DENVER METROPOLITAN AREA DOPPLER RADAR RAINFALL RECONSTRUCTION FOR JULY 8, 2001

Prepared for:

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1.0 Introduction

HDR Engineering Inc. was contracted by the Urban Drainage and Flood Control District (UDFCD) to produce a WSR-88D Doppler radar rainfall reconstruction for a precipitation event in and around the Denver, Colorado metropolitan area. The precipitation event was produced by strong and severe thunderstorm cells that moved through the area during the late afternoon of July 8, 2001. Numerous reports of severe weather, in the form of large hail 0.75" to 1.25" in diameter and straight-line winds of 60-65 MPH, were observed during the precipitation event. The winds knocked down trees and tree limbs throughout the Denver Metropolitan area and damaged exhibits at the Cherry Creek Arts Festival. The rainfall initiated flooding and flash flooding across portions of the Denver Metropolitan area resulting in standing water as deep as 5 feet, which led to the closure of portions of Interstates 25 and 225.

Doppler radar was used in the reconstruction process by relating radar reflectivity to rainfall. The radar rainfall estimation process will be discussed in detail, later in this report, along with factors that can have an effect on the relationship. HDR Doppler radar rainfall reconstructions incorporate a ground-truth process, which compares the HDR estimated rainfall depth and duration at a rain gage location, to observed rainfall depth and duration at that same location. Sixteen automated ALERT rain gages, owned and maintained by the UDFCD, were used in the ground truth process for this reconstruction. **Figure 1** depicts the location of the rain gauges within the established grid.

The rainfall reconstruction encompassed an area 10 miles by 12.5 miles, which is approximately 125 mi. The horizontal resolution of the grid cells within the grid covering this area (**Figure 2**) is approximately 0.6 miles by 0.6 miles.

The radar with the closest proximity to the grid is the Front Range, CO (FTG) Doppler radar, owned, maintained, and operated by the National Weather Service. The radar is located approximately 19 miles to the east of the reconstruction area. This is the radar that was utilized in the rainfall estimation process and was in VCP 11 mode for the entire event. In this mode the radar produces base reflectivity images every 5 minutes.

2.0 Use of radar to estimate rainfall

The utilization of radar to estimate rainfall has been in use for over 30 years by meteorologists in both the government and the private sector. In general, most current radar-derived rainfall techniques rely an assumed relationship between the strength of the radar reflectivity and the intensity of the rainfall rate. This relationship is described by the equation (1) below:

$$Z = A\,R^{b} \qquad (1)$$

where, Z is the radar reflectivity in dBZ, A is an empirically derived co-efficient related to the cloud physics of the storm cloud water droplets and b is another empirical co-efficient related to the type of storm cloud present. This relationship has proven to produce highly variable results. Since the values of both A and b are variables that must be assumed, opportunities for errors in the calculation are possible.

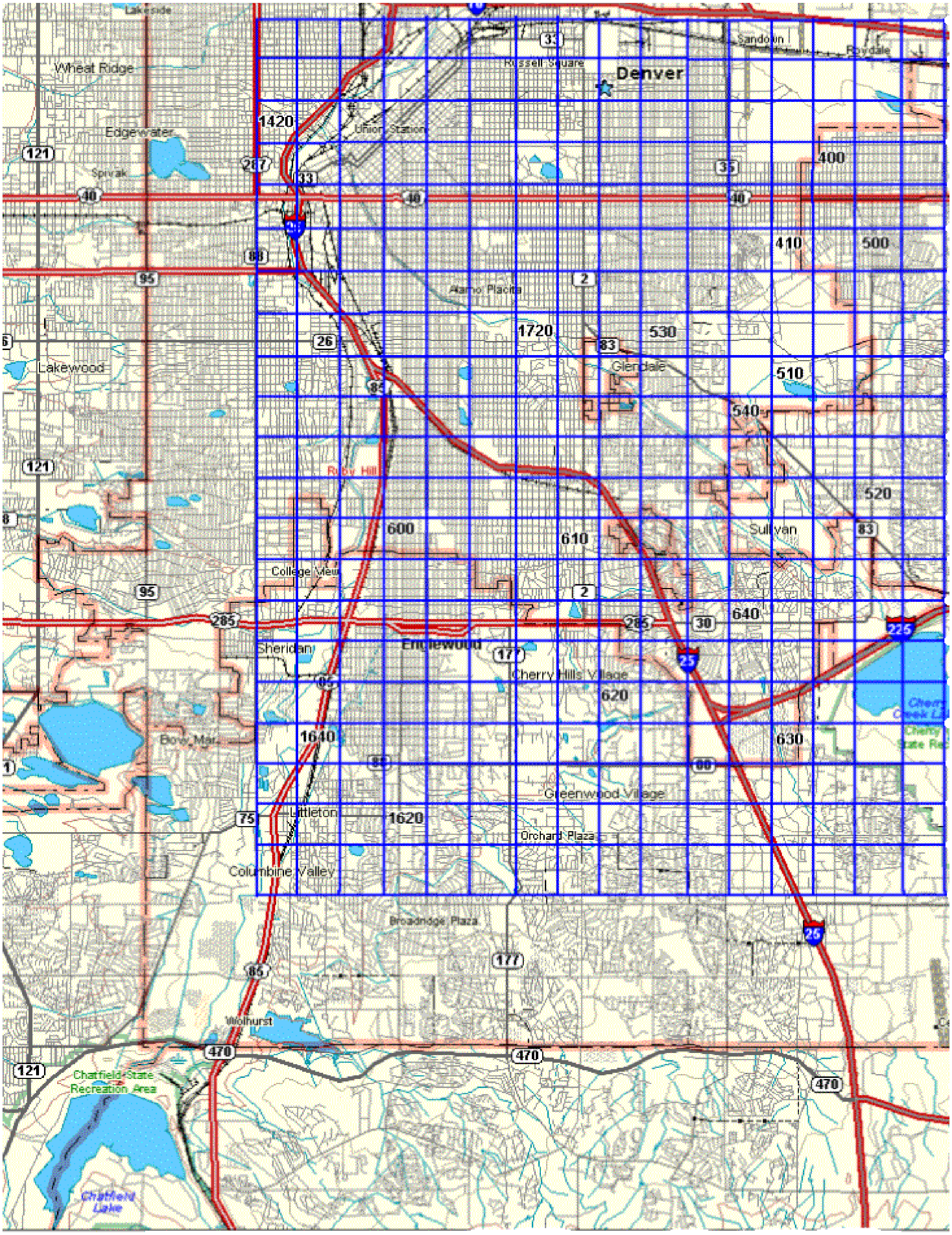

Figure 1. UDFCD ALERT rain gauge locations

The algorithms used to estimate the rainfall are standard for use around the country and have not proven to be responsive to local cloud variations. The r-squared or "goodness" of the rain to radar reflectivity statistical relationship has varied from 0.15 to 0.90 on a daily basis and for most storm seasons has been about 0.60. The good r's (values >0.75) have been for the low volume and low intensity rain events (stratiform rainfall), generally those of less than 0.25"/hr accumulation rates. The high intensity, high volume, thunderstorms (convective rainfall) have shown r-values of 0.15 to 0.45. Thus the standard products appear to be unreliable at this point. The storm rainfall has been both overestimated and underestimated for periods of less than three hours for storms within 25 miles of each other.

Finally, hail "contamination" of the equation has proven to be a troublesome problem to deal with as well. Since the strength of the radar signal is related objectively by the algorithm to the estimated rainfall, the strong radar return value of hailstones will usually cause an over-estimation of the rainfall.

HDR meteorologists use their own method to solve these problems related to rainfall over and under estimation. The HDR method uses the radar reflectivity to locate the portion of the precipitating cloud where the heaviest rainfall is located rather than to calculate a rainfall rate. In over 90 percent of the operational heavy rain days in the Urban Drainage & Flood Control District since 1985, HDR meteorologists have observed that the heaviest rainfall occurs when the strongest radar reflectivity field passes over the rain gauges. Given the validity of this assumption, the next step entails the calculation of the peak rainfall rate associated with the precipitating cloud, which in turn can be related to the strongest radar reflectivity values.

Since late 1981, HDR meteorologists have used a combination of surface weather station data and a 2-D cloud methodology to predict the peak rainfall rate associated with convective rainfall. HDR has found that the depth of a thunderstorm's updraft that is warmer than 0° Celsius is directly related to the rain-production potential of the cloud. When the warm depth of the updraft exceeds 1.5 km in Colorado, for instance, the rain-production potential of the cloud doubles. Equation (2-4) shows a simplified form of this relationship:

(2) Peak 60-minute rainfall = PWI X (Depth of updraft warm layer) X 2
1.5km

$$\text{(2) Peak 60-minute rainfall} = \text{PWI} \times \frac{\text{(Depth of updraft warm layer)}}{1.5\text{km}} \times 2$$

(3) Peak 30-minute rainfall = 0.70 X (Peak 60-min rain)

(4) Peak 10-minute rainfall = 0.60 X (Peak 30-min rain)

where the Precipitable Water Index (PWI) is a measure of the amount of water in the atmosphere from the surface to about 20,000 feet above the ground. A matrix of rainfall rates, which are derived from surface temperature and dew point fields are used to initialize the 2-D model output. For each set of surface temperature-dew point combinations, a unique radar-rainfall relationship is created for precipitation mapping. In effect the peak 60, 30, and 10-minute rainfall rates are related to the 50 dBZ or greater radar reflectivity values within the precipitating cloud. Lower rainfall rates are down-stepped to correspond with lower radar reflectivity values.

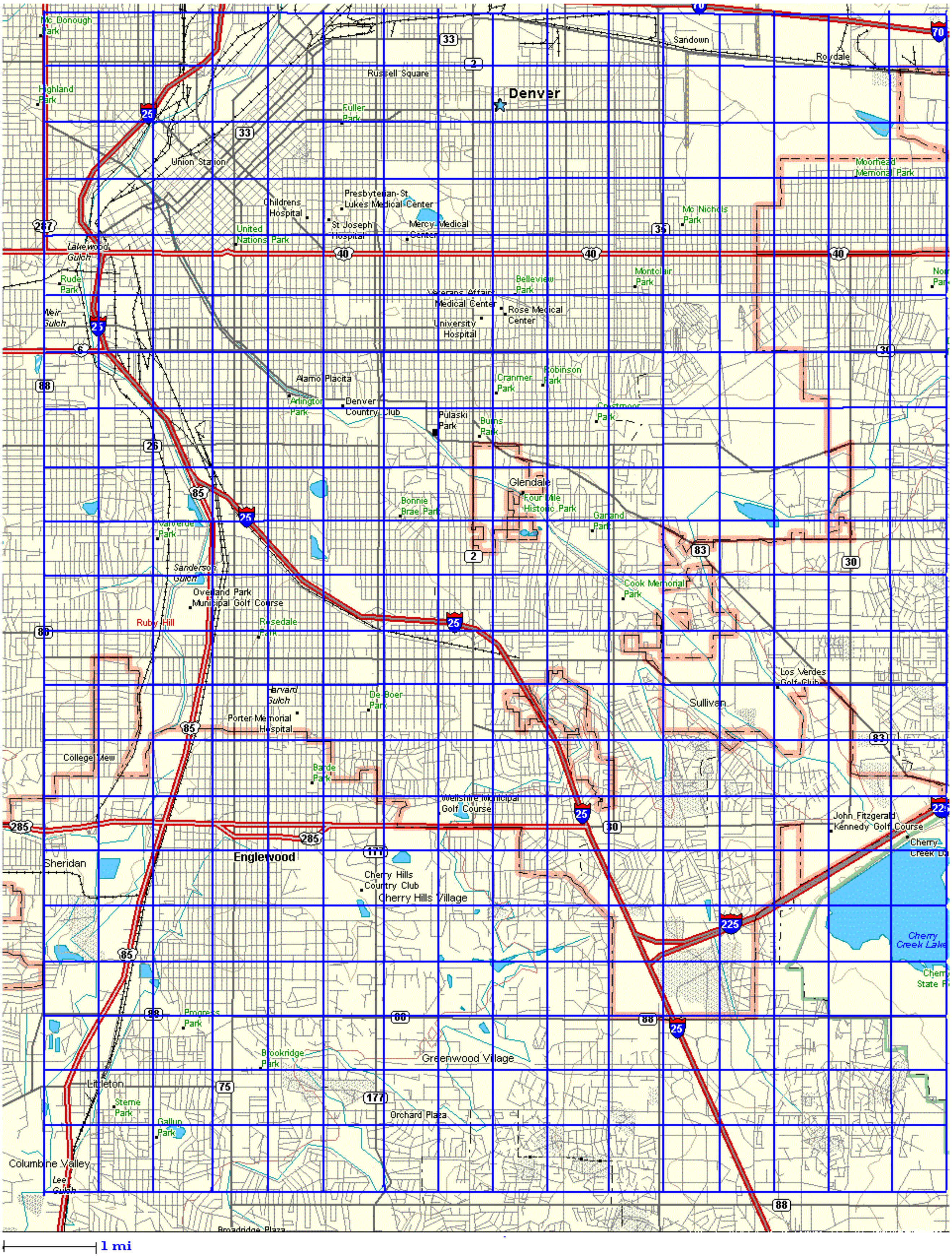

Figure 2. Rainfall estimate grid. Covers a 125 square mile area.

2.1 Event specific rainfall estimation methodology

UDFCD ALERT weather stations temperature/dew point values were used to initialize the HDR 2-D cloud model for the HDR rainfall estimation process. Four separate rainfall/radar reflectivity algorithms were derived for the precipitation event, which included a pre-storm (1), storm1 (2), Storm 2 (3), and post-storm (4) algorithm.

The temperature and dew point information was plotted on a Skew-T, Log P diagram, containing information derived from a radisonde, launched at Denver, Colorado around 0500 MDT July 8, 2001, to calculate the PWI. The calculated PWI was **1.24”** for algorithm 1, **1.25”** for algorithm 2, **1.25”** for algorithm 3, and **1.25”** for algorithm 4. The depth of the warm updraft layers were **1.8 km**, **2.2 km, 2.2 km,** and **1.8 km** respectively. The variables above were used to solve equation (2) and the result of equation (2) was used to solve equation (3).

The calculated values for PWI and the depth of the warm updraft layer were inserted into equations (2), resulting in peak 60-minute rainfall rates that were entered into equation (3) to derive the following peak 30-minute rainfall of **2.06”**, **2.57”, 2.57”** and **2.08”** respectively. The peak 30-minute rainfall rates were divided by 6; corresponding to a 5-minute peak rainfall for algorithms 1 and 2. The value **2.57”** (algorithm 3) was entered into equation (4) to derive the peak 10-minute rainfall of **1.54”**. The peak 10-minute rainfall was divided by 2, corresponding to a 5-minute peak rainfall for algorithm 3. Algorithm 3 was applied to portions of the grid where radar reflectivity identified the location of peak the rain core for a 10-minute time period supported by ALERT rain gages. The peak 60-minute rainfall rate of **2.98”** was used for algorithm 4 based on the fact that the lower levels of the atmosphere had stabilized to a point where new thunderstorm development was not occurring. Water already in the clouds continued to fall to ground however, for a period of 45-60min. The peak 60-minute rainfall rate was divided by 12; corresponding to a 5-minute peak rainfall. The peak 5-minute rainfall values for all the algorithms were assigned to the grid squares covered by radar reflectivity values of 50 dBz or greater. Lower rainfall rates were assigned to grid squares associated with lower reflectivity values and are shown in **Table 1**.

Radar dBz level	Estimated peak 5-min rainfall/dBz			
	Algorithm 1	Algorithm 2	Algorithm 3	Algorithm 4
25	0.06”	0.07”	0.13”	0.04”
30	0.08”	0.10”	0.19”	0.06”
35	0.12”	0.15”	0.26”	0.08”
40	0.17”	0.21”	0.38”	0.12”
45	0.24”	0.30”	0.54”	0.17”
50 or >	0.34”	0.43”	0.77”	0.25”

Table 1 Relationship between peak 5-minute rainfall rates and radar reflectivity values (dBz).

The radar reflectivity data field was navigated to their corresponding grid squares and assigned a reflectivity value of 0 through 11. **Table 2** shows the reflectivity values and their associated dBz values.

Radar reflectivity values (dBz)	Radar reflectivity levels
25	1
30	2
35	3
40	4
45	5
50	6
55	7
60	8
65	9
70	10
75	11

Table 2. Relationship between radar reflectivity values (dBz) and HDR derived radar reflectivity levels.

3.0 Ground-truth and error correction process

Most of the time there is a direct correlation between Doppler radar reflectivity and precipitation, however the correlation is not always good. High reflectivity values can be observed over a location while no precipitation is observed on the ground. This is due to the development phase of a thunderstorm. As the storm develops, moisture is drawn into the storm through the updraft causing water to be suspended in the cloud. The radar beam observes this suspended water; giving a false indication that precipitation is reaching the ground under the observed radar reflectivity. Over time the suspended water in the cloud will fall to the ground, which results in a good correlation between the Doppler radar reflectivity and observed precipitation.

For this event an estimated rain correction was applied to the rain gauge locations where reflectivity values equal to or greater than 25 dBz were observed over the grid cells where rain gauges were located but no precipitation was observed by the gauges. When this situation was observed, calculated rainfall rates were not substituted for observed reflectivity values within the grid cell. This correction was also applied to grid cells not containing rain gauges using a time/distance relationship.

The differences in ALERT rain gauge observed rainfall versus HDR estimated rainfall within corresponding grid cells for the event ranged from a **31%** over-estimation to **80%** over-estimation with an overall average over-estimation of **54%**. **Table 3** compares the HDR estimated rainfall amounts to the observed rainfall amounts at grid cells where the rain gauges are located. **Figure 3** depicts the locations of the rain gages within the grid along with the percent values of HDR estimated rainfall to observed rainfall. The rainfall over-estimation at the rain gauge locations can be attributed to the following factors outlined in a report authored by Dave Curtis, PhD and President of NEXRAIN Corporation, titled 'Inadvertent Rain Gauge Inconsistencies and Their Effect on Hydrologic Analysis'. The first factor involved rain gauge under-catchment errors resulting from thunderstorm-produced wind that accompanied the precipitation. It has been identified that rain gauges are subject to an under-catchment error of approximately 1% for every 1 mph of observed sustained wind at the gauge opening (Larson and Peck 1974). During this precipitation event straight line winds, gusting to as high as 62 MPH, were produced by the thunderstorm cells, and accompanied the rainfall. The second factor is rain gauge tip time.

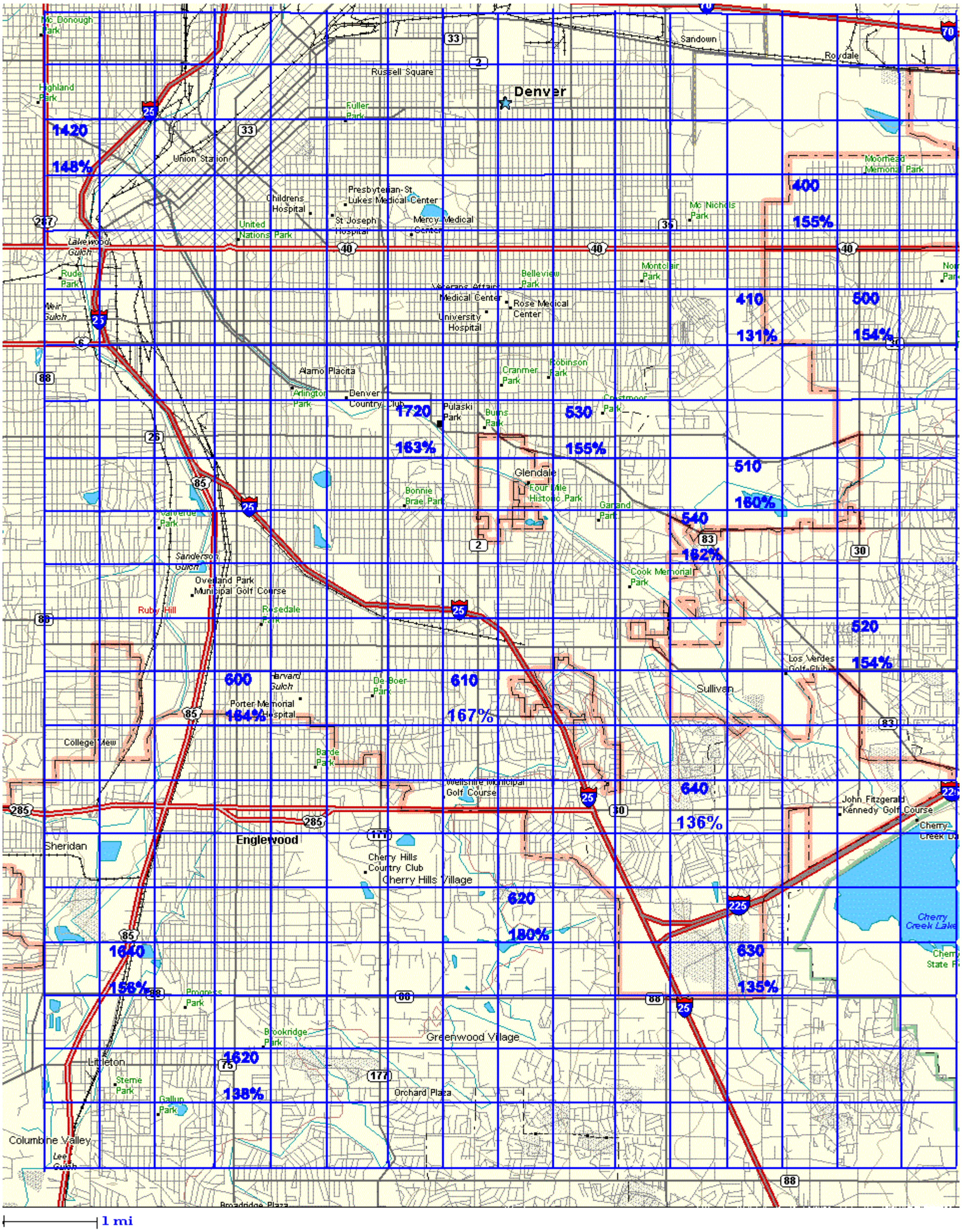

Figure 3. Rain gage locations and percent of estimated rainfall to observed rainfall for July 8, 2001.

GAUGE #	HDR ESTIMATED PPT (IN) Rest	OBSERVED PPT (IN) Rob	Rest/Rob (%)
400	0.56	0.36	155
410	0.68	0.52	131
500	0.74	0.48	154
510	1.39	0.87	160
520	2.25	1.46	154
530	1.52	0.98	155
540	1.85	1.14	162
600	2.13	1.30	164
610	4.08	2.44	167
620	1.98	1.10	180
630	2.56	1.89	135
640	3.04	2.24	136
1420	0.93	0.63	148
1620	1.35	0.98	138
1640	1.48	0.95	156
1720	2.31	1.42	163
AVG			154

Table 3. Comparison of estimated rainfall to observed rainfall.

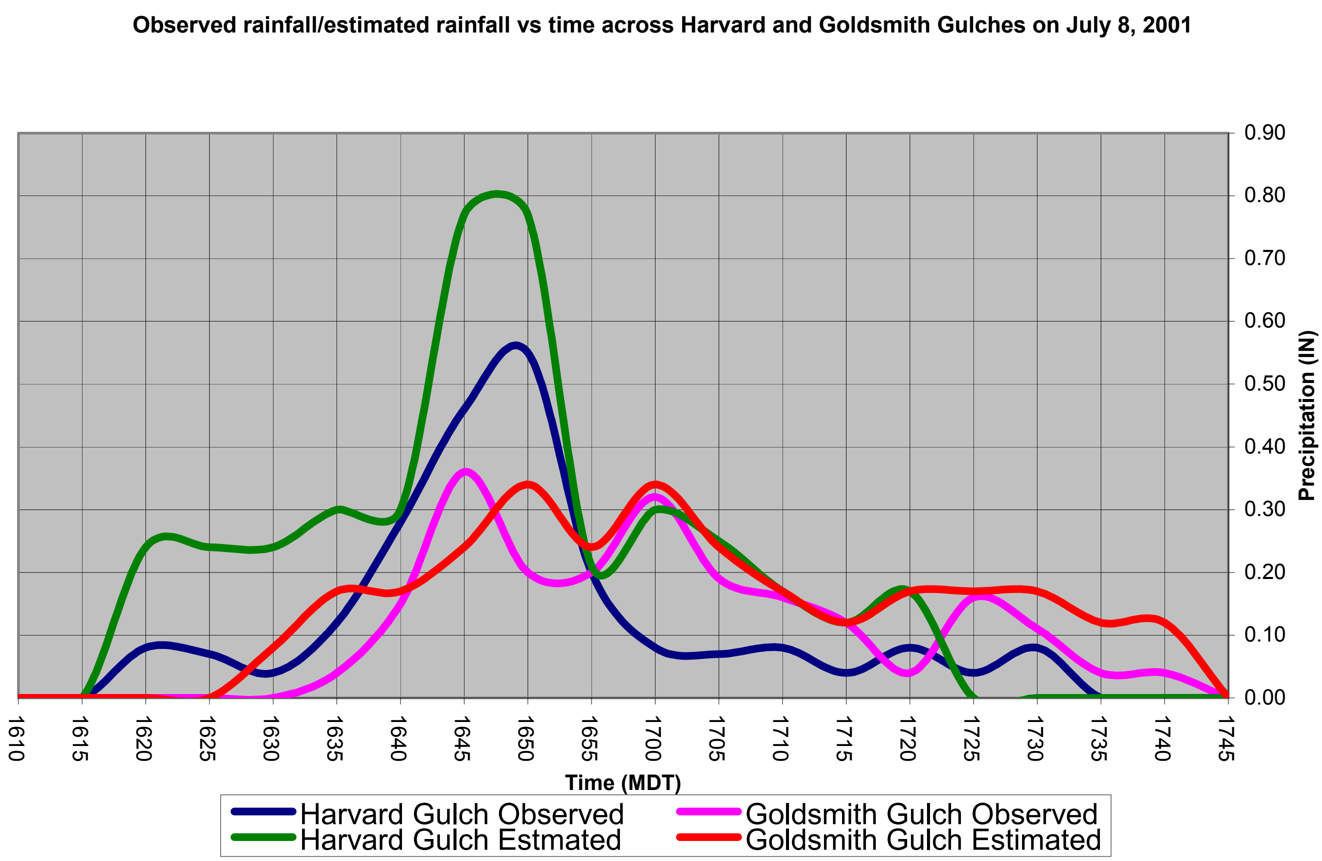

Figure 4: Estimated rainfall and observed rainfall at rain gage locations versus time across Harvard Gulch and Goldsmith Gulch basins.

Tipping bucket rain gauges do not record a small amount of rainfall during each tip of the bucket due to the travel time and tip time. With increased rainfall intensities comes an increase in volumetric loss of rainfall and hence a lower rainfall measurement by the rain gauge. When rainfall rates exceed 6.00"/hr, 1mm tipping buckets will under report rainfall on the order of 0-5% depending on how the gauge was calibrated (Curtis 1996). Rainfall rates as high as **7.68"/hr** were observed by rain gauge 610, located within the Harvard Gulch basin, during this precipitation event. **Figure 4** depicts a graph of the HDR estimated rainfall and observed rainfall at rain gage locations (gages # 610 & 640) versus time across Harvard Gulch and Goldsmith Gulch basins. A note of interest is the observed rainfall (blue line) across the Harvard Gulch basin (gage # 610) toward the end of the precipitation event while no rainfall is being estimated (green line). This may be attributed to hail, located in the rain gage, melting into the measuring container.

4.0 Radar estimated rainfall results

The precipitation event consisted of multiple east/northeast moving thunderstorm cells. An example of the thunderstorm cells can be found on **Figure 5**, which is a Front Range, Colorado (FTG) Doppler radar base reflectivity image for the time 442 MDT on July 8, 2001. The image depicts radar derived base reflectivity, which relates colors to reflectivity values. The reflectivity values are measured in dBz units, which are a direct measurement of radar energy that is reflected back to the radar. The more energy that is reflected back to the radar from a specific location, the higher the reflectivity value. Heavy rain and hail reflect more of the radar's energy than light precipitation, resulting in higher reflectivity values.

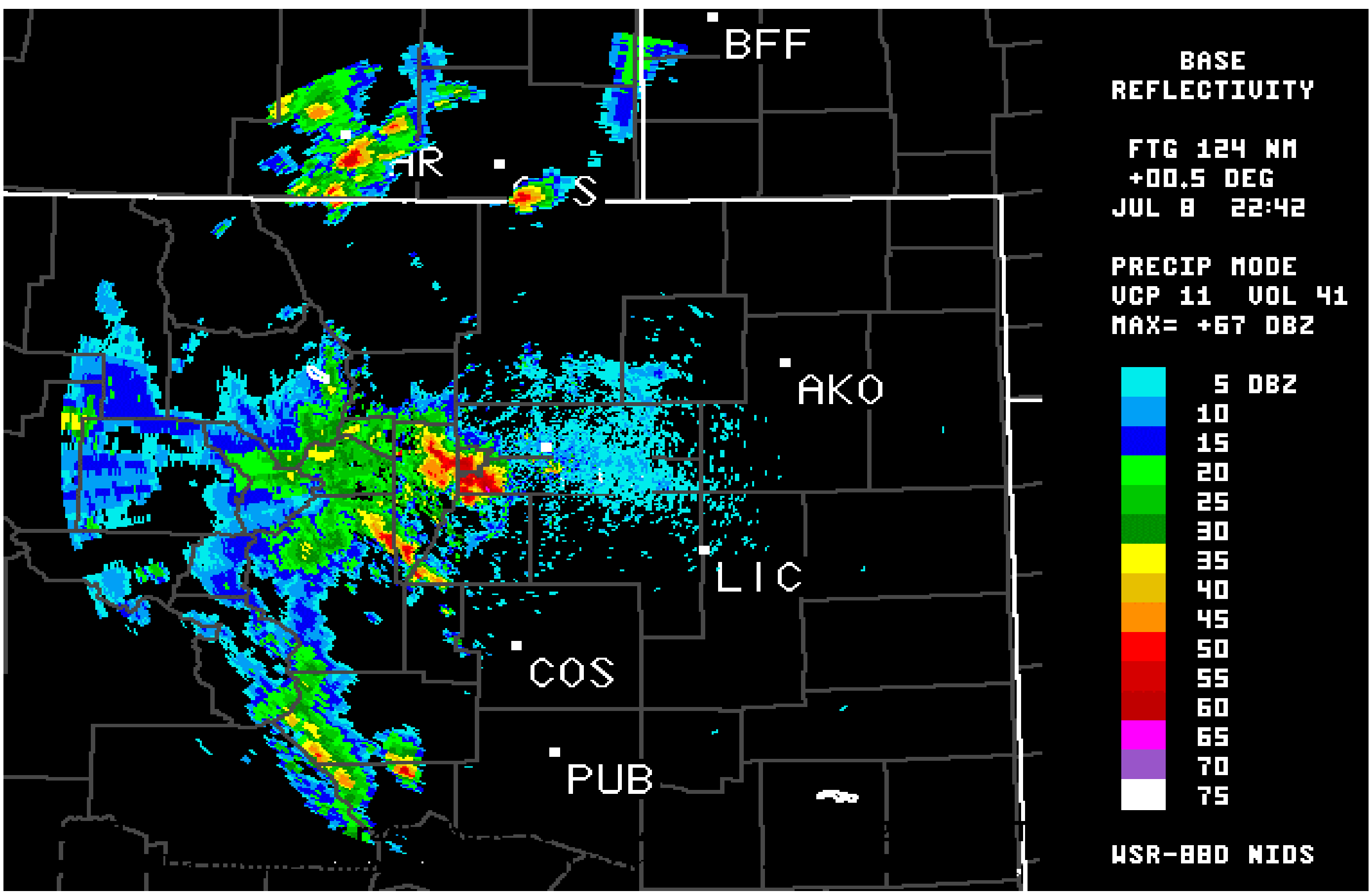

Figure 5: Front Range, CO. (FTG) Doppler radar base reflectivity image for the time 442 MDT on July 8, 2001.

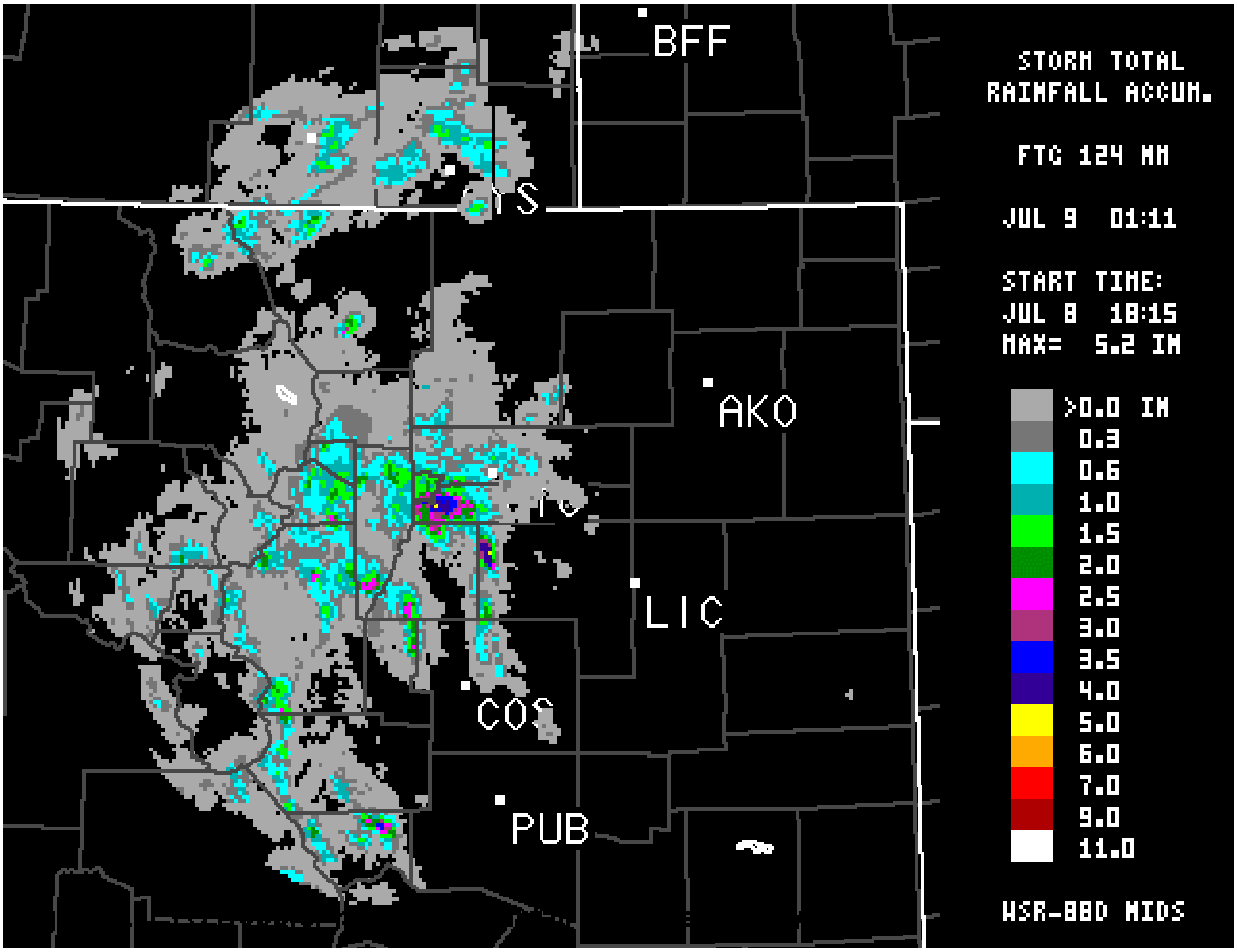

Figure 6: Front Range, CO (FTG) Doppler radar-rainfall estimate for the precipitation event on July 8, 2001.

Figure 6 depicts the FTG Doppler radar-rainfall estimate for the precipitation event of July 8, 2001. Estimates of up to **5.20"** of rainfall are depicted across southeast Denver and western Aurora. These estimates may be high due to the hail contamination error that was discussed in section 2.0. The HDR peak rainfall estimate across this area is **3.79"**, while the peak UDFCD ALERT rain gage observation is **1.89"**.

Figure 7 depicts a grid containing the HDR estimated rainfall for each grid cell for the rainfall event. The grid average HDR estimated rainfall for the event is **1.91**" with a peak grid cell (0.6 X 0.6 mi) rainfall of **4.10**", which fell in about a 70-minute period over the Harvard Gulch basin. **Figure 8** depicts an isohyetal analysis of the HDR estimated rainfall for the event and shows the highest amounts over the Goldsmith Gulch basin, Harvard Gulch basin, the upper portion of Cherry Creek basin and over Cherry Creek Reservoir**.**

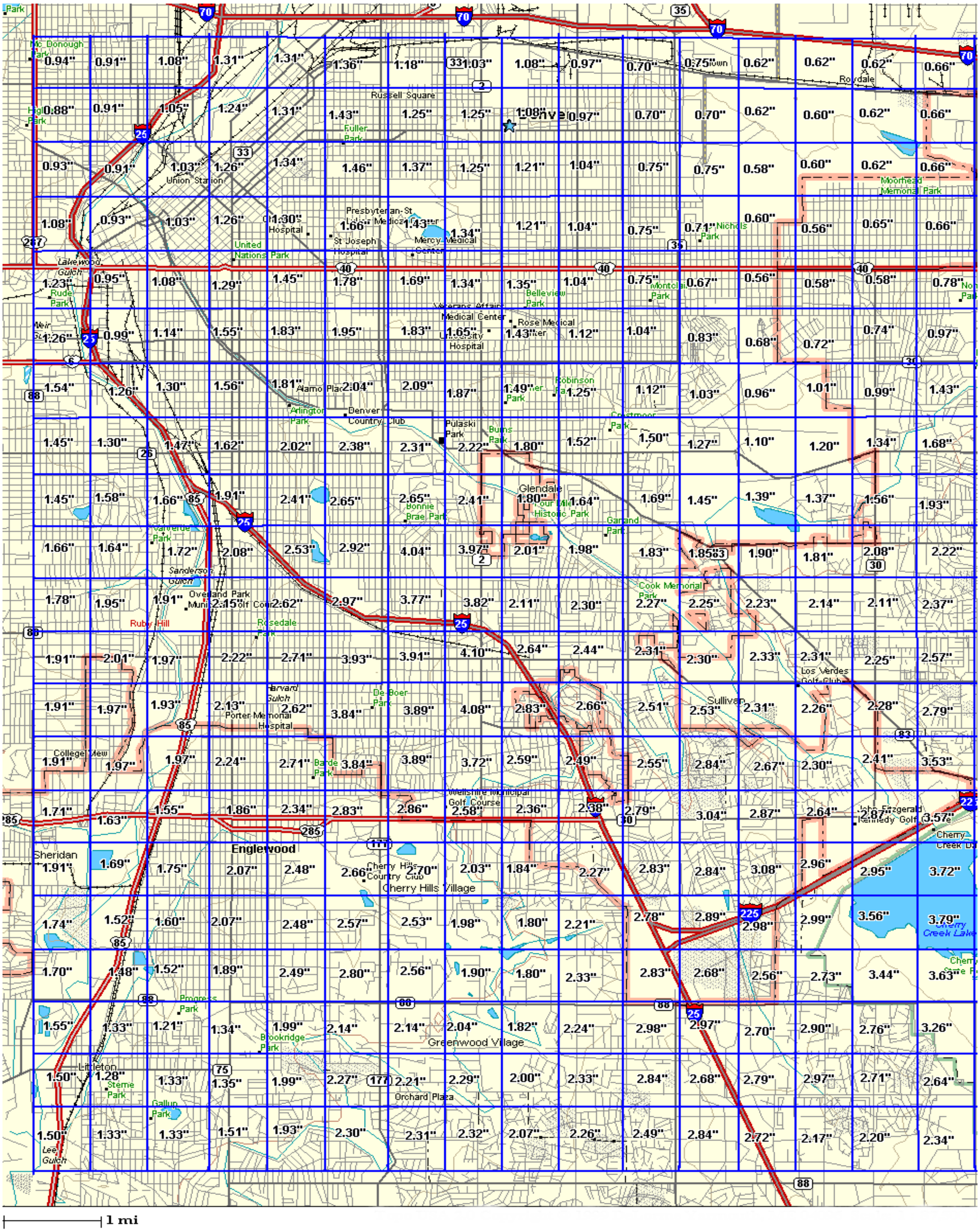

Figure 7. HDR estimated rainfall for July 8, 2001.

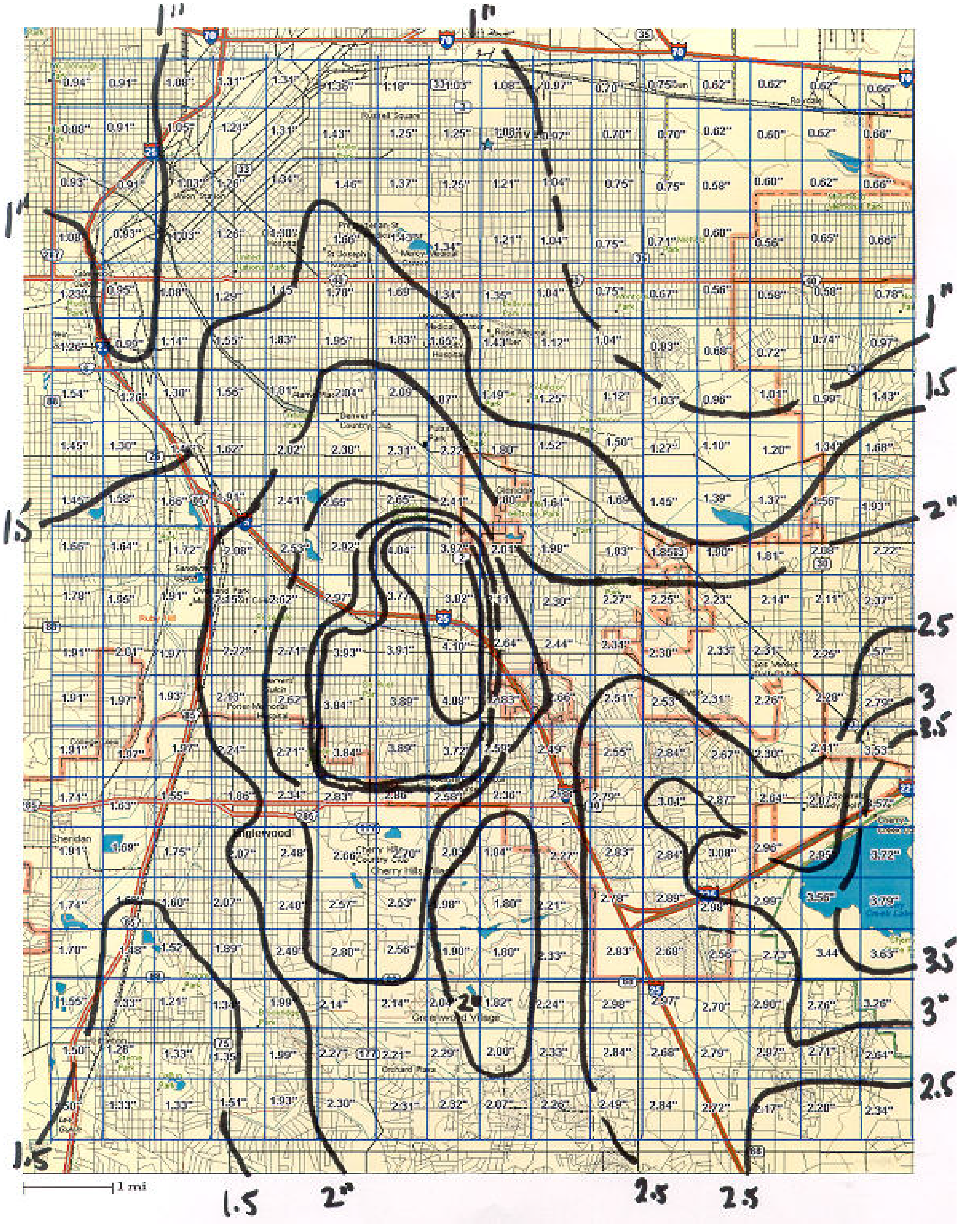

Figure 8: Isohyetal analysis of HDR estimated rainfall for July 8, 2001.

Figure 9 depicts the HDR estimated 5-minute rainfall versus time and **Figure 10** depicts estimated accumulated rainfall versus time. The graphed rainfall values are grid cell averages that are located within the three basins mentioned above.

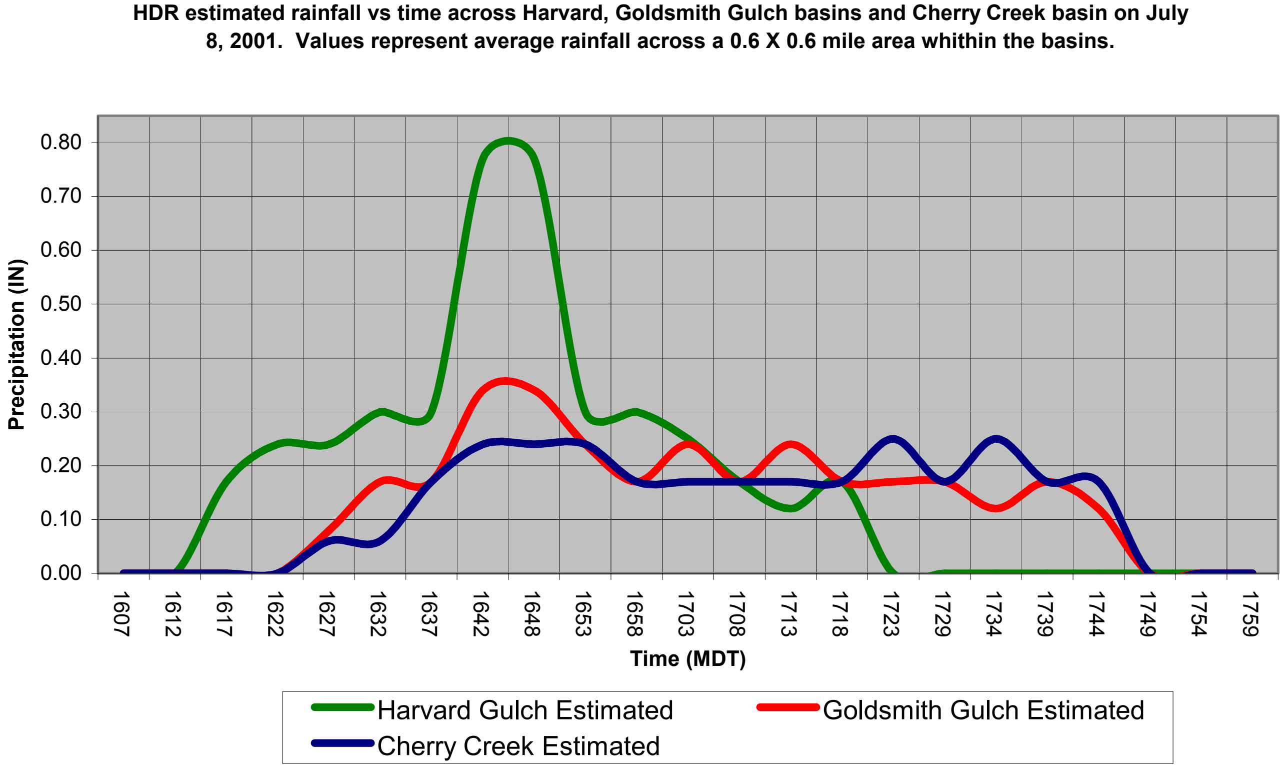

Figure 9: HDR estimated peak rainfall versus time

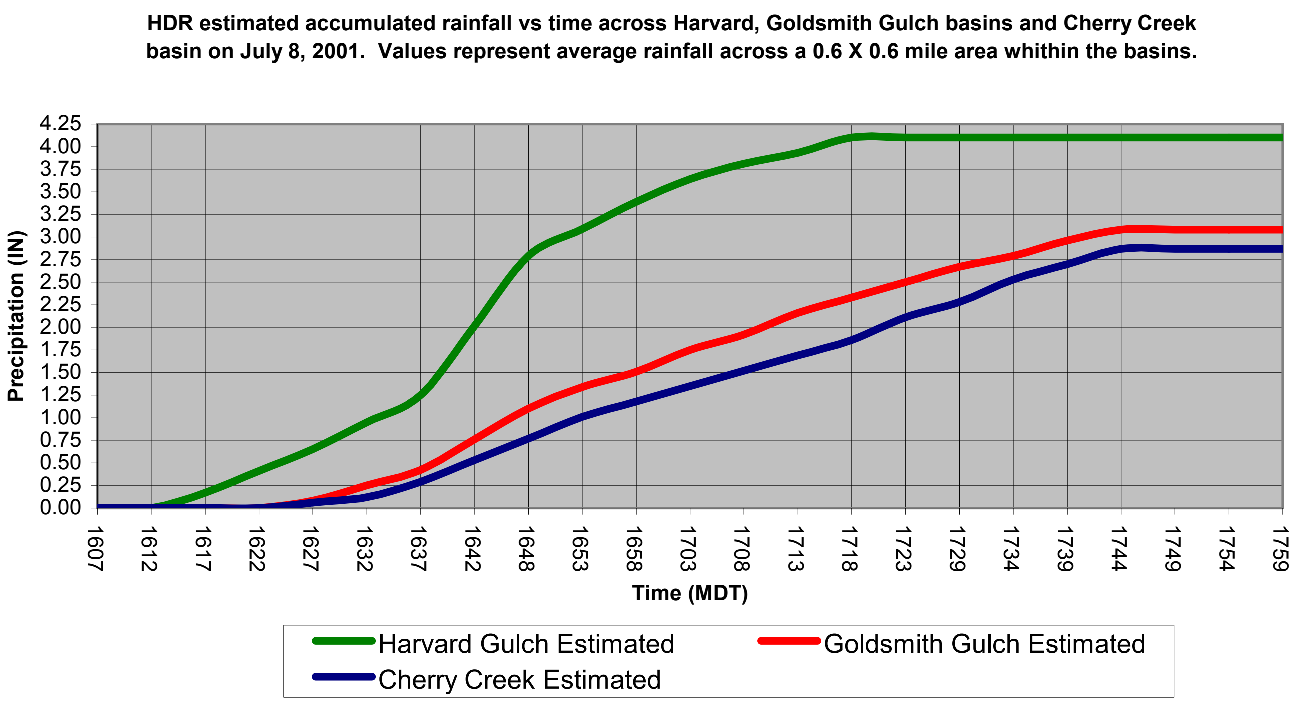

Figure 10: HDR estimated peak accumulated rainfall versus time

5.0 Conclusions

Multiple thunderstorms moved through the Denver, Colorado Metropolitan area during the late afternoon of July 8, 2001 producing very heavy rainfall and severe weather. Heavy rainfall initiated flooding and flash flooding across portions of the Denver Metropolitan area. Severe weather, in the form of straight-line winds greater than 55 MPH and hail 0.75” to 1.25” in diameter also accompanied the heavy rainfall.

HDR Engineering Inc. reconstructed the rainfall event using the Front Range, Colorado (FTG) Doppler radar, the UDFCD ALERT rain gauges and weather stations and the HDR 2-D cloud model. It is estimated that as much as **4.10”** of rainfall was observed across a 0.60 X 0.60 mi area over the Harvard Gulch basin. HDR estimated rainfall amounts of 2.75” of greater, were also observed over portions of the Goldsmith Gulch basin, in and around Cherry Creek Reservoir and the upper portion of the Cherry Creek basin.