P1.7

MONITORING RAINFALL AND PREDICTING FLASH FLOODING: INTEGRATING OBSERVATION NETWORKS AND RADAR DATA

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1. INTRODUCTION

The spring and summer of 2007 brought an extended period of heavy rainfall to north Texas. Flash flooding resulted in over a dozen deaths and millions of dollars in property damage. Runoff from the heavy rains eventually led to significant mainstream river flooding. Tools such as real-time rainfall networks with high temporal resolution, traditional rainfall networks, flooded roadway sensor data, and radar rainfall estimates were used by National Weather Service forecasters. Data from several events in June 2007 will be used to illustrate the marriage of in situ and remote sensing data. This paper will discuss how the integration of these tools improved the warning process.

2. NORTH TEXAS FLOODING 18 JUNE 2007

Heavy rainfall resulted in numerous flash flood events (see Appendix) across portions of north Texas (Fig. 1) during the spring and summer of 2007. The National Weather Service (NWS) Weather Forecast Office in Fort Worth, TX issued 156 flash flood warnings during the month of June 2007. Some of the most significant flooding occurred on 18 June 2007 as a series of atmospheric and localized conditions worked in tandem to create destructive flooding across portions of north Texas. Six people died on 18 June in the Haltom City, Gainesville, and Sherman/Denison areas with monetary damages totaling over $50 million.

2.1 *Atmospheric Conditions*

A strong mid- and upper-level shortwave trough moved into the south central Plains during the evening of 17 June and early morning hours of 18 June. Rapid Update Cycle (RUC) model analysis (0 hr) (Benjamin et al. 2004), WSR-88D VAD wind profiles (VWPs), and NOAA regional wind profilers from 1200 UTC depicted a compact shortwave trough across the south central Plains (Fig. 2).

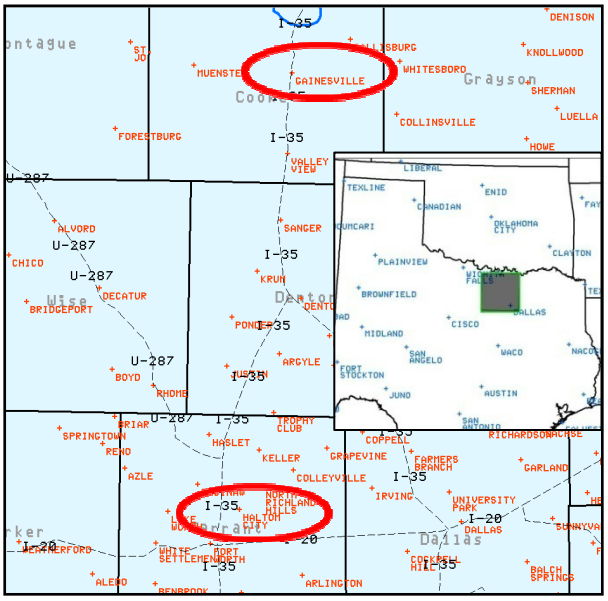

Fig. 1. Map of north Texas showing locations (Gainesville, TX and Haltom City, TX circled in red) that received severe impacts from 18 June 2007 flooding. Inset map of TX and OK indicates area shown in figure.

The Fort Worth, TX (KFWD) soundings of 18 June indicated large amounts of precipitable water, with 46.9 mm (1.85 in) observed at 0000 UTC (Fig. 3), and 43.7 mm (1.72 in) observed at 1200 UTC (Fig. 4). These amounts were almost 2 standard deviations above normal (Fig. 5) (Bunkers 2006). Integrated Precipitable Water (IPW) amounts derived via satellite from changes in global positioning signals (GPS) were used as an additional measure of measuring atmospheric moisture across north Texas. Those values estimated for sites across the region were also unseasonably high on the morning of 18 June (Table 1).

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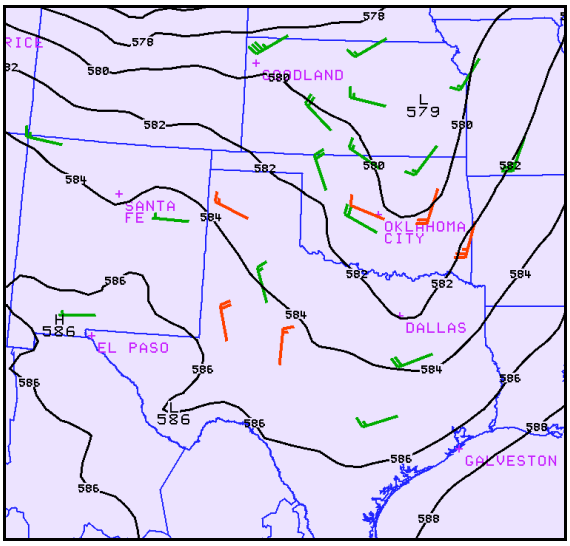

Fig. 2. RUC model analysis (0 hr) of 500 hPa heights (black contours), VWPs at 500 hPa in orange barbs, and NOAA wind profilers at 500 hPa in green barbs for 1200 UTC 18 June 2007. Wind speeds in knots.

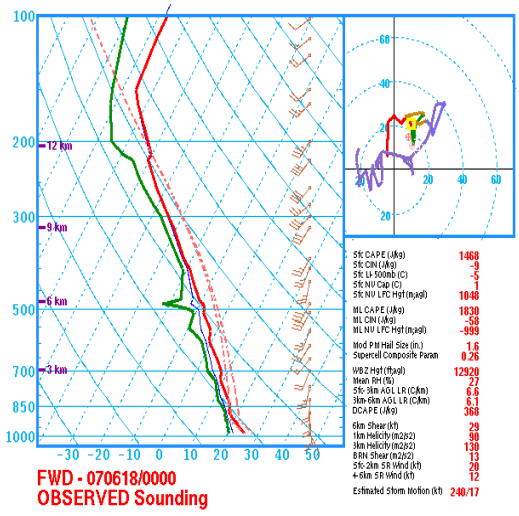

Fig. 3. KFWD sounding for 0000 UTC 18 June 2007 (Courtesy Storm Prediction Center).

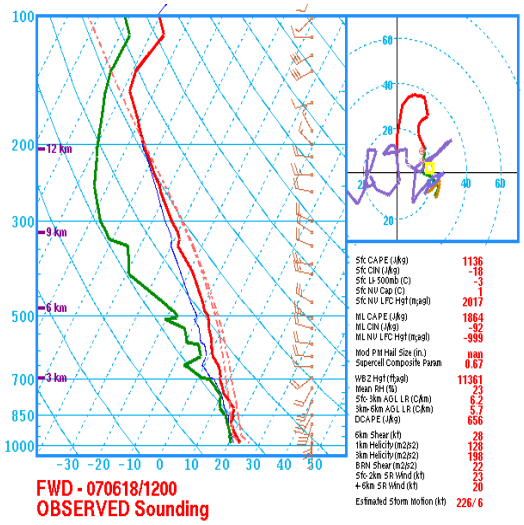

Fig. 4. KFWD sounding for 1200 UTC 18 June 2007 (Courtesy Storm Prediction Center).

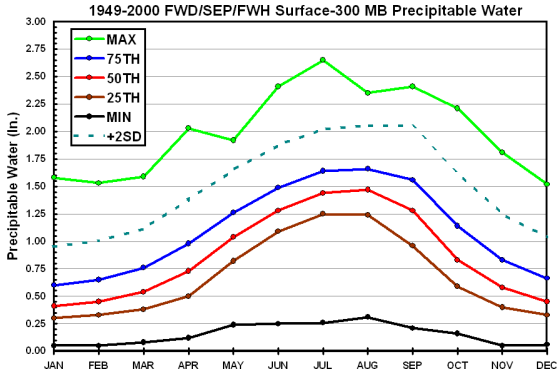

Fig. 5. Annual variation in climatological precipitable water values for north Texas from 1949-2000. Units in inches (from Bunkers 2006).

Table 1. Integrated Precipitable Water values from 18 June 2007. Missing data from Denton likely due to thunderstorms in the vicinity (from NOAA Global Systems Division website).

Hour (UTC)	Denton, TX (TXDE)	Paris, TX (TXPA)	Waco, TX (TXWA)
0615	2.05 in (5.21 cm)	1.95 in (4.96 cm)	1.84 in (4.68 cm)
0715	2.03 in (5.15 cm)	1.94 in (4.92 cm)	1.85 in (4.70 cm)
0815	--------	1.99 in (5.05 cm)	1.88 in (4.77 cm)
0915	--------	2.05 in (5.21 cm)	1.91 in (4.85 cm)
1015	--------	2.02 in (5.13 cm)	1.94 in (4.94 cm)
1115	--------	1.96 in (4.99 cm)	1.92 in (4.88 cm)
1215	--------	1.90 in (4.83 cm)	1.89 in (4.79 cm)

RUC model analysis (0 hr) pinpointed a mid-level absolute vorticity maximum near the base of the 500 hPa trough between 0900 UTC (Fig. 6) and 1200 UTC, which gradually moved northeast through the early morning hours. The most intense convection during the overnight period was concentrated in the vicinity of this mid-level vorticity maximum.

NOAA wind profilers measured a southerly low level jet at 850 hPa of 12.8 to 15.4 m s^{-1}, which veered to the southwest between 0500 UTC and 0700 UTC. The low level jet continued to veer and increased to near 20 m s^{-1} by 1200 UTC (Fig. 7). Winds at 925 hPa were also strong, measured at 15.4 to 18.0 m s^{-1} from the south southwest through the overnight hours. The strong low level jet assisted with maintaining a feed of moisture and instability for the thunderstorms. Storm Prediction Center hourly analyses (Bothwell et al. 2002) indicated mixed layer CAPE values near 1000 J kg^{-1} across north Texas at 1100 UTC (Fig. 8). Dewpoint temperatures at 850 hPa of 16°C at 1100 UTC were also noted near the heavy rains over north central Texas (Fig. 9). Wind profilers, the VWP from KFWS, and 0000 UTC and 1200 UTC Fort Worth soundings also depicted the strongest winds (15.4 to 20.5 m s^{-1}) within a layer from the surface to approximately 700 hPa, with lighter winds (7.7 to 10.3 m s^{-1}) higher in the column. Therefore, the strongest vertical wind shear was concentrated in the lowest 3 km.

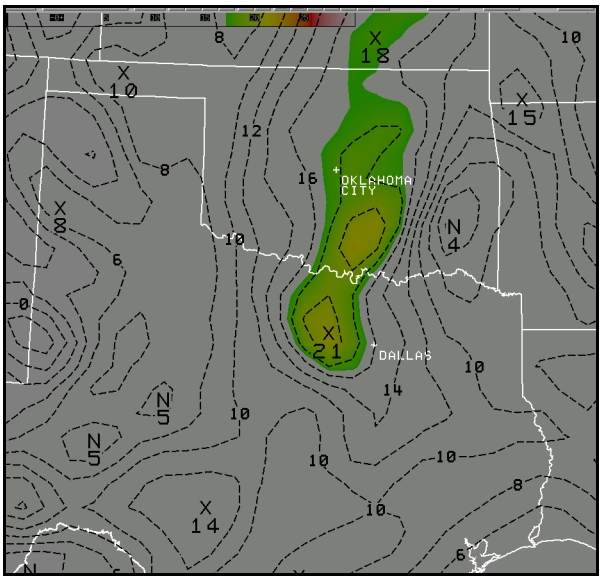

Fig. 6. RUC model depiction (0 hr) of 500 hPa absolute vorticity (black dashed contours) at 0900 UTC 18 June 2007. Highest values of absolute vorticity in yellow and green shading (17 to 21 x 10^{-5} s^{-1}) were aligned roughly along the Interstate 35 corridor from south central Oklahoma into north Texas.

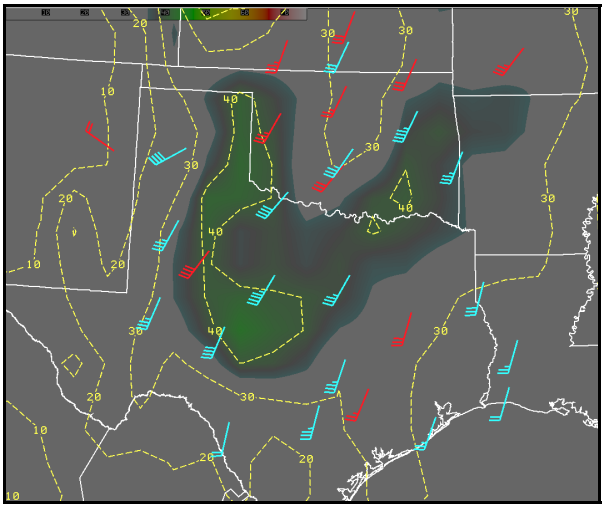

Fig. 7. RUC model depiction (0 hr) of 850 hPa winds at 1200 UTC 18 June 2007 with wind magnitude in green and blue shading and isotachs in yellow dashed contours. Wind barbs from VWPs are in blue and barbs from NOAA wind profilers are in red. Wind speeds in knots.

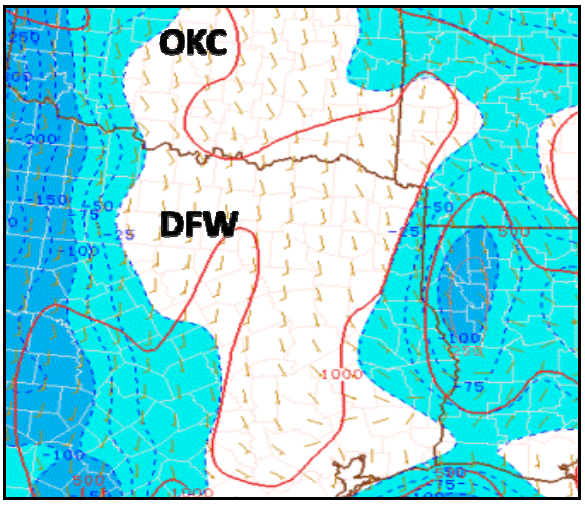

Fig. 8. Storm Prediction Center mesoanalysis of ML CAPE and CIN from 1100 UTC 18 June 2007. Red contours indicate ML CAPE (values of 500 and 1000 J kg^{-1}), while blue dashed contours and shades of blue and green indicate CIN. Oklahoma City, OK (OKC) and Dallas/Fort Worth (DFW) are annotated on image.

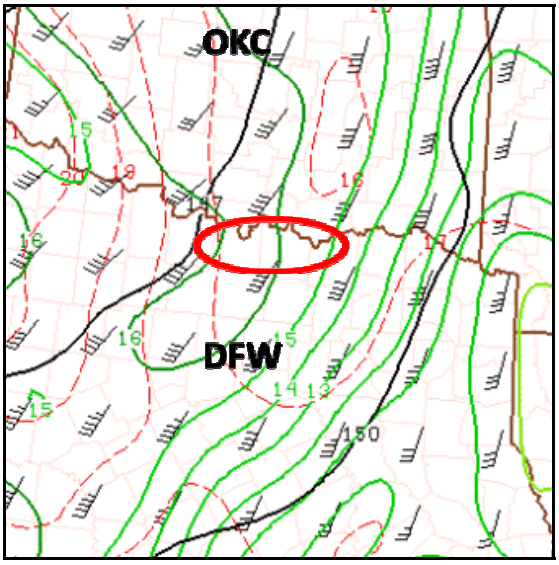

Fig. 9. Storm Prediction Center mesoanalysis of 850 hPa from 1100 UTC 18 June 2007. Solid green contours are dewpoints, black lines are heights, and dashed red contours are temperatures. Note a ribbon of high dewpoints of 16°C over north Texas in the vicinity of the heavy rains over Cooke and Grayson counties (shown in red oval). Oklahoma City, OK (OKC) and Dallas/Fort Worth (DFW) are annotated on image.

Surface observations showed light winds, generally less than 2.6 m s^{-1}, between 0300 UTC and 0400 UTC. However, by 0500 UTC, southeast winds sustained around 5.1 m s^{-1} were gusting from 7.7 to 10.3 m s^{-1} in many locations. Through the overnight period, surface winds remained gusty and veered to the south by 1100 UTC. Surface dewpoint temperatures increased slightly at some observation sites during the night, likely due to weak surface moisture advection.

2.2 *Heavy Rainfall and Flash Flooding*

The Hydrometeorological Prediction Center (HPC) day 1 excessive rainfall forecast valid from 1500 UTC 17 June through 1200 UTC 18 June depicted a moderate risk (40-69%) of exceeding flash flood guidance along the Interstate 35 corridor of north Texas (Fig. 10).

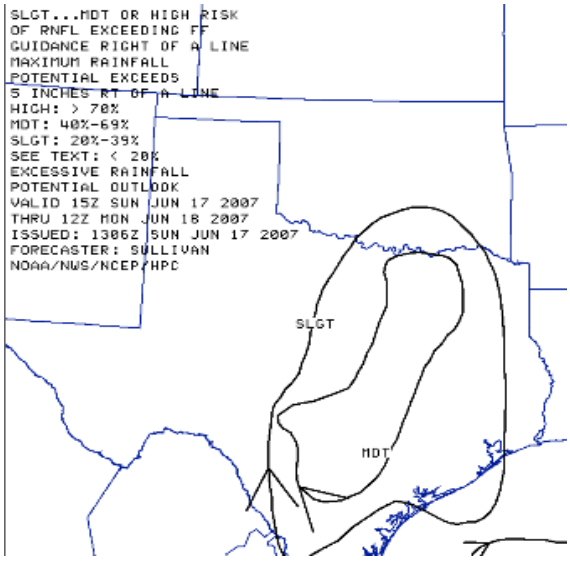

Fig. 10. HPC Day 1 excessive rainfall forecast valid from 1500 UTC 17 June 2007 through 1200 UTC 18 June.

Isolated convective cells developed in northern Hill County (approximately 40 km south of Fort Worth) by 0315 UTC, and these cells grew in areal coverage as they progressed northward into southern Tarrant County by 0400 UTC. Moderate to heavy rainfall began in Haltom City around 0430 UTC and continued through approximately 0600 UTC (Fig. 11).

The heavy rain producing storms over Tarrant County moved northward into Denton County by 0700 UTC. Shortly before 0800 UTC, the thunderstorm over Denton County (Fig. 12) produced a microburst of 35 m s^{-1} (68 kts), measured at the Denton airport. Around 0900 UTC, trees were blown down as a result of high winds southwest of Sherman in Grayson County. Although only two high wind events were reported during the early morning hours of 18 June, heavy

precipitation loading combined with downdraft CAPE between 500 and 600 J kg^{-1}, based on Storm Prediction Center hourly analysis, likely promoted an environment conducive to isolated microbursts.

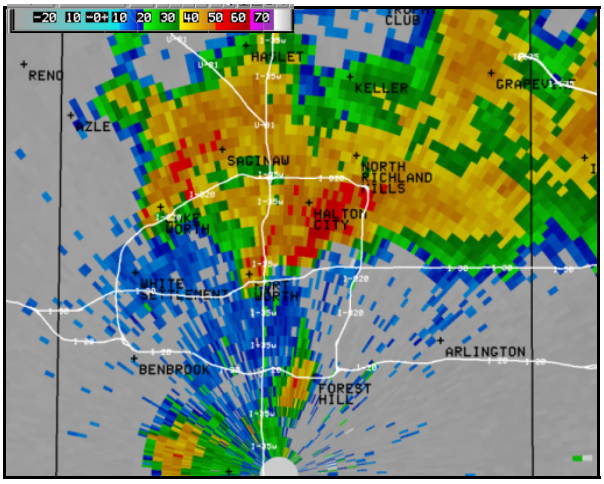

Fig. 11. 0.5° reflectivity image from KFWS at 0501 UTC 18 June 2007 showing convection across Tarrant County. White lines indicate major interstates.

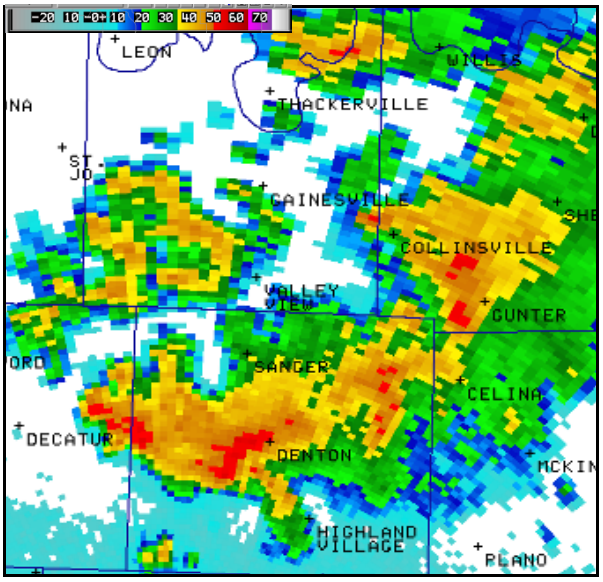

Fig. 12. 0.5° reflectivity image from KFWS at 0743 UTC 18 June 2007 showing convection across Denton County.

Additional heavy rain producing thunderstorms developed in western Cooke County, near Muenster (approximately 15 km west of Gainesville) and grew in areal coverage while moving eastward very slowly (Fig. 13).

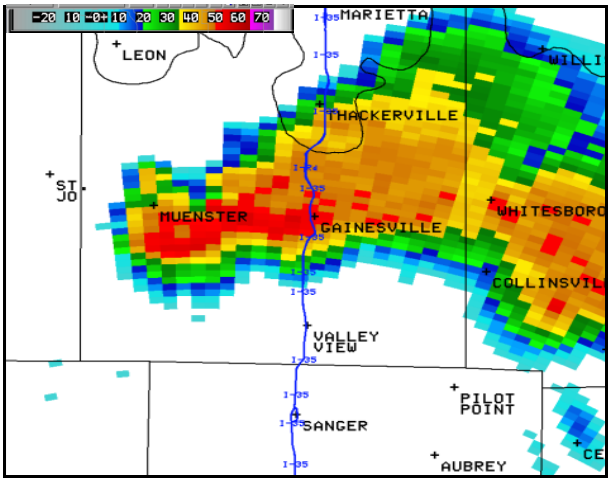

Fig. 13. 0.5° reflectivity image from KFWS at 1101 UTC 18 June 2007 showing convection across Cooke County. Note the high reflectivities from Muenster to Gainesville. Interstate 35 is shown as a blue line extending north to south.

A Texas Department of Transportation automated weather station, KGLE, measured 133.6 mm (5.26 in) of rain during the morning of 18 June. The station is located at the Gainesville airport, which is approximately 2 km west of the center of town. A Limited Automated Remote Collector near downtown Gainesville, and in close proximity to Pecan Creek, measured 91.7 mm (3.61 in) between 1100 and 1200 UTC and a storm total of 223.5 mm (8.80 in). A National Weather Service observer in Valley View, south of Gainesville near the Denton County line, reported a storm total of 84.8 mm (3.34 in).

Although no rain gages were in the immediate area of the Haltom City flooding, KFWS radar estimates and West Gulf River Forecast Center radar estimates biased by gages (Fig. 14) indicated between 2 and 3 inches fell in the area.

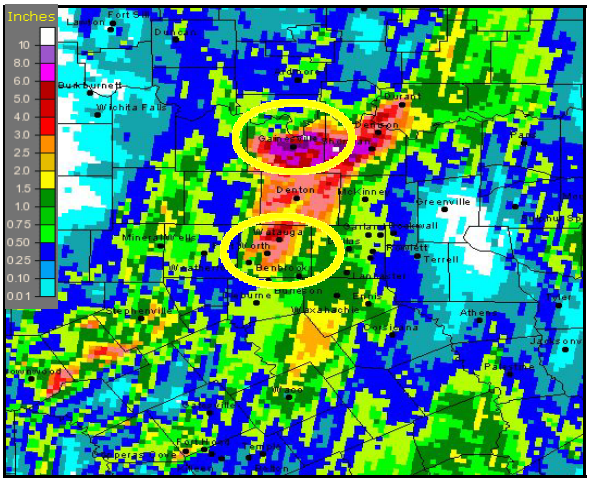

Fig. 14. Radar estimates biased by rain gages from the West Gulf River Forecast Center for the 24 hour period ending at 1200 UTC 18 June 2007. Gainesville and Haltom City areas are circled.

2.3 *Record River Flooding*

A new flood of record was measured on the Elm Fork of the Trinity River at Gainesville, TX on 18 June 2007. The U.S. Geological Survey (USGS) determined the new record stage of 28.01 feet occurred approximately at 1315 UTC, with a corresponding flow of 72,000 cubic feet per second (D. Brown, USGS Fort Worth 2007, personal communication). The previous USGS measured high water record was 25.33 feet and occurred on 16 May 1989. Fig. 15 shows the rapid rise of the gage on the Elm Fork on 18 June. This new USGS measured crest was taken from surveying high water marks near the river, since the automated equipment was not functioning at the time the crest occurred. There has been one other higher water event at the Elm Fork recorded by a Gainesville public official in October 1981, but this was not an official USGS measured crest since the proper river gage had not yet been established.

2.4 *Human and Monetary Impacts*

The heavy rains were already causing devastation shortly before midnight local time on 17 June in Haltom City. However, the bulk of the destruction occurred around 1 am LST (0600 UTC) when White's Branch of Big Fossil Creek overflowed its banks. Several homes were damaged by floodwaters in Haltom City and hundreds of high water rescues took place across northern Tarrant County. Nine mobile homes were destroyed and ninety were damaged by floodwaters, and one girl drowned after her rescue boat capsized.

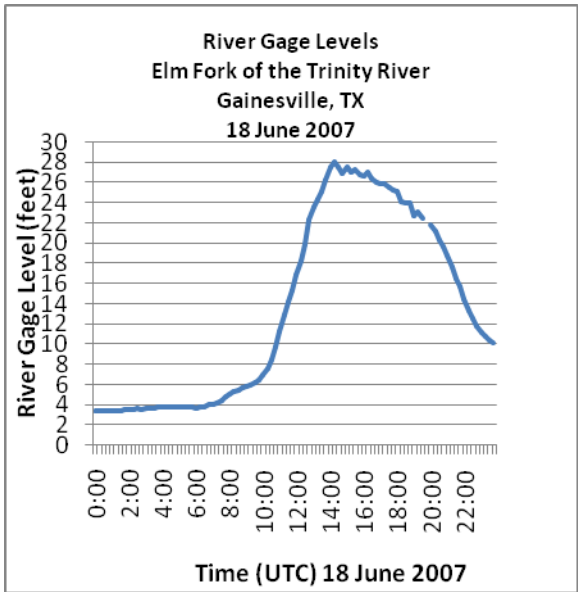

Fig. 15. Chart of river gage levels from the Elm Fork of the Trinity River at Gainesville on 18 June 2007.

Several fires were reported as rushing water interacted with electrical outlets. Fires resulted in the hospitalization of two people. The force of the water ripped up asphalt and pushed cars into each other. Seven baseball fields in Haltom City were also destroyed at a cost of $200,000. In total, $30 million in damages were estimated in Tarrant County.

In Cooke County, Valley View and Gainesville were most impacted by the event. Numerous high water rescues were reported around the county, and people were forced to cut holes in their roofs to escape floodwaters in Gainesville. A mobile home along Pecan Creek, near downtown Gainesville, was carried by the rushing waters and hit a bridge. Four people were thrown into the creek and three drowned. Interstate 35 was closed between Highway 82 and the Oklahoma border, just north of Gainesville. 300 homes and 75 businesses suffered water damage across the county, and 37,000 acres of crops were destroyed. The damages were estimated around $28 million in Cooke County, and the governor of Texas issued a disaster declaration.

Significant flooding also impacted Denton and Grayson counties. Several homes and apartments were flooded in Trophy Club, in southern Denton County, and two elderly couples had to be rescued from their apartments. One car was swept away in floodwaters, but no injuries were reported in Denton County. In Grayson County, numerous roads were closed and more than 450 people were rescued from high water.

Two people died as their vehicles were swept away. Over $20 million in damages were reported in Denton and Grayson counties.

The aforementioned damage accounts and monetary estimates were taken from NWS *Storm Data* (NCDC 2007b).

3. FLASH FLOOD MONITORING IN SITU AND REMOTE SENSING TOOLS

The National Weather Service in Fort Worth has access to multiple networks of real-time hydrologic data during flash flood events. The City of Dallas has a network of 86 sensors, including rain gages, stream gages, and "Flooded Roadway" sensors. This system gives real-time feedback to NWS Fort Worth meteorologists when high water begins to inundate low water crossings within the city. These low lying areas have flashing signals that are activated when water reaches the road surface. The City of Fort Worth also has installed a similar network of rain gages and "Flooded Roadway" sensors, but on a much smaller scale.

Additionally, NWS Fort Worth receives real-time rainfall, stream gage, and wind data every 15 minutes from the Tarrant Regional Water District network of gages. These gages are primarily located in the data sparse counties northwest of Fort Worth.

The Flash Flood Monitoring and Prediction (FFMP) software within AWIPS, the main data display system used at NWS Weather Forecast Offices, allows the user to estimate flash flood potential (Filiaggi 2007). The life threatening potential of flash flooding is directly related to the magnitude of flooding (Davis 2002). Flash Flood Guidance (FFG) is defined as the amount of Average Basin Rainfall (ABR) needed in a specific period of time to generate threshold runoff (Sweeney 1992). FFMP relies heavily on ABR computed from WSR-88D rainfall estimates.

The Flash Flood Index (FFI) was designed by Davis to estimate the potential severity of flash flooding by comparing ABR with FFG. The FFI is simply ABR minus FFG in inches (Table 2).

Table 2. Reference levels of the FFI (Davis 2002).

FF-Index Reference Level	ABR minus FFG (inches)	ABR minus FFG (mm)
FF0	0.00	0.0
FF1	1.00	25.4
FF2	2.00	50.8
FF3	3.00	76.2
FF4	4.00	101.6
FF5	5.00	127.0

According to Davis (2002) in his study of flood events in Pennsylvania, significant flash flooding occurs at FF1 and higher. Serious flash flooding consistently occurs when FF2 levels are reached, and severe flash flooding is likely with FF3 or greater (Arthur et al. 2003). For the 18 June 2007 event in north Texas, Table 3 depicts the FFI and resulting impacts. Fig. 16 and Fig. 17 show the KFWS estimated ABR, FFG, and difference for White's Branch of Big Fossil Creek in Haltom City and Pecan Creek in Gainesville from FFMP. Data obtained from the NWS West Gulf River Forecast Center indicated KFWS was underestimating rainfall from 0000 UTC to 2300 UTC 18 June with the exception of the 0500 UTC hour, when the radar overestimated.

Table 3. FFI levels and impacts for north Texas.

Creek	County	FFI Level	Impacts
White's Branch of Big Fossil Creek	Tarrant	FF2*	1 Death, 99 mobile homes affected
Pecan Creek	Cooke	FF5*	3 Deaths, $28 million in damages

* ABR minus FFG rounded to nearest integer to derive FFI.

Fig. 16. FFMP threat basin table for 3 hour Flash Flood Guidance ending at 0659 UTC. White's Branch of Big Fossil Creek is Area_Id 3500. Value assigned to FFI is circled.

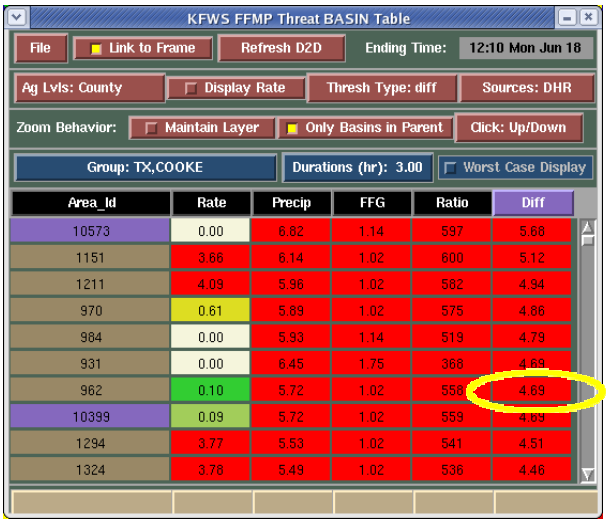

Fig. 17. FFMP threat basin table for 3 hour Flash Flood Guidance ending at 1210 UTC. Pecan Creek is Area_Id 962. Value assigned to FFI is circled.

4. SUMMARY

Several flash flood events occurred in north Texas during the spring and summer of 2007. Severe flooding resulted in 6 deaths and millions of dollars in property damage during the early morning hours of 18 June. Haltom City and Gainesville were two of the hardest hit areas, and record flooding was reported on the Elm Fork of the Trinity River. Rain rates and urban development, as well as the amount of rainfall, were important in the destructive outcome of the flood events.

The NWS used multiple tools to monitor rainfall and predict flash flooding, including radar, AWIPS-based systems, and observational networks. These resources allowed forecasters to monitor heavy rainfall in real-time and issue timely warnings.

Acknowledgments

Sincere thanks to Greg Patrick, Science and Operations Officer at NWS Fort Worth, for his insightful discussions and review of this paper. Special thanks to Gregg Waller, Patrick Sneeringer, and Paul McKee, NWS West Gulf River Forecast Center, and Gary Woodall and Stacie Hanes, NWS Fort Worth, for their assistance with data collection. The authors would also like to thank Fordham McElroy of the City of Fort Worth and David Brown of USGS Fort Worth for providing data.

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Appendix. List of flash flood events in north Texas with 1 or more deaths and/or damage estimates of $10,000 or more during May, June, and July 2007 (NCDC 2007a, NCDC 2007b, NCDC 2008).

Date	County	Nearest City	Deaths	Injuries	Property Damage Estimate
1 May	Milam	Thorndale	0	0	35K
2 May	Comanche	Gustine, Proctor	1	1	30K
2 May	Johnson	Cleburne	0	0	15K
2 May	Tarrant	Fort Worth	0	0	70K
2 May	Anderson	Frankston	0	0	40K
2 May	Collin	Frisco	0	0	50K
3 May	Cooke	Gainesville	0	0	40K
7 May	Cooke	Gainesville	0	0	30K
7 May	Tarrant	Fort Worth	0	0	10K
9 May	Young	Graham	0	0	20K
22 May	Lampasas	Lampasas	0	0	300K
22 May	Bell	Killeen	0	0	100K
24 May	Bell	Killeen	4	0	110K
24 May	Coryell	Copperas Cove	2	0	15K
26 May	McLennan	Speegleville	0	0	10K
26 May	Milam	Buckholts	0	0	100K
27 May	Coryell	South Mountain	0	0	25K
27 May	Young	Olney	0	0	20K
28 May	Milam	Cameron	0	0	10K
28 May	Anderson	Palestine	0	0	30K
29 May	Johnson	Godley	0	0	15K
29 May	Hunt	Quinlan	0	0	40K
30 May	Denton	Denton	0	0	25K
30 May	Collin	McKinney	0	0	10K

Date	County	Nearest City	Deaths	Injuries	Property Damage Estimate
17 June	Bosque	Clifton	0	0	10K
17 June	Hood	Lipan	0	0	20K
17 June	Hill	Abbott	0	0	40K
17 June	Palo Pinto	Mineral Wells	0	0	50K
17 June	Comanche	Hasse	0	0	30K
17-18 June	Tarrant	Haltom City, Keller	1	2	30M
18 June	Denton	Ponder	0	0	200K
18 June	Collin	Anna	0	0	10K
18 June	Grayson	Sherman, Collinsville	2	0	20M
18 June	Hunt	Greenville, Majors Field	0	0	10K
20 June	Grayson	Denison, Sherman	0	0	320K
24 June	Young	Olney	0	0	15K
25 June	Wise	Boyd, Decatur	0	0	30K
26 June	Kaufman	Terrell	0	0	25K
26 June	Jack	Antelope	0	0	10K
26 June	Wise	Boyd	0	0	10K
26 June	Collin	Celina, McKinney	0	0	20K
26 June	Dallas	Garland	1	0	0
26 June	Erath	Stephenville	0	0	40K
26 June	Hood	Lipan	0	0	60K
26 June	Somervell	Glen Rose	0	0	40K
26 June	Tarrant	Lake Worth, Haltom City	0	0	300K
26 June	Hamilton	Hico, Hamilton	0	0	2M
26 June	Comanche	De Leon, Comanceh	0	0	40K
26-27 June	Henderson	Malakoff	0	0	50K
26-27 June	Milam	Burlington	0	0	10K
27 June	Hamilton	Hamilton	0	0	600K

Date	County	Nearest City	Deaths	Injuries	Property Damage Estimate
27 June	Kaufman	Terrell	0	0	10K
27 June	Tarrant	Lake Worth	0	0	10K
28 June	Stephens	Breckenridge	0	0	20K
28 June	Fannin	Bug Tussle	0	0	200K
2 July	Tarrant	Fort Worth, Arlington	0	0	20K
3 July	Dallas	Dallas	0	0	10K
3 July	Bosque	Meridian	0	0	250K
3 July	Tarrant	North Richland Hills, Watauga	0	0	450K
6 July	Anderson	Palestine	0	0	200K
6 July	Van Zandt	Canton	0	0	150K
6 July	Henderson	Malakoff, Payne Springs	0	0	750K
6 July	Rains	Emory, Point	0	0	15K
8 July	Somervell	Glen Rose	0	0	400K
8 July	Hamilton	Carlton, Hico	0	0	600K
8 July	Erath	Stephenville	0	0	500K
10 July	Grayson	Sherman, Denison	0	0	200K
11 July	Montague	Bowie	0	0	10K
13 July	Hunt	Campbell, Commerce	0	0	400K
14 July	Milam	Buckholts, Hanover	0	0	800K
14 July	Leon	Jewett	0	0	350K
24 July	Coryell	Copperas Cove	0	0	20K
30 July	Fannin	Bonham	0	0	40K