An Analysis of Rainfall for the July 28, 1997 Flood in Fort Collins, Colorado

Nolan J. Doesken
Thomas B. McKee

Climatology Report 98-1

DEPARTMENT OF ATMOSPHERIC SCIENCE
COLORADO STATE UNIVERSITY
FORT COLLINS, COLORADO

An Analysis of Rainfall for the July 28, 1997 Flood in Fort Collins, Colorado

Nolan J. Doesken
and
Thomas B. McKee

Colorado Climate Center
Department of Atmospheric Science
Colorado State University
Fort Collins, CO 80523-1371

Climatology Report 98-1

February 1998

Table of Contents

An Analysis of Rainfall for the July 28, 1997 Flood in Fort Collins, Colorado

Purpose

Colorado is known for abundant sunshine, low humidity and a relatively mild climate. But from time to time through history, extreme rainstorms have occurred. Analysis of the largest reported rainstorms in Colorado has shown that the areas where the Great Plains meet the Front Range of the Rockies is particularly prone to extreme rainfall events and associated flooding (McKee and Doesken, 1997). Since 1920 at least 312 people have died in Colorado as a result of flash floods (Tunnell, 1998), with most of these deaths occurring along the Front Range. As the population of Colorado continues to grow, and as more and more people live and work in or near urban areas along the Front Range, the vulnerability of this region to catastrophic flash floods also grows. For large urban areas to exist in a flood-prone region and still provide relative safety to their residents, wise and careful planning is required that takes into account how much it has rained in the past and how hard it might rain in the future. Wise planning is especially important where dry weather is so often the rule and the potential for heavy rains is quickly forgotten.

On July 27-28th, 1997, very heavy rains fell over portions of eastern Larimer County in north central Colorado. Extreme urban flooding conditions developed on July 28 in Fort Collins that swept five residents to their death and caused over $100 million dollars in property damages. The purpose of this report is to thoroughly document the area, duration and intensity of the rains associated with this Fort Collins flood. By defining the rainfall patterns as precisely as possible, it is our hope that many can learn from this experience. Hydrologic modeling and design, urban planning, emergency management, public policy and education are just of few of the applications that stand to benefit.

Many of the extreme storms of the past along the Front Range have been studied (Follansbee and Sawyer, 1948, Maddox et al, 1977, Glancy and Daselar, 1986, Hansen et al, 1988, and others). However, many of these historic storms occurred in areas where precipitation data were sparse. Results of "bucket surveys" produced estimates of rainfall patterns, but confidence in some of the analyzed rainfall patterns from past storms has been low. Interestingly, there had just been a meeting in Denver on July 17, 1997 of the Colorado Extreme Precipitation Committee, a small group of predominantly state and federal officials with common concerns. At that July meeting, the importance of thoroughly documenting future extreme storms was discussed. While no group is currently funded to survey and study extreme storms, several groups agreed that if a huge storm were to occur, they would attempt to gather as much information as possible. Coincidentally, in less than two weeks, the opportunity presented itself. Since the Fort Collins storm occurred over an urban area where many individuals and organizations took gauge rainfall measurements, and since remotely

sensed rainfall data were also collected from the National Weather Service WSR-88D Doppler radars at Cheyenne, Wyoming, and near Denver, Colorado, and also from the Colorado State University CHILL dual-polarized research radar near Greeley, this storm presented one of the best opportunities in Colorado history to accurately define rainfall patterns from an extreme storm.

Weather Conditions Associated with the July 27-28, 1997 Rains

From mid June into the final week of July 1997, the Fort Collins area and much of Colorado had been experiencing several weeks of dry weather. At the official Fort Collins weather station on the campus of Colorado State University, only 0.36 inches of precipitation had fallen since June 15, just 16 percent of average for that time period Temperatures had also been persistently hot since July 7. Beginning around July 18, humidity increased over Colorado as tropical moisture began its typical mid-summer northward drift into the southwestern U.S. Afternoon thunderstorms became more numerous, and a few were locally quite heavy such as the one that dropped 3.83 inches of rain in just over one hour at the National Weather Service Forecast Office at Denver Stapleton on the afternoon of July 19.

Despite increasing humidity, thunderstorm activity remained fairly isolated until an unusually strong mid-summer cold front reached eastern Colorado on July 27. A large high pressure area perched over southern Canada pushed cooler air southward toward Colorado. Early on Sunday morning (July 27) the cold front extended from approximately Minnesota to southern Wyoming (Figure 1). At the same time, moisture continued to stream northward into Colorado from the south. As the cold front moved southward over Colorado during the day, easterly surface winds developed that began to push very humid surface air that had been over Kansas and adjacent plains states into eastern Colorado. These conditions set the stage for the very heavy rains that fell in the ensuing hours July 27-28, 1997 over the Fort Collins area and were surprisingly similar to the conditions of July 31, 1976 which produced the disastrous Big Thompson flash flood.

Several atmospheric scientists are investigating the weather conditions preceding and during the Fort Collins storm. Detailed meteorological analyses will be available when these studies are completed. This report does not attempt to duplicate those efforts.

Following the Fort Collins flood on July 28, very moist air continued to linger over Colorado for several days, and more extreme rainfall events occurred. The very next evening, Fort Collins experienced a near miss as heavy downpours again developed. Fortunately, these storms took a different track and dropped most of their rain north and east of Fort Collins. Portions of Larimer County received more than two inches of rain during the evening of July 29th. But farther to the east a truly remarkable nighttime storm inundated the Pawnee Creek watershed northwest of Sterling, Colorado. This storm likely surpassed the Fort Collins storm significantly in terms of both total rainfall and storm area. At least 14 inches of rain in 6 hours is believed to have fallen over an area of perhaps 15 square miles with 4 inches or more over nearly 500 square miles (Browning and Lang, 1997). The resulting flood inundated large portions of Sterling and Atwood along with thousands of acres of farmland.

SUNDAY, JULY 27, 1997

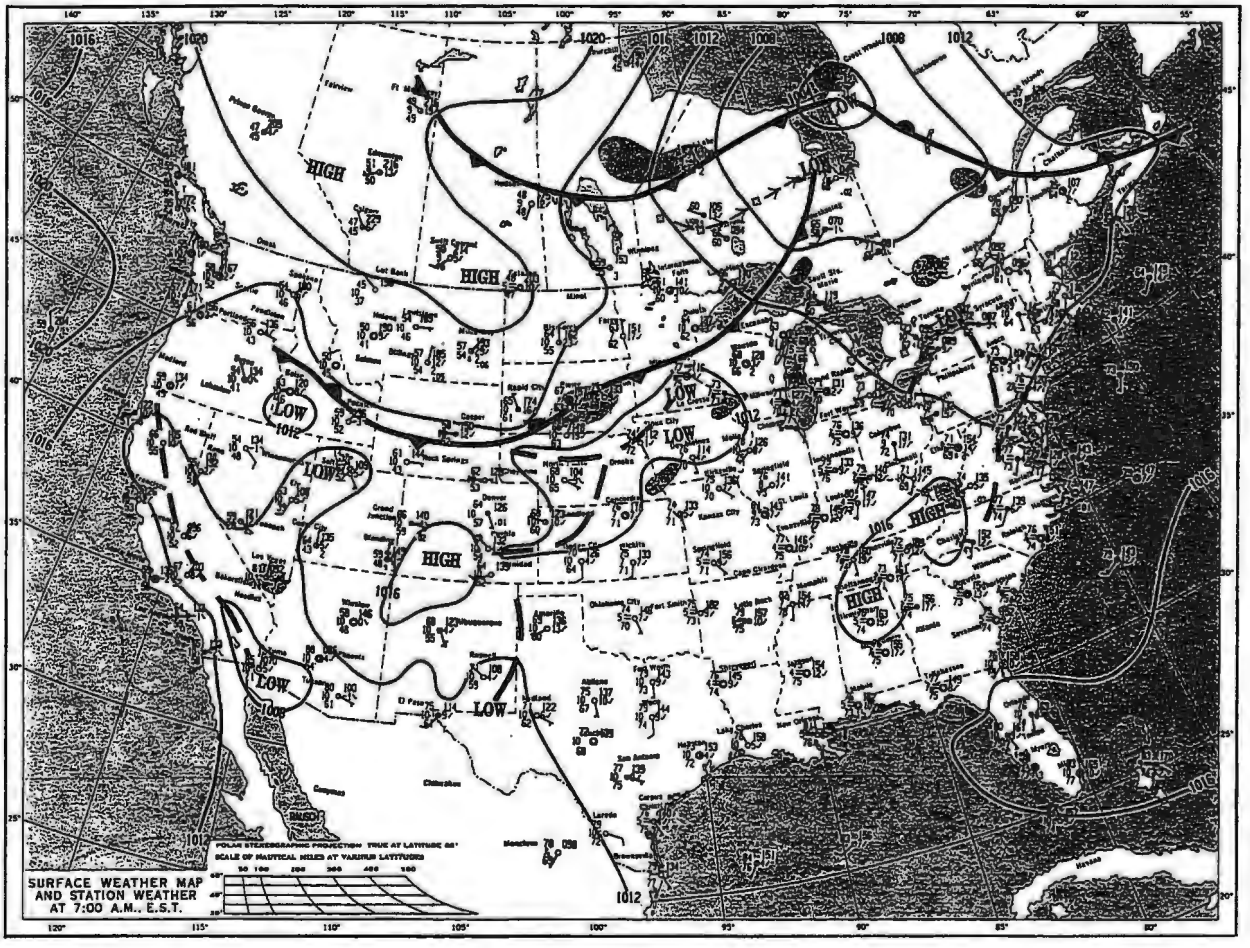


Figure 1. U.S. surface weather map at 0600 MDT Sunday, July 27, 1997 (from "Daily Weather Maps, Weekly Series," for week July 21-27, 1997, published by NOAA, NWS, Climate Prediction Center, Washington, DC).

Remarkably, no fatalities were reported. A summary of rainfall and runoff from this huge storm is being prepared by the Colorado Water Conservation Board in Denver. Other very heavy rains occurred in Phillips and Elbert Counties. Heavy local downpours continued in early August and caused more local flooding, most notably in southeastern Colorado. A Presidential Disaster Declaration resulted (DR-1186-CO) which eventually included a total of 13 counties in eastern Colorado. This report focuses only on the rains of July 27-28, 1997 in and near Fort Collins.

Data Collection

In order to thoroughly document the rainfall patterns from the July 27-28, 1997 storms in the Fort Collins area, an intensive effort was made to obtain rainfall information from any potential source of data. Under ideal conditions, the effort to collect precipitation data would have begun early on the morning after the flood. However, due to the widespread flood damage on the Colorado State University campus, including minor damage at the official weather station just north of the severely damaged Lory Student Center, and due to personal emergencies associated with the flooding, and the nearly continuous barrage of media calls and contacts from many sources seeking information about the flood, a systematic effort to collect data did not begin until July 30th. The Colorado Climate Center had previously performed an intensive survey of precipitation in 1994 as a part of a special radar-rainfall research project (Clement et al, 1995), so some expertise in storm surveying existed. Unfortunately, no systematic plan had been developed to help guide a rapid and coordinated data collection effort of the magnitude needed to survey this storm.

A data collection effort was hastily initiated. The following methods were used to obtain precipitation data.

1) **National Weather Service Stations**. The National Weather Service (NWS) maintains a national network of several thousand temperature, precipitation and snowfall measurement sites or sites that measure only precipitation. Ten of these cooperative weather stations are in Larimer County including the official Fort Collins weather station on the CSU campus. These data are routinely transmitted to the National Weather Service in Denver at the end of each month and were used in this study.

2) **Mountain States Weather Services volunteer observers**. For the past 20 years, Jim Wirshborn, director of Mountain States Weather Services (MSWS) in Fort Collins, has maintained a network of volunteer weather observers in Fort Collins, Larimer County and surrounding areas. Many of these observers call in precipitation reports to MSWS during and after each significant storm, and most of them record 24-hour precipitation totals on observation forms that are mailed in at the end of each month. These data were all provided to the Colorado Climate Center in early August to assist in the storm documentation. A total of 44 rainfall reports were included from MSWS volunteer observers who fill out observation forms A few of these were redundant with NWS reports. Other reports from MSWS spotters were received by phone.

3) **Department of Atmospheric Science**. For many years, some faculty and staff of the CSU Department of Atmospheric Science (ATS) have attempted to maintain a cooperative precipitation network in the immediate Fort Collins area. A map of the Fort Collins area was posted on a bulletin board near the foyer of the building early on July 29, and several employees who maintain rain gauges, recorded their rainfall totals there. Most of these observers use 4" diameter clear plastic precipitation gauges which are known to be very accurate for measuring rain. In all, 12 faculty and staff of ATS provided rainfall reports.

The first three categories provided some very reliable rainfall reports. However, they did not give complete spatial coverage over Fort Collins and eastern Larimer County. Therefore, a campaign was mounted to obtain data from as many other sites as possible. The majority of this was done without leaving the office.

4) **Public service announcements**. On July 30, 1997, Colorado Climate Center staff contacted a local radio station, KCOL, which was doing nearly continuous flood related broadcasting. The station agreed to broadcast, as a public service, the request for rainfall measurements. Several phone calls resulted from this announcement which probably was aired only on July 30.

5) **Radio weathercasts**. Jim Wirshborn of Mountain States Weather Services made requests for rainfall reports during his local radio weather broadcasts on the local station KIIX during the days immediately following the storm. Several calls came in as a result of this radio announcement.

6) **Newspaper.** The Fort Collins Coloradoan willingly published a special sidebar to a lead article about the flood on Thursday, July 31. This prominent announcement yielded dozens of responses. Jim Wirshborn also included a call for reports in other newspaper stories. In exchange, the newspaper requested permission to publish a story about volunteer storm reporters and the subsequent rainfall analysis that they helped generate (published August 29).

7) **E-Mail inquiries.** A 1990's approach to surveying precipitation was used very effectively – the Internet. Electronic mail messages were transmitted to all City of Fort Collins and all Colorado State University employees with e-mail addresses. A limited distribution was also made at Hewlett-Packard Company, one of the largest employers in the area. Many responses resulted from these e-mail requests. A benefit of the e-mail surveys was that the original request contained a set of questions about the location of the measurement, type of rain gauge, and times and amounts of precipitation. Many of the responses contained most of the information needed to process the information without needing a follow-up. A copy of the e-mail message distributed to a few thousand addresses in Fort Collins appears in Appendix A.

8) **Driving surveys.** On several different occasions within a few days after the flood, Colorado Climate Center personnel took driving tours of areas affected by the flood. Visits were made to some of the sites that had reported extreme rainfall totals to check on the type and location of gauges. Residents in a few neighborhoods were interviewed, and additional rainfall measurements were discovered.

9) **Phone searches**. As information from all data sources was compiled, preliminary analyses were performed which then pointed out a few areas north and southwest of Fort Collins for which very few rainfall reports had been obtained. Special focused efforts were then initiated to identify possible data sources for those areas. Using personal contacts, irrigation companies, and a variety of referrals, additional rainfall reports were identified to help fill in data voids.

10) **Supplemental Data**—Radar (National Weather Service, CSU CHILL) At the same time that precipitation data were being assembled, contacts were made to obtain radar data from two independent meteorological radar sites: 1) The operational WSR-88D National Weather Service weather surveillance radar located east of Denver, and 2) the Colorado State University CHILL research radar near Greeley. The use of radar data will be discussed later in this report.

The initial efforts were focused on e-mail, newspaper and radio announcements in order to collect data from as many sources as quickly as possible while evidence and memories were still fresh. Known sources of data such as National Weather Service official stations and cooperative observers for Mountain States Weather Services were not initially pursued, since it was assumed that these sources would be available in writing and would not require much follow up efforts.

A special form was developed for recording each rainfall report (Appendix B). For each report received, a variety of information were obtained and recorded.

- "Observer Information." The location of each measurement site was recorded, and information on how to contact the observer was noted. This was important since many observers were contacted two or more times with follow-up questions as the analysis proceeded.
- "Rainfall Amounts." The observed rainfall totals were recorded along with any objective information about how that rainfall was distributed over time. Since the rain began Sunday evening (July 27, 1997), fell in several distinct periods, and culminated Monday night, many observers had time to read and empty their gauges more than once during the period. In fact, many gauges would have spilled and their readings would have been useless were it not for the great diligence of many individuals who took multiple measurements. While most reports were either a single total for the whole storm period or perhaps two separate measurements, some observers read their gauge and noted the measurement times as many as 10 times. Some got totally soaked in the process, but the resulting information made it possible to deduce the time history of the rainfall with good accuracy.
- "Type of rain gauge." When interviewed, each observer was asked to describe the type of rain gauge they were using. This is helpful information in interpreting observations. Also, for many sites, especially those receiving heavy rainfall totals, more information about precise gauge location and exposure was obtained.
- "Other Remarks/Information." Observers were asked to provide any additional supporting information either about their rainfall observations or about their storm

experiences. Many recollections were shared, but only those remarks pertinent to the actual observations were recorded.

In all, 307 rainfall reports were obtained. At least two-thirds of these involved phone conversations or e-mail messages. This process of information gathering consumed, on average, about 30 minutes per rainfall report. With one full-time professional working on this activity with additional part-time support, it was still only possible to process about 20 to 25 rainfall reports each day. Driving surveys were even more time consuming since it often took several stops and conversations in order to track down a single report. The easiest data collection was the existing National Weather Service cooperative stations and those maintained by Mountain States Weather Services. The advantages of these sites were that they recorded their observations on standardized forms, used known types of rain gauges and their locations were already known and indexed. There were simply not enough of these existing stations, however, to adequately describe the storm. Despite being consistent and well documented, follow-up calls were sometimes still needed to obtain more detailed information from these observing sites.

Of the 307 rainfall reports, 281 were actual gauge measurements. Measurements came from a variety of rain gauges ranging from official National Weather Service eight-inch diameter standard manual rain gauges and a variety of electronic recording gauges to several types of low-cost hardware-store-type gauges. While the Fort Collins area did not have an existing special precipitation network, 19 recording gauges were identified in the region which offered hourly or finer time resolution data for documenting rainfall rates and time distributions. Of the many manual gauges, nearly one third were quality gauges meeting National Weather Service guidelines for quality. The majority of these were the 4-inch diameter clear view gauge that is thought to be as accurate as the official NWS 8-inch diameter standard gauge.

This large number of high quality gauges made a remarkable contribution to the validity of data collected about this storm. The unusually large number of privately owned high quality rain gauges may have been the result of many years of promotion of volunteer weather observing by Jim Wirshborn, Mountain States Weather Services. During the past twenty years he has circulated dozens of the 4-inch diameter gauges in Larimer County. Credit could also be given to the relatively large number of working or retired foresters and hydrologists in this area, many with professional experience recording precipitation. But even low cost calibrated gauges can provide fairly accurate information when read properly and mounted in representative locations. For this reason, Colorado Climate Center personnel visited many of the observing sites where very heavy rainfall amounts were reported in order to check and verify the readings. Observers that were not visited were still asked to describe their gauge location and potential obstructions. Some observations were found to be of poor quality or low confidence due to close proximity to obstacles such as trees, fences and buildings. Obstacles can either decrease or exaggerate rainfall totals depending on factors such as wind speed, direction and rainfall intensities.

The Colorado Climate Center used the information about types and exposures of rain gauges and other information about each observation to qualitatively assign a data quality evaluation to each rain report. Excellent observations using quality gauges were assigned "A" status.

"B" ratings were given if the reports appeared to be reasonably accurate, but the type of gauge or its placement may have been satisfactory but not ideal. "C" ratings were given to observations that contained useful information but with obvious deficiencies in the quantitative observations. Observations that were obviously erroneous or unusable for other reasons were assigned "D" status. These assessments were used later in the analysis. Some measurements were assigned a "C" or "D" status simply because they came from uncalibrated collectors such as buckets or trash cans. Only 19 of the rainfall observations received were accumulations measured in buckets or other uncalibrated collectors. If thoroughly analyzed, these non-gauge containers could provide useable readings.

In past extreme storms in Colorado, investigators have normally found very little gauge data from which to determine rainfall magnitudes and patterns. Therefore, "bucket surveys" were conducted in which extreme rainfalls were deduced from a variety of indirect measurements from receptacles ranging from paint buckets to kiddy pools and stock tanks. Some significant amount of uncertainty has always accompanied bucket surveys. Therefore, the Larimer County storms of July 1997 may be the most accurately measured and documented extreme rainstorms in Colorado history to date.

The primary data gathering activities were completed within 15 working days after the storm event. However, it took several weeks to compile and check all reports, visit selected sites and evaluate data quality. This effort required more than two months of full-time commitment by the Assistant State Climatologist. Several others contributed greatly to the data collection effort including Jim Wirshborn at MSWS and other staff members of the Colorado Climate Center who assisted part time. Based on the initial data gathering activities, a preliminary report was released August 4, 1997 with updates issued August 12 and again on August 29. It then took an addition six weeks for final verification, computer data base development, and the application of radar data. The final set of rainfall maps for the storm was completed October 9, 1997. Mapping procedures will be described later in this report. The writing of this narrative report then proceeded at a more leisurely pace to accommodate other work responsibilities.

In looking back at this data collection effort, the enthusiastic and willing assistance from many organizations and individual citizens was exceptional. In particular, the successful use of specially authorized wide distribution electronic mail must be noted. While there was at least a 24-hour delay due to official approval processes in sending out wide-distribution electronic mail requesting rainfall reports, still the method showed great effectiveness as close to 25% of the data collected on this storm was obtained in this manner. Also, we were able to pose more specific questions in our e-mail request, so that many questions about station location, rain gauge type and exposure and also details about the storm were answered directly.

Other potentially effective methods of data collection were not attempted such as a special National Oceanic and Atmospheric Administration (NOAA) Weather Radio broadcasts, an official press release to all regional print and voice media, or television announcements via the major Denver broadcasters. Clearly, it could be possible to reach a very large number of potential weather observers in a short time with a well organized and facilitated action plan supported with a prepared and adequately staffed center to receive and process reports.

While this was not the case, our relatively disorganized but enthusiastic effort still appears to have been highly effective.

Database Development

As storm reports were coming in and being processed, other office staff developed a simple spreadsheet database to enter all reports for later analysis. One of the complicating factors in developing this database was the irregular observation intervals. Some observers only recorded total rainfall for the entire 2-day period. Others read and emptied their gauges once each day at the same precise time. There were also some very motivated individuals who made a special effort to read their gauges several times during the storm and note the time of each reading. This information, along with even more detailed reports from the few recording gauges, made it possible to develop a thorough time history of rainfall throughout this exceptional event.

The resulting database was set up to accommodate any time interval measurement from hourly values on up to simple storm totals. Each report was assigned a precise latitude and longitude using special mapping software currently available. Accurate coordinates were critical for objective plotting and computer analysis of rainfall. Colorado Climate Center staff also made use of a Global Positioning System (GPS) unit to pinpoint observations coordinates. Visiting each site with the GPS proved to be much more time consuming and no more accurate than using mapping and address software, so most of the coordinates were found using the computer without leaving the office.

Storm Analysis and Rainfall Mapping

As the database was assembled, analysis and mapping began. Figure 2 shows the locations of rainfall reports that were gathered in the weeks immediately following the Fort Collins flood. The majority of these reports came from the immediate Fort Collins area, but others were scattered around the county. A few data points from adjacent counties were included to more clearly define the limits of this rather small storm system. In some portions of the Fort Collins area, data reports were numerous with several reports per square mile. Rainfall reports were very sparse for other areas, particularly immediately west and southwest of Fort Collins.

The wide variety of rainfall measurements: recording rain gauges, official weather stations, hobby weather watchers, casual onlookers, mixed with uncalibrated bucket measurements, produced an awkward data set. Varied measurement intervals ranging from detailed minute-by-minute reports to single storm totals added another dimension of complexity. But while posing a great challenge, these diverse data also contained additional valuable information. The combination of overlapping measurement intervals from a very large number of locations sometimes only blocks from each other, offered an opportunity to extract detailed information about the storm's time history. This would not have been an issue had the storm been just one downpour. However, by looking at the data, it was very evident that there were several distinct periods of rain, some locally very heavy, that fell during the 24 hours prior to the

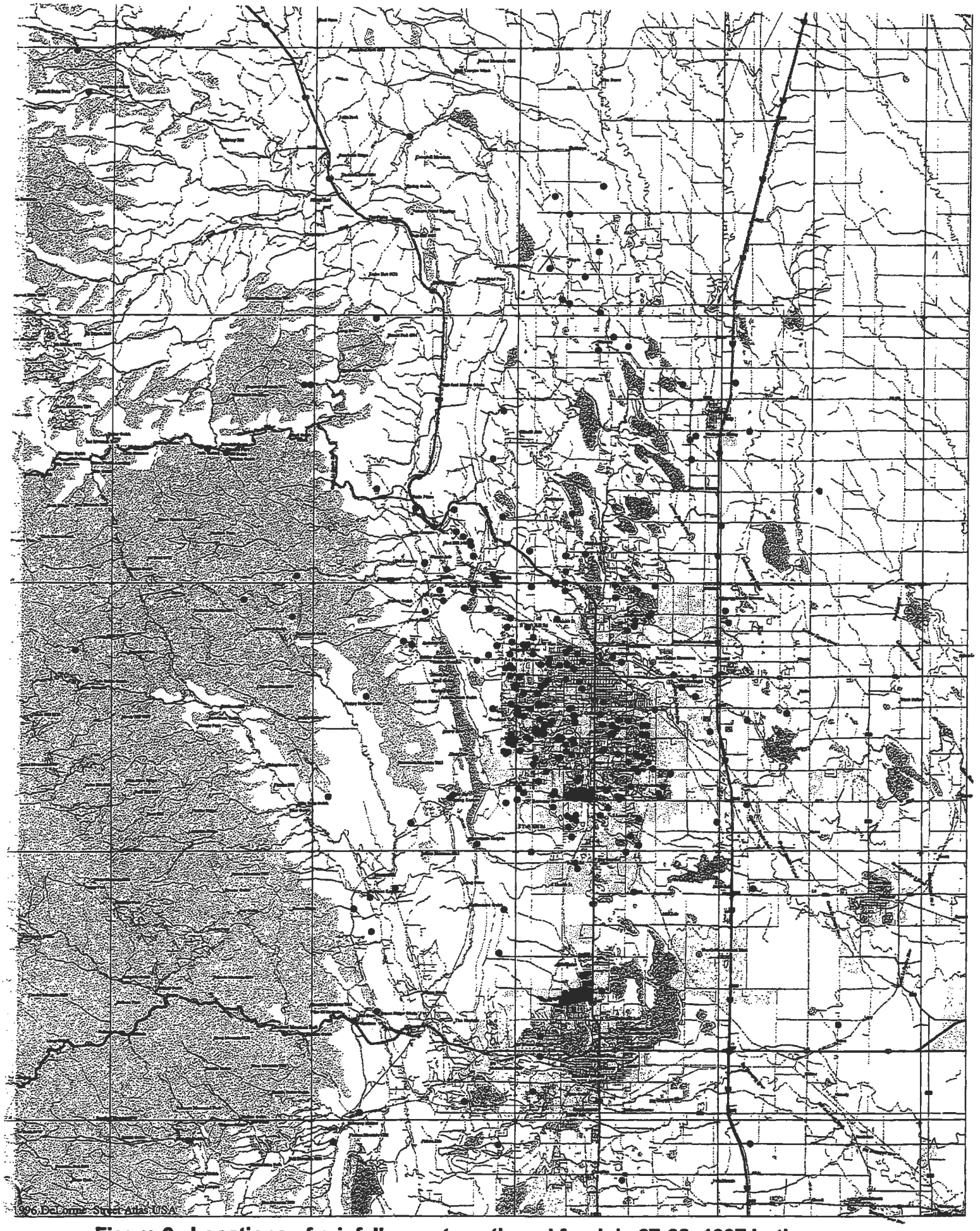


Figure 2. Locations of rainfall reports gathered for July 27-28, 1997 in the vicinity of Fort Collins, Colorado, and eastern Larimer County.

major flood-producing deluge on the evening of July 28th. The contribution of each rainfall episode needed to be documented in order to understand the subsequent flood.

The first step was to identify all sites where automated gauges had collected rainfall totals for hourly or even shorter intervals. A total of 19 recording gauges were found with credible precipitation measurements for the entire period from the afternoon of July 27 through the evening of July 28. Figure 3 shows the locations of the 14 sites closest to Fort Collins. Several of these sites were not in the area hard hit by the flooding rains, but several were. Hourly precipitation rain gauge locations and totals for these stations are shown in Table 1 and 2, respectively. A graph of accumulated precipitation for several of these sites is presented in Figure 4. These reports provided an excellent picture of the time history of rainfall during the two-day period of interest.

Most of these hourly measurements came from tipping bucket rain gauges. This is a very common type of gauge for recording rainfall data electronically. However, a characteristic of this type of gauge is a tendency to report less rain than what actually fell, particularly during periods of very intense rainfall. Fortunately, one observer (site F) also operated a manual gauge directly beside his recording gauge. At that site, the recording gauge reported about 20% less rainfall than the manual gauge. A correction was made to account for this difference. There is no guarantee, however, that the correction was the same at each site. Observed values were used directly without correction for all other sites.

Table 1.
List of Hourly Precipitation Locations for the Fort Collins Study

Code	Description
A	U.S. Forest Service, Redstone Canyon
B	West Fort Collins Water District, Laporte
C	Colorado State University, Atmospheric Science Department, Foothills Campus
D	Colorado State University, Agricultural Engineering Research Center (AERC)
E	Colorado State University, Main Campus
F	Fort Collins Water Department, Wakefield Drive
G	Northern Colorado Water Conservancy District, Loveland
H	South Fort Collins
I	City of Fort Collins, Collindale Golf Course
J	Mountain States Weather Services
K	City of Fort Collins, Resource Recovery Farm
L	Colorado State University, Horticulture Farm
M	Colorado State University, Agricultural Research Development and Education Center (ARDEC)
N	Forensic Meteorology Associates, Inc.

Table 2.
Hourly rainfall totals (inches) for recording rain gauges in eastern Larimer County for the period beginning at 1600 MDT on July 27 and ending at midnight MDT July 28, 1997.
(Refer to Figure 3 for site locations.)

July 1997	Hour Ending at (MDT)	Station Identification (see Figure 3)													
		A	B	C	D	E	F	G	H	I	J	K	L	M	N
Sunday 7/27/97	1600	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	1700	0	0.02	0	0	0	0	0	0	0	T	0	0	0	0
	1800	0.20	0.11	0.22	0.19	0.14	0.28	0	0.04	0.08	T	0	0	0	0
	1900	0.02	0	0.08	0.02	0.04	0.02	0.83	0.05	0.04	0.03	0.01	0.02	0	0.01
	2000	0	0	0	0	T	0	0.33	0.06	0.03	0.01	0.04	0.03	0.04	0.02
	2100	0	0	0	0	T	0.01	0.01	0.01	0.02	0	0.05	0	0	0
	2200	0	0	0	0	0	0	0	0	0	T	0	0	0	0
	2300	0	0.17	0.04	0.05	T	0.04	0	0.65	0.16	T	0.05	0.05	0.16	0
	Midnight	0.02	0	0	0.02	0	0	0	0.02	0.03	0.02	0.03	0.01	0	0
Monday 7/28/97	0100	0.01	0	0	0	0	0	0	0	0	0.03	0	0	0	0.11
	0200	0.01	0.15	0.04	0.09	0.03	0.08	0.01	0.02	0.14	0	0	0	0	0
	0300	0.04	0.31	0.38	0.35	0.35	0.39	0.03	0.08	0.31	0.27	0.24	0.27	0.24	0.34
	0400	0.06	0.62	0.64	0.75	0.30	0.25	0.01	0	0.14	0.22	0.26	0.55	0.20	0.15
	0500	0.38	0.22	0.20	0.18	0.02	0.06	0	0	0	0.07	0.05	0.09	0.16	0.13
	0600	0.14	0.54	0.62	0.56	0.02	0.02	0.01	0	0	0	0	0.01	0	0.01
	0700	0	0.09	0.16	0.06	0.01	0	0.01	0	0	T	0	0	0.04	0
	0800	0.01	0.01	0.04	0.03	0.01	0.21	0.06	0.03	0.01	0.01	0	0.01	0	0.01
	0900	0.21	0.86	1.00	0.91	0.12	0.38	0	0.04	0.02	0	0	0	0.03	0
	1000	0.09	0.52	0.48	0.46	0.02	0.19	0	0	0	0	0	0	0	0
	1100	0.28	0.50	0.16	0.06	T	0.02	0.01	0	0	0	0	0	0	0
	Noon	0.14	0.02	0.04	0.02	0	0	0	0	0	0	0	0	0	0
	1300	0.01	0	0	0	0	0	0	0	0	0	0	0	0	0
	1400	0.01	0	0	0	0	0	0	0.01	0	0	0	0	0	0
	1500	0	0	0	0	0	0	0	0	0	T	0	0	0	0
	1600	0	0	0.02	0	0	0	0	0	0	0	0	0	0	0
	1700	0.02	0	0	0	0	0	0	0	0	T	0.01	0	0	0
	1800	0.15	0.03	0.04	0.05	T	0.11	0	0.01	0.01	T	0	0	0	0
	1900	0.03	0.58	0.54	0.79	0.37	0.71	0.39	0.24	0.12	0.06	0.02	0.03	0.11	0.09
	2000	0.12	0.27	1.12	0.90	0.51	1.63	0.17	0.89	0.64	0.31	0.32	0.17	0.12	0.09
	2100	0.48	0.92	1.58	1.31	1.47	1.37	0.06	0.23	0.31	0.22	0.12	0.20	0.27	0.27
	2200	0.08	1.08	2.54	2.17	2.31	3.16	0	0.01	0.01	0.01	0.01	0.03	0.16	0.08
	2300	0	0.14	0.78	0.54	0.64	0.72	0	0	0	T	0	0	0.24	0.18
	Midnight	0	0	0	0	T	0	0	0	0	0	0	0	0.04	0.09
Tuesday, 7/29/97	0100	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Sum	2.51	7.16	10.72	9.51	6.36	9.65	1.93	2.39	2.07	1.26	1.21	1.47	1.81	1.58

* = Clock times approximate on some gauges.

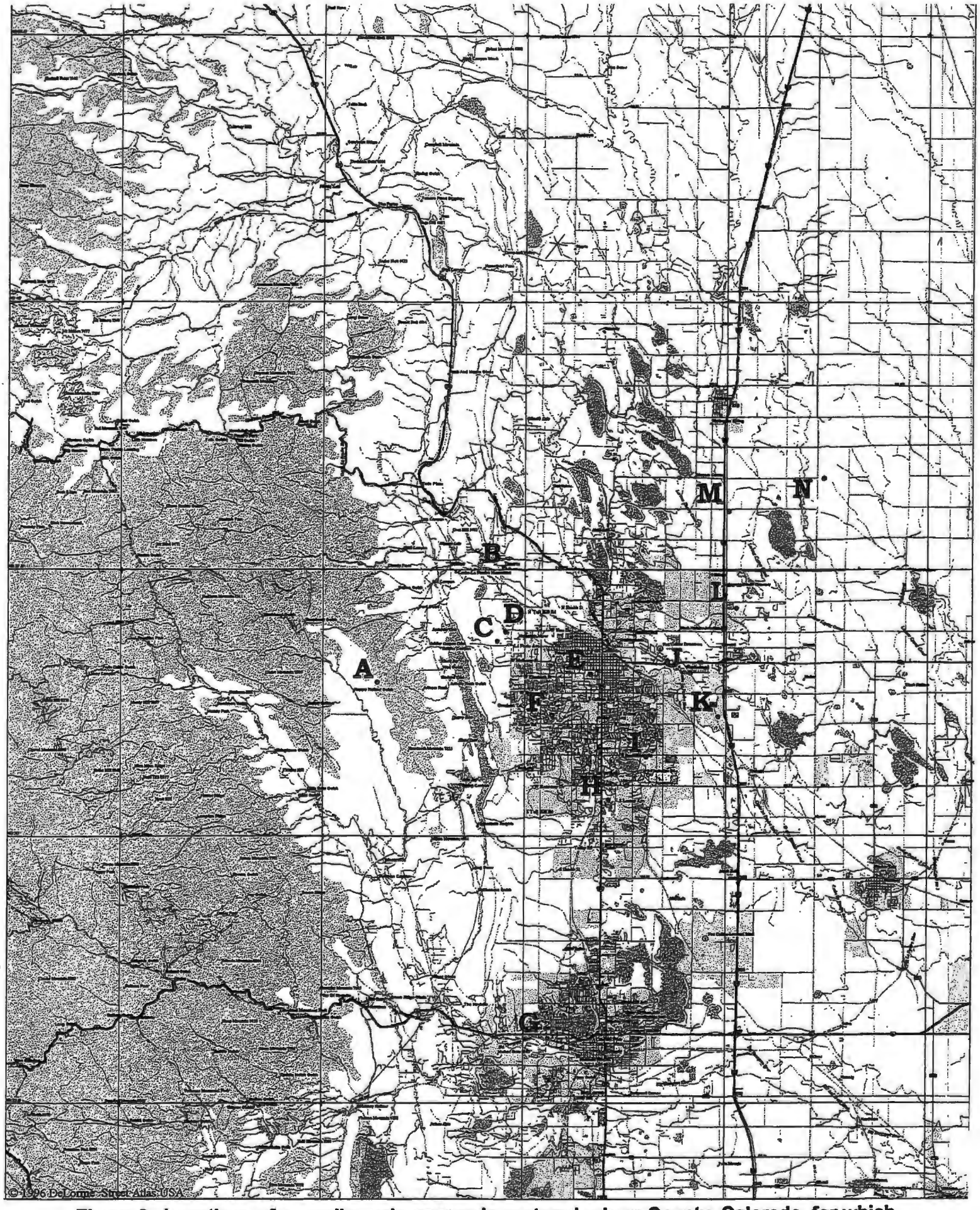
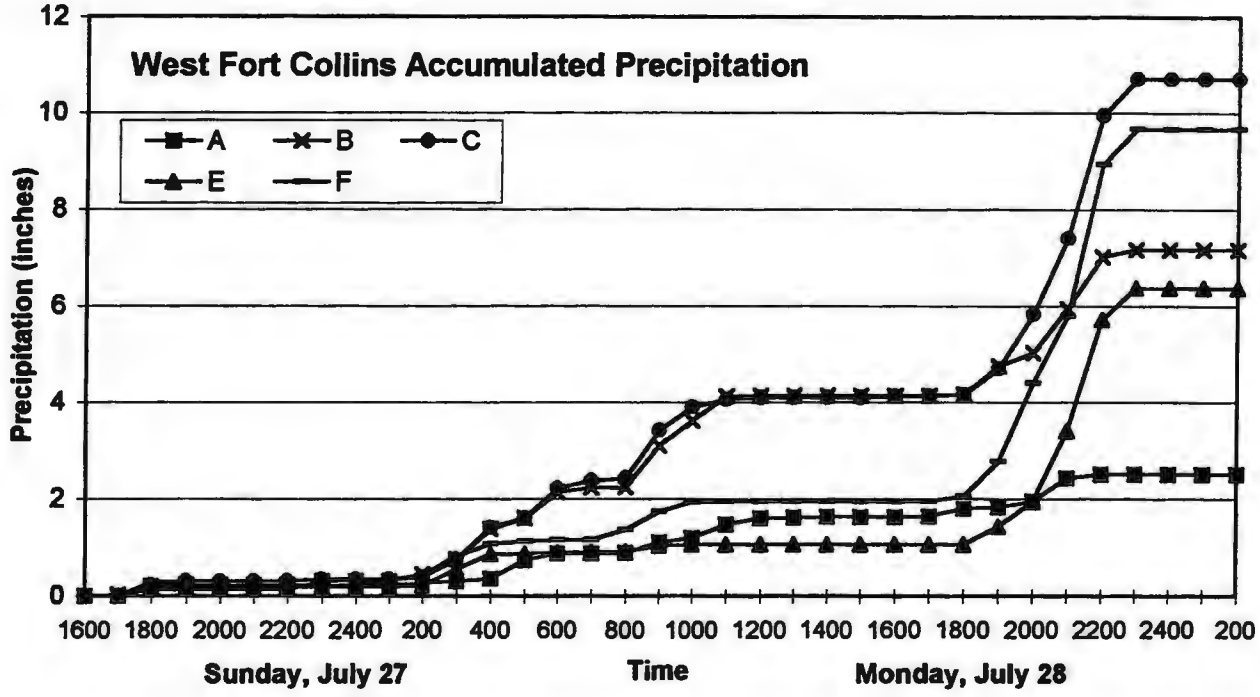


Figure 3. Locations of recording rain gauges in eastern Larimer County, Colorado, for which hourly rainfall totals have been gathered for the July 27-28, 1997 rain episode.



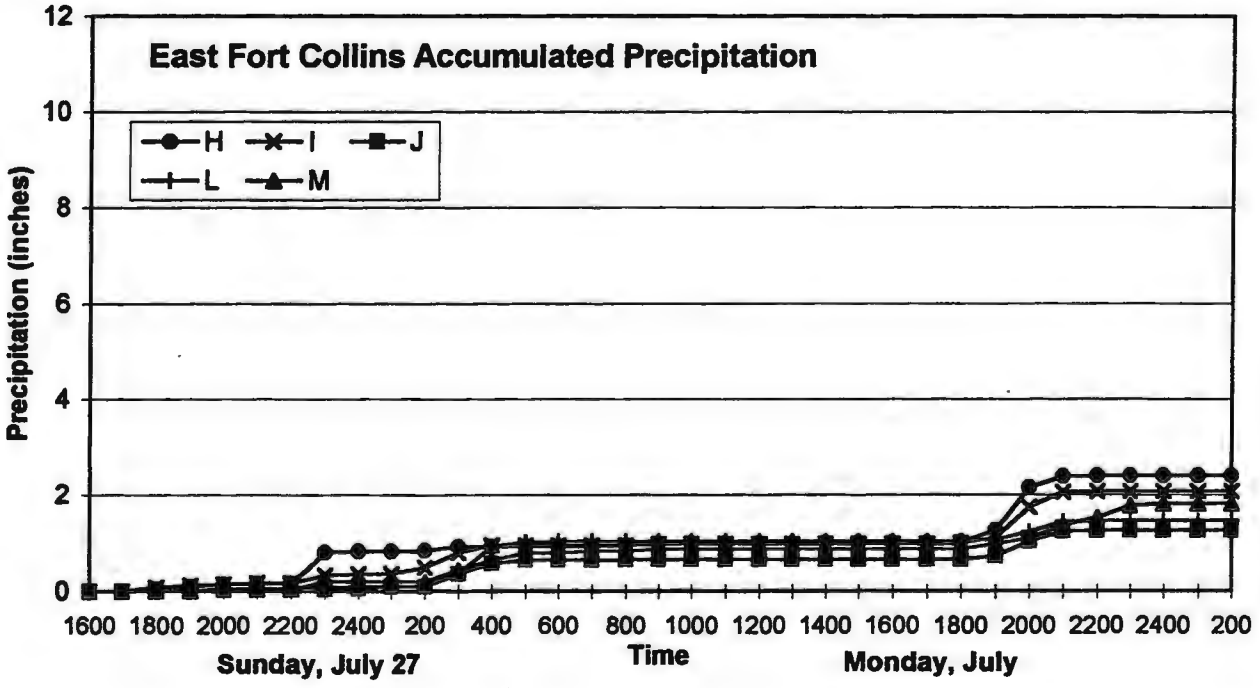


Figure 4. Time history of accumulated rainfall for selected locations in eastern Larimer County, Colorado with recording rain gauge data for July 27-28, 1997. Refer to Figure 3 for site locations.

Hourly precipitation data clearly showed that there were four primary rainfall episodes (Table 3). Large accumulations of rain had already fallen over areas just west and northwest of Fort Collins hours before the major flood-producing storm even began to develop.

Table 3.
Periods of significant rainfall in the Fort Collins, Colorado, area
July 27-28, 1997 (based on recording rain gauge data).

	Date	Time
1)	Sunday, July 27, 1997	1600 - 2200 MDT
2)	July 27-28, 1997	2200 - 0700 MDT
3)	Monday, July 28, 1997	0700 - 1200 MDT
4)	July 28, 1997	1700 - 2300 MDT

Once the primary rainfall periods were identified, the next step was to determine rainfall patterns for each period. To accomplish this, all rainfall reports were examined to determine if measurements had been made for intervals that coincided with any or all of these four periods (see Table 4). Although more than 300 rainfall reports had been received, relatively few reports were sufficiently detailed and thorough to define rainfall precisely for each specific rain episode. However, all but 33 of the reports were useful in determining rainfall amounts for one or more of the various accumulation periods.

Table 4.
Rainfall Reports for Eastern Larimer County for Specific Time Periods

Rainfall Period	Highly Reliable ("A" and "B" quality reports)	Helpful ("C" quality)	Total
1) Sunday evening	67	2	69
2) Overnight	41	1	42
3) Monday morning	70	2	72
Periods 1-3 combined	97	5	102
4) Monday evening	110	16	126
Total 2-day Rainfall	209	42	251

Rainfall totals for each rain episode were summed and tabulated. Rough hand-plotted maps were drawn using approximate measurement locations. Computer-generated maps were also produced with precise locations. These formed the basis of an estimation procedure to make use of the many incomplete rainfall reports.

Using the initial set of analyzed rainfall maps for eastern Larimer County, the location of each site which had good quality measurements of rainfall totals for all or most of each storm period were placed on each map. Linear interpolation was then used to produce an initial estimate for each point for each rain episode. In many cases, very confident estimates were possible since the density of measurement sites with data was quite high, especially in the immediate Fort Collins area. The rainfall patterns for each period were also fairly systematic and predictable. For example, for the initial rain period late afternoon on July 27, rainfall in excess of 0.50 inches was limited to areas northwest, west and south of Fort Collins. Across most of the city, only relatively light rain fell, mostly between 0.10 and 0.50 inches. Most

estimates for that time period were likely accurate to within about 0.20 inches. While there were only 69 locations which had actually measured the rainfall specific to the 1600 - 2000 MDT time period July 27, confident estimates of rainfall for that period were made for an additional 116 locations. Similarly, rainfall patterns Sunday night into Monday morning were quite systematic, increasing nearly uniformly from east to west across Fort Collins. As a result, confident estimates could again be made. Table 5 shows the number of point estimates made during each rainfall period and the total number of point values: estimates plus measurements.

Table 5.
Number of point estimates of rainfall for each rainfall period during the July 27-28, 1997 heavy rain episode in eastern Larimer County, Colorado.

Rainfall Period	Number of Confident Point Estimates	Estimates + Measurements
1) Sunday evening	116	185
2) Overnight	127	169
3) Monday morning	98	172
Periods 1-3 combined	97	199
4) Monday evening	85	211
Total 2-day Rainfall	0	251

To check the validity of rainfall estimates for each measurement point, estimated rain amounts for each of the rainfall periods were summed and compared to the measured precipitation total. When the sum of the rainfall estimates for each rain episode did not match the total observed rainfall at a particular location, then a more thorough site investigation was performed. Data for each location within approximately one mile of the point in question were examined. Based on the surrounding data, the confidence of each interval estimate was evaluated. The most confident estimates were left unchanged while the least confident estimates were modified so that the sum of each interval estimate would then equal the observed storm total. Many minor adjustments to initial estimates were required to "force" the sum of estimated values for the individual rain episodes to equal the observed rainfall total for the entire storm. Most of these adjustments were less than 0.50 inches and did not significantly alter the subsequent analyzed rainfall patterns. However, over the western portion of Fort Collins and areas of eastern Larimer County close to the first hogback where the eastern foothills begin, some adjustments of two inches or more were required to make totals match. When these adjusted values were replotted and new rainfall patterns drawn, significant differences were found. As an example, adjusted estimates suggested much heavier rainfall totals during the Sunday night through Monday morning period in the area northwest of Fort Collins near the town of Laporte. Reports of severe local flooding near Laporte during the day on Monday, July 28, provided good confirmation that these adjustments were appropriate.

Using both the observed data and estimates, a new set of maps was produced. Figure 5 shows an example of a computer-generated analysis with and without estimated data. Confidence in

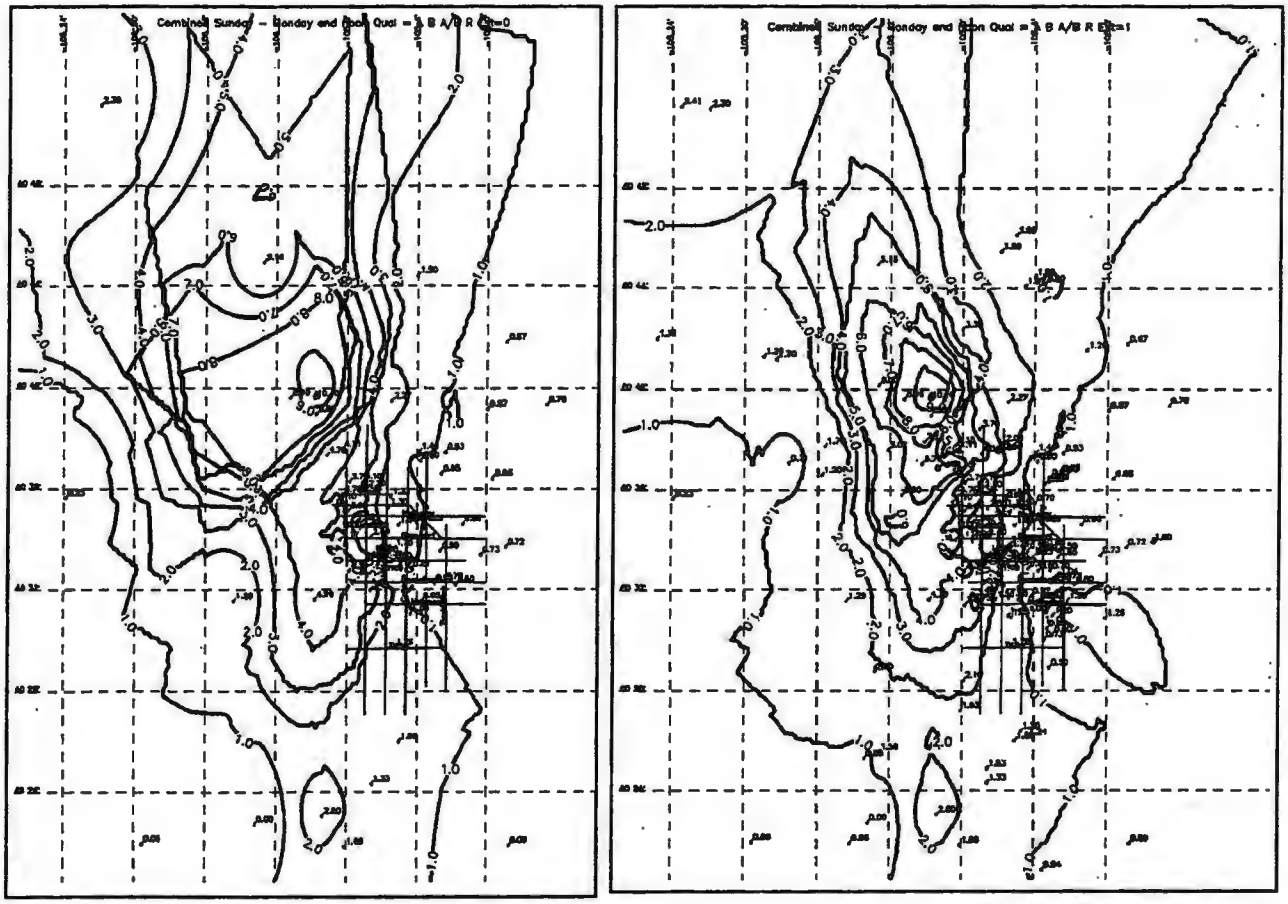


Figure 5. Computer analyzed rainfall for the period 1600 MDT July 27, 1997 through 1300 MDT July 28, 1997. The map on the left was generated from observations only. The map on the right included both observations and estimates. Contours were generated at one-inch intervals.

these analyzed precipitation patterns is very high in the immediate Fort Collins area due to the concentration of data. However, outside of Fort Collins, data were much sparser, and the confidence in the analysis was lower.

To increase confidence and to add important details in data-sparse areas, an independent source of data was obtained. The National Weather Service (NWS) weather surveillance radar (WSR-88D) just east of Denver had operated continuously throughout the storm period, and the radar reflectivity data were archived. With excellent assistance from Larry Tunnell, the hydrologist at the Denver NWS forecast office, maps of estimated precipitation were computed from radar reflectivity patterns. An example is provided in Figure 6. Radar-derived rainfall estimates may differ significantly from actual measured values since reflectivity is a function of not only rainfall rate, but also raindrop size, the presence of hail, and the distance from the radar transceiver (which determines the height above ground and the sampling volume). In this case, rainfall totals compared exceptionally well during the early portion of the storm on Sunday afternoon. The relationship between rainfall and radar reflectivity changed dramatically later Sunday evening. From late Sunday evening through the end of the storm Monday night, the WSR-88D radar severely underestimated surface rainfall. The general spatial patterns, however, were captured well. These patterns were used to qualitatively adjust precipitation isohyets (rainfall contour lines) in areas with little or no surface data. Data from the Cheyenne, WY NWS radar were also available but were not included in this analyses because of time limitations.

Colorado State University operates a special research radar facility northeast of Greeley. The CHILL radar was operated during a portion of the storm and captured most of the intense rainfall period on the evening of Monday July 28. Due to its proximity to Fort Collins, and some of the special features of this research radar, it afforded a particularly detailed remotely sensed view of rainfall characteristics that fateful evening. We will not go into special detail about the CHILL radar results, since other publications on that topic are planned by CHILL scientists and engineers. However, the radar output proved very helpful in completing the final high resolution rainfall map of the immediate Fort Collins area. From the few rainfall reports from the lower foothills immediately southwest and west of the city, it was apparent that rainfall totals diminished rapidly west of the city. There were not enough surface measurements, though, to positively define the gradients. The CHILL radar data provided an objective approach to estimating these gradients and more accurately defining the storm's area.

The NWS and the CSU-CHILL are both Doppler radars. However, the CHILL is a dual polarization radar which allows more information about the precipitation particles to be determined. Two comparisons were made of radar derived precipitation to surface observations. The radar estimates were provided by Lawrence Carey and Walt Petersen members of Professor Steve Rutledge's research group. One comparison was made using the CHILL reflectivity only in a manner similar to the method used by the NWS. The results showed a ratio of observed surface precipitation to the radar derived precipitation with values of approximate 2.6 in the northwest portion of the storm and 1.5 in the southeast portion of the storm. These large variations in the ratio of radar reflectivity to surface rainfall suggest a

Figure 6. Example rainfall map for east central Larimer County, Colorado for the period 1524 MDT July 27 through 1131 MDT July 28, 1997. Rainfall estimates were derived from the National Weather Service WSR-88D meteorological radar located east of Denver, Colorado. Map illegibility is due to the fact that the map was originally provided in color.

difference in the size distribution of the rain drops may have occurred between these two regions of the storm.

The second comparison was accomplished by using a combination of reflectivity and phase differences between the two polarizations. This was an exploratory research methodology that will be tested more in the future. It produced a ratio of observed precipitation to radar derived precipitation of approximately 1.4 which was quite uniform over the storm area. This ratio was then applied to estimate surface rainfall in the data sparse areas west and south of the storm center. Estimates of rainfall amounts were calculated on a 1 mile by 1 mile grid over and south of Horsetooth Reservoir. Approximately 20 data points were added to the surface observations in this data sparse region to provide enough data to complete the map of precipitation for the Monday evening period (Figure 10 and 14).

The addition of the radar information did not change the rainfall magnitudes or observed precipitation patterns over the city of Fort Collins. However, it did add detail to define the patterns and gradient over the western and southwestern edges of the storm. Further research on development of rainfall algorithms for the CHILL radar have indicated closer agreement with surface observations but have not changed the areal pattern of precipitation.

After combining radar data for data sparse areas with the measured data, final computer-generated maps were produced. These were carefully scrutinized, manually smoothed and graphically enhanced for visual clarity. The final result of this lengthy effort was a set of detailed rainfall maps for each of the following four accumulation periods:

1) Sunday, July 27, 1997, 1600-2100 MDT.
2) July 27, 1600 MDT through Monday July 28, 1300 MDT.
3) Monday, July 28, 1997, 1730-2300 MDT.
4) Total Rainfall, July 27, 1997, 1600 MDT through July 28, 1997, 2300 MDT.

Figures 7-10 are regional maps covering much of eastern Larimer County. Figures 11-14 show the same four time periods in expanded form for the immediate Fort Collins area.

The Rain that Caused the Flood

The following narrative accompanies the rainfall maps (Figure 7-14) and briefly describes the rains that culminated in the devastating Fort Collins flood of July 28, 1997.

Cloudy skies greeted residents of eastern Larimer County on Sunday, July 27, 1997. After many days of hot, dry weather, cooler temperatures were a welcome change. Skies remained cloudy into the early afternoon, but in mid afternoon the sun broke through. As the temperatures rose briefly into the 80s (Fahrenheit), the air felt oppressively humid. Dewpoint temperature measured on campus at Colorado State University climbed to near 60 degrees.

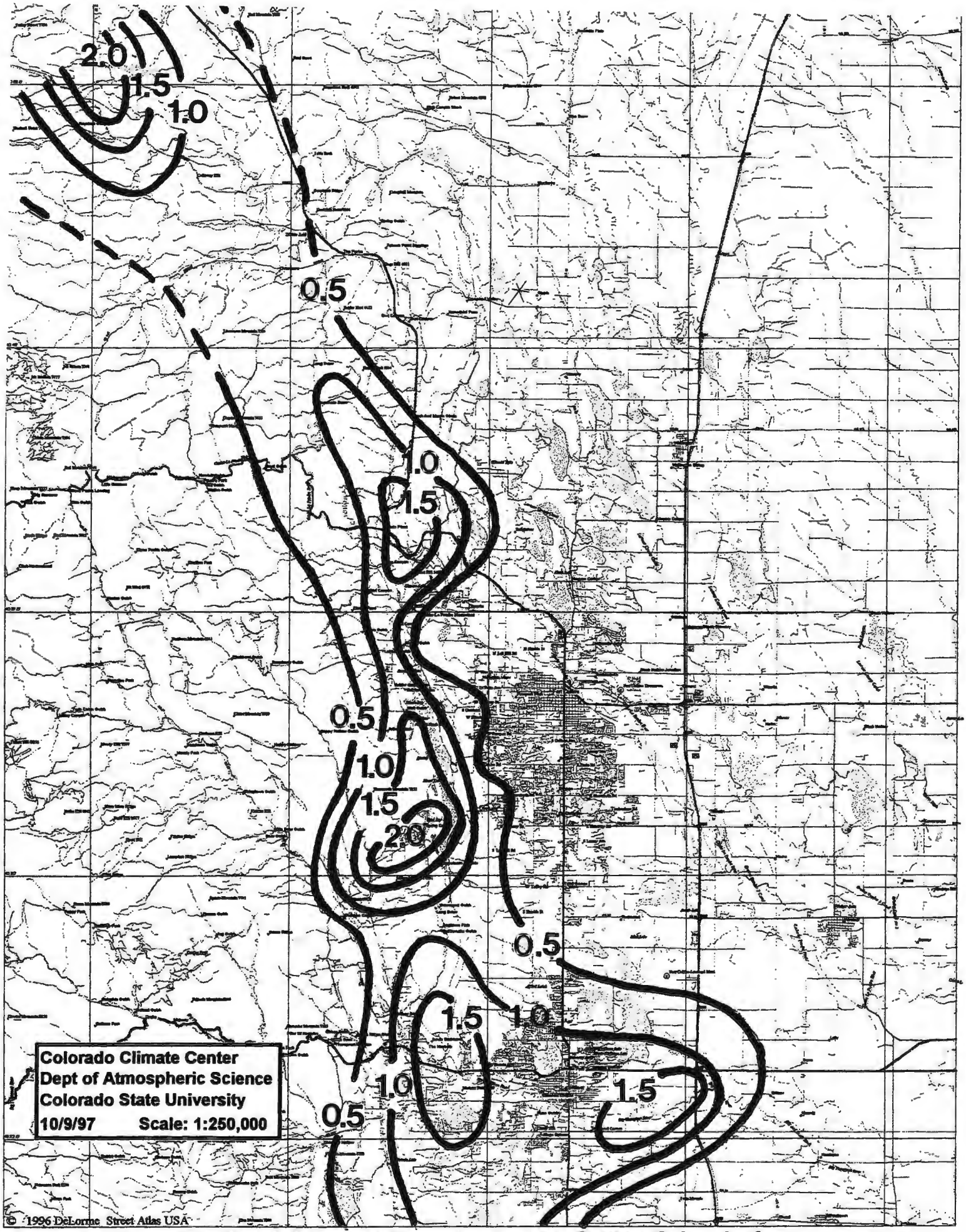


Figure 7. Rainfall (inches) for eastern Larimer County, Colorado, for 4:00-9:00 p.m. MDT for July 27, 1997

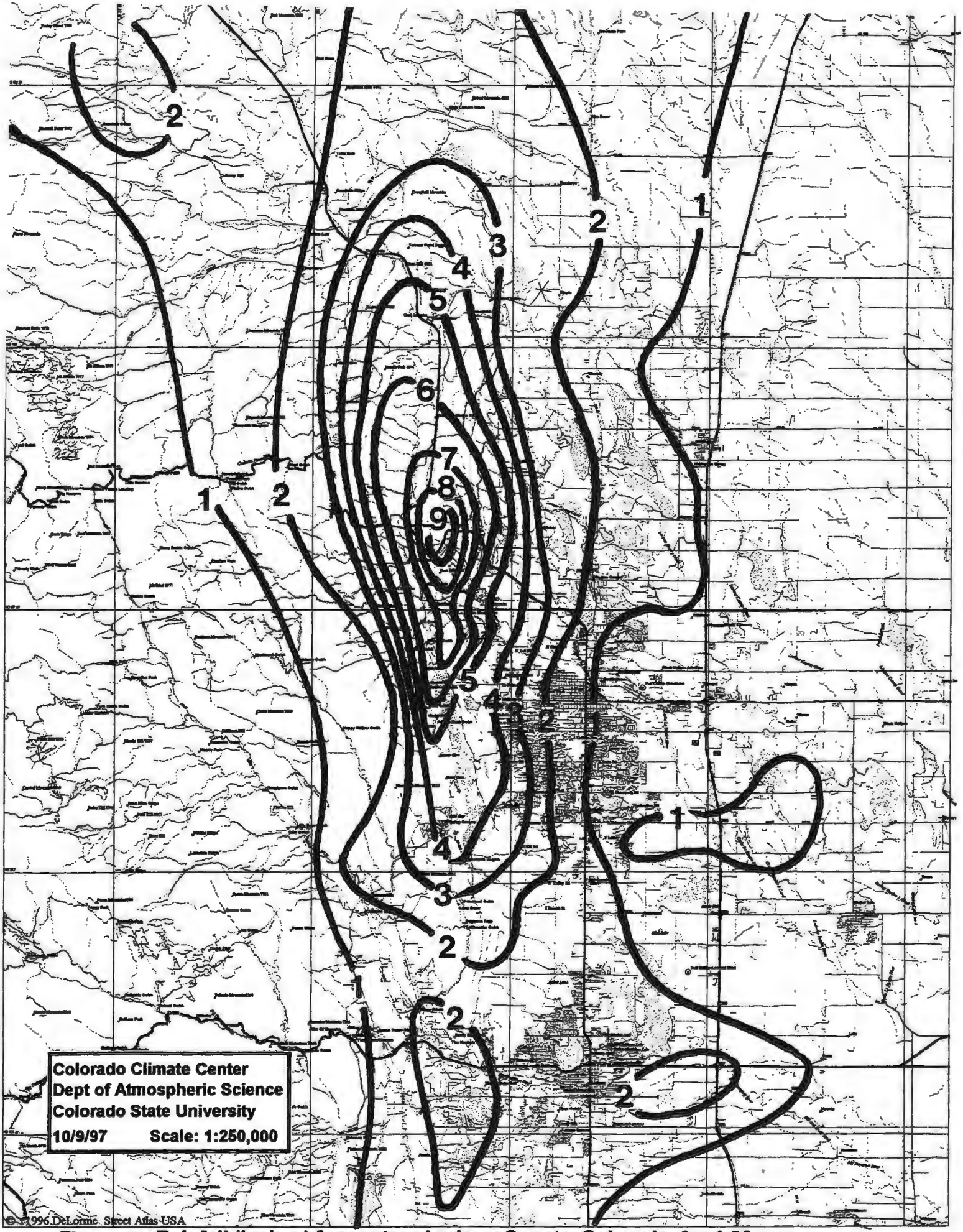


Figure 8. Rainfall (inches) for eastern Larimer County, Colorado, for 4:00 p.m. MDT July 27, 1997 through 1:00 p.m. MDT July 28, 1997

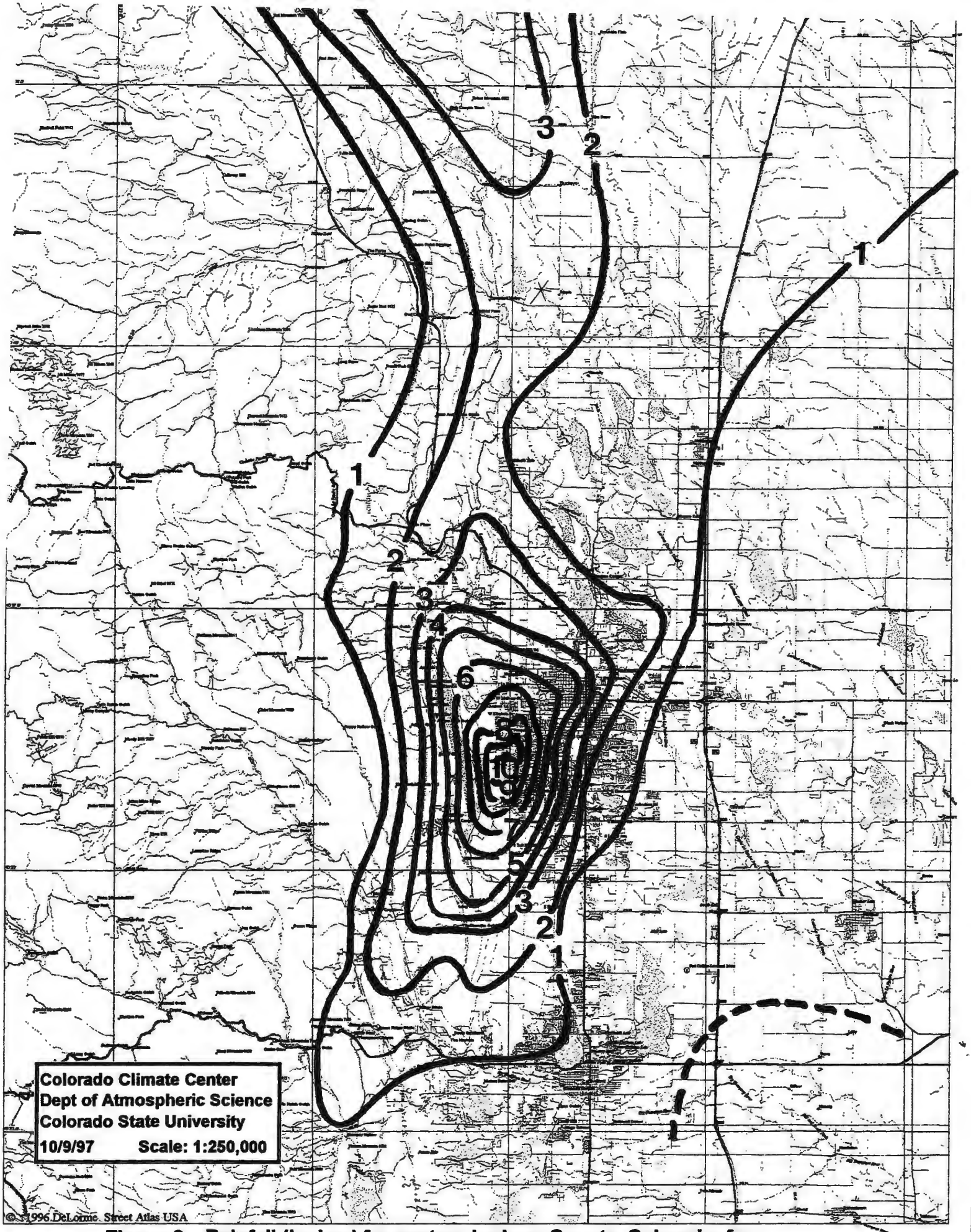


Figure 9. Rainfall (inches) for eastern Larimer County, Colorado, for 5:30-11:00 p.m. MDT for July 28, 1997

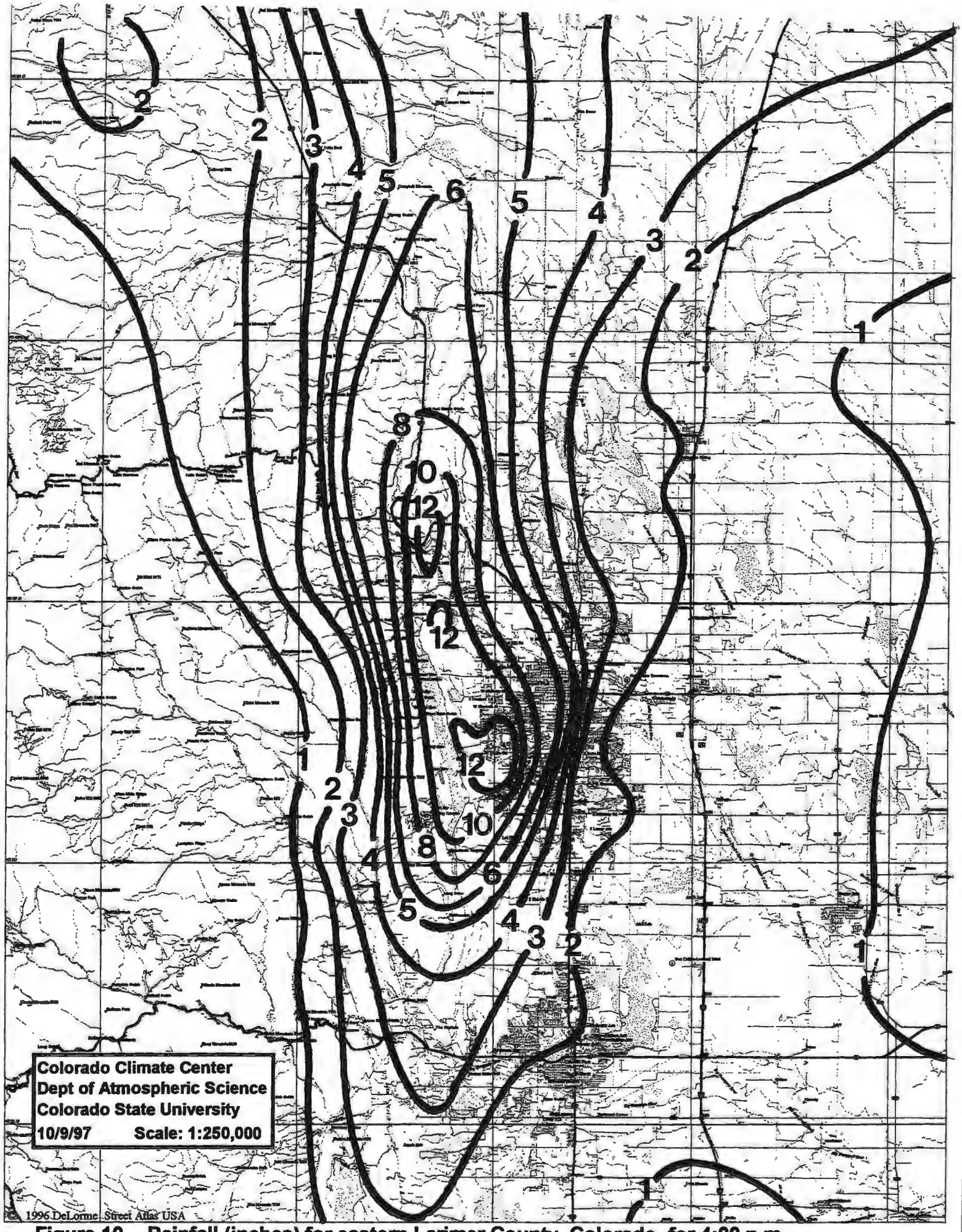


Figure 10. Rainfall (inches) for eastern Larimer County, Colorado, for 4:00 p.m. MDT July 27, 1997 through 11:00 p.m. MDT for July 28, 1997

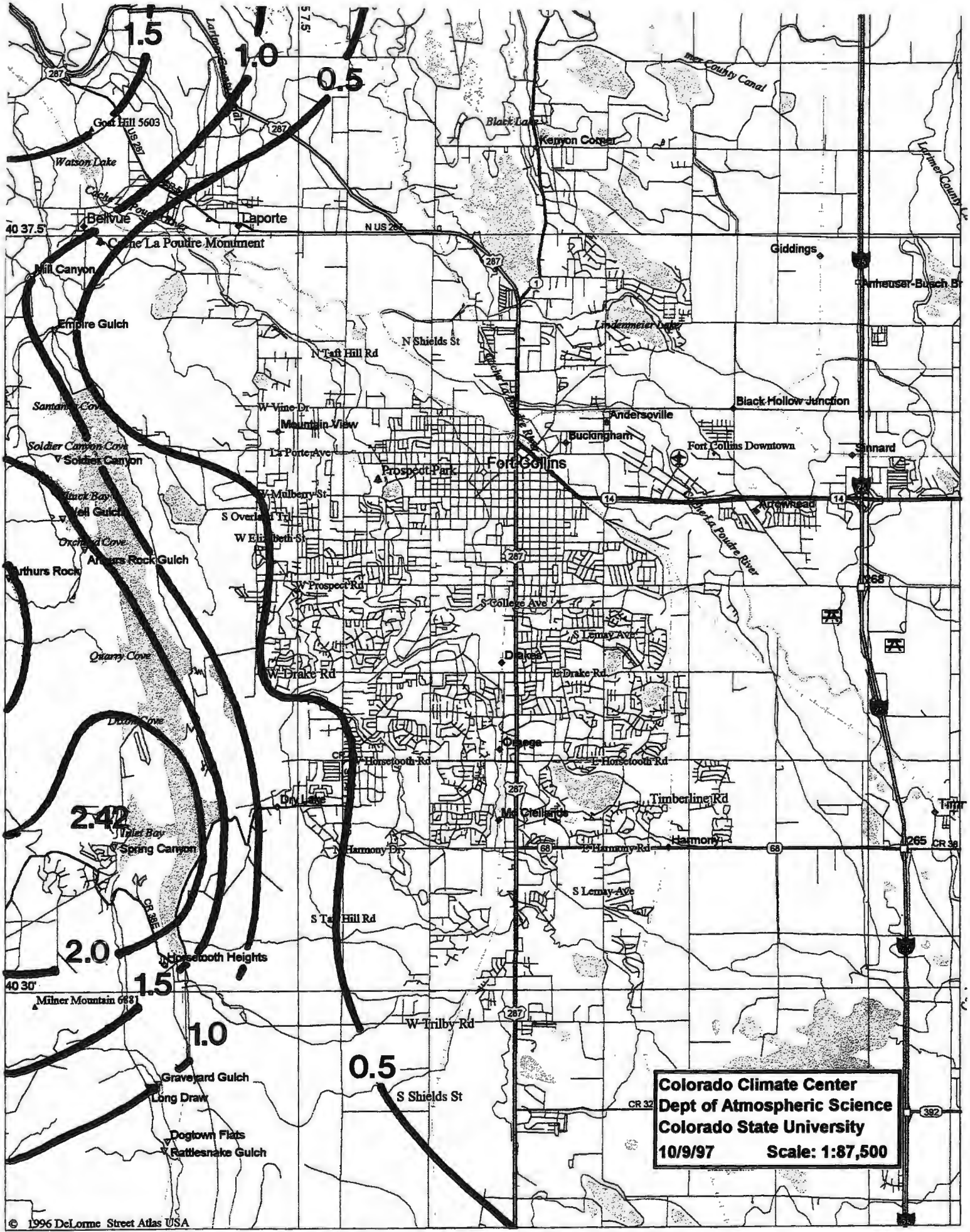


Figure 11. Rainfall (inches) for Fort Collins, Colorado, for 4:00-9:00 p.m. MDT for July 27, 1997

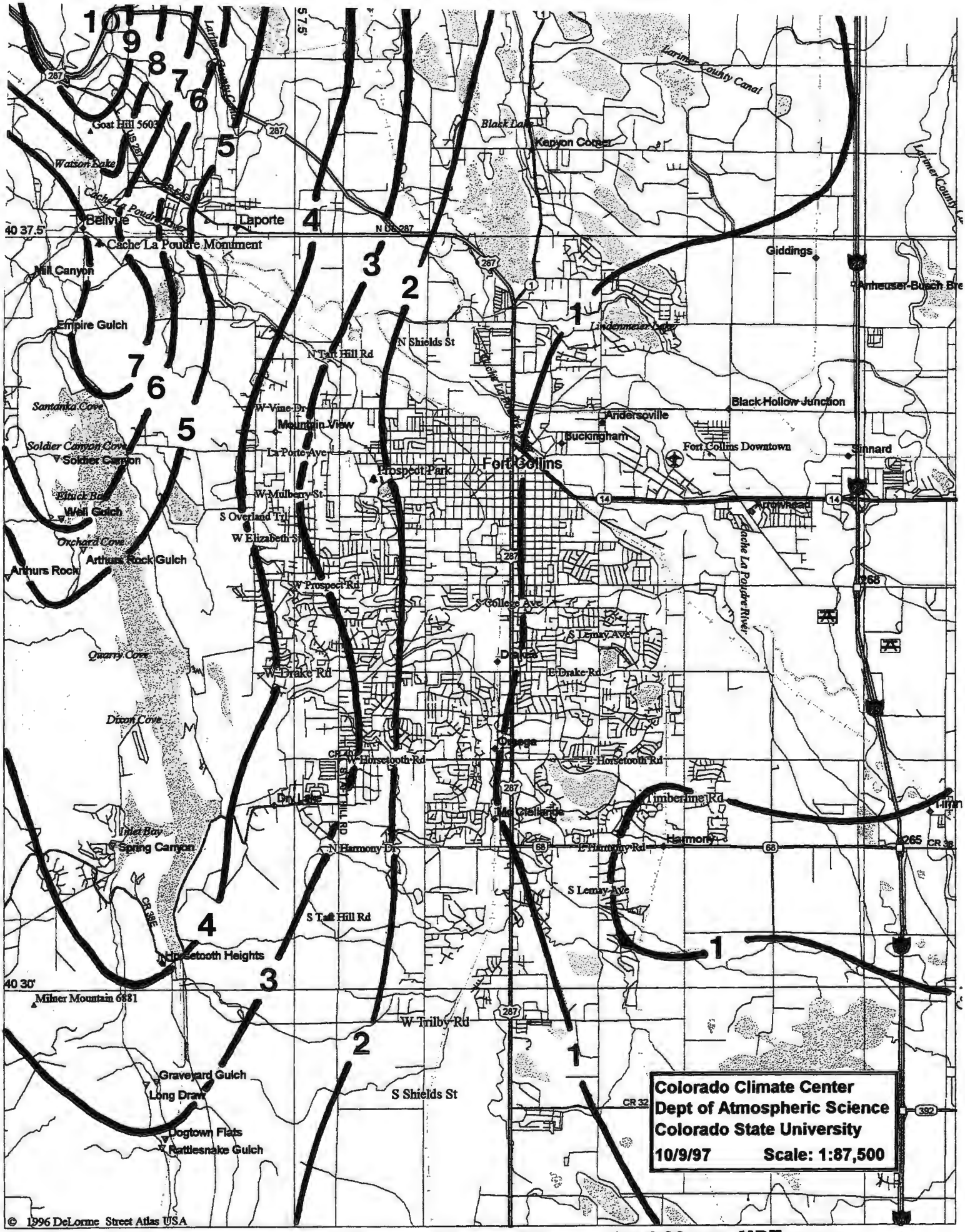


Figure 12. Rainfall (inches) for Fort Collins, Colorado, for 4:00 p.m. MDT July 27, 1997 through 1:00 p.m. MDT July 28, 1997

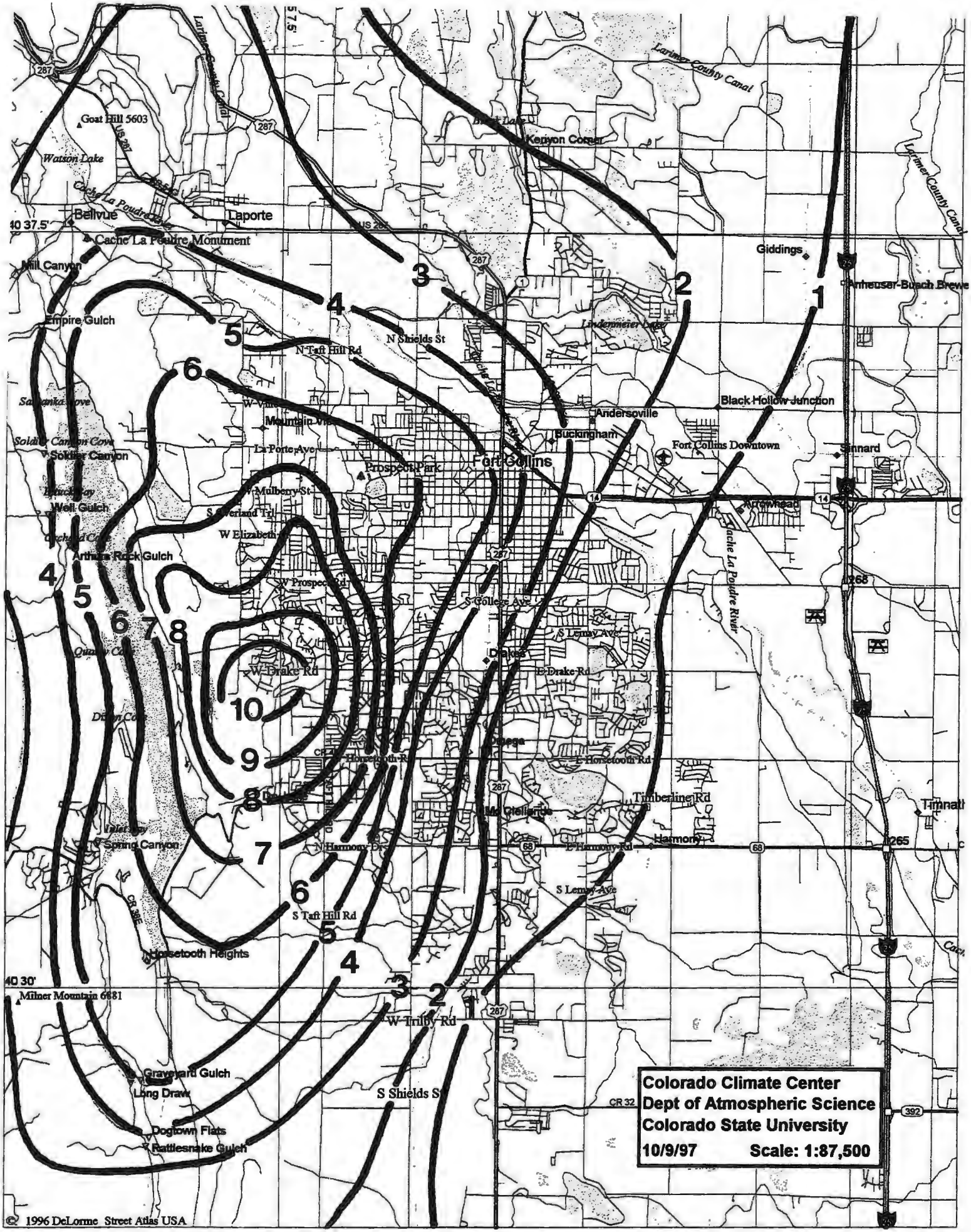


Figure 13. Rainfall (inches) for Fort Collins, Colorado, for 5:30-11:00 p.m. MDT for July 28, 1997

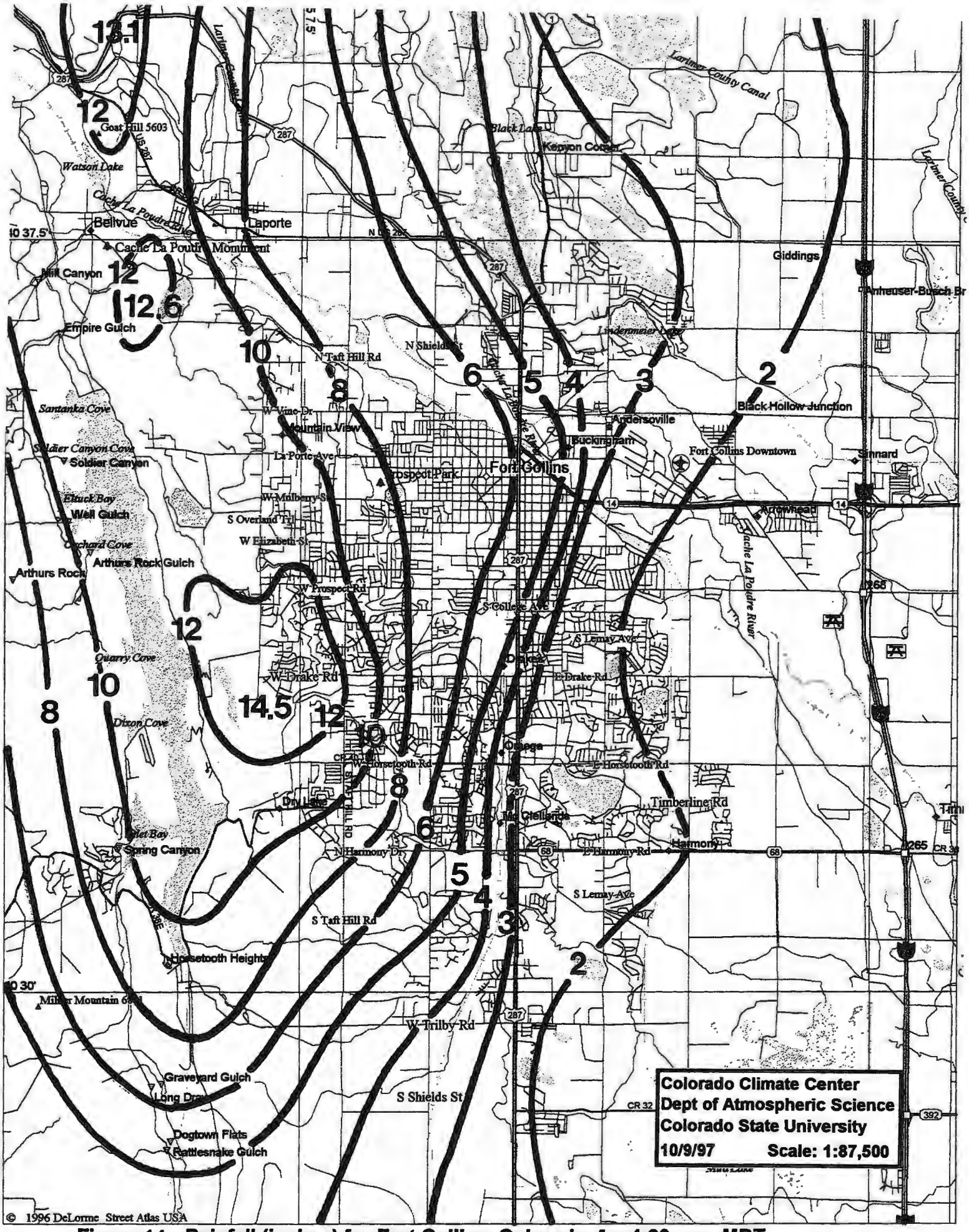


Figure 14. Rainfall (inches) for Fort Collins, Colorado, for 4:00 p.m. MDT July 27, 1997 through 11:00 p.m. MDT for July 28, 1997

At that time, 4:00 p.m. (1600 MDT), cloud masses began to bubble upwards forming towers of billowing dark-bottomed cumulus clouds over the foothills northwest of Fort Collins. Thunder began to rumble, and by 5:00 p.m., the first torrents of heavy rain poured down northwest of Laporte. Close to 1.50 inches of rain fell in just over 30 minutes not far from Ted's Place (four miles northwest of Laporte), and another core of heavy rain fell farther northwest beyond Livermore. Quickly the storm expanded southward, and within minutes sheets of rain splashed onto Horsetooth Reservoir, hiding the foothills behind them. Thunder crashed and storm clouds spread eastward and southward out across Fort Collins. People ran for shelter expecting a downpour, but the heavy rains were limited to the lower foothills and diminished quickly to the east. Except for extreme western Fort Collins, most of the city received less than one quarter inch of rain, but near the south inlet bay of Horsetooth Reservoir, 2.42 inches of rain was measured from this quick storm. These first heavy rains were mostly over by 6:30 p.m. with only occasional sprinkles and light showers after that. Damp, rain-chilled air spread out across Fort Collins, but thunder continued to rumble east and south of town. Most areas of Loveland were drenched with one to two inches of welcome rains before the storm diminished after 8:00 p.m.

This first round of thunderstorms was quite typical of late July. The storms developed and struck quickly, with a commotion of lightning and thunder, only to end just as quickly. While some areas were soaked, other nearby locations were nearly dry (Figure 7). This was just the beginning, though. The air remained humid and fragrant. Instead of clearing off at sunset like a normal summer evening, dense, dark clouds continued to hug the foothills and the temperature remained steady. The air was still, and sounds seemed to carry a long way.

Around 10:00 p.m. (2200 MDT), a few flashes of lightning lit up the sky just south of Fort Collins. As thunder rumbled, a brief shower of rain fell on some south-side neighborhoods in Fort Collins. The rain began to spread northward, and a similar brief but localized shower fell near Bellvue, but ended quickly. Perhaps 0.50 inches of rain fell from each of these showers, but over very small areas. The rain and thunder ended, and most residents of Fort Collins went to bed enjoying the refreshing dampness that summer storms bring – happy to know that they could skip watering their yards or gardens for at least a day or two.

After midnight, southeasterly winds, behind the cold front that had triggered the evening storms, increased and pushed more moist air up against the eastern foothills. Sometime around 0100 MDT Monday, rain began again. Without the excitement and fanfare of lightning and thunder, steady rains developed – not hard enough to wake most sleepers. At first the rains were limited to a very narrow band right along the first hogback from the southwest edge of Fort Collins northward to near Owl Canyon (15 miles northwest of Fort Collins). For a few hours the rains intensified. Between 0200 to 0400 MDT rain fell over much of eastern Larimer County. Rainfall rates in excess of one inch per hour developed northwest of the town of Laporte while rates were much lower farther east. The rains diminished again after 0400 MDT, and by the first light of dawn rain ended except in a very narrow band along the foothills from southwest of Fort Collins northward over Horsetooth Reservoir and then continuing northward approximately following U.S. Highway 287 to Livermore. Residents of this area awoke to gloomy, dark skies. Water was standing or

flowing in this hilly area, and rain intensity fluctuated from light showers to occasional downpours.

Between 0600 and 0730 MDT, the rain tapered off along the foothills and stopped completely elsewhere. Around 0800 rain began again. A brief but soaking shower caught many morning commuters in Fort Collins, while to the northwest the heaviest rain of the morning began to cause major flooding around Laporte. From southwest Fort Collins near Hughes Stadium northward to Ted's Place (northwest of Laporte), one to two inches of rain fell between 0800 and 0900 MDT. The area of heavy rain shrank after 0930, but remarkably heavy and highly localized torrents continued northwest of Laporte until after 1100 MDT. People driving northwestward out of Fort Collins were shocked to go from dry roads in town to pouring rains and flood waters covering highways near Laporte – all of this without the accompaniment of lightning or thunder.

The rains ended across all of Larimer County by noon, but not before six to eight inches of early morning rain had fallen northwest of Laporte. North and south of this storm center, three to six inch rain totals were common in the narrow band along and east of U.S. Highway 287 northward to Owl Canyon (15 miles northwest of Fort Collins) and south to Lory State Park and Horsetooth Reservoir immediately west of Fort Collins. Rainfall totals dropped off quickly to the east (Figure 8), but two to four inches fell over portions of west Fort Collins west of Taft Hill Road. All of the Fort Collins area received some rain early Monday morning but most totals were only 0.50 to 0.75 inches over the eastern half of the city. South of Fort Collins in the vicinity of Loveland and Berthoud, only a few scant showers had fallen.

Many irrigation canals exit the Poudre River near Laporte. While the localized rains had little effect on the morning flow rates on the main river, irrigation canals were a different story. Headgates were shut early that morning, and still the ditches filled with runoff from the Laporte and Bellvue floodwaters. Many downstream residents were surprised by the high water, many of whom were not aware of the heavy rains near Laporte.

Skies remained cloudy over the Fort Collins area Monday afternoon. Clouds hung low along the foothills, as steady southeasterly surface winds continued to push very moist surface air into Larimer County. Dewpoint temperatures, a measure of the water content of the air, stayed in the low 60s all day. With weather conditions not unlike those that preceded the infamous Big Thompson flood in Larimer County 21 years previous, weather forecasts called for "locally torrential rains." Hallway, phone and e-mail conversations among climatologists, meteorologists and hydrologists along the Front Range from Denver to Cheyenne speculated on where the flash flood might occur this time. Weather forecasters familiar with Front Range flash flood conditions knew that this situation was potentially dangerous. But with all the rain that had already fallen, no one knew where or even if another flash flood producing storm would erupt.

During the afternoon of July 28th, heavy thunderstorms began to develop west of Denver and in other areas of the state. In eastern Larimer County, the first showers appeared around 5:00 p.m. (1700 MDT). They began innocently enough – brief showers moving from south to north with little or no lightning and thunder. Just before 6:00 p.m. (1800 MDT) the first wave

of heavy showers moved into Fort Collins. Like the early rains, these evening showers seemed to hug the base of the foothills. The rains increased in both area and intensity between 1800 and 1900 MDT with hourly accumulations of close to one inch in southwest Fort Collins, but with lighter rains over most of the Fort Collins area from the lower foothills out onto the plains. A few bolts of lightning accompanied these rains, but electrification was surprisingly little considering the intensity of the rains. Unlike so many Colorado storms, no hail was reported. Many individuals independently noted how warm the rain seemed. Raindrop sizes were not large, considering the intensity of the rain, and no strong winds accompanied the rains – at least not in the immediate Fort Collins area. One report of strong winds blowing out of the north (out from the storm center) was filed by a weather watcher a few miles northwest of Loveland.

Extreme rainfall rates may have begun earlier, but the first burst to reach the recording rain gauge at the Atmospheric Science Department on the Foothills Campus of Colorado State University (extreme west Fort Collins just east of Horsetooth Reservoir) began shortly before 7:00 p.m. (1900 MDT). For a few minutes, rainfall rates approached three inches per hour and then tapered off again. Surges of extremely heavy rains seemed to emanate from southwest Fort Collins and spread northward in waves over the west side of the city. Heavy rains also reached northern portions of Fort Collins and continued northward into the county, while only light to moderate rains were observed over southeast Fort Collins.

Lightning activity increased around 2000 MDT as heavy rains continued to fall. What began as minor street flooding became increasingly more serious over the western half of Fort Collins as the downpours continued. Then for a few minutes parts of town experienced a lull in rainfall intensity before 8:30 p.m. (2030 MDT). Soon after that, the rains let up or ended completely just a few miles south of town, in the vicinity of Masonville southwest of Fort Collins and over southeastern portions of the city. At the same time, cloud watchers east of Fort Collins noted the storm clouds that had seemingly been spreading eastward and northward appeared to retreat back towards the west and condense into a small but ominous cloud mass over and west of the city.

Most summer thunderstorms would have begun to dissipate or move away by this time, but this storm was an exception. Instead of weakening, rainfall intensities increased again, and the most intense rains were still ahead. From about 8:30 to 10:00 p.m. (2030 to 2200 MDT) extremely heavy rain, of a magnitude rarely experienced in northern Colorado, was localized over an area of a few square miles centered not far from the corner of Drake Road and Overland Trail in extreme southwestern Fort Collins. Based on a variety of individual observations and numerous reports of over-topped rain gauges, it appeared that rainfall totals for this 90-minute period approached or exceeded five inches over the approximate area delineated by Taft Hill Road on the east, the crest of the hogback formation that forms the eastern edge of Horsetooth Reservoir on the west, the western extension of Horsetooth Road on the south and approximately Elizabeth Street on the north (see Figure 13). This area includes much of the Spring Creek watershed. Maximum instantaneous rainfall rates likely exceeded 5-6 inches per hour at times. With these extreme rainfall rates falling on a surface already covered with flowing water, incredible volumes of water accumulated that moved downhill from approximately west to east across Fort Collins initiating the devastating

flooding. Other reports are being written by hydrologic experts that focus on the flooding produced by this remarkable rainstorm.

Mercifully, the rains came to a sudden halt. In southwest Fort Collins near Harmony Road, eyewitnesses reported the rain ended abruptly a few minutes before 10:00 p.m. (2200 MDT). Farther north along Drake Road the rain ended just after 10:00 p.m. On the campus of Colorado State University, the rain ended right about 10:30 p.m. (2230 MDT) while in extreme northern parts of the Fort Collins area, lighter rains continued until at least 11:00 p.m. (2300 MDT). As the rain ended, a cool, damp stillness again covered the area, just like the night before – except for the sounds of sirens and the roar of local flood waters searching for a path to the Poudre River. Some distant lightning flashed, but the Fort Collins storm was over.

The rainfall pattern from the July 28, 1997 evening storm over eastern Larimer County is shown in Figure 9 with an expanded view over the immediate Fort Collins area in Figure 13. Compared to many U.S. storms, the rains that produced the severe flooding in Fort Collins were remarkably localized. The heaviest documented rainfall totals exceeded ten inches in less than five hours and were found in extreme southwest Fort Collins. An extremely tight rainfall gradient was observed southeastward from the storm center, with less than two inches of rain reported less than three miles east and southeast from the maximum. This is an excellent demonstration of the huge variations in rainfall over short distances that are possible with summer convective storms.

The core of the heaviest rains was immediately east of the hogback that marks the beginning of the foothills and serves as the eastern bank of Horsetooth Reservoir. The band of heaviest rains reached northward from the storm center toward the towns of Laporte and Bellvue and remained oriented parallel to the foothills. This positioning strongly suggests that topography played an important and perhaps controlling role in positioning this storm. North of Fort Collins, the rainfall diminished and spread out, but a secondary rainfall maximum was observed in the upper Boxelder watershed east of Virginia Dale.

Total accumulated rainfall for the period beginning at 1600 MDT on July 27, 1997 through 2300 MDT July 28 is shown in Figures 10 and 14. While probably not a coincidence, it is still quite remarkable that each episode of heavy rain during this 31-hour period produced its maximum rainfall totals right at the base of the foothills. As a result, the accumulated totals look very much like a single storm rainfall pattern. Three separate maxima appear on the map all in a similar location with respect to the local topography: 1) a 14.5 inch total in southwest Fort Collins produced primarily by the July 28 evening storm but with significant contributions from both the Sunday evening and the Monday morning rains, 2) a 13.1 inch total northwest of Laporte produced primarily by the morning rains July 28 but with contributions from the two other major rainfall periods, and 3) A total of over 12 inches near Claymore Lake northwest of Fort Collins which coincidentally received nearly the same amount of rain both Monday morning and then again Monday evening.

The composite rainfall pattern shows that rainfall totals exceeded ten inches over an area approximately 12 miles long and two to three miles wide for a total area approaching 30 square miles.

Historical Perspective

State and Regional perspective

Extreme rainfalls in excess of ten inches in 24 hours or less in Colorado are rare but not unprecedented. Just two months prior to the Fort Collins storm, the Colorado Climate Center completed a study of extreme precipitation in Colorado (McKee and Doesken, 1997) for the Colorado Department of Natural Resources, Division of Water Resources. This study identified twelve events during the Twentieth Century that most likely produced ten or more inches of rain and caused extreme flooding along the east slope of the Rocky Mountains (Table 6). This list included three storms in similar topographic regions outside of Colorado such as the Rapid City, South Dakota, storm of June 9, 1972.

Table 6.
Chronological List of Extreme Rain Events on the "Front Range" during the Twentieth Century (from McKee and Doesken, 1997)

Storm	Date	Maximum Precipitation
Livermore/Boxelder	May 20-21, 1904	8+ inches
Pueblo/Penrose	June 2-6, 1921	6 - 12"
Savageton, Wyoming	Sept. 27-29, 1923	17"
Cherry Creek/Hale	May 30-31, 1935	12 - 24"
Northern Colorado Front Range	Sept 2-3, 1938	6 - 10"
Rye (Southern Colo Front Range)	May 18-20, 1955	6 - 13"
Gibson Dam, Montana	June 6-8, 1964	16"
Plum Creek	June 16-17, 1965	14 - 16"
Big Elk Meadows	May 4-8, 1969	6 - 14"
Rapid City, South Dakota	June 9, 1972	15"
Big Thompson	July 31, 1976	12"
Frijole Creek	July 2-3, 1981	8 - 16"
Fort Collins	July 27-28, 1997	14.5"
Pawnee Creek	July 29-30, 1997	15.1"

The Fort Collins storm was smaller in area than several of these earlier huge rains. For example, the storm(s) of June 1965 struck several portions of eastern Colorado and caused widespread severe flooding. The Fort Collins storm, however, was of sufficient short-term intensity, and the combined precipitation from the earlier rain episodes during the 24 hours preceding the final downpour were sufficiently great, to place this storm on the list of most extreme Front Range rain events of the century. Prior to the Fort Collins storm, it had been 16 years since the last giant rainstorm. The Frijole Creek storm occurred near Trinidad,

Colorado July 2-3, 1981, but fell over a largely unpopulated area. Based on observed floodwaters, maximum rainfall of up to 16 inches in less than six hours was estimated. In contrast, much of the Fort Collins storm occurred over heavily populated areas. By all indications, this is the largest rainfall ever documented over a developed urban area in Colorado.

Remarkably, just 24 hours after the Fort Collins storm, another huge rainstorm developed. The Pawnee Creek storm developed over eastern Weld County and western Logan County during the evening of July 29, 1997. By the time the rains ended early on July 30th, more than 15 inches of rain had fallen near the storm center. Rainfall rates were comparable to the Fort Collins storm but the storm was several times larger in area. As a result, the Pawnee Creek storm will rank near the top of the list of Colorado's most extreme rainstorms.

It is interesting to note that three of the largest historic storms identified in the McKee and Doesken study occurred in Larimer County:

- Livermore/Boxelder (North Fork Poudre River and Boxelder Creek) May 20-21, 1904. Few rain measurements were available, but 8.00 inches was measured and heavier rainfall totals were likely.

- Redstone Canyon, September 2-3, 1938. 6-10" estimates (Very heavy rains were observed along the Front Range from west of Denver northward to Fort Collins and adjacent foothills.)

- Big Thompson Canyon, July 31, 1976. 12" in less than 6 hours with 139 confirmed fatalities.

All three of these storms produced severe flooding, but the Big Thompson flood claimed by far the most lives. In terms of meteorological conditions, the Big Thompson storm seemed similar to the Fort Collins storm. However, since it occurred over mountainous terrain, the floodwaters were funneled into a single steep-gradient channel therefore concentrating damage and fatalities.

Local Perspective

How often in the past has Fort Collins experienced extremely large or intense rainstorms? Was this a 100-year storm, a 500-year storm or worse? These questions have been asked countless times by those experiencing the flood and those planning for the potential for future floods. Fort Collins is fortunate to have an excellent source of data for historical analysis and comparison. Daily weather observations have been taken without interruption since 1889 on the campus of Colorado State University. Several analyses have been conducted in order to define what place in history this recent rainstorm deserves.

As we interpret these results, it is important to note that a single measurement point in the middle of town may not accurately reflect the amount of rain that may have fallen in other parts of the city. Just as we experienced in the July 28, 1997 storm, in nearly every storm

some parts of town may get more rain while others get less. If storms are randomly located, over the course of many years these variations will average out so that the campus data will provide representative information for all parts of the city. In the case of Fort Collins, which is situated such that the foothills and mountains rise abruptly just west of the city, storms may not be randomly located. However, there is no other consistent long term data to compare to at this time.

The following analyses are based on daily rainfall observations taken each day at 7:00 p.m. (1900 MST, 2000 MDT when daylight time is in effect). Table 7 shows the greatest daily precipitation totals since 1889. Table 8 shows the greatest 2-day totals. Keep in mind that daily measurements through history have been taken at the fixed time of 7:00 p.m. MST (8:00 p.m. MDT). If it happens to be raining at the time of observation, rainfall from that storm will be split between two daily reports. That was the case with the July 28, 1997 storm. Most of the rain fell after the 8:00 p.m. (2000 MDT) observation, and that rain appears on the climatological report for July 29.

There are many ways that heavy rain can fall, and not all of the heaviest storms (in terms of total rainfall) ever caused significant runoff and flooding. Some of the heaviest one and two-day storms partially fell as heavy, wet snow. To more thoroughly describe and historically document the heaviest precipitation events, a brief description of each storm from Table 7 and Table 8 is recorded in Appendix C.

Table 7.

Greatest one-day precipitation totals measured at the Fort Collins weather station on the campus of Colorado State University for the period January 1, 1889 - December 31, 1997.

(All totals are for the 24-hour period ending at 1900 MST on the date indicated.)

Rank	Precipitation Total (inches)	Date of Observation	Remarks *
1	4.63	July 29, 1997	Flash flood, 5 killed, most fell in less than 5 hrs
2	4.43	July 25, 1977	Rain, most fell in 15 hours
3	4.34	September 21, 1902	Rain, intense at first, then gentle
4	3.54	September 3, 1938	Cloudburst, flooding west of town
5	3.54	June 4, 1949	Steady rain but not too intense
6	3.48	March 6, 1990	All snow, heavy and wet, 12.4 inches
7	3.21	May 13, 1961	Steady rain changing to snow
8	3.06	May 13, 1982	Long and steady rain
9	3.02	August 3, 1951	Very intense rain, fell in less than 4 hours
10	3.01	May 2, 1904	Long and steady rain
11	2.98	August 4, 1951	Very intense rain, fell less than 4 hours
12	2.97	June 8, 1974	Rain, steady but briefly intense
13	2.85	July 9, 1918	Probably intense rain
14	2.71	June 17, 1965	Brief but intense rain
15	2.69	June 16, 1963	Widespread steady rain
16	2.58	August 19, 1961	Steady rain changing to snow
17	2.49	June 24, 1992	Heavy thunder and hail, fell less than 1.5 hrs
18	2.40	June 11, 1970	Long and steady rain
19	2.39	April 29, 1900	Mixed rain and snow, long and steady
20	2.32	May 22, 1901	Heavy rain and hail

* Expanded description of each event is given in Appendix C.

Table 8.
Greatest two-day precipitation totals measured at the Fort Collins weather station on the campus of Colorado State University for the period January 1, 1889 - December 31, 1997.
(All totals are for the 48-hour period ending at 1900 MST on the last date indicated.)

Rank	Precipitation Total (inches)	Date of Observation	Remarks *
1	6.22	September 20-21, 1902	Rain intense at first, then gentle
2	6.17	July 28-29, 1997	Flash flood, 5 killed, most fell in less than 5 hrs on evening of 28th
3	6.07	August 3-4, 1951	Very intense rain, fell less than 4 hours
4	4.76	July 24-25, 1977	Rain, mostly in 15 hours
5	4.68	September 2-3, 1938	Intense rain and flooding
6	3.99	May 12-13, 1982	Long and steady rain
7	3.83	March 6-7, 1990	All snow, heavy and wet
8	3.80	May 2-3, 1904	Long and stready rain
9	3.73	June 3-4, 1949	Steady rain but not too intense
10	3.70	May 21-22, 1901	Rain and hail, 2 successive heavy rain events. 3.24 inches in 4 hrs late on 20th and 2.36 inches in 4 hrs late on 21st.
11	3.66	May 12-13, 1961	Steady rain changing to snow
12	3.32	October 16-17, 1942	Briefly intense then long and steady
13	3.27	May 28-29, 1975	Long and steady rain
14	3.09	April 28-29, 1900	Mixed rain and snow, long and steady
15	3.04	June 15-16, 1963	Widespread steady rain
16	3.03	June 24-25, 1992	Heavy thunder and hail, fell less than 1.5 hours
17	2.99	July 9-10, 1918	Probably intense rain
18	2.96	June 11-12, 1970	Long and steady rain
19	2.89	June 8-9, 1974	Rain, steady but briefly intense
20	2.86	June 16-17, 1965	Brief but intense rain.

* Expanded description of each event is given in Appendix C.

Figures 15 and 16 show the maximum one-day and two-day rainfall totals for each year since 1889. Based on these data, the July 1997 storm ranks as the greatest one-day rainfall (4.63 inches for the official climatological day) and the second greatest two-day total in recorded history (6.17"). The totals, however, are not greatly different than two other storms. For one-day totals, July 25, 1977 and September 21, 1902 were only slightly less. For two-day totals, the July 1997 storm ranks 2nd behind the 1902 event with August 2-3, 1951 (also a significant flood episode in Fort Collins) a close third.

In recent decades, the use of recording rain gauges has made it possible to determine hourly rainfall totals as well as daily or other intervals. This provides information on rainfall intensity which, of course, is a crucial factor in determining flash flood potential. The maximum rainfall for each year beginning in 1940 for periods of one, three and six hours are shown in Figure 17. The maximum one hour rainfall on the CSU campus for the July 1997 storm was 2.31 inches (keep in mind that the campus weather station was not at the center of the storm). This is very heavy rain, but not unprecedented. Comparable rainfall rates at the campus weather station were observed for a one hour time period August 18, 1961 (2.33 inches) and on June 17, 1965 (2.31 inches). The greatest one hour rainfall total measured at the campus weather station was 2.40 inches on June 24, 1992. The June 1992 storm was very intense, accompanied by hail and strong winds. Areas one to three miles northwest of the main campus received even heavier rains from that storm with maximum hourly totals close to 3.50 inches. Some flooding resulted.

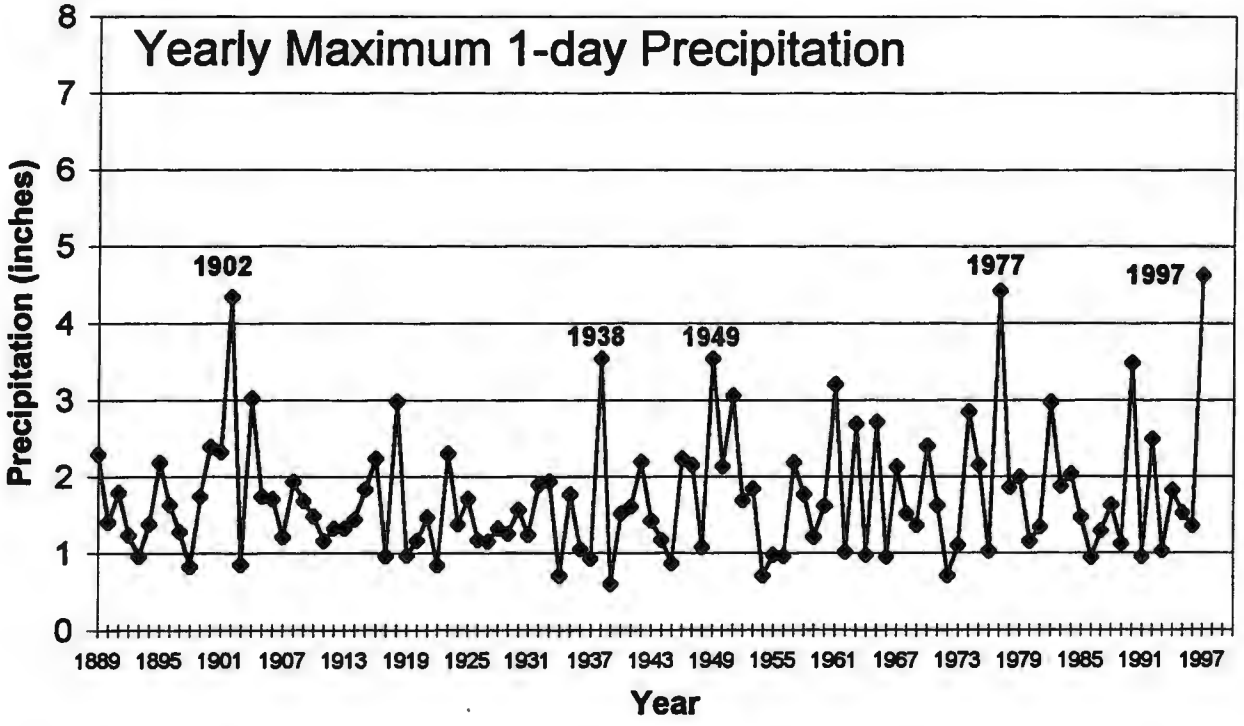


Figure 15. Time series, 1889 through 1997, of the Fort Collins, Colorado, annual maximum one-day precipitation totals (24-hour period ending at 1900 MST) measured on campus.

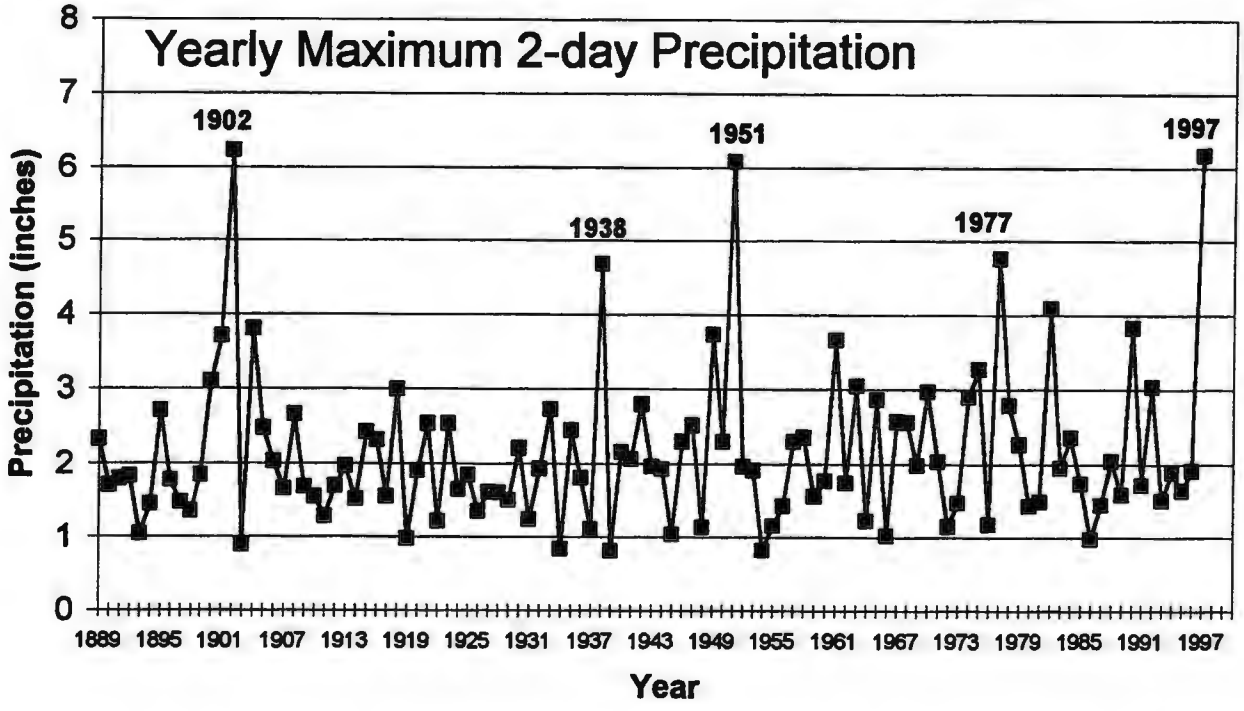


Figure 16. Time series, 1889 through 1997, of the Fort Collins, Colorado, annual maximum two-day precipitation totals (48-hour period ending at 1900 MST) measured on the campus of Colorado State University.

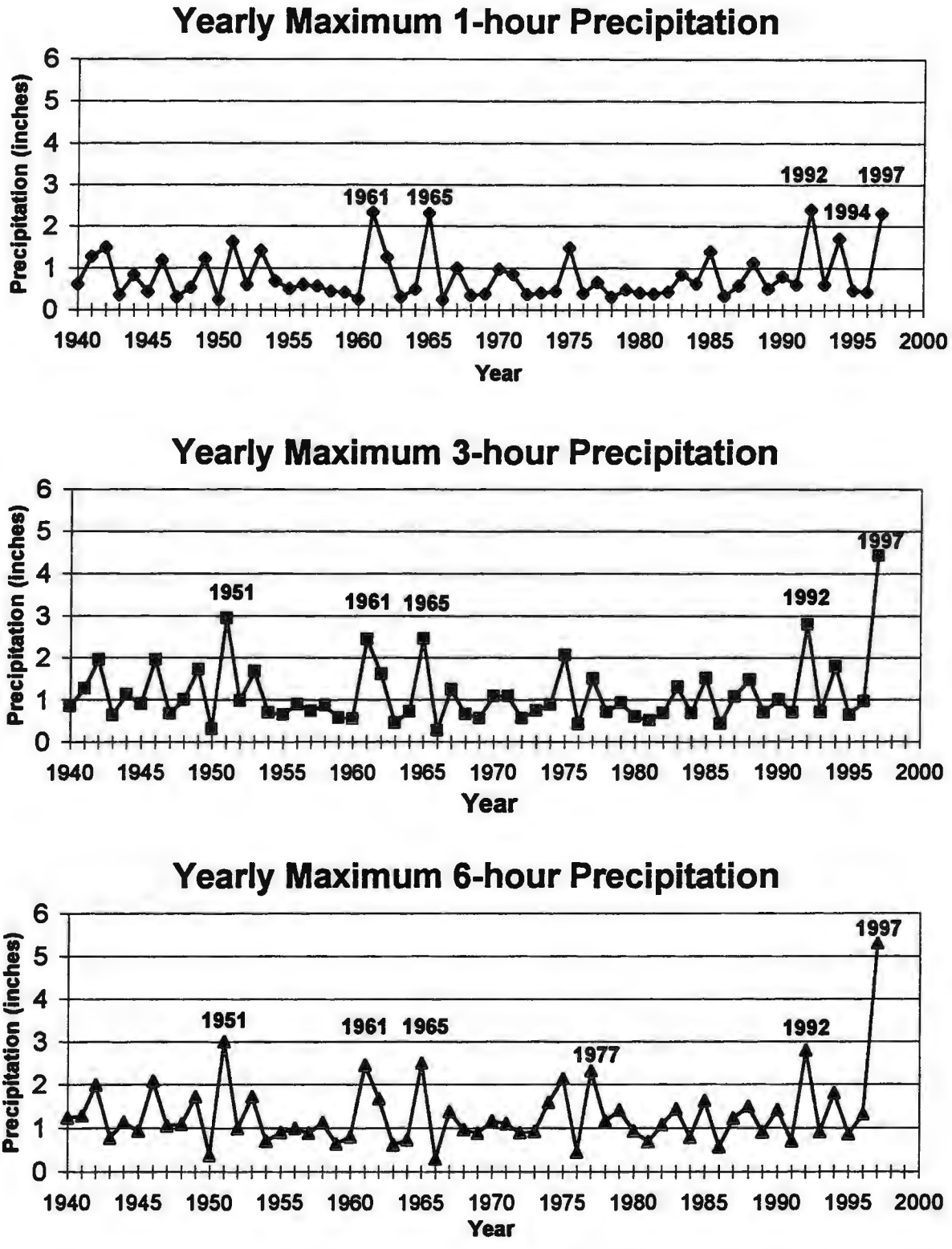


Figure 17. Time series, 1940 through 1997, of the Fort Collins, Colorado, annual maximum one-hour, three-hour and six-hour rainfall totals measured on the campus of Colorado State University.

Most summer thunderstorms, and the 1992 event was a good example, do not last long. It is rare for such storms to continue at a high intensity much beyond one hour. The Fort Collins storm of July 1997 stands out because of its prolonged high intensity. At durations of three and six hours (Figure 17) this recent storm is unprecedented among observed rains on campus. 4.42" was measured in three hours 2000-2300 MDT July 28, 1997 which was nearly 1.50 inches more than the previous three-hour record established August 3, 1951. The six-hour total was 5.30" on campus compared to 3 inches from the August 1951 storm. While impressive in its own right, the campus measurement was only about one-half of the rainfall total for that period at the storm's center three miles southwest from the main campus.

Flooding from heavy rains September 2-3, 1938 is well documented in the Fort Collins area. However, the observed rainfall for that storm of 3.54 inches in one day and 4.68 inches in two days places that storm as only the 5th largest rainstorm in 109 years of Colorado State University measurements. The reason that flooding was severe appears to be that the storm was more intense over the foothills immediately west and southwest of Fort Collins.

Comparison to the 100-year storm

The 100-year storm is a statistical rainfall amount derived from historical rainfall observations and used by hydrologists, engineers and planners. Figures 18 and 19 show the 100-year rainfall estimates for the Larimer County area for 6-hour and 24-hour periods, respectively. Interpolation from these federally-produced maps indicates that for central Fort Collins, the 6-hour 100-year rainfall is approximately 3.5 inches while the 24-hour 100-year event is 4.8 inches. These maps were produced in the early 1970s and have served as the primary information source for estimating design rainfall amounts. An update to these maps is available for neighboring states south and west of Colorado and is planned for Colorado and neighboring states to the east and north.

Based on the campus rainfall measurements, the maximum 6-hour rainfall on the evening of July 28, 1997 of 5.30 inches exceeded the 100-year value for that time period by a significant amount, 1.80 inches. However, since most of the rain on campus was confined to a 6-hour period, the storm only slightly exceeded the 100-year, 24-hour value. Near the center of the storm over southwest Fort Collins, these comparisons were much more impressive. For the intense rainfall period during the evening hours of July 28, 1997, the maximum rainfall was three times greater than the 100-year 6-hour value. A direct comparison with the 100-year 24-hour storm rainfall is tricky since the storm totals from Figures 10 and 14 were actually 31-hour totals. However, for those areas of maximum rainfall along the base of the foothills, the storm total rainfall was 2 to 3 times greater than the 100-year 24-hour values.

A great deal of misunderstanding has developed regarding the 100-year storm (Doesken, 1996) and what it means. In many people's minds, it appears that 100-year and greater storms occur "all the time" and they question the accuracy and usefulness of the values. In applying storm statistics like these, it is necessary to realize that these are "single point" values. A rainfall of 4.8 inches in 24 hours may, in fact, have only a 1 percent likelihood of occurrence on the Colorado State University Campus. However, if you look at all storms each summer over all of northeast Colorado, it is almost a certainty that rainfall will exceed

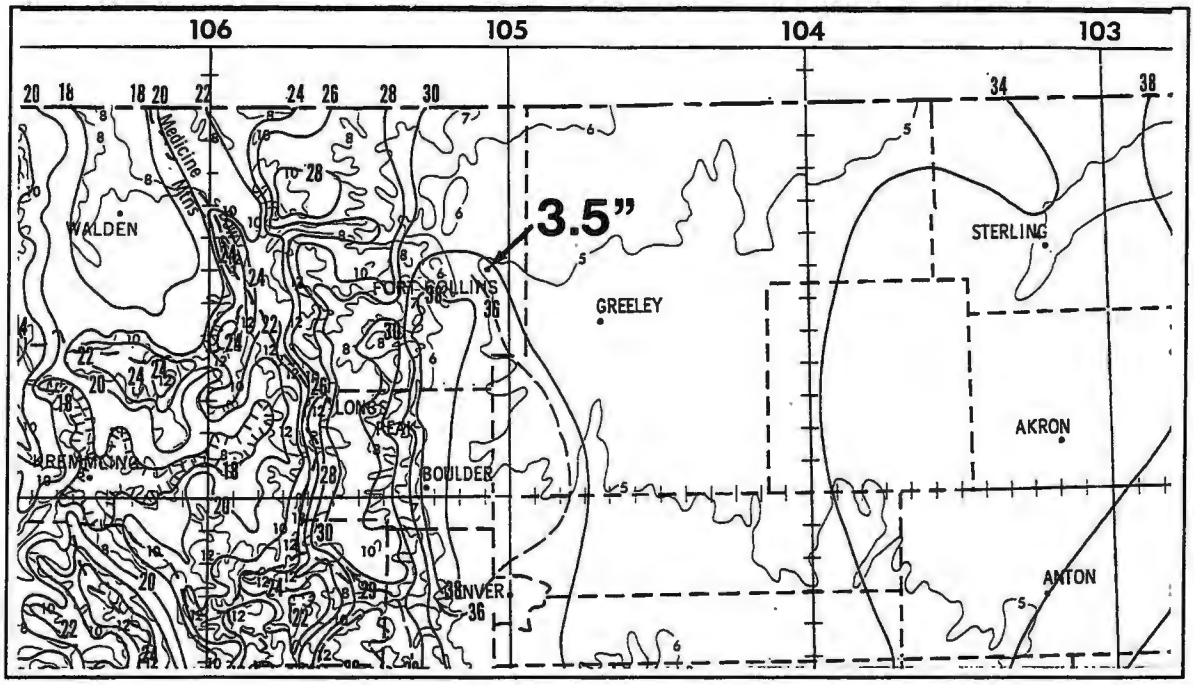


Figure 18. Isopluvials of the 100-year 6-hour precipitation in tenths of an inch for north central Colorado (From "Precipitation Frequency Atlas of the Western United States – NOAA Atlas 2, Volume III (Colorado), Miller et al, 1973.)

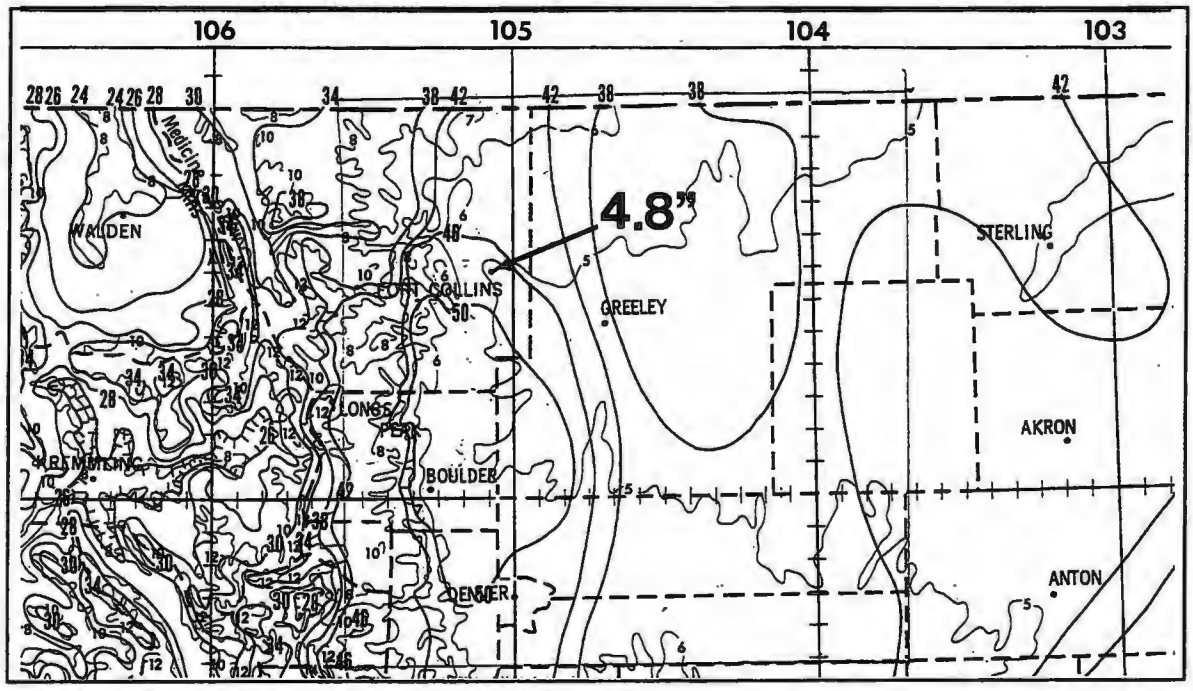


Figure 19. Isopluvials of the 100-year 24-hour precipitation in tenths of an inch for north central Colorado (From "Precipitation Frequency Atlas of the Western United States – NOAA Atlas 2, Volume III (Colorado), Miller et al, 1973.)

4.8 inches at a few locations over the region. Similarly, the likelihood of receiving 10 inches of rain in 24 hours over Fort Collins is extremely small, but the chances of receiving 10 inches of rain somewhere in Colorado in any given year is quite high – about ten percent. The 100-year storm concept is useful and has an important place in design and planning, but its definition must be understood. Figure 20 shows the 109 largest one-day rainfall totals measured at the Fort Collins weather station from 1889 through 1997. This is called a partial duration ranked series and is the foundation for precipitation frequency computations and estimating the magnitude of design storms for stormwater planning. Figure 20 (top) shows the partial duration series for the period 1889 through 1970 which was used to compute the published design storm values in Figure 19. Updating local rainfall statistics to include the recent heavy rains needs to be completed. Including recent data may result in higher estimates of design rainfall, but the changes will likely be small.

Conclusions

The Fort Collins storm on the evening of July 28, 1997 in combination with the rains that fell in eastern Larimer County from late afternoon July 27 through midday July 28 produced the heaviest documented rainfall in Colorado since 1981 and one of the 11 most severe rainstorms of the Twentieth Century along the Colorado Front Range. From all available data, this appears to be the heaviest rainfall ever recorded over a developed urban area in Colorado. The area of high intensity rainfall was small and covered only a few square miles. Gradients of rainfall were so remarkable that many residents of Fort Collins and outlying areas were unaware that flood-producing rains had fallen while other neighborhoods only a short distance away were inundated with heavy rain and flooding.

Many large storms of the past have been documented and described based on limited rain gauge data supplemented by "bucket survey" analyses. With nearly 300 gauge measurements over a relatively small area, the Fort Collins storm is the most thoroughly documented of any extreme rainfall event in Colorado up to this time.

Acknowledgments

The authors wish to thank the many, many individuals and organizations who helped compile rainfall information for this storm. Jim Wirshborn of Mountain States Weather Services was an incredible asset to this effort and has done so much over the past 20+ years to help the citizens of Fort Collins to watch and appreciate daily weather. The City of Fort Collins, including such individuals as Marsha Hilmes with the Storm Water Utility and Dennis Bode of the Fort Collins Water Utility, provided prompt, cheerful and ongoing assistance. We appreciated the cooperation from the Fort Collins Coloradoan in publishing appeals for rainfall information. Similar thanks go to KIIX and KCOL radio stations for broadcasting our requests. Thanks to Dr. Richard Johnson of the Colorado State University Department of Atmospheric Science for compiling rainfall reports. Investigative work by John Weaver, Poudre Fire Authority Volunteer and Meteorologist with the National Oceanic and Atmospheric Administration, was very helpful. Larry Tunnell, National Weather Service

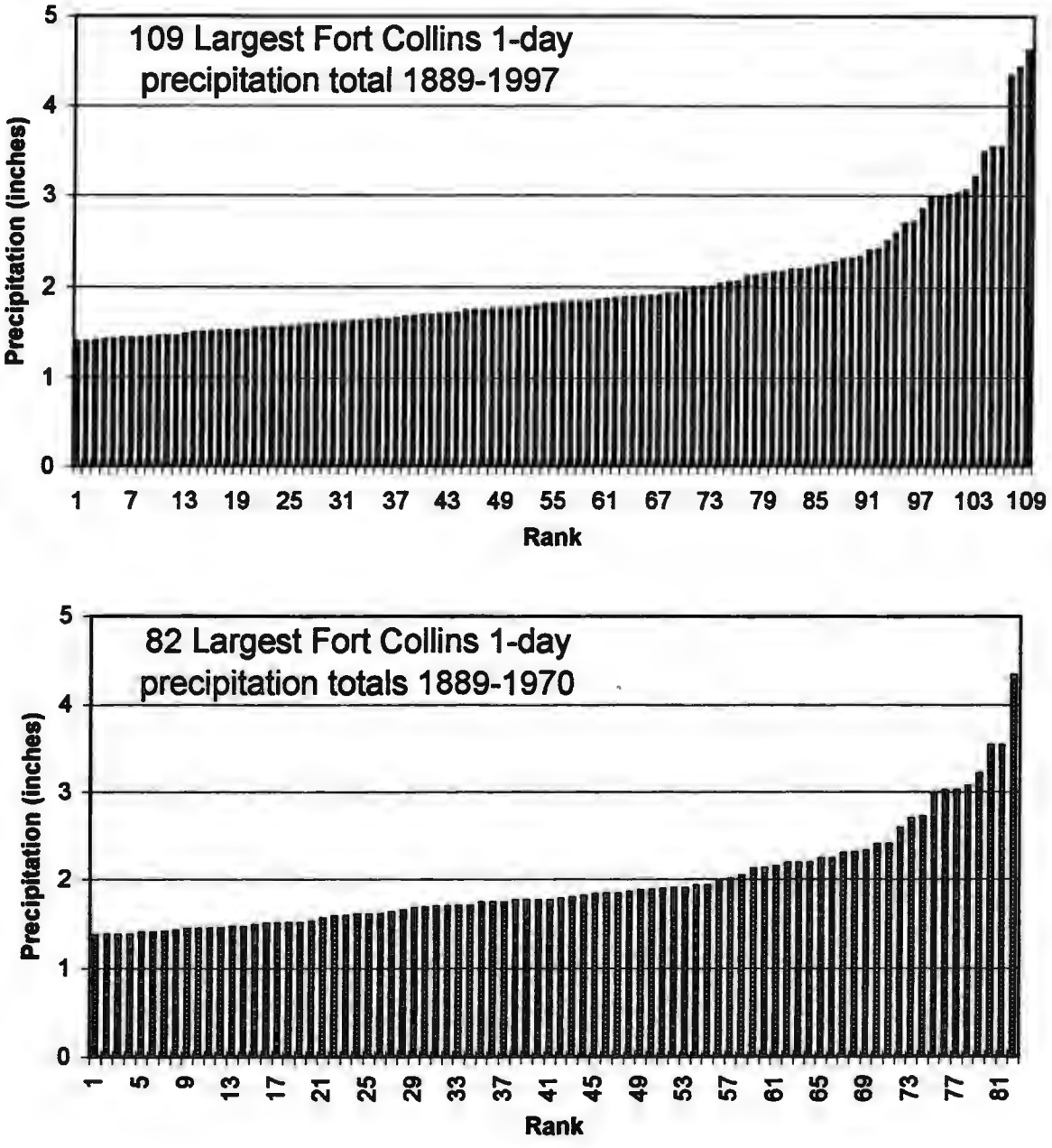


Figure 20. Ranked partial duration series of maximum one-day precipitation totals at the Fort Collins Weather Station on the campus of Colorado State University. Top: based on all daily data 1889 through 1997. Bottom: based on 1889 through 1970 data.

Hydrologist from Denver, provided radar data from the Denver WSR-88D radar along with considerable assistance and expertise. We also appreciate the cooperation and help provided by Walt Petersen, Larry Carey and Dr. Steve Rutledge in developing rainfall estimates from the CSU CHILL radar for comparison with ground measurements. The efforts of the staff of the Colorado Climate Center (Odie Bliss, John Kleist, Natalie Marquez and Jim Harrington) in gathering data, developing data bases, producing maps and preparing reports were certainly appreciated and were essential in completing this study.

Compiling data and producing rainfall maps and descriptions proved to be more time consuming than originally planned. We appreciate the patience shown to us by many managers, administrators, planners, consultants, engineers, attorneys and researchers who needed information about this storm but were willing to wait so that we could assemble a more complete and accurate summary.

Most importantly, thank you so much to all of the citizens of Fort Collins that weathered this storm and still made the effort to share their measurements and their experiences and recollections so that we could document and describe this remarkable storm.

This study was made possible by the ongoing support of the Agricultural Experiment Station at Colorado State University. Other research projects took a back seat so that this special study could be completed.

References

Browning, T., and L. Lang, 1997: Preliminary analysis of the Pawnee Creek Flood of July 29-30, 1997 (internal document). Colorado Water Conservation Board, State of Colorado, Department of Natural Resources, Denver, CO, October.

Clement, P. C., and T. B. McKee, 1995: A comparison of radar-derived precipitation and rain gage precipitation in Northeastern Colorado. Department of Atmospheric Science Paper No. 579, Colorado State University, Fort Collins, CO, 86 pp.

Doesken, N. J., 1996: The 100-Year Storm – Do we really know what that is? *Colorado Climate*, Vol. 19, No. 4, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, pp 40-43.

Follansbee, R., and L. R. Sawyer, 1948: Floods in Colorado. Geological Survey Water-Supply Paper 997. U.S. Geological Survey, U.S. Department of the Interior, Government Printing Office, Washington, D.C., 151 pp.

Glancy, R. T., and J. A. Daselar, 1986: Meteorological analysis of the conditions which produced the record flood at Cheyenne, Wyoming. Preprints, 11th Conference on Weather Forecasting and Analysis, American Meteorological Society, Kansas City, MO, June 8-12, Paper P4.12, p. 119-123.

Hansen, E. M., D. D. Fenn, L. C. Schreiner, R. W. Stodt, and J. F. Miller, 1988: Probable Maximum Precipitation Estimates – United States Between the Continental Divide and the 103rd Meridian. Hydrometeorological Report No. 55A. U.S. Dept. of Commerce, U.S. Dept. of Army and U.S. Dept. of Interior, Silver Spring, MD, 242 pp.

Maddox, R. A., F. Caracena, L. R. Hoxit, and C. F. Chappell, 1977: Meteorological aspects of the Big Thompson flash flood of 31 July 1976. NOAA Technical Report ERL 388-APCL 41, 84 pp.

McKee, T. B. and N. J. Doesken, 1997: Final Report: Colorado extreme precipitation data study. (Summary of accomplishments and work performed February 15, 1995 through October 31, 1996) Climatology Report #97-1, Department of Atmospheric Science, Colorado State University, Fort Collins, CO, 107 pp.

Miller, J. F., R. H. Frederick, and R. J. Tracey, 1973: Precipitation Frequency Atlas of the Western United States, NOAA Atlas 2, Volume III – Colorado. U.S. Department of Commerce, NOAA, NWS, Silver Spring, MD, 67 pp.

Tunnell, L, 1998: Personal communication. National Weather Service, Service Hydrologist, Denver, Colorado, January.

Appendix A.

Electronic mail message transmitted July 30-31, 1997 to a few thousand addresses in the Fort Collins area.

Date: Thu, 31 Jul 1997 14:14:19 +0000
From: address@lamar.colostate.edu
To: campus@yuma.acns.colostate.edu
Subject: CSU- RAIN STORM DOCUMENTATION

Reply-to: nolan@ulysses.atmos.coloState.edu

Sender: Nolan Doesken <nolan@ulysses.atmos.coloState.edu>
Subject: RAIN STORM DOCUMENTATION

RAIN STORM DOCUMENTATION

Attention all University Personnel

DID YOU (OR SOMEONE YOU KNOW) MEASURE THE RAINFALL # #

? ? ? ? ? FROM THE RECENT STORMS ? ? ? ? ?

A thorough collaborative study of the recent incredible rains in the Fort Collins area is being conducted. It is important to define as accurately as possible the rainfall patterns and the timing of intense rainfall during the total storm period which began late afternoon on Sunday July 27 and culminating in the rain episode Monday evening (July 28).

If you took measurements with a trustworthy rain gauge, or if you know people in your neighborhood that are diligent weather observers, please contact the Colorado Climate Center.

WE ARE, OF COURSE, INTERESTED IN THOSE LOCATIONS THAT RECEIVED VERY HEAVY RAINS, BUT WE ARE ALSO INTERESTED IN REPORTS FROM AREAS N, E, S AND WEST OF THE CITY THAT MAY HAVE RECEIVED LESSER AMOUNTS OF RAIN.

We will accept whatever information you can provide, but what we would really like to know is:

1) location of observation (street address and other specifics so we can accurately pinpoint your measurement)

2) name and phone number of person to contact for more information

3) type of raingauge (such as "wedge gauge, 4" diameter clear plastic gauge with funnel and inner measuring tube, etc.)

4) Rainfall amount from 4 PM to 8 PM Sunday July 27

5) Rainfall amount from 8 PM Sunday through mid-morning Monday July 28

6) Rainfall amount from 5 PM to midnight Monday July 28 (any finer time increments would be great in order to evaluate rainfall rates)

7) Special remarks and other pertinent observations

Reply by e-mail to:

nolan@ulysses.atmos.colostate.edu

or call the Colorado Climate Center:

491-8545

We only have one phone line, so be persistent, or leave a brief message that we can reply to.

Many, many thanks to all of you, and hope you are recovering from whatever experiences you may have had.

By the way, at the official weather station on the main campus of Colorado State University, here are the rainfall reports for the storm.

Sunday, July 26	12-hour period ending 8 PM	0.16"
Monday, July 27	12-hour period ending 8 AM	0.73"
Monday, July 27	12-hour period ending 8 PM	0.81"
Tuesday, July 28	12-hour period ending 8 AM	4.63"

A total of 5.31" fell from 5:50 PM to about 11 PM Monday evening.

This is the largest rainfall for a 6-hour period in the 108+ year history of the station and even exceeded the previous record 24-hour rainfall that occurred back in July 1977.

MANY THANKS!!!!

Nolan Doesken
Colorado Climate Center
Dept. of Atmospheric Science
(970) 491-8545

Appendix B.

Example data sheet for recording rain reports and supplemental information.

Rainfall amounts for the storm of July 27-28, 1997

1. **Observer Information**

Name	
Phone Number	
Address	
Location	
Email Address	

2. **Rainfall amounts**

Date	Time of Observation	Rainfall Total
Storm Total		

3. **Type of Raingauge** _____

_____

_____

4. **Other remarks/observations** _____

_____

_____

_____

Appendix C.

Largest recorded precipitation events as measured on the campus of Colorado State University, 1889-1997.

Description of **largest recorded precipitation events as measured on the campus of Colorado State University** from 1889 through 1997. Events are listed in chronological order based on the dates on which the rainfall were reported. Remember that the official climatological day for the CSU weather station ends at 1900 MST. Therefore, rains that fall between 1900 and midnight are reported on the following day.

Most descriptive information was obtained or inferred from data and remarks recorded by CSU weather observers. Larger events could have occurred in the Fort Collins vicinity such as the May 20-21, 1904 storm in northern Larimer County, but these storms did not produce heavy precipitation on campus.

April 28-29, 1900 2.39 inches in one day, 3.09 inches in two days

Some fairly heavy showers accompanied by hail began late on the afternoon of April 27. Lighter intermittent showers on the 28th turned into a hard, steady, cold rain overnight on the 28th, all day on the 29th and then turned to snow before finally ending around 8 a.m. on the 30th. Total precipitation for the entire storm period was 4.77 inches in 54 hours with 2.89 inches falling from 7 p.m. on the 28th until 8 a.m. on the 30th. This was clearly a major "upslope" storm, and it is likely that precipitation was heavier west of campus but likely fell primarily as snow immediately west of Fort Collins in the lower foothills. As a result, foothills flooding was unlikely. However, since most of Larimer County had already been extremely wet in the weeks preceding this storm, standing water and low-level flooding was a distinct possibility east of the foothills.

May 21-22, 1901 2.32 inches in one day, 3.70 inches in two days

The rain began around 4:30 p.m. on the 20th as an intense thunderstorm accompanied by hail. 1.90 inches fell by 7 p.m. with an additional 1.34 inches by about 8:30 p.m. for a total of 3.24 inches in just over four hours. Very little rain fell during the day on the 21st, but another burst of heavy rain and hail developed during the evening of the 21st with an additional 2.36 inches in roughly four hours. In all, 5.60 inches of rain fell in less than 48 hours (spread over 3 observational days) at the campus weather station. No information was given on how much rain may have fallen in surrounding areas near Fort Collins, but the intensities of these back-to-back storms were likely sufficient to produce significant runoff.

September 20-21, 1902 4.34 inches in one day, 6.22 inches in two days

Intense rains began over Fort Collins around 5 p.m. on the 20th. 1.88 inches fell by 7 p.m. that evening with an additional 2.72 inches by 7 a.m. on the 21st. Thereafter, the rain diminished into a steady, cold rain with another 1.62 inches by 7 p.m. and 0.62 inches more by the time the rain stopped around noon on the 22nd for a storm total of 6.84 inches. No information was located describing rainfall amounts elsewhere in the vicinity of Fort Collins.

May 2-3, 1904 3.02 inches in one day, 3.80 inches in two days

A chilly, light rain began afternoon on May 1 and increased to a steady, moderate rain overnight. The intensity increased during the day on the 2nd as 2.31 inches of rain accumulated in the 12-hour period from 7 a.m. to 7 p.m.. The intensity decreased, but an additional 0.76 inches fell overnight. The rains, ended early on the 3rd. While there was a large accumulation of rain, there was no indication of intense, convective storms. Overall, this storm appears to have been a widespread, beneficial soaking rain.

Special note: 17 days later, a very heavy storm north-northwest of Fort Collins produced a major flood on the Poudre River and several of its tributaries.

July 9-10, 1918 2.82 inches in one day, 2.99 inches in two days

Little was said about this storm, and the written weather reports for the campus weather station were difficult to decipher. Most likely there was a very intense thunderstorm late on the 8th with high rainfall rates for a short period of time followed by light precipitation continuing on and off on the 9th. No information on rainfall patterns elsewhere in the Fort Collins area were obtained, but it might be worth checking newspaper accounts to see if any flooding was reported in the vicinity.

September 2-3, 1938 3.54 inches in one day, 4.68 inches in two days

Rain developed in the region late on August 31 with intermittent heavy showers on the 1st and 2nd. Intense rains began late afternoon on the 2nd in the foothills west of Denver northward to west of Fort Collins. Heavy rains expanded eastward across Fort Collins during the evening with 1.14 inches measured on campus by 7 p.m. on the 2nd. Heavy rains continued overnight with an additional 3.54 inches reported at 7 p.m. on the 3rd but likely most of that fell during the evening of the 2nd and then tapered off to lighter rains. All indications suggest that rainfall totals were heavier to the west. An official weather station near the mouth of the Big Thompson Canyon measured a storm total of 8 inches. Severe flooding was reported on Spring Creek, Buckhorn Creek, and Redstone Creek, as well as other rivers and streams along the Front Range southward to Denver.

October 16-17, 1942 3.32 inches in two days

More than two inches of rain had already fallen October 12-14, so ground conditions were already very wet when heavy rain began to fall early on the 16th. During the most intense rain period on the 16th, 1.49 inches was reported in one hour. This is a very heavy rainfall rate for so late in the season. Lighter precipitation continued into the early morning of October 17th with a storm total of 3.32 inches in less than 30 hours. The spatial pattern of this rainfall is not known, but some potential for flooding existed.

June 3-4, 1949 3.54 inches in one day, 3.73 inches in two days

Rain began on the 3rd and appeared to be widespread and fairly steady with maximum rainfall rates during the day on the 4th, but not very intense. Maximum two-hour rainfall from recording gauge was only 0.74 inches suggesting a soaking rain with little or no flash flood potential. No information was obtained concerning rainfall amounts elsewhere near Fort Collins, but all of northeastern Colorado received beneficial rains.

August 3-4, 1951 3.06 inches in one day, 6.07 inches in two days

Very heavy rains began around 7 p.m. on August 2 dropping 1.25 inches in an hour. Rains then diminished but continued steadily overnight until about 9 a.m. on the 3rd. Then, on the evening of the 3rd, an even more intense storm struck approximately 8-11 p.m. dripping 1.62 inches in one hour, 2.59 inches in two hours, and a total of 3 inches in just over 3 hours. Flooding occurred in Fort Collins from this rainstorm. There was evidence of potential even heavier rains west of Fort Collins. Fatalities were reported from flooding near Bellvue and also in Buckhorn Canyon.

May 12-13, 1961 3.21 inches in one day, 3.66 inches in two days

This was a strong winter-like storm which produced widespread heavy precipitation but without the intensity required to produce flash floods. Heavy rain began around 6:20 p.m. on the 12th and continued into the 13th changing to snow late in the day. In all, 3.85 inches of moisture fell on campus in about 32 hours. No information on precipitation amounts elsewhere in the Fort Collins area was obtained.

August 19, 1961 2.58 inches in one day

A brief but very intense storm struck Fort Collins on the evening of August 18th dropping 2.58" of rain in about 90 minutes. No additional information on rainfall patterns elsewhere in the Fort Collins area was obtained.

June 15-16, 1963 2.69 inches in one day, 3.04 inches in two days

Moderate afternoon showers on June 15th gave way to widespread, heavy but not particularly intense cool rains. 2.69 inches fell between 9 p.m. on the 15th and 1:30 p.m. on the 16th on campus. No additional information on rainfall patterns elsewhere in the Fort Collins area was obtained.

June 16-17, 1965 2.71 inches in one day, 2.86 inches in two days

Fort Collins got only a small taste of the torrential rains that fell in many areas of eastern and southeastern Colorado during mid June of 1965. After ten days of showery weather, a brief but intense downpour dropped 2.71 inches with 2.31 inches falling in just one hour. Heavier rains were reported elsewhere in Larimer County, but the locations of these heavier rains were not described.

June 11-12, 1970 2.40 inches in one day, 2.96 inches in two days

Steady, hard rain began during the evening of June 10th and continued all day on the 11th ending early on the 12th. Rainfall rates were not intense, and temperatures with this storm were very chilly. No spatial rainfall patterns were available showing rainfall totals elsewhere near Fort Collins. However, soaking, beneficial rains were widespread over northeastern Colorado.

June 8-9, 1974 2.85 inches in one day, 2.89 inches in two days

Chilly, light rain began during the evening of June 7th and became heavier overnight with a 6-hour accumulation of 1.58 inches. Steady, soaking rains then continued throughout the 8th and tapered off. Intensities were too low to produce significant flooding. No information was obtained to describe rainfall patterns elsewhere in the Fort Collins area.

May 28-29, 1975 3.27 inches in two days

Rain began very late May 27th and continued all day on the 28th and ended during the afternoon of the 29th. A wonderful, soaking rain but intensities were only moderate with a maximum 6-hour total of only 1.00 inches. No information was obtained to describe rainfall patterns elsewhere in the Fort Collins area.

July 24-25, 1977 4.43 inches in one day, 4.76 inches in two days

Late evening thunderstorms erupted July 23rd north and west of Fort Collins with locally heavy rains. Rains developed in the foothills west of Fort Collins again on the afternoon of the 24th. Heavy rains began over Fort Collins around 8 p.m. and continued well past midnight with 2.59 inches on campus by 5 a.m. on the 25th but with 3-5 inches in areas east, west and north of the city. Another period of heavy rain fell over the city from 7 a.m. to about noon on the 25th with an additional 1.84" on campus and slightly more in some other parts of town. This rain episode was more localized in the immediate Fort Collins area.

May 12-13, 1982 3.17 inches in one day, 3.99 inches in two days

Steady, pouring cold rains began on the 12th and were heaviest overnight into the early morning on the 13th. Hourly rainfall rates, however, were not extreme. This was mostly a good soaking spring rain. No information was obtained regarding rainfall totals elsewhere near Fort Collins, but heavy rains were widespread.

March 6-7, 1990 3.48 inches in one day, 3.83 inches in two days

Evening rain and thunder March 5th turned to wet snow and snow pellets which continued into the evening of March 7th with a total of 17 inches of dense snow reported. The heaviest precipitation fell during the day on March 6. Traffic came to a near standstill, and some roofs bent or collapsed under the load. This storm produced the greatest water content ever observed in Fort Collins in one day in the form of snow. The three-day total for this storm was 4.17 inches. Extremely heavy snowfall amounts in excess of 50 inches were measured in the foothills immediately west and northwest of Fort Collins causing considerable tree damage in some areas. Water contents in the foothills were about the same as in Fort Collins, but the snow was less dense at higher elevations.

June 24-25, 1992 2.49 inches in one day, 3.03 inches in two days

A ferocious but brief storm accompanied by heavy rains, frequent lightning, hail and strong winds lasted less then 90 minutes mid afternoon on June 24th. 2.49" was recorded on campus, but precipitation was likely more as some windblown hail bounced out of the gauge. Rainfall was heavier one to three miles northwest of campus. In the vicinity of Taft Hill Road and Vine Drive, 3.5 inches of precipitation was reported. Local flooding occurred and would have become severe had the rains continued. Rainfall totals diminished greatly south from campus. Another moderate shower fell on the afternoon of June 25th.

July 28-29, 1997 4.63 inches in one day, 6.17 inches in two days

Rains began July 27th early evening with light rain in town but with significant rainfall of 2 to 9 inches near the foothills overnight through midday July 28th southwest through northwest of Fort Collins. Very intense rains fell during the evening of July 28 over western and central Fort Collins causing severe flash flooding and five fatalities. As much as 10 inches fell in less than five hours 3-4 miles southwest of campus. The maximum observed rainfall was 14.5 inches in approximately 30 hours 3-4 miles southwest of campus. Ten inch storm totals were common near the base of the foothills.