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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 that occurred within the West Cherry Creek, East Cherry Creek and the upper portions of the Cherry Creek drainage basins in Douglas County, Colorado. The precipitation event was produced by thunderstorms that began late at night on August 26, 2002 and continued into the early morning hours of August 27, 2002. The rainfall from these thunderstorms initiated heavy flows within the Cherry Creek drainage basin. The Castle Oaks Road Stream gage (# 2830 on Figure 2), owned and maintained by the UDFCD, indicated that the height of the water on Cherry Creek at Castle Oaks Road went from 1.18 feet at 313 am to 7.24 feet at 425 am (Figure 1) on the morning of August 27, 2002 which can be attributed to the heavy rainfall that was observed upstream of the gage.

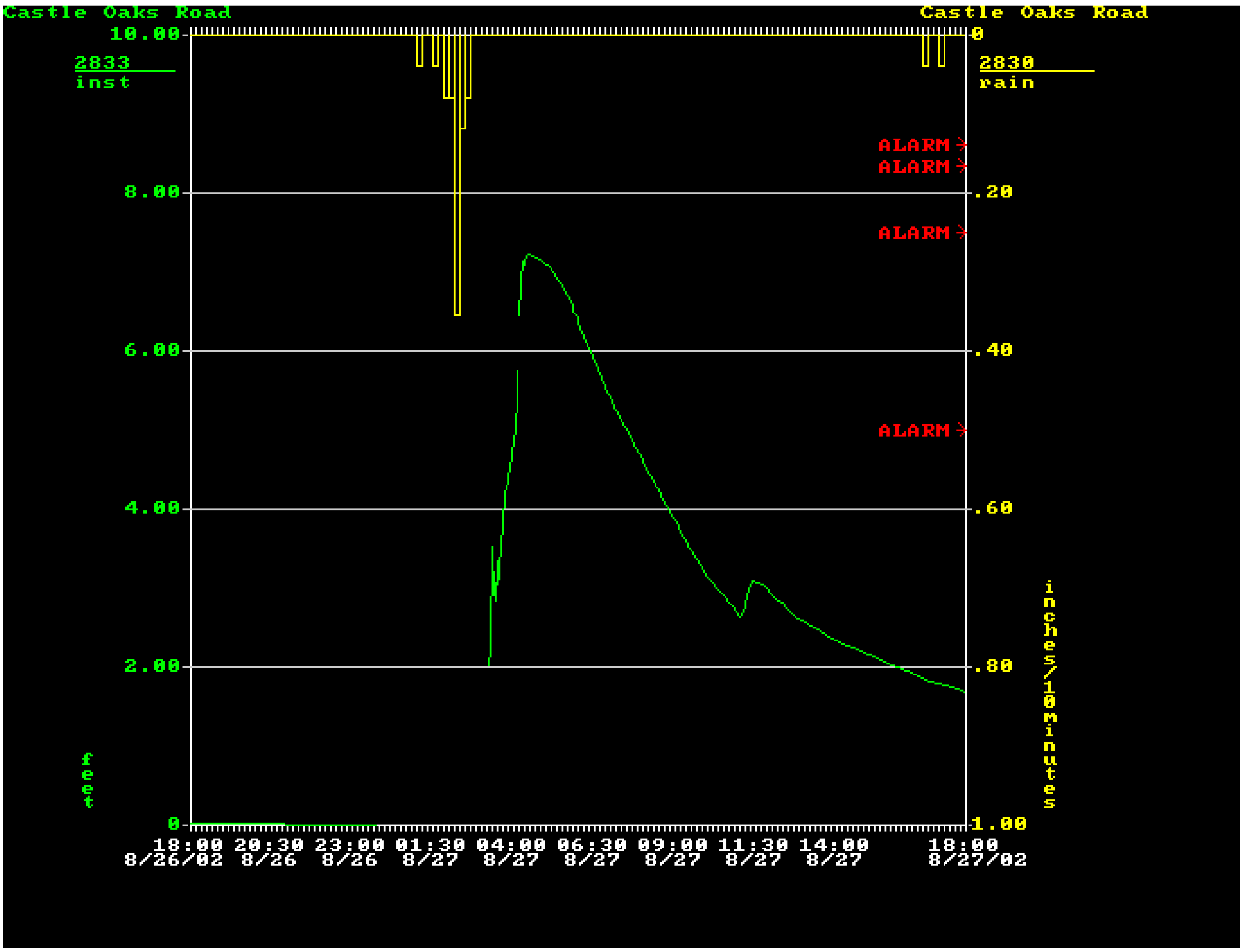

Figure 1. Observed rainfall and water height on Cherry Creek by UDFCD ALERT gage # 2830 located on Castle Oaks Road and Cherry Creek.

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. **Figure 2** depicts the location and names of the rain gages and the stream gage utilized in the ground truth process. Two ALERT rain gages (blue in color, #2750 and #2830), one ALERT stream gage (blue in color, #2830), owned and maintained by the UDFCD, and three co-operative rainfall observers (red in color, DG9, DG4, and EL5) that are part of the Community Collaborative Rain and Hail Study (CoCoRaHS) were used in the ground truth process for the reconstruction. **Figure 3** depicts the areal outline of the rainfall reconstruction, which covers the West Cherry Creek, East Cherry Creek and the upper portion of the Cherry Creek drainage basins.

GIS based (Shapefile) composite Doppler radar reflectivity images produced by Meteorlogix Inc. were used in the reconstruction process. The composite images contain combined base reflectivity level (dBz) information from the Front Range, CO (FTG) Doppler radar, located approximately 26 miles to the north-northeast of the reconstruction area and the Pueblo, CO (PUX) Doppler radar located approximately 90 miles to the south-southeast of the reconstruction area. The horizontal resolution of the radar reflectivity information over the reconstruction area is approximately 0.6 miles by 0.6 miles and the radar reflectivity information is available every five minutes.

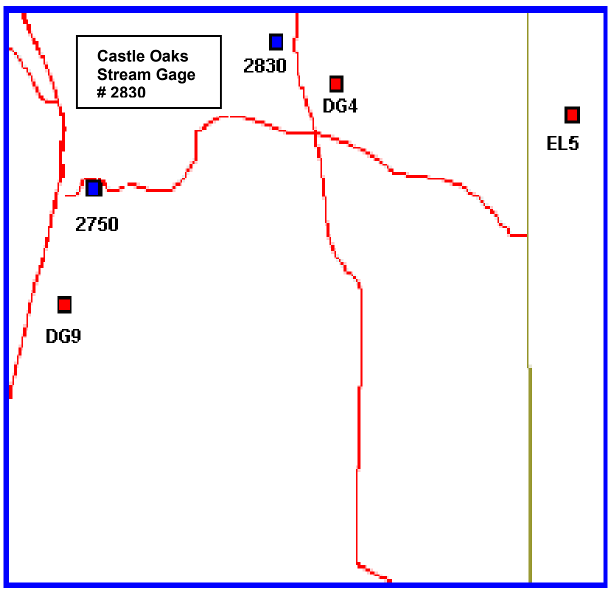

Figure 2. Rain Gage locations used in the rainfall reconstruction process.

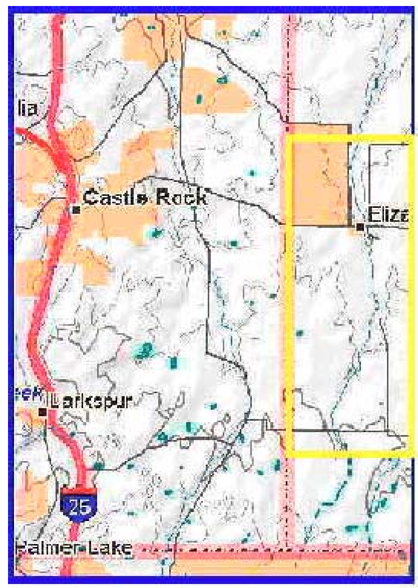

Figure 3. Rainfall reconstruction area outline and “hail area” (yellow rectangle) outline.

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:

(1) $$Z = A\ R^b$$

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.

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 gages. 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:

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

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

(4) Peak 15-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 values 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.

2.1 Event specific rainfall estimation methodology

ESRI's ArcView was used to determine the radar reflectivity levels, using the (Shapefile) composite Doppler radar reflectivity images, at intervals of five minutes, for the duration of the reconstruction process. The radar reflectivity level determination process was completed for a period from 2300 MDT August 26, 2002 through 0330 MDT August 27, 2002.

UDFCD ALERT weather stations temperature and temperature dew point values were taken from the Castle Rock, Elbert and Parker stations and were used to initialize the HDR 2-D cloud model to produce the radar-rainfall algorithm. Representative temperature and dew point values, from the weather stations above, were plotted on a Skew-T, Log P diagram, containing information derived from radisondes, launched at Denver, Colorado around 1700 MDT August 26, 2002 and around 0500 MDT August 27, 2002, to calculate the PWI. The calculated PWI was 0.95" and the depth of the warm updraft layer was 2.4 km. The calculated value for PWI and the depth of the warm updraft layer were inserted into equations (2), resulting in a peak 60-minute rainfall value that was entered into equation (3) to derive the following peak 30-minute rainfall value of 2.13". The peak 5-minute rainfall value of 0.36" was determined by dividing the peak 30-minute rainfall, 2.13", by 6.

Radar dBz level	Rainfall Value/5min
25	0.06"
30	0.09"
35	0.13"
40	0.18"
45	0.25"
50 or >	0.36"

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

Using ESRI's ArcView the peak 5-minute rainfall value was assigned to geographic areas covered by radar reflectivity levels of 50 dBz or greater. Lower rainfall values were assigned to lower reflectivity levels as depicted in **Table 1**. The peak 30-minute rainfall value was used within this reconstruction based on the fact that the individual thunderstorm cells produced rainfall that had point durations of around 30 minutes.

3.0 Ground-truth and error correction process

A correlation between radar reflectivity and precipitation exists, however, that 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 thunderstorm develops, moisture is drawn into the cloud 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 radar reflectivity and observed precipitation.

For this event an estimated rain correction was applied to the geographic area corresponding to the UDFCD ALERT rain gage locations where reflectivity levels are equal to or greater than 25 dBz were observed but no precipitation was observed by the gages. When this situation was observed, calculated rainfall values were not substituted for observed reflectivity levels. This correction was also applied to the whole reconstruction area, using ESRI's Arcview Spatial Analyst.

It was determined through observations taken by CoCoRaHS observers and observations in the National Climatic Center's Storm Data database and the presence of radar reflectivity values of 55 dBz and greater (indication of hail within the cloud as depicted by the radar beam) that hail ranging in size from pea size to 1.00" in diameter was observed across portions of the reconstruction area along with the rain. It was also determined that hail lasted as long as twenty-five minutes across portions of the reconstruction area. An area (depicted in Figure 3 by the yellow rectangle) bounded by State Road 154 to the north, the Douglas/Elbert County line to the west, State Road 96 to the south, and State Road 25-41 to the east recived the largest size hail that lasted from ten to twenty-five minutes. A rain gage owned and maintained by UDFCD (#1440) located in southwest Elbert County, is located in the area described above. Gage 1440 was located within the "hail area" and there was an observance of high radar reflectivity levels of 55 dBz and greater over the gage location. By contrast there was only an observation of 0.28" of rainfall by the gage. The assumption was made that hail accumulated on top of the gage opening, precluding it from measuring all the rainfall that fell at the gage site. Therefore gage # 1140 was not utilized in the ground truth process due to the very poor correlation between the observed radar reflectivity over the gage and the observed rainfall by the gage.

The differences in HDR estimated rainfall (R_{est}) versus rain gage observed rainfall (R_{ob}) for the event ranged from a **1%** under-estimation to a **53%** over-estimation with an overall average over-estimation of **21%**. **Table 2** compares the HDR estimated rainfall amounts to the observed rainfall amounts at the rain gage locations. The rainfall over-estimation at the rain gage locations may be attributed to some or all of the following factors outlined in a report authored by Dave Curtis, PhD and Co-owner of One Rain Corporation, titled 'Inadvertent Rain Gage Inconsistencies and Their Effect on Hydrologic Analysis'. The first factor involves rain gage under-catchment errors resulting from thunderstorm-produced wind that accompanied the precipitation. It has been identified that rain gages are subject to an under-catchment error of approximately 1% for every 1 mph of observed sustained wind at the gage opening (Larson and Peck 1974). During this precipitation event surface winds produced by the thunderstorms averaged around 16 MPH across the reconstruction area.

RAIN GAGE	**HDR ESTIMATED PPT (IN) R_{est}**	**OBSERVED PPT (IN) R_{ob}**	**R_{est}/R_{ob} (%)**
# 2830 - Castle Oaks (UDFCD)	**0.93"**	**0.78"**	**119**
# 2750 - Castle Rock (UDFCD)	**0.67"**	**0.44"**	**153**
DG9 - Castle Rock (CoCoRaHS)	**0.81"**	**0.75"**	**108**
DG4 - Franktown (CoCoRaHS)	**2.00"**	**2.02"**	**99**
EL5 - Elizabeth (CoCoRaHS)	**1.70"**	**1.32"**	**129**
Average			**122**

Table 2. Comparison of estimated rainfall to observed rainfall.

A second factor is rain gage under-catchment with height. It has been demonstrated that elevated rain gages catch less rainfall than gages located at ground level due to turbulent airflow above the ground. This demonstration showed that a rain gage located 30 feet above the ground observed just 80% of the rainfall observed in a ground level rain gage. Similarly a rain gage located 150 feet above the ground observed just 50% of the rainfall observed in a ground level gage (Frisinger 1971).

The relatively large rainfall over-estimation at the Castle Rock rain gage (#2750) may be attributed to the fact that the rain gage is located at a higher elevation (a butte located just north of the town of Castle Rock at an elevation of 6560 feet), than the surrounding area. This elevation difference of approximately 250 feet may have caused the observed rainfall to be less than what would have been observed if that gage was in the same location but at ground level.

The small rainfall under-estimation at the Franktown rain gage (DG4) may be attributed to melting hail that was measured (observation was taken at 0900 MDT August 27, 2002) in the rain gage after the time period that this rainfall reconstruction covered which ended at 0330 MDT August 27, 2002.

4.0 Radar estimated rainfall results

The precipitation event consisted of multiple east/northeast moving thunderstorm cells that were initiated by a series of gravity waves, and an intrusion of a moist air mass that originated in northeast Colorado from a thunderstorm complex. A depiction of the thunderstorm cells can be found on **Figure 4**, which is a Pueblo, Colorado (PUX) Doppler radar base reflectivity image for the time 0123 MDT on August 27, 2002. The image depicts radar derived base reflectivity, which relates colors to reflectivity levels. The reflectivity levels 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 level. Heavy rain and hail reflect more of the radar's energy than light precipitation, resulting in higher reflectivity levels.

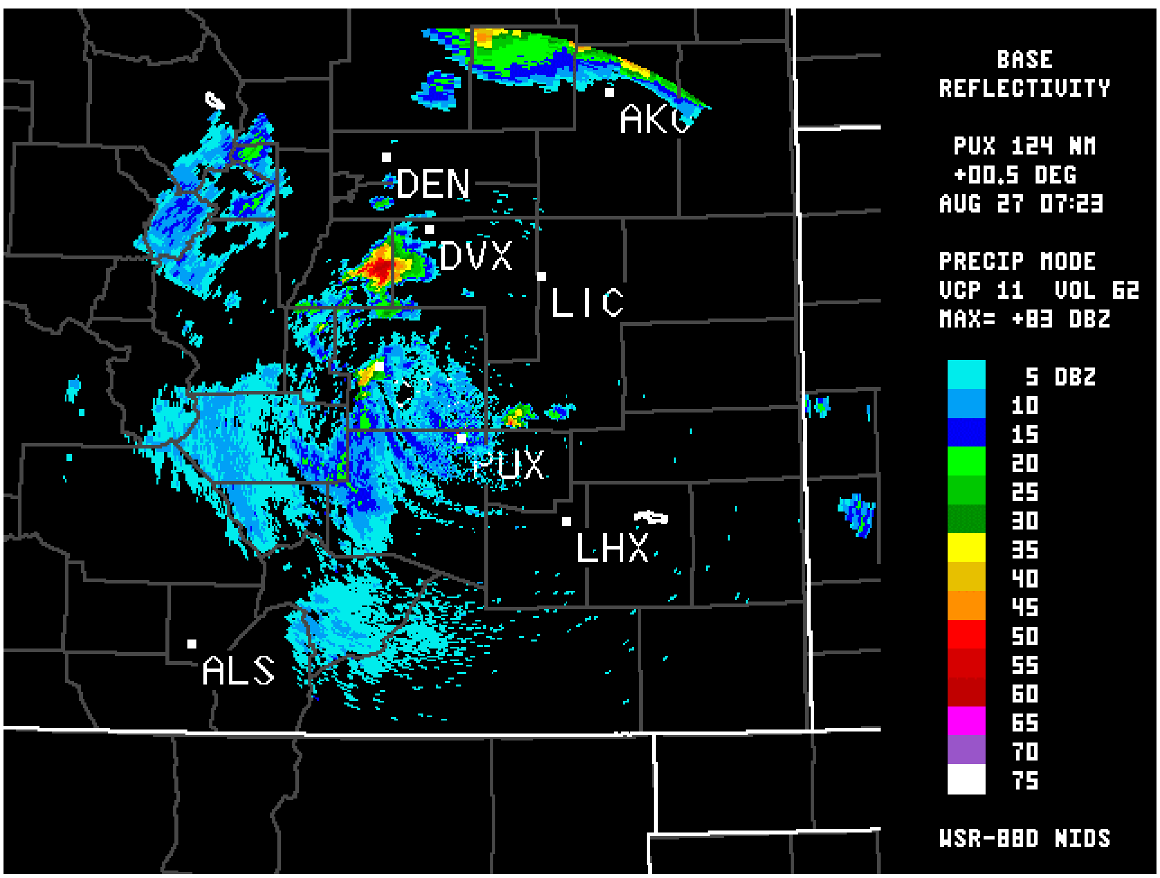

Figure 4: Pueblo, CO. (PUX) Doppler radar base reflectivity image for the time 0123 MDT on August 27, 2002.

An image containing the gridded HDR estimated rainfall is depicted in **Figure 5**. **Figure 6** depicts the HDR estimated rainfall, color-coded with respect to rainfall depths. The round circles on the **Figures 5 and 6** depict the locations of the rain gages used in the ground truth process. Also contained on the figures are the West Cherry Creek, East Cherry Creek and Cherry Creek drainage basins. Larger versions of these figures can be found in the Appendix accompanying this report.

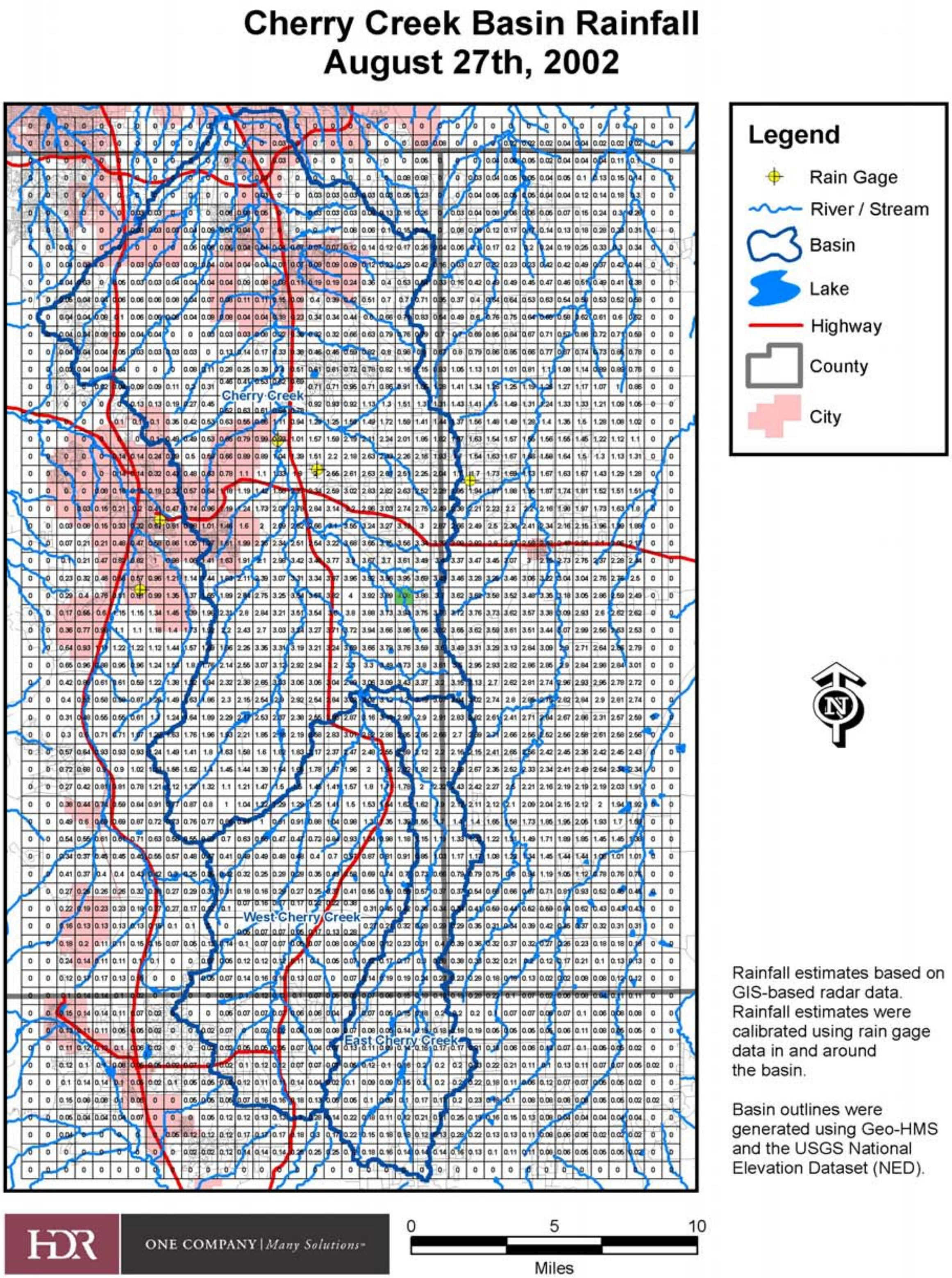

Figure 5. HDR gridded estimated rainfall for August 26-27, 2002. A larger version of this image can be found in the appendix.

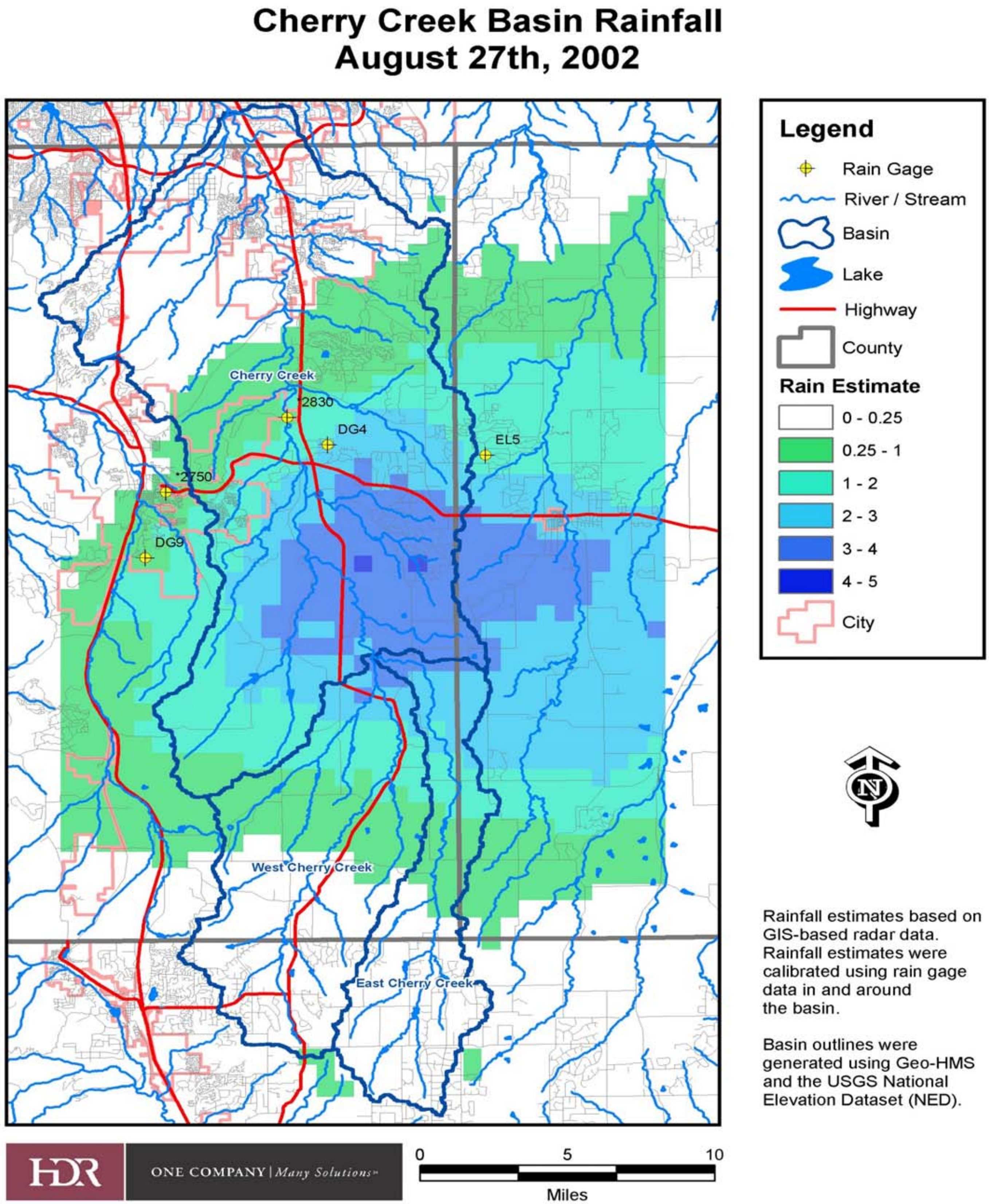

Figure 6. HDR estimated rainfall for August 26-27, 2002; color-coded. A larger version of this image can be found in the appendix.

The total average estimated rainfall within the West Cherry Creek Drainage Basin was 0.60” with a maximum amount of 3.18”, 0.77” within the East Cherry Creek Drainage Basin with a maximum amount of 3.20” and 1.34” within the Cherry Creek basin with a maximum amount of 4.08”. The peak estimated rainfall amount within the reconstruction area across a 0.60 X 0.60 mi area (grid cell) was determined to be 4.08”, which accumulated in about a 3-hour period within the upper portion of the Cherry Creek basin. This area is depicted by the color green in **Figure 5**. **Figure 7** shows the depth and duration of this peak estimated rainfall amount. A larger version of this graph can be found in the Appendix.

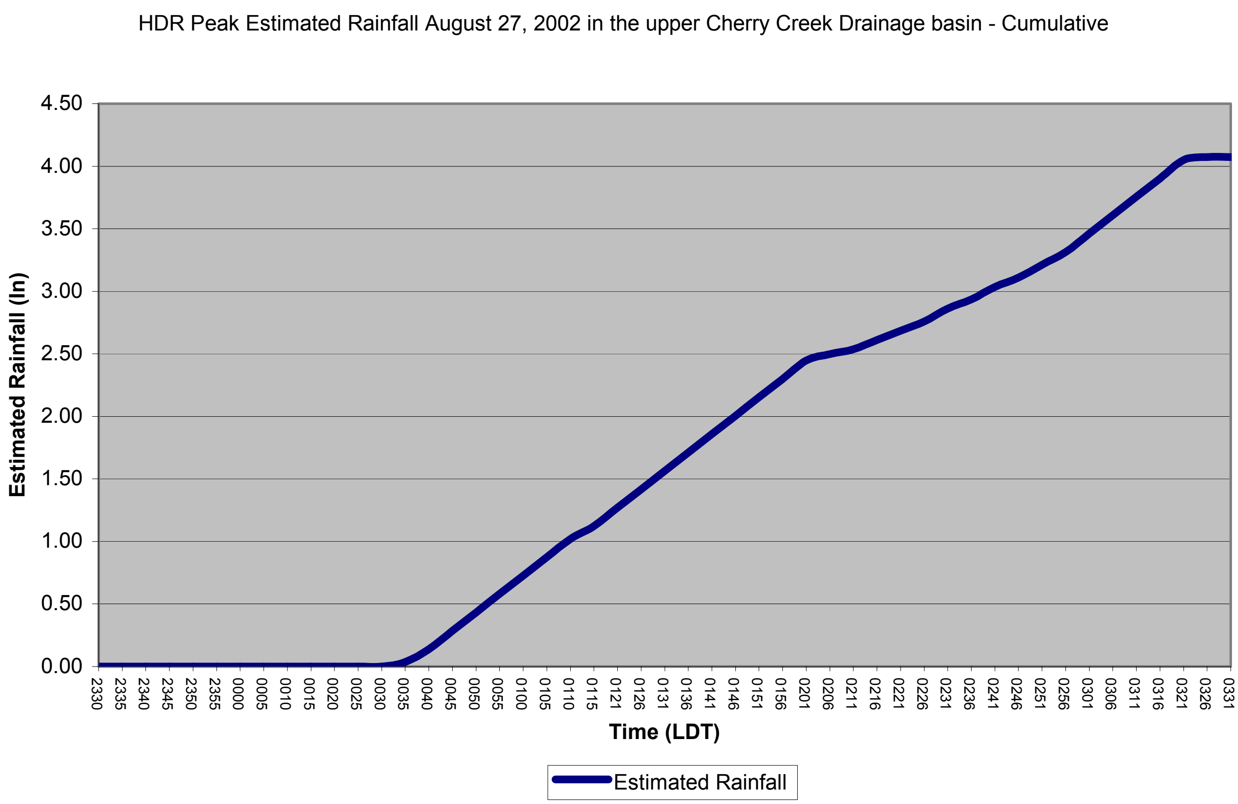

Figure 7. HDR peak estimated rainfall amount; accumulated depth vs. time.

5.0 Conclusions

Strong thunderstorms erupted during the evening hours of August 26, 2002 over eastern plains of Colorado. Cool and moist air initiated from these thunderstorms moved towards the southwest and increased the surface dew points temperatures in eastern Douglas County from the mid 20’s around 2100 MDT to the lower 50’s around 2200 MDT.

The constant thunderstorm development over the eastern Colorado plains created a series of gravity waves that propagated towards the southwest, moving over the elevated terrain of Douglas County. The upward vertical motion produced by these gravity waves and the elevated terrain allowed the moist air in the lower levels of the atmosphere to overcome a layer of stable air located at the middle levels of the atmosphere. The result was the development of slow moving heavy rain and hail producing thunderstorms that developed around 2330 MDT. Rainfall from the thunderstorms initiated heavy flows within the upper portions of the Cherry Creek drainage basin and the West and East Cherry Creek drainage basins. Evidence of this heavy rainfall and heavy flows are observations at a stream gage located on Cherry Creek at Castle Oaks Road. The stream gage (co-located with UDFCD ALERT rain gage #2830) measured a water depth of 1.8 feet at 0313 MDT and then measured a maximum depth of 7.24 feet at 0425 MDT August 27, 2002; a rise of 5.44 feet in 72 minutes.

HDR Engineering Inc. reconstructed the rainfall event using Doppler radar, rain gage observations, weather station observations and the HDR 2-D cloud model. It is estimated that as much as 4.08” of rainfall was observed, in about a 3-hour time period, across a 0.60 X 0.60 mi area (grid cell) over the reconstruction area. Average estimated rainfall amounts included 1.34”, 0.77”, and 0.60” within the Cherry Creek, East Cherry Creek and West Cherry Creek drainage basins respectively.