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11.6 Some Unusual Aspects of the Fort Collins, Colorado Flash Flood of 28 July 1997

by

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1. Introduction.

In many ways the flash flood that occurred in Fort Collins, Colorado on 28 July 1997 was a "classic" High Plains severe weather event. First, the flood took place within a two-week period during which a catastrophic weather event is expected somewhere in the northern Rocky Mountain Front Range region (Weaver and Doesken 1990). Second, it occurred within a synoptic environment considered ideal for the occurrence of severe thunderstorms (Doswell 1980) -- the two primary factors being the existence of post-frontal upslope, and high dewpoint air in, and east of, the region of interest. Finally, conditions were especially favorable for flooding, since wind flow in the storm-bearing layer was weak, and there was a deep layer of tropospheric moisture brought on by a pre-existing monsoonal flow pattern (Hales 1974, Weaver and Doesken 1990).

Several facets of the flood, however, were not "classic." Examples of some of these include; 1) a complete absence of severe thunderstorm signatures (esp. heavy precipitation) on satellite imagery, 2) a "tropical" airmass on the High Plains, leading to a serious underestimate of rainfall by Doppler radar, 3) sheeting and runoff playing as great a role as streams and ditches in bringing about the catastrophe, and 4) a buildup of a large body of water which went completely undetected until it was too late to allow for the most effective emergency response possible.

This paper focuses on the unusual aspects of the event. It offers information and suggestions aimed at providing weather forecasters and emergency managers new insight into the nature of flash floods, especially those not confined to canyons, or rivers.

2. Satellite Imagery.

Satellite data discussed in this section are from the Geostationary Operational Environmental Satellite, GOES-9, positioned directly over the equator at 135° west longitude.

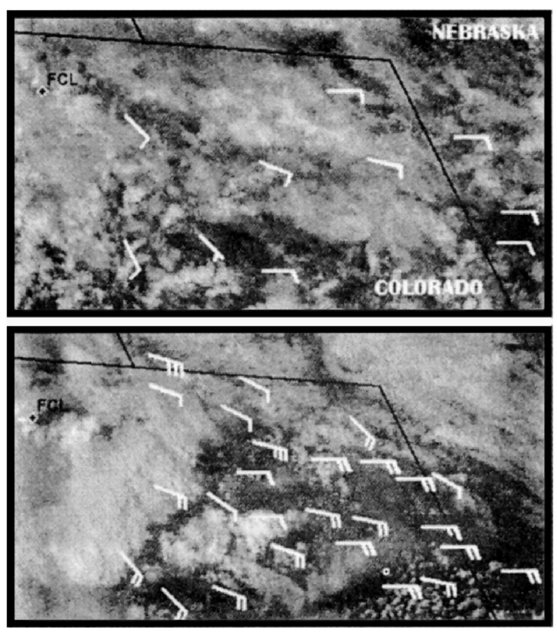


Figure 1. Low-level winds (in kt) from cumulus cloud motions on GOES-9 visible imagery, 28 July 1997. Upper panel is calculated for the period 1400 - 1600 MDT, lower panel for the period 1600 - 1730 MDT. (More traceable tags exist for the later period.)

From the real-time forecast point-of-view, satellite imagery supplies useful information on the broader-scale evolution. For example, cloud tracking algorithms applied to sequential visible imagery (figure 1) show upslope flow speeds accelerating in the lower layers of the atmosphere during the late afternoon of the 28th. Also, both visible and infrared data identify large thunderstorms in eastern Colorado. There may even have been a pulse of thunderstorm outflow which triggered the initial activity in the Fort Collins area. All of these observations certainly would have proven useful in real-time.

On the other hand, the heaviest rains occurred after sunset, when visible data are not available. Also, the storms were relatively shallow in the Fort Collins vicinity, and the tops relatively warm, making it difficult to extract any information on severity utilizing "classical" clues from the satellite data (figure 2). One aspect that seems a little more obvious in retrospect, is the transient nature of the larger storms in eastern Colorado, as opposed to the nearly stationary location of the very small top near Fort Collins. An "average image" shows this aspect more clearly (figure 3).

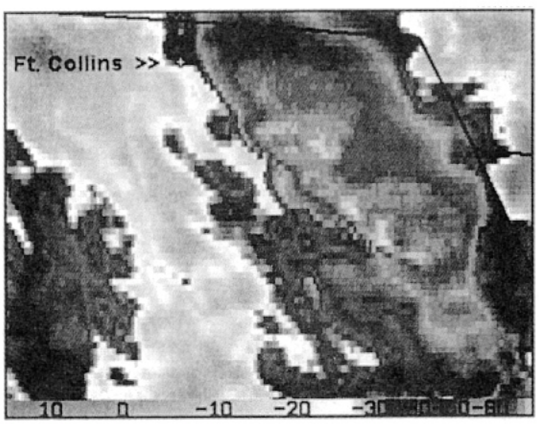


Figure 2. GOES-9, 10.7 μm image from 28 July 97 taken over northeastern Colorado at 2046 Mountain Daylight Time[1] (MDT). Note the small storm near Fort Collins.

3. Precipitation measurements.

A thorough search for reliable rainfall reports was begun in the days immediately following the storm in an effort to accurately describe rainfall patterns. A combination of local radio and news-

[1] *Add 6 hr to convert to Universal Time*

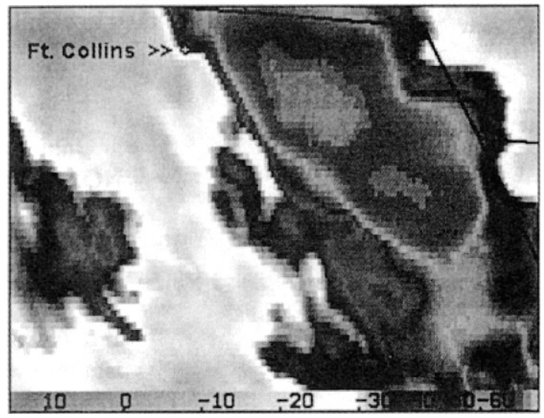
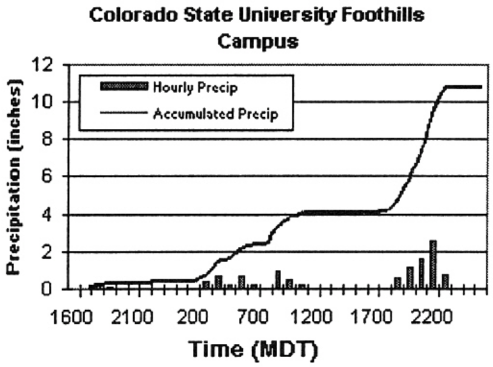


Figure 3. Average of 12, GOES-9 10.7 μm images over northeastern Colorado for the period 2016 - 2230 MDT on 28 July 1997.

paper announcements, e-mail inquiries over local networks, telephone solicitations, and door-to-door surveying was employed. The results were assembled and collated with data from existing automated weather stations, and local volunteer weather observers. In the end more than 300 rainfall reports, most of relatively high quality, were obtained for Fort Collins and vicinity. Among these observations were nearly 20 *recording* rain gauges that were owned and operated by a variety of organizations. Five of these were in the vicinity of the heaviest rains. The recording sites proved helpful in interpreting and utlizing the hundreds of rainfall reports from interested citizens. Additionally, the density of observations was excellent in most areas, with several observations per square mile over much of the urbanized Fort Collins area. However, there remain deficiencies in both data quality and spatial coverage. The analysis was further complicated by the fact that many gauge readings were total accumulated values for periods that did not correspond exactly to the periods analyzed in this report.

The rainfall measurements confirm that the flood was not simply the result of a single intense storm, or even a single evening's rain. Instead, there were a series of rain episodes beginning late on July 27th that were concentrated near the base of the foothills immediately west of Fort Collins. This is reflected in hourly rainfall data collected at the Foothills Campus of Colorado State University, some two miles north of the maximum rainfall region (figure 4). The time-trend in this chart is similar to what occurred further south, though absolute amounts are less. The important point to note in this time-history is that heavy rainfall had occurred over the previous 24-hr, saturating the ground throughout the region before activity started up again on the 28th.



The culmination of the flooding came with a new round of heavy rains which began just before 1800 MDT on July 28th -- rains which fell onto the totally saturated soils, or into the swollen creeks and irrigation canals, on the western edge of the urban area. Moreover, these storms did not behave like those in the majority of floods, wherein rain rates peak during early - to middle - portions of the event, then taper-off

Figure 4. Hourly rainfall amounts in inches and accumulated totals from 1600 MDT, 27 Jul 1997 through 1159 MDT on 28 Jul 1997 as measured at the Colorado State University Foothills Campus just west of Fort Collins, Colorado.

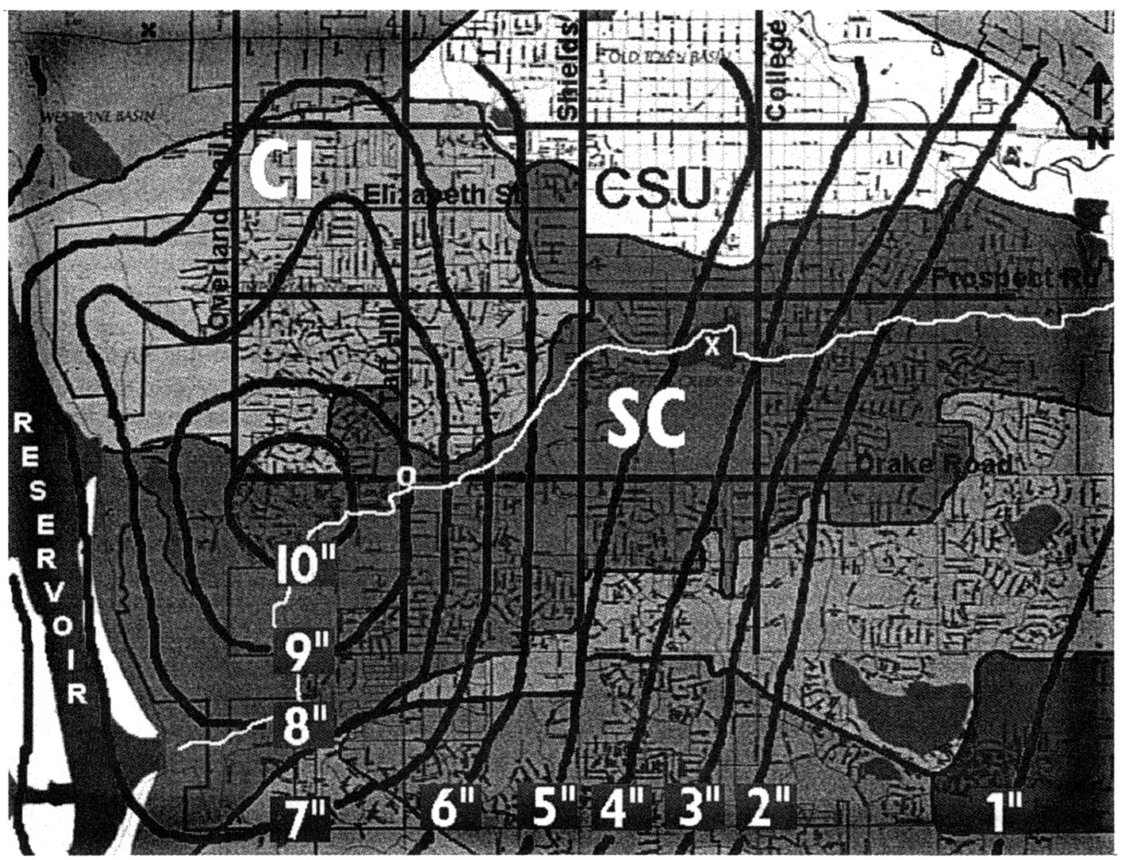


Figure 5. Rainfall (in inches) for Fort Collins for the period 1730 - 2300 MDT, 28 July 1997. The small circle at the intersection of Drake and Taft Hill corresponds to the radar fiducial mark discussed in the next section. Main arterial roads are shown in dark black (roads separated by one mile). Local drainage basins are shaded. "CI" shows the Canal Importation Basin, "SC" the Spring Creek Basin. Spring Creek is depicted as a light colored ribbon in the SC basin. Black "X" in upper left is where Foothills observations are taken. Light "X" marks the 50+-acre detention area discussed in text.

slowly as flooding begins (unpublished results, see acknowledgements). In this case, rain rates increased steadily throughout the evening. Rainfall totals near the geographical center of the storm exceeded five inches during the 90-minute period from 2030 - 2200 MDT. The significant rains ended quickly after about 2215 MDT.

Figure 5 shows rainfall totals over Fort Collins for the evening of the 28th. Notice how the heaviest rains were concentrated over the western portion of the city. In fact, the area that received more than 10" of rain was less than one square mile. Rainfall amounts decreased rapidly both east and west of the storm center. Residents in extreme eastern Fort Collins were unaware that an unusual storm was taking place.

In historic perspective, the July 28th storm ranked as one of the top-ten extreme rainstorms in Colorado's recorded history based on total rainfall (McKee and Doesken, 1997). It was the heaviest rain ever to fall in Colorado on a developed urban area. A detailed summary of the 28 July rainfall analysis can be found in Doesken and McKee (1998).

4. Doppler Radar.

Doppler radar data were collected at three sites "locally." These were the National Weather Service WSR-88D site at Denver, Colorado, the WSR-88D site at Cheyenne, Wyoming, and the CSU-CHILL research Doppler radar located in Greeley, Colorado.

On the night of the flood the CSU-CHILL radar was collecting a mixture of 6-min and 15-min interval volume-scans, composed of 3-9 tilts each. Comparisons of derived rainfalls, and storm structure between CHILL and NEXRAD radars for this case provide valuable insights into the potential pitfalls associated with relating reflectivity data (Z) directly to rain rate (R) -- i.e.,the so-called Z-R relationships.

The CSU-CHILL radar differs from the NWS WSR-88Ds in that the CHILL interrogates a volume of the atmosphere by sending/receiving microwave radiation polarized in *both* the horizontal and vertical planes. NWS Doppler radars process only the horizontally polarized component. The backscattered power returned from precipitation particles in two polarizations together provide a bulk measure of hydrometeor shape and thermodynamic phase.

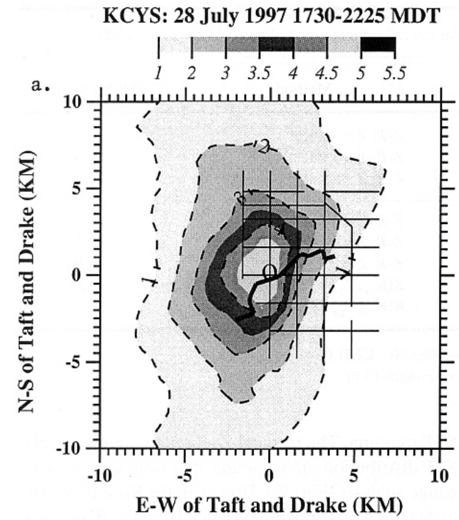


Figure 6. Accumulated rainfall in inches for the period 1730 - 2215 MDT on 28 July 1997 using reflectivity data collected by the Cheyenne NEXRAD radar at 5 minute temporal intervals (i.e., VCP-11, severe weather mode). NEXRAD Z-R relationship used is $Z=300R^{1.4}$. *The white circle at 0/0 is positioned at the intersection of Drake & Taft Hill roads. Main arterials and collector roads highlighted.*

The CSU-CHILL radar also utilizes the *phase* of the backscattered signal in both polarizations. When the phase information is combined with the dual-polarized power-return measurements a great deal of information about the bulk microphysical properties of the medium (e.g., precipitation characteristics such as water versus ice, etc) is obtained. Specifically, a more accurate measure of rainfall is facilitated using combinations of polarimetric radar variables (Ryzhkov and Zrnic 1995).

Comparisons of the accumulated precipitation computed from both radars for the time period 1730-2215 MDT on the 28th illustrate the marked difference that can occur in rainfall measurement as a function of measurement platform. Compare the accumulated rainfall computed by the conventional WSR-88D (figure 6) with rain gauge totals (figure 5). While the overall pattern seems fairly well represented by the Z-R estimate, the absolute totals are low by a factor of nearly 2.

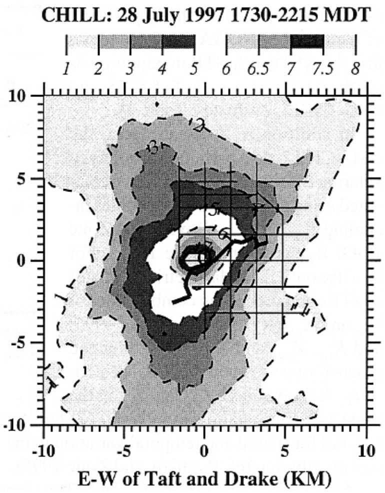


Figure 7. Accumulated rainfall for the period 1730 - 2215 MDT on 28 July 1997 using a combination of CHILL reflectivity, differential reflectivity, and differential phase data. Main arterials and collector roads highlighted.

Figure 7 shows a "blended" precipitation product computed using a combination of polarmetric and Z-R estimates from CHILL. In this case, the overall pattern is even closer to that generated by the gauges, as is the absolute maximum rainfall estimate of roughly 8 inches (approximately 80% of the gauge values). This closer match is due to the fact that the dual-polarization techniques more accurately capture microphysical variations in individual storms, while the WSR-88D radars use pre-determined relations that are susceptible to not only variations in microphysical properties (e.g., the presence/absence of ice), but also drop-size distribution, various types of sampling error, and/or radar calibration problems.

The microphysical anomalies associated with the Fort Collins rainstorms were a direct result of the unusual characteristics of the local airmass on 28 July. Radiosonde data from Denver, Colorado (not shown) found a temperature and dewpoint profile similar to that observed in tropical oceanic or monsoon convective regimes (e.g., Johnson et al., 1996). Such airmasses -- very warm, near neutral stability, and copious moisture throughout -- generally result in warm-rain convection. This type of storm is highly anomalous relative to that typically observed in northeast Colorado, wherein rain droplets form as the result of the initial riming of small ice particles (Knight, et al., 1974). In this case, vertical profiles of radar reflectivity from CSU-CHILL suggest the presence of enhanced collision-coalescence processes with a marked lack of precipitation-ice mass. Also, as is common for tropical monsoon/oceanic convection very little lightning occurred on the evening of the 28th, and the periods during which ice phase particles *were* detected, did have associated lightning.

One segment of the event currently being examined in greater detail is the period from 2030-2100 MDT. It was just after 2030 MDT when storm motion changed from 200 at 8 ms^{-1}, to around 220 at 3 ms^{-1}. It was also during this period that the heaviest rainfall was recorded (see previous section). An intriguing and coincident observation comes from WSR-88D and CSU-CHILL dual Doppler velocity analysis which finds a narrow ribbon of accelerated easterly flow arriving in southwest Fort Collins shortly after 2030 MDT. We believe this enhanced upslope flow was associated with outflow from large storms located far to the south-southeast, and was responsible for the unexpected, and atypical, period of extreme rain near the end of this event. The source of the acceleration is currently under investigation, and will be discussed in more detail in a formal article to appear in the Bulletin of the American Meteorological Society later this year.

5. Hydrological Flow.

The drainage picture in the city is complex. In addition to the Poudre River which runs through northern Fort Collins, a series of creeks and irrigation ditches crisscross the landscape, transporting water from north-to-south and west-to-east across the urban area.

There are also large drainage basins which slope downward toward the east (figure 5). The larger of these basins lose some 300 feet of elevation from west-to-east across the city, and are generally lower in the center than on the edges. They are shaped such that water drains north and south toward the center, as well as eastward with the overall slope of the terrain away from the foothills. The Canal Importation (CI) basin has an outlet into a shallow extension of the Spring Creek (SC) basin on west Elizabeth Street. This extension is not topographic, but is an artifact of drainage pipes which have been added to supplement drainage from a historically troublesome area.

In heavy rains, the water on Elizabeth drains directly into the campus of Colorado State University (CSU). This is what occurred on the evening of the 28th. At 9:30 p.m., white water some four-feet deep was observed at the intersection of Elizabeth and Shields. According to some witnesses, industrial-sized dumpsters "bobbed around like corks" as they headed east onto the CSU grounds. The water flowed into the campus, flooding the lower levels of many buildings, including such major structures as the Lory Student Center, and the CSU library. The school sustained over $100m worth of damage to structures and contents, and a year later is still trying to recover.

The heaviest rainfall on 28 July, however, fell almost entirely into the western ends of the SC and CI basins. Most business and residential properties in both of these areas -- at least those in local low spots -- experienced serious problems. Flooded basements and automobile damage were the chief complaints. Plots of E-911 calls with time show the area of complaints expanding eastward within individual basins as the heavy rains continued. The most catastrophic problems, including 5 deaths and numerous injuries, occurred just east of where the CI and SC drainages converge. By 2200 MDT flow rates[2] along the main channel of Spring Creek were running in excess of 6,000 cubic feet per second (cfs) just east of the primary exit of the CI basin. This flow converged with greater than 1,300 cfs flow exiting the CI basin directly, and 850 cfs overflow south of the main SC channel. Combined flows sent a total of 8,250+ cfs of water directly into a large 50-acre lowland area (darkened area in figure 5, denoted by an "X"), which was contained on the east side by a 19 foot high railroad bed. The area is designed to be a massive flood detention pond, and is meant to collect and hold greater than the predicted 500-year flood overflow. Its total capacity of 362 acre-feet was reached by 2230 MDT. No stream or depth gauges had been installed, so the buildup went unmonitored. Also, since the area is large and free from human habitation, there was virtually no way for the general public to observe these catastrophic buildups. Shortly after the volumetric capacity of the detention area was reached, a combination of a culvert failure and overtopping of the railroad bed, produced the most devastating results of the night (see next section).

[2] *Estimates by the U.S. Geological Survey and Fort Collins Stormwater Utility.*

5. Concluding Remarks.

A catastrophic weather event is nearly always the result of meteorological circumstance interacting with a unique local environment. In flash flood situations factors such as local terrain, population density, land use, and a plethora of other variables can all play critical roles in buildup to disaster.

Exact figures for the destruction wrought by the events of 28 Jul 1997 in Fort Collins, CO are still being compiled. We do know that 5 people were killed, and more than 60 injured. These casualities were in addition to several hundred rescues performed the night of the flood. We also know that at least 120 mobile homes, 19 multi-family dwellings, and 2 single-family homes were completely destroyed. Over 2,000 other homes suffered problems ranging from minor to serious. Damage to Colorado State University is now estimated to exceed $100m, and damage to homes, businesses and other property around the rest of the city may be as high as $150m. Automobile claims alone have reached $4.7m acccording to local insurance companies.

For this flood, nowcasters and short range forecasters were hampered by the unusual characteristics of the storms. Satellite severe weather signatures (such as cold tops, warm wakes, etc) were not present. In fact, the storm over Fort Collins was *so* small, that it likely would have gone completely unnoticed in the absence of other data. Moreover, there was a gross underestimate of rainfall rates as computed by the NWS WSR-88D radars using standard Z-R relationships. Meteorologists at the Denver NWS warning desk that night had no idea of the quantities of rain actually falling on the city. Had they have had the option of switching the "standard" Z-R table to one that was more tropical in nature, perhaps warnings could have been issued somewhat earlier. As it is, the first flash flood warning was not issued until 2140 MDT, long after flood damage had already begun, and as people in the afflicted trailer parks were getting ready for bed. However, a note of caution. The nearly 100% liquid-phase storms that occurred over Fort Collins on the night of the 28th were isolated. Z-R estimated rain rates for other storms in northeast Colorado (e.g., in southern Weld county), occurring at the same time were relatively accurate. Furthermore, plots of lightning data for the six hour period encompassing the flood event (not shown) indicate significant electrification for the storms in Weld county, as well as others further to the east. The best solution might be for future generations of NWS radars to be equipped with dual-polarization capabilities. Meanwhile, a simple, "applied" forecasting study -- one that looks at lightning data as a tool for judging whether standard Z-R relationships are valid for cases in which storms form in "tropical" airmasses -- might be useful.

A unique combination of weather and local environment was required to produce the massive damage that occurred in the Fort Collins flood. Remember that storms which occurred from late on the 27th through midday on the 28th produced rainfall totals of over 9" just 10 miles to the north of the Fort Collins urban area. What would have happened had these storms occurred in western Fort Collins on that day? As it was, this "first round" of activity had only a moderate effect on lives and property. It did, however, condition the region for events the following day. The rains which fell between 1730 - 2300 MDT on the evening of July 28th brought approximately the same rainfall totals, but at a higher intensity, and this time the rain fell into two heavily-populated drainage basins. The dangerous combination of localized heavy rainfall, saturated soils, dense population and converging drainages all contributed to a catastrophic flash flood.

Rain and stream gauges would have helped in developing a better lead time for people downstream from the large detention area (as well as for other detention areas around the city). As it was, the first clue that something was amiss east of the railroad bed was when flash flooding had actually begun.

6. Acknowledgements.

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