SAMPLE REPORT: Names and dates have been changed to protect client confidentiality

Forensic meteorological investigation of local climatology and rainfall near downtown Tulsa, OK, on July 14, 1994, June 1, 2008, and September 9, 2009.

PREPARED ON:	August 21 – 30, 2013
PREPARED FOR:	Tiffany Bates
ASSOCIATION:	Client of Harold Anderson, Esq.
PREPARED BY:	Megan Walker-Radtke, M.S., Forensic Meteorologist
INCIDENT DATE:	July 14, 1994 (afternoon, ~3pm CDT) June 1, 2008 (10am CDT) September 9, 2009 (7pm CDT)
INCIDENT LOCATION:	near downtown Tulsa, OK

SUMMARY:

Tiffany Bates states that on July 14, 1994, June 1, 2008, and September 9, 2009, she observed or was given first-hand accounts of street flooding on and adjacent to her residential property near downtown Tulsa, OK, during and immediately following heavy rain events. Blue Skies Meteorological Services was contracted by Ms. Bates to perform a forensic meteorological analysis to determine rainfall rates and total rainfall amounts during heavy rainfall events on the given dates and to determine the climatological recurrence interval(s) of those rain events.

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DATA

The use of high-quality, reliable data is crucial to ensure the accuracy of forensic meteorological analyses. In the performance of our meteorological investigations and in accordance with industry best practices, Blue Skies Meteorological Services utilizes only quality-controlled data from trusted, official sources that specialize in the collection, quality control, and analysis of meteorological, climatological, and hydrological data for research and operational purposes. Much of the data from the National Oceanic and Atmospheric Administration (NOAA) that was obtained and reviewed for this report can be certified by the Department of Commerce, if necessary.

The following data were reviewed and analyzed during this forensic meteorological investigation. The conclusions drawn in this report are based upon the data that were available at the time of report preparation. Any new, updated, or revised data relevant to these incidents may be incorporated in a later revision of this report.

Surface Weather Observations

- Source: The National Oceanic and Atmospheric Administration (NOAA): National Climatic Data Center (NCDC):
    1. Quality Controlled Local Climatological Data (QCLCD)
    2. Global Historical Climate Network Data (GHCND)
- Product(s):
    1. QCLCD for Station 13968/TUL (Tulsa, OK, International Airport): Hourly Observations Table, Hourly Precipitation Table for 1 June 2008, 9 Sept 2009
    2. GHCND for USW00013968 (Tulsa, OK, International Airport): Daily Summary for 14 July 1994

Severe Weather Reports

- Sources:
    1. National Oceanic and Atmospheric Administration (NOAA): National Climatic Data Center: National Environmental Satellite, Data, and Information Service (NESDIS): Severe Weather Data Inventory
    2. The National Oceanic and Atmospheric Administration (NOAA): National Climatic Data Center (NCDC): Storm Events Database
    3. National Weather Service: Local Storm Reports
- Product(s):
    1. Preliminary Local Storm Reports from the NOAA National Weather Service for Tulsa County, OK
    2. Storm Event Reports for Tulsa County, OK
    3. Local Storm reports for Tulsa County, OK

Radar:

- Source: The National Oceanic and Atmospheric Administration (NOAA): National Climatic Data Center (NCDC): Radar Data
- Product(s): KINX-Inola/Tulsa, OK: Base Reflectivity; Digital Storm Total Precipitation; 1-Hour Precipitation Total; 3-Hour Precipitation Total

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In Situ Rain Observations:

- Source: The National Oceanic and Atmospheric Administration (NOAA): National Climatic Data Center (NCDC): Quality Controlled Local Climatological Data (QCLCD)
- Products(s): QCLCD for Station 13968/TUL (Tulsa, OK, International Airport): Hourly Precipitation Table

Rainfall Climatology:

- Source:
    1. The National Oceanic and Atmospheric Administration (NOAA), Hydrometeorological Design Studies Center (HDSC), Precipitation Frequency Data Server (PFDS)
    2. The National Weather Service Weather Forecast Office: Tulsa, OK
- Product(s):
    1. PDS-based Precipitation Frequency Estimates for Site ID: 34-8987 (downtown Tulsa, OK)
    2. Tulsa, OK Climatology

Non-meteorological Data:

- "Storm Causes Flooding, Outages". Tulsa World. 15 July 1994. Newspaper article accessed online and provided to BSMS by Ms. Tiffany Bates.

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METHODOLOGY

Graphical Representation of Data:

Radar data was preliminarily analyzed and exported via NOAA's Weather and Climate Toolkit. Further analysis and graphical representation of the data was then undertaken using Quantum GIS (QGIS) calculation and visualization features.

Time Stamp Adjustments:

Meteorological data, including weather radar data, are typically reported using Coordinated Universal Time (UTC), an international time standard that is functionally equivalent to Greenwich Mean Time (GMT). To convert from UTC to Central Daylight Time (CDT), one must subtract 5 hours. To convert from UTC to Central Standard Time, (CST) one must subtract 6 hours. Although this report specifies time in CDT and CST throughout, you may notice UTC timestamps on the original data.

Rainfall Climatology:

Local rainfall climatology and recurrence intervals for Tulsa, OK were determined from NOAA's Hydrometeorological Design Studies Center (HDSC), Precipitation Frequency Data Server (PFDS). The raw rainfall data utilized in the precipitation frequency analyses are sourced primarily from the National Climatic Data Center. The raw NCDC precipitation data are quality-controlled and can be certified, if needed.

Table 1 lists the depth of rainfall that can be expected to recur on the intervals listed across the top of the table for the rainfall event durations listed down the left-most column of the table. For example, one would expect a 30-minute (duration) rainfall total of 1.52" to recur every 5 years at this location. Another way to express this same data would be to say that receiving 1.52" of rain over a 30-minute period is a "5-year event".

PDS-based precipitation frequency estimates with 90% confidence intervals (inches)						
Duration	Average rainfall recurrence interval (years) for Tulsa, OK **Site ID: 34-8987**					
	1	2	5	10	25	50
5-min	**0.424** (0.332-0.550)	**0.489** (0.382-0.634)	**0.603** (0.469-0.784)	**0.706** (0.547-0.922)	**0.861** (0.650-1.17)	**0.99** (0.728-1.36)
10-min	**0.621** (0.486-0.806)	**0.716** (0.559-0.928)	**0.883** (0.687-1.15)	**1.03** (0.800-1.35)	**1.26** (0.951-1.71)	**1.45** (1.06-1.99)
15-min	**0.758** (0.593-0.982)	**0.873** (0.682-1.13)	**1.08** (0.838-1.40)	**1.26** (0.976-1.65)	**1.54** (1.16-2.09)	**1.77** (1.30-2.42)
30-min	**1.06** (0.829-1.37)	**1.22** (0.956-1.59)	**1.52** (1.18-1.97)	**1.78** (1.38-2.32)	**2.18** (1.65-2.97)	**2.52** (1.85-3.46)
60-min	**1.4** (1.09-1.81)	**1.64** (1.28-2.12)	**2.05** (1.60-2.67)	**2.43** (1.88-3.17)	**2.98** (2.25-4.05)	**3.44** (2.53-4.72)

Table 1: Rainfall Recurrence Intervals for Tulsa, OK. Data source – NOAA HDSC PFDS.

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Recurrence intervals are simply one way of expressing the statistical frequency of an event and the probability of that event occurring. For instance, an event that has a 20% probability of occurring in any given year can be expressed as having a 1-in-5 chance of occurrence per year. One would expect, therefore, that such an event would recur on average once every 5 years, and it would be referred to as a 1-in-5-year event.

The use of recurrence intervals to express event probabilities is common practice across many fields/industries, including climatology and insurance. In this investigation, the frequency and duration of each rainfall event in question is analyzed to determine the expected recurrence interval. Recurrence intervals are assigned using the rainfall climatology in Table 1.

Comparison of Radar-Indicated Precipitation to Rain Gauge Data:
Rainfall rates and total rainfall amounts during the dates and times of interest in this investigation were determined by examining both radar estimates of rainfall rates and totals as well as in-situ (rain gauge) observation data. These two data types have complementary advantages and disadvantages.

Quality-controlled rain gauge data has the advantage of being a direct observation that does not depend on the calibration or operational parameters and limitations of a remote sensing device (e.g. a radar). It is therefore considered a highly accurate and reliable measurement of surface precipitation in most situations. Notable errors are introduced by wind/turbulent losses, gauge wetting, splash into and out of the gauge, and evaporation; all errors except evaporation are most prevalent during events involving very strong winds and heavy rain.

Rain gauge data are available only at specific locations, however, and with distances between reporting stations often exceeding 50 miles, spatial coverage is relatively sparse. Because rainfall from a single storm event can vary significantly over a small area, rainfall at the nearest rain gauge may not accurately represent rainfall at the incident location.

Weather radar, on the other hand, offers nearly continuous spatial and temporal coverage, providing information about storm features, precipitation rates, and precipitation totals at any location within the coverage area of the National Weather Service weather radar array. However, the radar does not directly measure precipitation amounts; rather, it estimates precipitation rate through empirical relationships between the characteristics of the radar targets (e.g. rain drops) and the signal that those targets create when they scatter the radar's transmitted energy back toward the radar dish.

These empirical relationships are generally fairly accurate – accurate enough, in fact, for the National Weather Service to rely on radar-indicated rainfall rates and rainfall totals to issue flood advisories and warnings. However, any fixed relationship cannot describe with absolute accuracy all situations. Hail, very intense rainfall, sleet, melting snow, precipitation far from the radar dish, and complex terrain, for instance, pose known challenges for radar estimations of precipitation.

Although radar coverage is more spatially complete than rain gauge coverage, radar data is less precise at any given location due to radar resolution and display characteristic limitations (discussed in depth in the "Radar Basics" section). Because radar and in-situ measurement techniques have unique and often complementary advantages and disadvantages, it is beneficial to compare radar-estimated precipitation with in-situ rain gauge data if rain gauge data is available for the storm or event of interest. In light of the sparse spatial distribution of rain gauge stations in many regions of the country, however, this is not always possible.

BACKGROUND/REFERENCE:
For detailed information about radar operations, interpretation, and limitations, please consult "Appendix A: Background and Reference Material" at the end of this report. This information is intended to provide necessary context for the radar analyses performed by Blue Skies Meteorological Services for this forensic meteorological report.

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<u>ANALYSIS – JULY 14, 1994</u>

Weather Summary: A severe thunderstorm developed west of Tulsa, OK, during the early afternoon hours of July 14, 1994, and moved eastward across the city at less than 20mph. The storm affected the incident location from approximately 2:35pm through 3:46pm local time (CDT) and affected the Tulsa International Airport ASOS reporting station (KTUL) from 2:58pm through 4:09pm. After the storm passed, the Tulsa metropolitan area was affected by light to moderate rainfall from approximately 5:30pm through 9:20pm

According to a newspaper article published the day after the storm, wind gusts of up to 80 mph, torrential rainfall, and storm rotation were reported with this cell. Because this event occurred 19 years ago, meteorological data is much more scarce than for recent events. Doppler radar storm relative velocity data, archived NWS storm event reports, and sub-daily rain gauge data are unavailable to confirm the reports of rotation, wind speed, and hourly rainfall, respectively; however, radar reflectivity is available and corroborates a very intense thunderstorm producing extremely heavy rainfall.

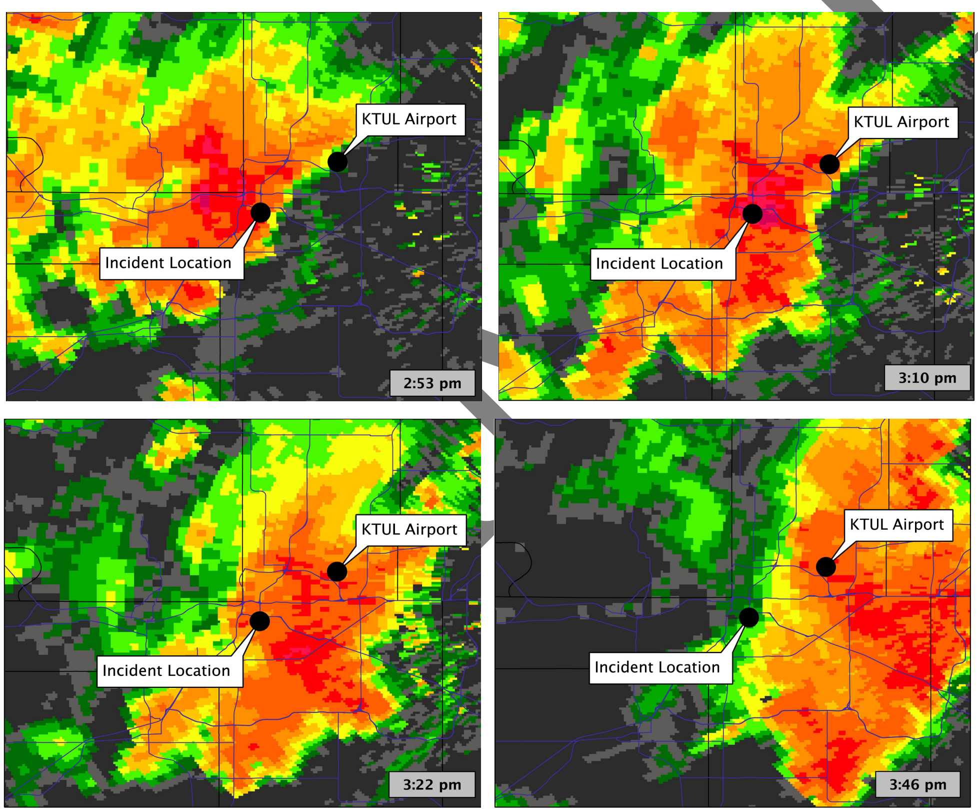

Figure 1: Base reflectivity from KINX radar on 14 July 1994 as the severe thunderstorm moved over Tulsa, OK at 2:53pm, 3:10pm,3:22pm, and 3:46pm CDT. KINX radar is located near Inola, OK, approximately 20 miles from the incident location.

Precipitation Measurement and Accuracy Verification:
Radar-indicated storm total precipitation and rain gauge precipitation totals for this event from the KINX (Inola, OK) radar site do not agree well at the Tulsa International Airport reporting station (KTUL), the closest location for which rain gauge data are available. KTUL is located 6.3 miles northeast of the incident location and was affected by both the severe thunderstorm and the lighter, stratiform precipitation on 14 July.

At 11:52pm CDT (after all precipitation had ended for the day), radar indicated a storm total precipitation (STP) amount of 1.00" for both the incident location and KTUL. However, rain gauge data at KTUL indicated that by that same time, 3.25" of rain had fallen. Based on radar reflectivity data, KTUL did not experience rainfall as intense as the incident location during this storm event, so it is likely that the incident location, located near downtown Tulsa and in the track of the core of the storm, received more rainfall than was reported at KTUL.

Storm total precipitation is a derived radar product, and due to its inaccuracy (impossibly low rainfall total estimates and unrealistic spatial uniformity of estimated rainfall totals) with this particular storm, rainfall totals were also calculated manually from reflectivity. To determine rainfall rate and total rainfall at the incident location and, for comparison, at KTUL, each radar time slice was analyzed and assigned, via the WSR-88D default Z-R relationship between radar return (dBZ) and associated rainrate (in/hr), a total rainfall amount ($z=300*R^{1.4}$). Because this storm showed strong spatial variability near its core, with large differences in storm intensity (and therefore rainfall rates) indicated at nearby locations, the rainfall rates at adjacent range gates were also examined for each location.

At a distance of approximately 20 miles from the radar site, the radar base reflectivity display resolution (range gate size) is 1km x 0.5 km (~0.5mi x 0.25mi) at the incident location. The range gate value simply provides a measure of the average storm intensity over a 1km x 0.5km area – the actual storm intensity and rainfall rate observed at locations *within* that range gate could vary.

Strong spatial variability between range gates was observed with this storm, especially near the core, which tracked over the incident location, indicating likely variability within range gates, as well. Comparing radar return values (dBZ) at adjacent range gates provides an indication of the probable variability that is also occurring *within* each range gate, and therefore of the probable range of precipitation rates occurring within each range gate.

At the incident location, radar indicated that 2.32" of rain fell during the storm, with adjacent range gates indicating between 1.15" and 2.57". This wide range of precipitation totals was indicated within a half mile of the incident location. During the most intense part of the storm, from 2:58pm – 3:17pm, 2.00" of rain were indicated to have fallen during 19 minutes, with 1.51" indicated to have fallen during one particularly extreme 7-minute period (see Figure 2). At KTUL, radar-indicated precipitation was 1.07", with adjacent range gates indicating between 0.90" and 1.25".

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The total precipitation calculated manually still represents a significant underestimation ("undercatch") when compared to rain gauge data at the airport. The KTUL ASOS reported that 3.25" of rain had fallen by day's end. Although additional, stratiform precipitation fell for several hours after the storm passed, this rainfall was relatively light and likely did not exceed 0.5" total. The total amount that fell during the severe thunderstorm was therefore a minimum of 2.75". However, the maximum rainfall total indicated by radar reflectivity in the vicinity of KTUL is only 1.25" (indicated at the range gate immediately to the southwest of the airport). This discrepancy represents a radar underestimation of precipitation totals by a factor of 2.2 when compared to rain gauge observations.

Given these facts and eyewitness reports of major street flooding in the vicinity of the incident location, it is nearly certain that the rainfall at the incident location during the storm exceeded the amounts calculated here by manual analysis of radar reflectivity, although quantifying precisely how much more precipitation fell incurs substantial uncertainty. Based on the level of radar underestimation at the airport, however, it is possible that more than twice the amount of precipitation indicated by radar actually fell at the incident location. This implies that up to 4.5" of rain may have fallen at the incident location during the one-hour duration of the storm.

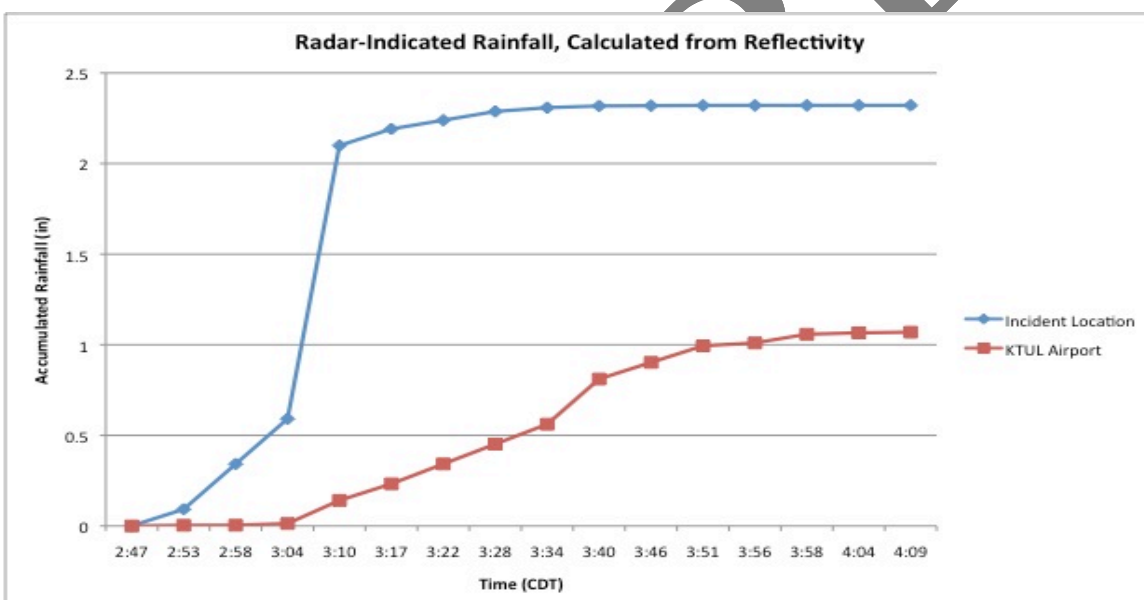

Figure 2: Radar-indicated precipitation at the incident location and KTUL Airport, manually calculated from radar reflectivity during the 14 July 1994 severe thunderstorm.

Recurrence Interval for the Rainfall Event:

Unfortunately, because only daily, not hourly, in-situ rainfall data is available for this incident, it is not possible to precisely tease apart how much rain fell during the severe thunderstorm and how much rain fell during the subsequent light-to-moderate shower activity from the rain gauge data. However, radar reflectivity data indicate that a maximum of 0.5" of rain fell during the shower activity following the severe thunderstorm. Given that 3.25" of rainfall were measured by the KTUL ASOS (rain gauge) station, it is probable that a minimum of 2.75" of rain were received at the airport during the hour-long duration of this storm. As previously mentioned in this report, even more intense rainfall fell at the incident location, as indicated by radar reflectivity.

Recurrence interval calculations require knowing both how much rain fell and how quickly that rain fell (see Table 1). 1.5" of rain falling over the course of 2 hours is an event of little note, with a recurrence interval of less than one year (meaning that several such events should be expected to occur in any given year). However, if that 1.5" of rain fell during 30 minutes, it would be a much more unusual event with a recurrence interval of 5 years.

Assigning a recurrence interval to the rainfall associated with the severe thunderstorm that affected Tulsa, OK on 14 July 1994 from only daily in-situ rainfall totals and rainfall totals calculated from radar reflectivity that do not agree closely with the in-situ data incurs substantial uncertainty.

Several things are certain, however. Extremely intense rainfall affected the incident location between 2:58pm and 3:17pm. This rainfall was sufficient to cause documented, rapid and substantial street flooding in downtown Tulsa, OK, 1.5 miles from the incident location.

Radar indicates that at least 1.51" of rain fell from 3:10-3:17pm when the core of the thunderstorm passed overhead. Given the documented underestimation of radar-indicated precipitation rates (as compared to rain gauge data) with this storm, the actual rainfall during that period was likely greater. Even if only 1.51" of rain did fall during that 7-minute period, it would still be a greater than 1-in-50-year event (i.e. the return period would be greater than 50 years).

If one is conservative and considers only the in-situ (rain gauge) storm total precipitation of 2.75"-3.00" of rain during a one-hour period at the Tulsa International Airport (KTUL), the recurrence interval is 10 to 25 years. However, radar reflectivity data indicates that significantly more rain fell at the incident location than at KTUL (as much as 200% more). Even if only 25% more rain fell at the incident location than at the airport, a resultant total of 3.45" during a one-hour event would have a recurrence interval of 50 years. This extreme rainfall event therefore almost certainly has a recurrence interval greater than 50 years. Unfortunately, though, inconsistencies among the data available for this event preclude a more well-constrained assignment of the recurrence interval.

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Soil Saturation:
During the week preceding the 14 July 1994 storm, 3.38" of rain fell, with 1.75" falling the day before. The average July precipitation in Tulsa, OK, is 3.36", so the incident location received its total monthly average precipitation within a single week. The soil was therefore quite moist, especially for mid-summer, although likely not entirely saturated, before the 14 July storm.

Saturated soils are less able to absorb new rainfall than drier soils. This can result in enhanced overland flow (runoff) during heavy precipitation events and might have contributed to the street flooding observed on July 14, 1994 in Tulsa, OK, although the primary contributor was extremely intense rainfall with a climatological recurrence interval of greater than 50 years.

Results:
The storm that impacted Tulsa, OK, on 14 July 1994 was extremely intense and produced unusually high rainfall amounts, resulting in widespread reports of street flooding in the downtown area.

However, sparse data availability for this event, nearly 20 years ago, challenged standard methodologies for providing well-constrained precipitation estimates. Discrepancies between precipitation estimates calculated directly from radar reflectivity data and precipitation measurements from the KTUL rain gauge station indicate significant radar rain undercatch. However, analysis of the available data revealed the following:

- **Event rainfall total:** 3.5-4.5" during the one-hour duration of the storm, with over 90% of this rainfall occurring during the first 30 minutes of the event.
- **Recurrence interval:** This event has a minimum 50-year recurrence interval.
- **Role of soil saturation:** Soils were quite saturated prior to onset of this storm. 3.38" of rain fell during the previous week, with 1.75" just on the day before (July 13, 1994). Saturated soils are less able to absorb rainfall than drier soils, and the soil moisture content during this event may have contributed to enhanced surface runoff.

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ANALYSIS – JUNE 1, 2008

Weather Summary:

A large complex of intense-to-severe thunderstorms moved southeastward over south-central Kansas and northeastern Oklahoma during the early through late morning hours of June 1, 2008. During their traverse of northeastern Oklahoma, these storms produced winds in excess of 60kts (69 mph) and hail of up to 2.5-inch diameter. By 9am local time, the leading edge of this convective complex was approaching the Tulsa metropolitan area. Over the course of the following 2.5 hours, two rounds of heavy precipitation affected the incident location as the thunderstorm complex moved over downtown Tulsa, OK.

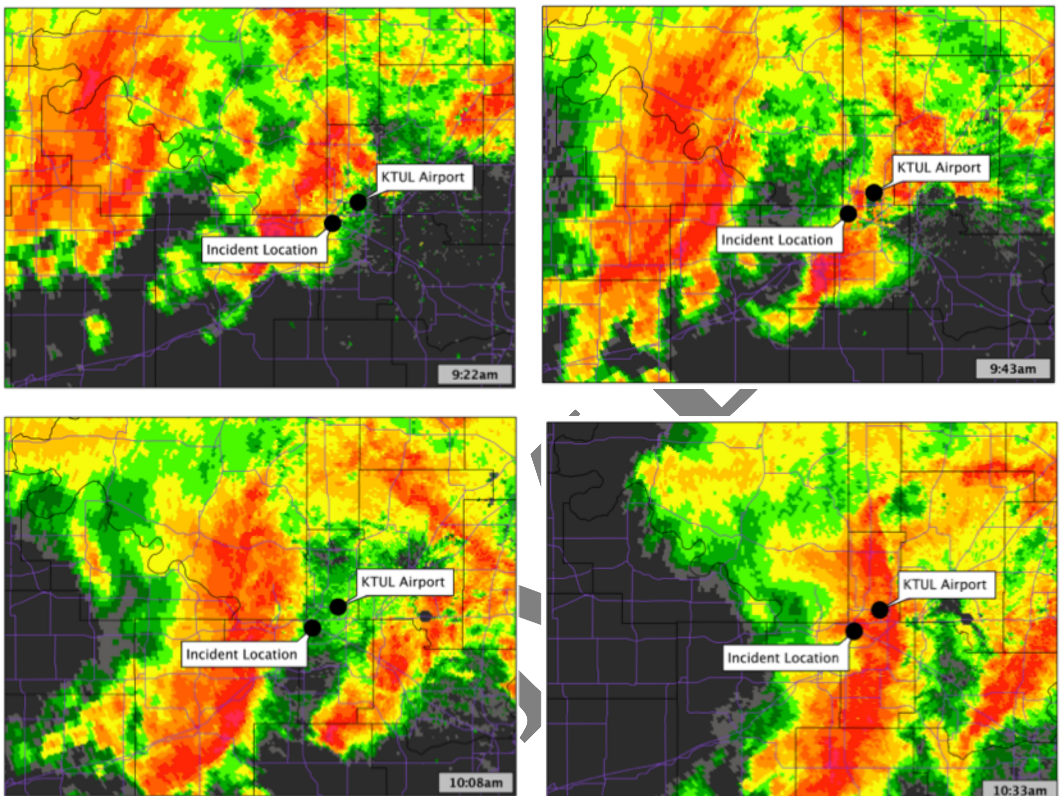

Figure 3: Base reflectivity from KINX radar on 1 June 2008 as the convective complex moved over Tulsa, OK, at 9:22am, 9:43am, 10:08am, and 10:33am CDT.

Precipitation Measurement and Accuracy Verification:

The first storm moved over the incident location from 9:22am through 9:43am, producing 0.20" of rainfall, as indicated by radar. Light to moderate rain followed for a half hour until a larger, more intense convective line segment traversed the incident location from 10:17am through 10:42am, producing an additional 0.76" of rainfall. In total, the thunderstorm complex dropped 0.96" of rain in one hour and twenty minutes.

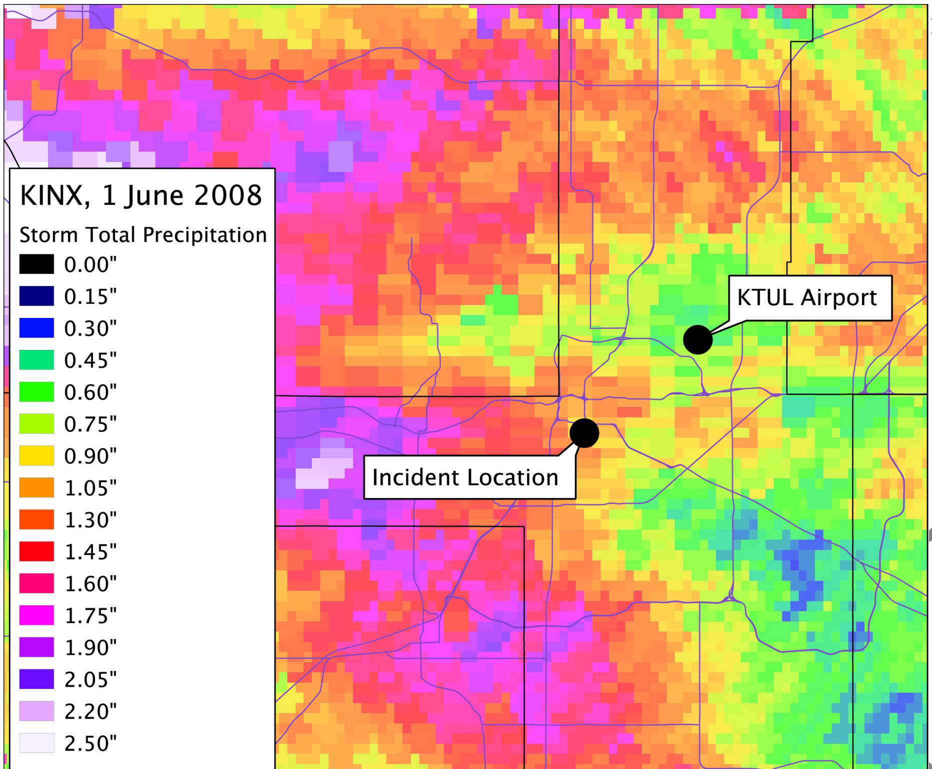

Figure 4: Digital storm total precipitation from KINX radar on 1 June 2008 after the convective complex had moved over Tulsa, OK.

Radar indicated precipitation totals and rain gauge precipitation totals for this event agree closely at the Tulsa International Airport reporting station (KTUL), the closest location for which both data types are available. KTUL is located 6.3 miles northeast of the incident location and was affected by both waves of heavy precipitation on June 1.

At KTUL, the two measurements agree within 10% of each other, with the radar estimate slightly lower than the rain gauge observation. This close agreement between radar-indicated and in-situ rainfall measurements indicates that the radar was accurately capturing precipitation rates and totals for this particular storm. The radar-indicated precipitation totals at the incident location on this date can therefore also be trusted as reasonably accurate.

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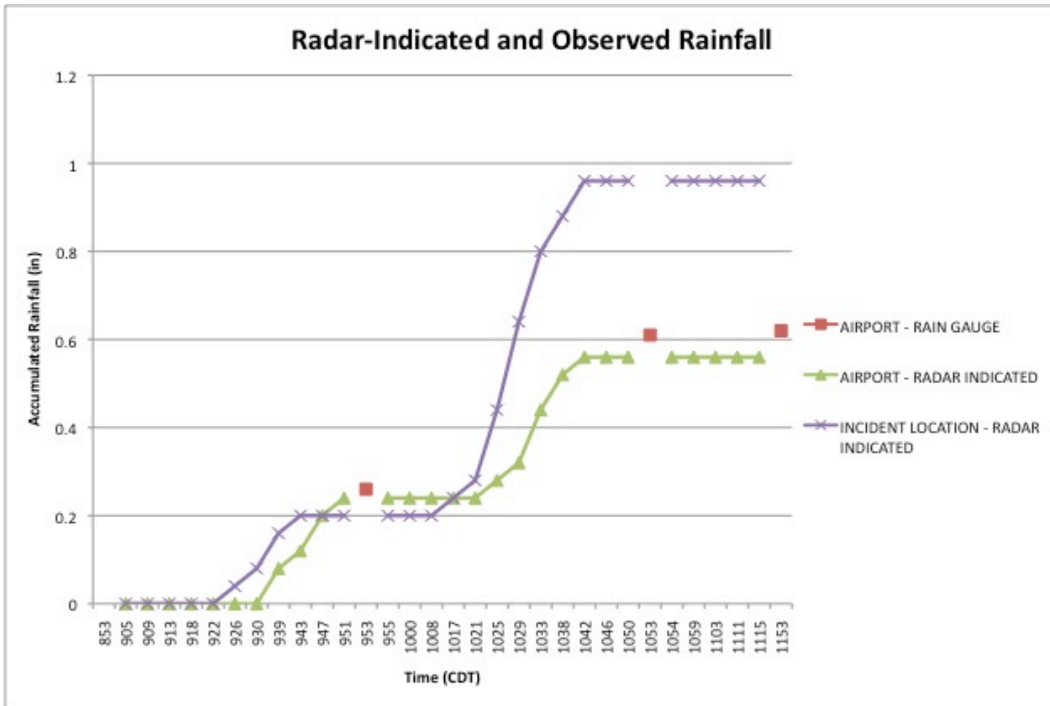

Figure 5: Accumulated storm total precipitation for 1 June 2008. The purple and green lines represent radar-indicated rainfall totals at the incident location and the Tulsa International Airport, respectively. The red data points represent ASOS rainfall observations at the Tulsa International Airport (KTUL).

Recurrence Interval of the Rainfall Event:

Two distinct periods of rainfall comprise this event:

- 9:22am – 9:43am: During this 21 minute period, 0.20” of rain fell
- 10:17am – 10:42am: During this 25 minute period, 0.76” of rain fell

Neither the two periods of heavy rainfall taken individually nor the total rainfall from the system (0.96” during an 80 minute period) exceeds the 1-yr recurrence interval for this location (see Table 1). Likewise, no 5-, 10-, 15-, or 20- minute period during the event exceeds the 1-yr recurrence interval.

Even if the radar estimates of rainfall at the incident location were 10% below observed values (as they were at the airport), the event remains well below 1-year recurrence interval criteria.

Soil Saturation:

The rain that fell on June 1, 2008, did so onto a relatively wet watershed. 5.37 inches of rainfall were recorded at the airport reporting station (KTUL) during the week prior to June 1, 2008. For comparison, the climatological average rainfall for the entire month of May in Tulsa, OK, is 5.91 inches. 1.48” of rain fell during the early morning hours of May 26th, with an additional 3.30” of precipitation occurring during a widespread and prolonged convective event less than 24 hours later, on May 27th. Four days later, during the midmorning of May 31st, another 0.59” of rain fell.

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Saturated soils are less able to absorb new rainfall than drier soils. This can result in enhanced overland flow (runoff) during heavy precipitation events and might have contributed to the street flooding observed on June 1, 2008 in Tulsa, OK, during a thunderstorm that produced only climatologically moderate rainfall.

Results:
The precipitation events that occurred on June 1, 2008, in midtown Tulsa, OK, were heavy but not climatologically unusual. Strong agreement between radar-indicated and rain gauge data enables well-constrained estimates of precipitation rates, totals, and recurrence intervals.

- **Event rainfall total:** 0.96" of rain fell during two distinct periods of precipitation. The first period of precipitation was 21-minutes long and produced 0.20" of rain, while the second, more intense, period produced 0.76" of rain during 25 minutes.
- **Recurrence interval:** Taken together as well as individually, the two waves of precipitation that affected the incident location fail to meet even the 1-year recurrence interval criteria, meaning that events of this magnitude can be expected to occur multiple times per year.
- **Role of soil saturation:** Very heavy rainfall that occurred during the week prior to 1 June 2008, meant soils that were already wet when this storm impacted the area. The inability of the wet soil to quickly absorb additional precipitation may have contributed to enhanced surface runoff and street flooding during an event that was otherwise climatologically unremarkable.

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ANALYSIS – SEPTEMBER 9, 2009

Weather Summary:

Light-to-moderate rain in the form of passing showers affected the incident location from the evening of 8 September 2009 through late morning hours on 9 September 2009. Around 4pm CDT on September 9, a thunderstorm began to develop to the west-southwest of downtown Tulsa, OK, and the incident location. The storm drifted slowly south-southeastward while also building to the north and intensifying. By 6:30pm CDT, the northern tip of the storm was positioned just west of the incident location. Over the course of the next half-hour, this northern portion of the storm cell intensified and transited the incident location.

Later that evening, starting at approximately 8:45pm CDT, additional storm cells began to develop west-northwest of downtown Tulsa, OK. These cells quickly intensified, slid south-southeastward, and impacted the city of Tulsa through midnight of 9 September 2009.

None of the storms that affected the incident location on 9 September 2009 were severe warned.

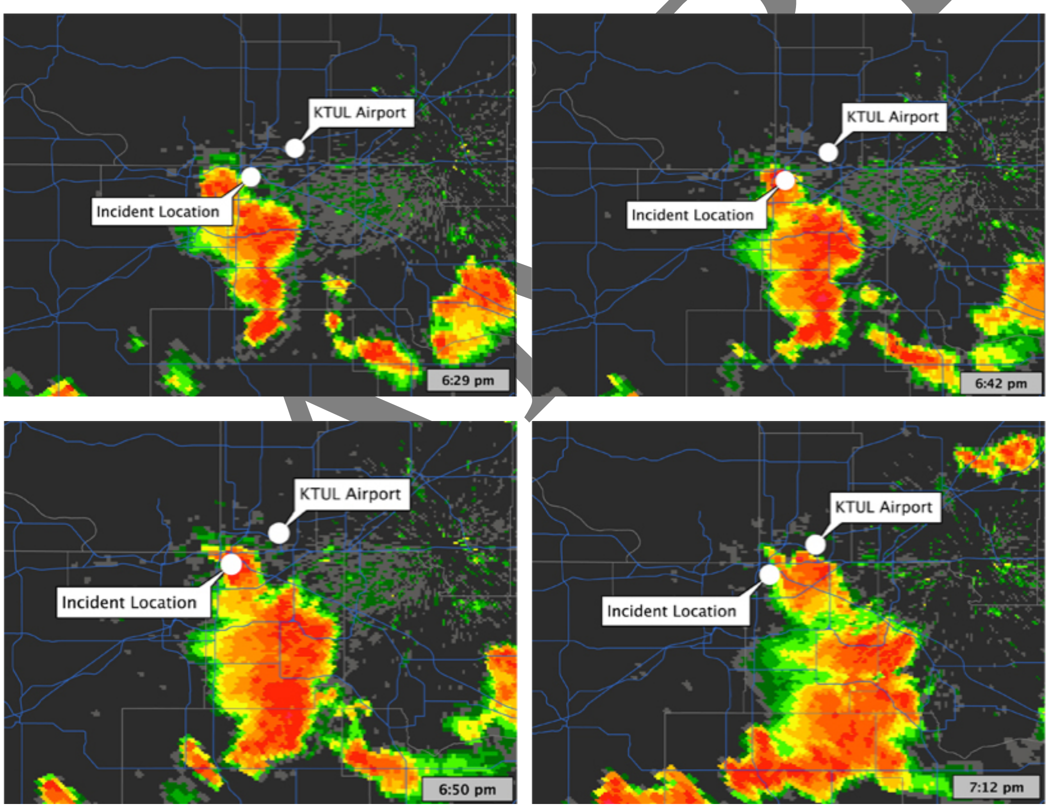

Figure 6: Base reflectivity from KINX radar on 9 September 2009 as the strong thunderstorm moved over Tulsa, OK, at 6:29, 6:42, 6:50, and 7:12pm CDT.

Precipitation Measurement and Accuracy Verification:
The largest extent of the thunderstorm affected southern Tulsa, northern Okmulgee, and Wagoner counties, with activity remaining generally south of Oklahoma Highway 412. The storm almost entirely missed the Tulsa International Airport (KTUL), with only a trace of precipitation reported during storm passage.

The fact that the intense precipitation did not pass over the KTUL rain gauge during this event unfortunately precludes a "ground truth" comparison of in-situ rain data with radar-indicated precipitation for this particular storm cell. However, previous and subsequent precipitation on the 9th and 10th of September did affect the KTUL station, so radar-indicated and in-situ rain data can be compared for events that occurred in nearly identical atmospheric conditions to determine whether the radar was accurately capturing rainfall rates and totals during the 24-hour period surrounding the main incident (the small but intense thunderstorm that caused street flooding from approximately 6:30 - 7:15pm CDT on 9 September 2009).

Radar indicated that 1.12" of rain fell between 6:29pm and 6:59pm CDT, the time during which minor street flooding was reported at the incident location. During the following 15 minutes, as the storm exited the area, an additional 0.04" of rain fell at the incident location. Highest rainfall totals with this storm cell occurred across a 1.5 square mile area that encompasses the incident location and areas to the south and west. Radar range gates adjacent to the incident location indicated 0.70" – 1.12" of rainfall during the same time period.

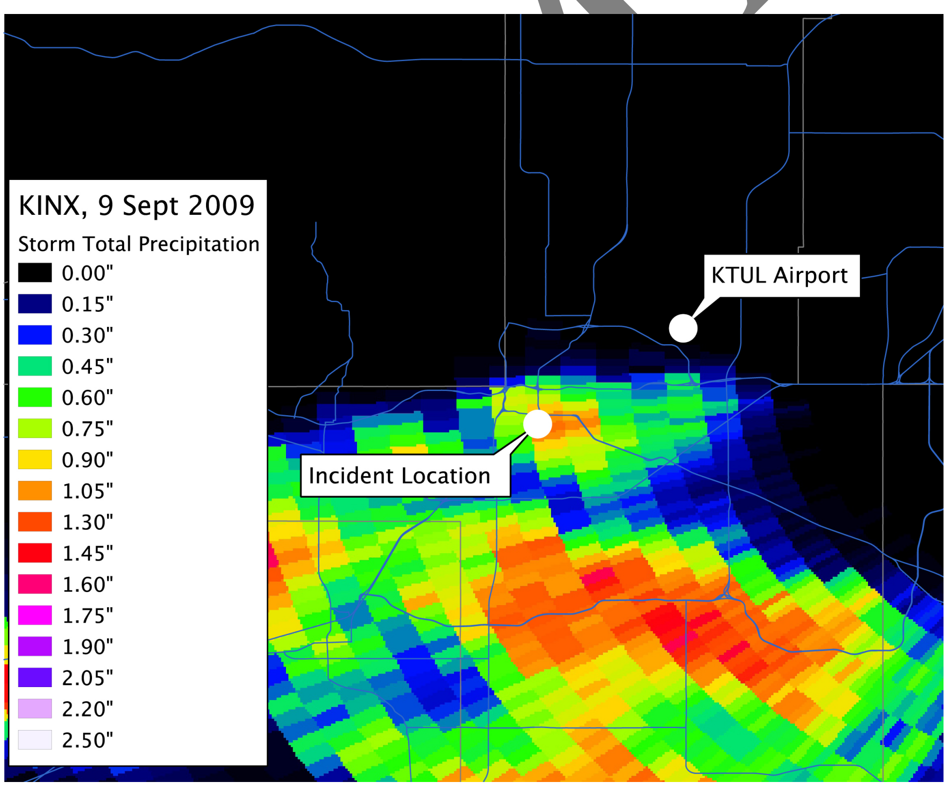

Figure 7: Digital storm total precipitation from KINX radar on 9 September 2009 after the strong thunderstorm had moved over downtown Tulsa, OK.

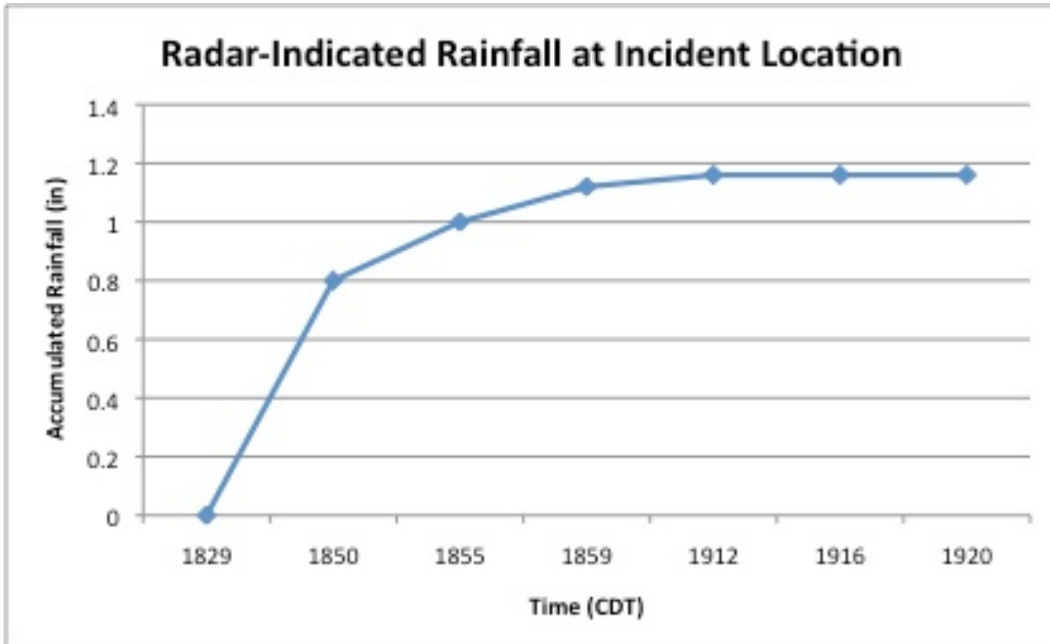

Figure 8: Accumulated rainfall (from the Digital Storm Total Precipitation radar product) at the incident location on 9 September 2009 as the strong thunderstorm passed over downtown Tulsa, OK.

As previously mentioned, while the storm cell responsible for street flooding at the incident location did not impact the KTUL rain gauge station, additional storm cells associated with this two-day rainfall event did pass over KTUL and can be analyzed to determine the skill with which the radar was capturing rainfall rates and totals during that 36-hour period. That analysis (comparison of radar-indicated precipitation totals with rain gauge precipitation totals for three discrete periods of precipitation that impacted KTUL station on the 9th and 10th of September 2009) reveals that radar estimates of precipitation with this event were 50% lower than rain gauge observations.

Recurrence Interval for the Rainfall Event

Taken as-is, radar indicates that the storm on 9 September 2009 that produced 1.12" of rainfall during a 30-minute period was an event with a 1 to 2 year recurrence interval. If radar underestimated the precipitation with this particular cell by 50% (as it did with other storm cells that affected KTUL earlier and later that same day), up to 2.2" of rain may have actually fallen during the 30-minute duration of the storm. 2.2" of rain during 30 minutes would qualify as 25-year recurrence interval event, and this should be considered the upper limit for the recurrence interval.

Soil Saturation:

0.61" of rain was reported at the KTUL rain gauge station during the week prior to 9 September 2009. This weekly total is slightly below climatology, and the rainfall was clustered from 9/2 – 9/5, with no rain falling during the three days leading up to the 9 September event. Soil saturation was therefore relatively low and did not provide

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conditions for enhanced surface water runoff during the reported street flooding at the incident location on September 9th.

Results:

The storm responsible for street flooding at the incident location on 9 September 2009 did not impact the KTUL (airport) rain gauge station, so a direct comparison of radar-indicated to observed precipitation for that particular cell was not possible. However, this storm was part of a broader convective event that did impact the airport location. Comparisons between radar-indicated and rain gauge precipitation measurements during this broader event revealed consistent radar undercatch (underestimation).

- **Event rainfall total:** 1.12" of rain were indicated by radar to have fallen during the 30-minute duration of this storm. However, based on the level of radar undercatch with other storm cells during this event, up to 2.2" of rain may have actually fallen at the incident location.
- **Recurrence interval:** Due to discrepancies between radar-indicated and observed precipitation measurements during this event, the recurrence interval is not well-constrained. Taken as-is, the radar estimated precipitation totals indicate a 1-in-2 year event. However, if the radar estimates were 50% lower than observed precipitation totals (as occurred with other storm cells during the broader convective event), the storm responsible for street flooding at the incident location would qualify as a 1-in-25 year event.
- **Role of soil saturation:** Given the lack of significant rainfall during the days preceding this event, soil saturation was not a factor and did not contribute to surface runoff during the 9 September 2009 storm.

CONCLUSIONS

The three convective rainfall events examined in this report represent a range of intensities, yet all were identified by the plaintiff as having caused notable or significant street flooding at her residential property near downtown Tulsa, OK.

The thunderstorm that impacted the incident location on 1 June 2008 was strong, but did not produce climatologically unusual rainfall totals. The recurrence interval for this storm is less than 1 year. However, the soil in northeastern Oklahoma was already quite saturated prior to this event due to heavy rainfall during the week leading up to 1 June. Saturated soils are less able to absorb rainfall, and this factor may have contributed to enhanced surface runoff during the 1 June 2008 storm.

The thunderstorm that impacted the incident location on 9 September 2009 was more intense but occurred over a watershed with relatively dry soil. Ms. Bates reported that the street flooding during this event was "minor curb flooding," as opposed to major flooding that inundated the front yard during the 1994 and 2008 storm events. Assigning a precise recurrence interval to this (9 September 2009) storm is difficult due to discrepancies between radar-indicated and rain gauge precipitation measurements; however, data agreement is sufficient to state that the storm has a less than 25-year recurrence interval, with a likely recurrence interval range of 2-10 years.

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Analysis of the 14 July 1994 storm posed a significant challenge due to the scarcity of data available for an event that occurred nearly 20 years ago. Radar-indicated precipitation estimates were highly inaccurate, and rain gauge observations were only available in daily intervals. However, radar reflectivity and daily rain gauge data both indicated an extremely intense and climatologically unusual storm with a recurrence interval of greater than 50 years. This storm also dumped its precipitation load on a saturated watershed, over which 3.38" of rain had fallen during the previous week, with 1.75" of rain falling during the day before the storm. High soil saturation may therefore have contributed to enhanced surface runoff during an already extremely intense event.

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Note: At Blue Skies Meteorological Services, we specialize in providing our forensic meteorology clients with reports that are both rigorous and accessible to non-experts. To that end, we have developed extensive educational background and reference material that we include, as applicable, in each report. This material explains in clear language and with accompanying graphics the tools and methodologies used in our meteorological analyses and investigations. Due to the proprietary nature of this material, we have removed it from our online samples. If you would like to see the full version of this sample report, please contact Blue Skies Meteorological Services at info@blueskiesmeteorology.com. Thank you for your understanding.

APPENDIX A: Background and Reference Material

Radar Basics:

- ***Overview***
- ***Radar Beam Characteristics and Resolution***
- ***Measuring Reflectivity***
- ***Rainfall Rates and Reflectivity***
- ***Measuring Velocity***
- ***Radar Limitations***
- ***Limitation Mitigation and Radar Estimate Verification***

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