QPE may be unrepresentative of the flash flooding threat.

Flash flooding reports are often untimely or may even be unreported in rural areas, especially during the overnight period. The combination of these factors does increase uncertainty in the onset time and location of reported flash flood events. Finally, this study only analyzed FLASH data for observed flash flooding reports, so null cases were not included. This omission could have significant implications on the FAR if the results are used in warning operations. Future work should also focus on the addition of null cases to the database.

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[†] Imperial units are used in AWIPS by NWS forecasters.

[‡] It is recommended to use ARI to assess the rarity of an event, not as a proxy for flash flooding.

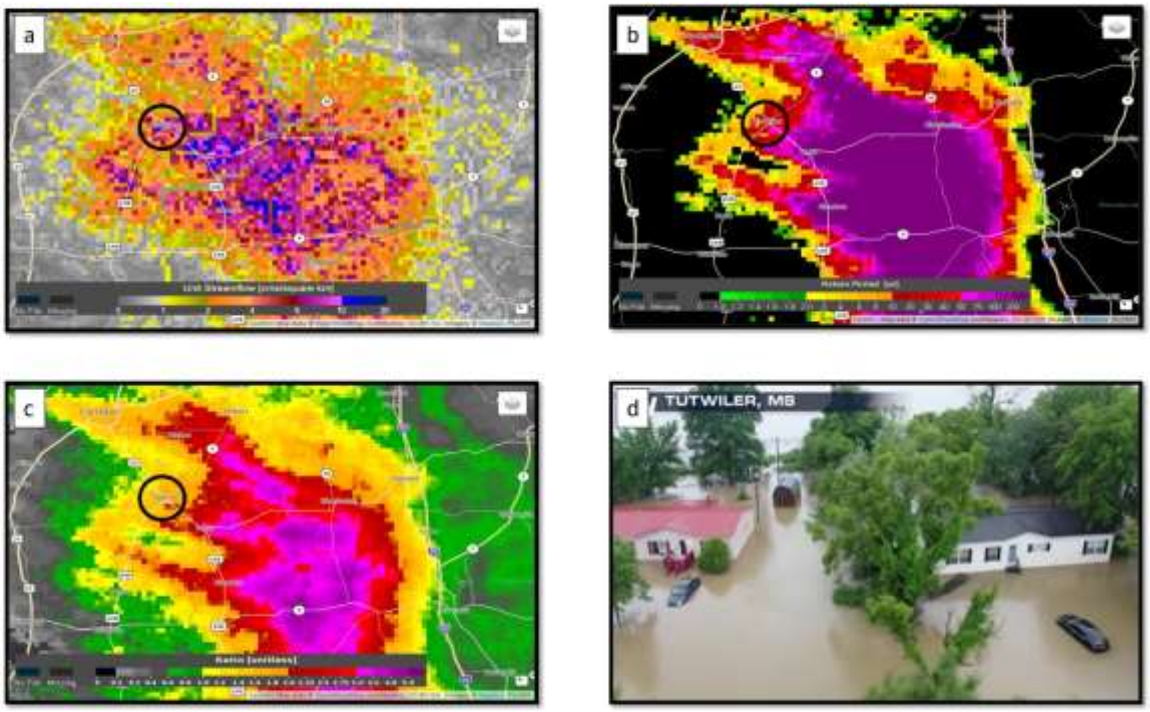

Fig. 7. A comparison of the FLASH variables and ground truth during a Flash Flood Emergency. a) CREST maximum unit streamflow, b) maximum ARI, c) maximum QPE/FFG ratio from 1400 UTC 10 Jun 2021. d) Widespread flash flooding ongoing in Tutwiler, Mississippi. Photo courtesy of WeatherNation.

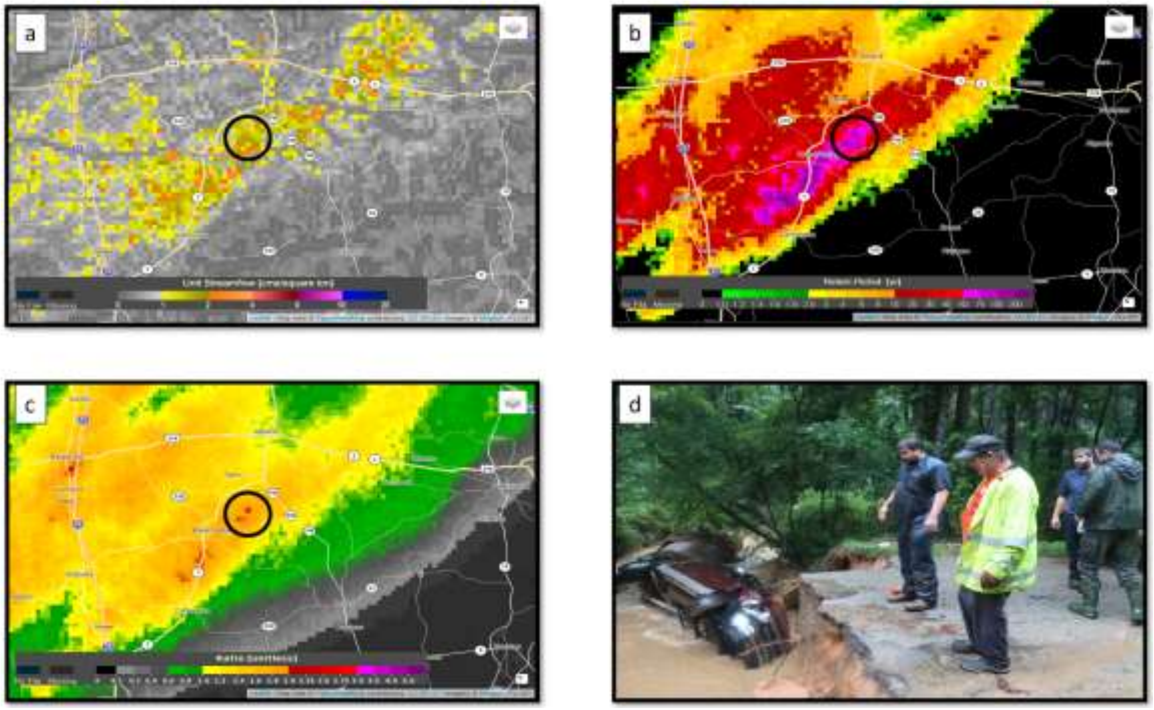

Fig. 8. A comparison of the FLASH variables and ground truth during a Flash Flood Warning. a) CREST maximum unit streamflow, b) maximum ARI, c) maximum QPE/FFG ratio from 1700 UTC 8 Jun 2021. d) Flash flooding along County Road 224 east of Water Valley, Mississippi, washed out a bridge and swept this vehicle into the creek. Photo courtesy of the North Mississippi Herald.