4.1 ASSESSING GAUGE ADJUSTED RADAR RAINFALL ESTIMATION FOR USE IN LOCAL FLASH FLOOD PREDICTION

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1. Introduction

The Urban Drainage and Flood Control District (UDFCD) operates a Flash Flood Prediction (FFP) Program, to forecast rainfall events up to 24 hours in advance within the Denver Metropolitan Area (Figure 1). Program meteorologists from the private sector communicate directly with local governments to prepare for and assess flash flood threats. Spatially comprehensive rainfall estimates that are both timely and accurate are critical in this mission.

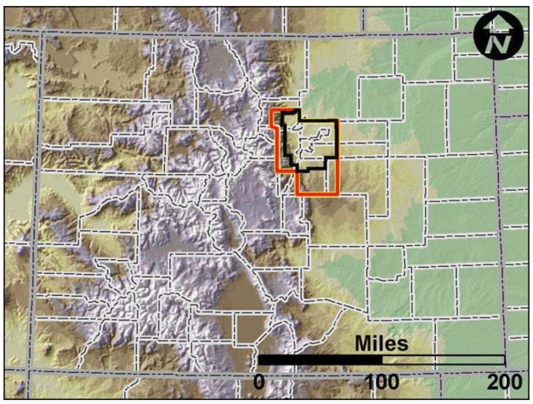

Figure 1. Location of Urban Drainage Flood Control District (Black outline) and Forecast Zone (Red outline).

As part of the FFP program, UDFCD maintains an ALERT gauging network, for real-time monitoring of rainfall. Weather Decision Technologies (WDT) Inc. provides UDFCD with rainfall estimates in real-time that are automatically derived from NEXRAD Level II mosaicked radar data. The WDT rainfall estimates are derived on a CONUS scale, 'clipped' and then adjusted using the ALERT rain gauge data (Figure 2).

The WDT rainfall data are provided in Geographic Information System (GIS) format on a high-resolution 1 km grid. Traditionally, meteorologists for UDFCD have used, coarser resolution, NWS single site radar data in conjunction with their point ALERT data to estimate basin rainfall and communicate the potential flash flood threat with local agencies.

During the 2007 program, WDT integrated the ALERT rain gauge data into their high resolution gridded radar rainfall mosaics, updated every 15 minutes. WDT provided both the radar-only Quantitative Precipitation Estimates (QPE) using multiple radars and the gauge-adjusted QPE products (QPE_GC) at 1 km resolution in real-time.

Significant rainfall events were archived over the 2007 season. Observations of 24-hour rainfall from the Community Collaborative Rain Hail and Snow (CoCoRaHS) database provided a dense network of independent rain gauge data to perform statistical assessment of gauge adjusted QPE products on a daily basis. The National Weather Service 24-hour precipitation analysis is used as a baseline comparison to measure the performance of the WDT QPE against.

This paper will discuss the gauge-adjusted radar QPE techniques, the integration of QPE products in local flash flood prediction processes and verification of the rainfall estimates for cases from the 2007 season.

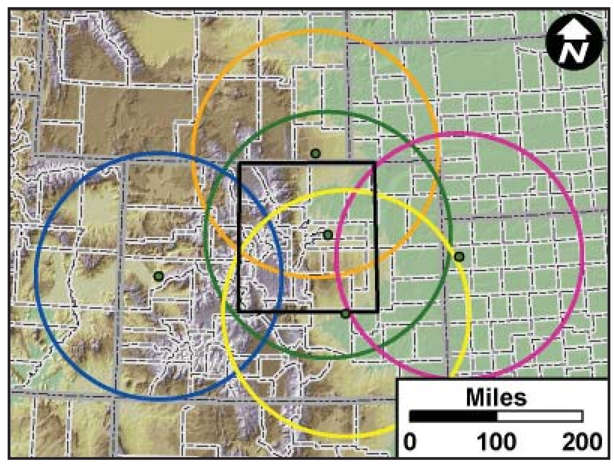

Figure 2. Radars covering the Denver Metropolitan Area. Circles show the 230 km range rings. Clipped region outlined in black.

2. WDT Quantitative Precipitation Estimation Algorithm

a. Nationwide Level-II NEXRAD Mosaics

The fundamental requirement for high quality radar (QPE) is a high quality radar mosaic. WDT accesses real-time NEXRAD Level-II radar data from 134 radars across the US through a program called "iRADS", hosted by the University of Oklahoma. The "iRADS" data center is manned 24/7 and is fully redundant, guaranteeing Level-II data from all CONUS radars with less than a 10 second delay. WDT hosts a computer cluster architecture for radar data processing that includes automated quality control, and sophisticated techniques to combine data from all available radars, which results in a seamless nationwide mosaic at 1 km resolution with updates every 5 minutes

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(Lakshmanan, 2006). WDT derives timely, high quality precipitation estimates and forecasts from this Level–II mosaic, using rain gauge data to calibrate the radar-derived rainfall.

WDT, in partnership with the National Severe Storms Laboratory (NSSL), has implemented and enhanced the NSSL's radar data quality control and Level-II Mosaic algorithms in an operational environment.

b. Radar Data Quality Control (RDQC)

A significant source of error in hydrologic products is the quality of the QPE input. Radar clutter or "false echoes" in radar data can lead to considerable overestimation of reflectivity–based QPE. The WDT and NSSL Radar Data Quality Control Algorithm (RDQC) removes non-precipitation artifacts from base Level–II radar data. These artifacts include ground clutter, sea clutter, anomalous propagation, sun strobes, clear air returns, chaff, biological targets, electronic interference and hardware test patterns. The RDQC algorithm uses sophisticated data processing and a Quality Control Neural Network (QCNN) to delineate the precipitation echoes from those echoes caused by radar artifacts (Lakshmanan, 2004). All 3 Doppler moments (Reflectivity, Radial Velocity and Spectrum width) are used where available to ascertain the characteristics of precipitation. The Neural Network (NN) approach combines local horizontal and vertical features detected in radar data to discriminate between precipitating and non-precipitating areas. Beam blockages due to terrain are mitigated by using 30m DEM data to compute and then discard data from a radar beam that clears the ground by less than 50m and incurs more than 50% power blockage.

A diurnal clear-air echo removal scheme is applied to radars in clear-air mode when there is no precipitation reported from observation stations within the vicinity of the radar and the observed surface temperature at all stations are above a dynamic threshold.

Once the data from individual radars have passed through the RDQC they are merged to create a seamless National Mosaic. A novel multi-sensor quality control is applied by post-processing the mosaic to remove any remaining "false echoes". This technique uses observations of infra-red cloud top temperatures by GOES satellite and surface temperature to create a precipitation/no-precipitation mask.

The RDQC combined with post-processing QC, results in a clean radar mosaic that will produce accurate estimates and forecasts of precipitation for more accurate prediction of hydrologic events (Figure 3).

c. Nationwide Radar Quantitative Precipitation Estimation

Radar-based precipitation estimates provide critical information in regions where rain gauge reports are sparse. WDT uses their high resolution, rapid update, national 'Low-Altitude' mosaic to derive quantitative precipitation estimates. There are numerous advantages of using multiple radars over the classic 'radar centric' approach that utilize single radar rainfall estimation techniques. The benefits include more accurate depiction of the storm at far range from the radar, ability to assign differential Z-R relationships (radar reflectivity to rainfall rate) to each grid point (as opposed to each radar umbrella), built-in redundancy when radar outages occur, gap-filling for radar data voids, and better monitoring of approaching storms.

a)

b)

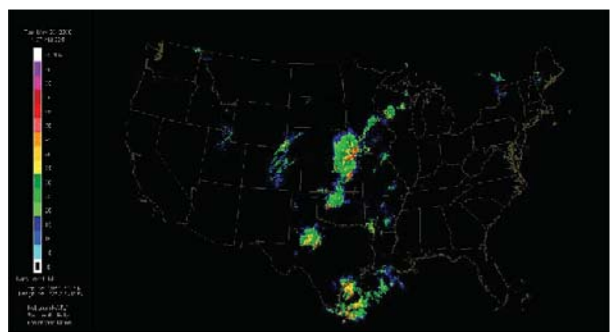

Figure 3. a) Mosaic of CONUS radars with no quality control and b) WDT quality controlled mosaic of CONUS radars.

The seamless, real-time WDT Nationwide QPE (NQPE-II) utilizes high precision Level-II radar data and has 1km horizontal resolution with updates every 5 minutes. Reflectivity data from each radar are remapped from their native spherical coordinates to a Cartesian coordinate system. All radar data are combined in real-time using an innovative mosaic algorithm licensed from the National Severe Storms Laboratory. In areas of radar coverage overlap, a distance weighting scheme is applied to assign reflectivity to each 1 km grid, for multiple vertical levels, from the nearest radar that is unblocked by terrain. From the 3D Mosaic, a 'Low Altitude' mosaic is built by selecting the value of reflectivity closest to the ground at each 1km grid, creating a hybrid scan mosaic that is most representative of precipitation falling at the ground. The Low

Altitude mosaic is used to derive precipitation rates and accumulated over time intervals ranging from 15 minutes to 72 hours.

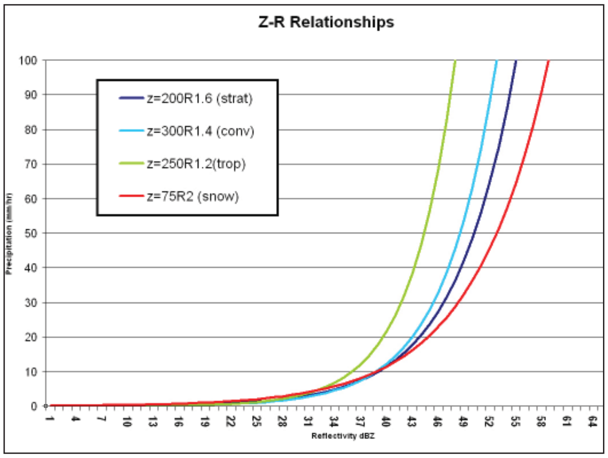

Figure 4. Graph to show standard NWS Z-R relationships.

The NQPE-II technique segregates snow and rain areas and determines convective versus stratiform precipitation regions, applying the appropriate Z-R relationship to each 1 km grid in the reflectivity field (Figure 4). Each grid cell is classified based on precipitation type and phase. The type of precipitation is determined by WDT's proprietary precipitation type mask that is generated as part of our operational WRF numerical model forecasts, which are updated every 15 minutes and blended with observed precipitation type whenever reports are available (Bourgouin, 2000, Wandishin, 2005).

d. Rain Gauge Adjusted radar QPE for UDFCD

It is widely known that radar-based estimates of precipitation suffer from deficiencies that may lead to over or under-estimation of rainfall. Amongst others, these include lack of radar calibration, uncertainty in Z-R relationships, beam overshooting, hail contamination, and vertical profiles of reflectivity.

To overcome some of these inadequacies in the Denver area, WDT uses the UDFCD rain gauges to calibrate a clipped region of NQPE-II for the Denver Metropolitan Area. These rain gauge reports are used to correct the radar QPE at each 1km grid in real-time. Each rain gauge report is compared to its co-located NQPE-II grid value. The difference between the point gauge report and the precipitation estimate for each match is stored as a bias in the database. A local gauge adjustment is applied using the bias information and an inverse distance weighting approach to interpolate the bias, correcting each 1 km grid value of NQPE-II within a custom pre-computed radius of influence (Figure 5).

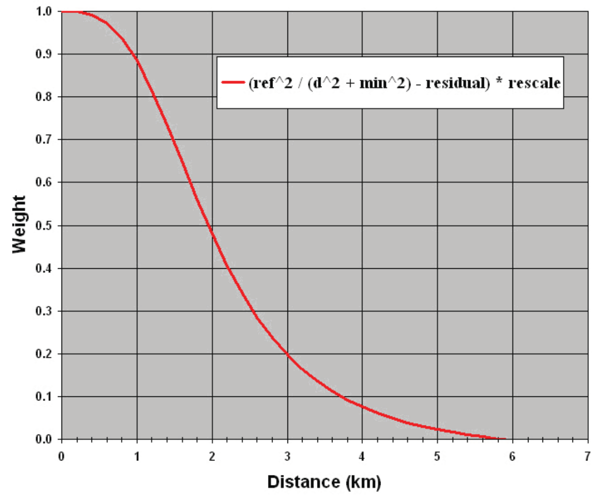

Figure 5. Graph to show the weighting function used in the WDT gauge correction algorithm.

The WDT hourly and 3 hourly local gauge-adjusted radar QPE product (QPE_GC) is provided to UDFCD every 15 minutes. Multi-hour products, up to 24-hour accumulations, are updated every hour. Both the radar QPE and the QPE_GC products are provided in real-time in shapefile format.

3. Flash Flood Prediction Program

The UDFCD FFP has evolved significantly over the last 29 years. They incorporate ALERT mesonet and numerous other weather data sources to develop quantitative precipitation forecasts on a daily basis to inform local government officials of heavy rainfall potential.

Each morning the FFP meteorologists fax, email and update their website with the Heavy Precipitation Outlook. If the forecast rainfall exceeds 1.5 inches, a basin-specific Quantitative Precipitation Forecast is also issued. Other products include notifications to local governments, storm tracking messages and an all clear at the end of a threat. The storm tracking product utilizes a map of single-site level II base reflectivity data, storm progression polygons drawn by the meteorologist and a short discussion of each storm cell.

The WDT QPE_GC product has the potential to provide a more comprehensive spatial perspective of flash flood threats and this paper represents the first phase of the analysis to determine the accuracy and related value to the UDFCD program. Beginning April, 2007 the QPE_GC product was widely used to help calculate storm statistics for the flash flood season. The increased spatial resolution and precision of the QPE product when compared with standard NWS products was beneficial (Figure 6). Operationally, the QPE_GC product can be used in combination with surface observations to more accurately assess flood threats on a basin-specific basis. After an evaluation of the results from 2007, District staff are considering using basin-averaged QPE_GC to drive real-time runoff models and inundation mapping.

The provision of rainfall data by WDT in a GIS format enables the District and their meteorology consultant to overlay any number of custom layers such as basin and political boundaries and provides the capability to zoom into a desired extent to better analyze the flood threat for any area in the District.

4. Verification Analysis

Seven cases were analyzed from the summer season 2007 to assess the improvement of WDT gauge-adjusted radar QPE over the WDT radar QPE and also compare results to the National Weather Service precipitation analysis (http://www.srh.noaa.gov/rfcshare/precip_download.php). The NWS precipitation analysis is derived from the 12 River Forecast Centers and provided in GIS point shapefile at 4 km grid resolution. The NWS observed multi-sensor precipitation data is a 24-hour accumulation, estimated using radar and rain gauges, valid at 1200 UTC. The NWS precipitation analysis is available at approximately 16 UTC each day. The UDFCD has not used the NWS product operationally as it is not available in a 1-hour accumulation product and is not updated in a timely enough manner. The UDFCD has used the NWS single site radar rainfall products (OHP, THP and STP). However, it was not possible to perform any statistical comparison between WDT QPE and NWS single site precipitation because the single site data is only provided in classes of rainfall (i.e. 0.1-0.3, 0.3-0.6 inches etc) and the WDT QPE data is continuous. Consequently the NWS precipitation analysis will be used as the baseline comparison in this verification analysis to determine how accurate WDT QPE is in comparison.

5. Results

An independent set of rainfall gauges was used to assess and compare the performance of the WDT radar-only product (QPE), the local gauge corrected (QPE_GC) product and the NWS precipitation analysis.

The independent 24-hour rain gauge reports were obtained from Community Collaborative Rain and Hail Snow network (CoCoRaHS) (Figure 7). The number of independent rain gauges available for verification ranged between 178 and 223 over the 2007 season. The performance of the WDT QPE, QPE_GC product and the NWS product was assessed during this case study by comparing the grid-

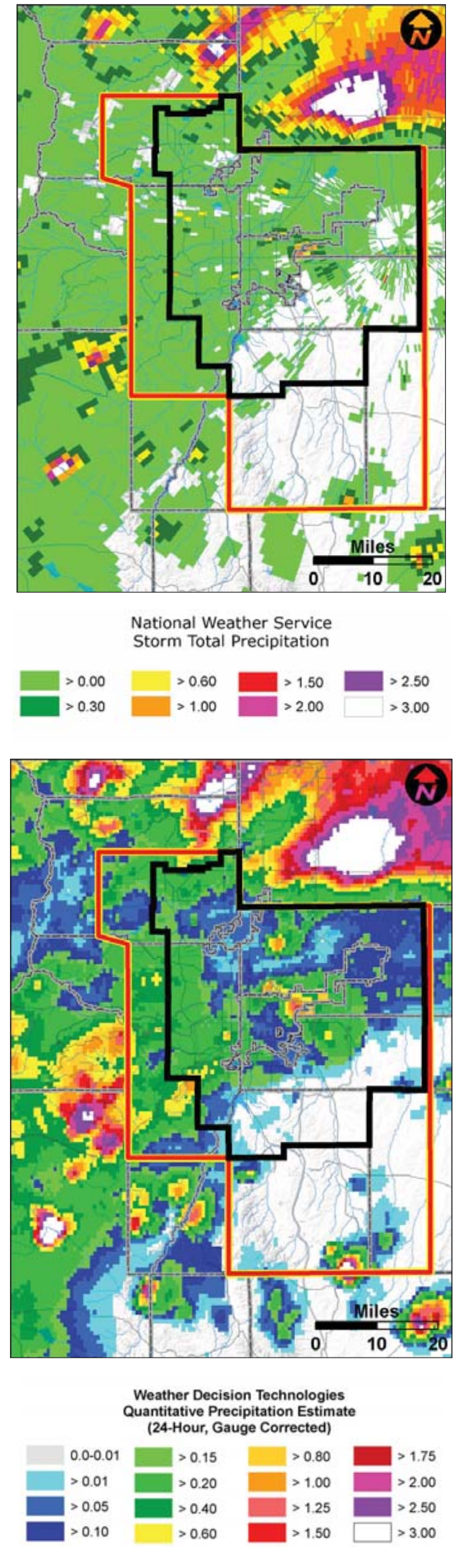

Figure 6. a) NWS single site radar precipitation product (OHP) previously used at UDFCD, and b) WDT 24-hour QPE_GC precipitation used currently used at UDFCD valid August 4th, 2007 at 1200 UTC.

24h Event (ending 12 utc)	No. of Obs	MAX (in.)			MEAN (in.)			Standard Deviation			Correlation Coefficient		BIAS (G/R)		MAE (in.)	
		G	GC	N	G	GC	N	G	GC	N	GC	N	GC	N	GC	N
6/13/07	218	1.52	1.42	1.13	0.34	0.49	0.31	0.20	0.22	0.16	0.79	0.72	1.06	1.70	0.10	0.23
7/05/07	186	1.29	1.30	0.25	0.34	0.30	0.08	0.37	0.35	0.07	0.81	0.69	1.23	4.94	0.04	0.08
7/06/07	196	1.07	1.00	0.13	0.10	0.10	0.02	0.19	0.17	0.03	0.53	0.09	1.08	5.86	0.02	0.02
7/20/07	189	2.62	2.25	0.94	0.46	0.33	0.09	0.61	0.47	0.16	0.84	0.39	0.73	2.73	0.07	0.08
7/28/07	203	2.57	2.41	1.57	0.79	0.57	0.38	0.61	0.38	0.38	0.77	0.65	0.94	1.41	0.19	0.25
8/04/07	178	3.05	3.29	0.86	0.37	0.35	0.08	0.58	0.62	0.13	0.71	0.59	0.38	1.74	0.20	0.08
8/24/07	223	2.16	1.50	1.04	0.63	0.50	0.44	0.38	0.34	0.21	0.75	0.66	0.90	0.72	0.17	0.14

Table 1. Summary of statistics for summer events 2007 within the UDFCD forecast zone. 'G' refers to the CoCoRaHS rain gauges, 'GC' refers to the local gauge adjusted QPE product and 'N' refers to the NWS precipitation analysis product.

ded rainfall estimation products with corresponding independent rain gauge reports using GIS software.

The performance of each product was quantified by computing the following statistics 1) Sum, 2) Mean, 3) Maximum, 4) Bias (Gauge/Radar), 5) Correlation Coefficient, 6) Standard Deviation and 7) Mean Absolute Error (MAE). A bias greater than 1 indicates underestimation of rainfall by the WDT or NWS product, assuming that the gauges were accurate. The quantitative comparisons are used to demonstrate the improvement of the WDT product over the NWS product (Table 1).

a. Case Study: 06/13/07

A combination of low level moisture, moderate day time heating and an upper level disturbance over the Four Corners tracking north east resulted in heavy rainfall over the Denver Metropolitan Area. Storms initiated in the early afternoon and into the evening of Tuesday June 12th, bringing widespread heavy rainfall and thunderstorms. FFP program meteorologists predicted peak rainfalls of up to 2.50 inches in 60 minutes associated with the strongest storms and 0.5 inches associated with weakest storms.

During the 24-hour period ending at 12 UTC on 06/13/07, the average rainfall reported in the forecast zone by CoCoRaHS gauges was 0.52 inches (Table 2). The histogram shows that over 50% of rainfall reports were below 0.50 inches during this event and the maximum gauge report was 2.19 inches (Figure 8).

This event produced widespread rainfall over the entire forecast zone, with higher rainfall amounts occurred in the south west of the UDFCD forecast zone (Figure 9). Rainfall maps in Figure 9, show the gridded QPE with overlays of rain gauge reports. The same color scale is used for the QPE and rain gauge amounts to allow easy comparison.

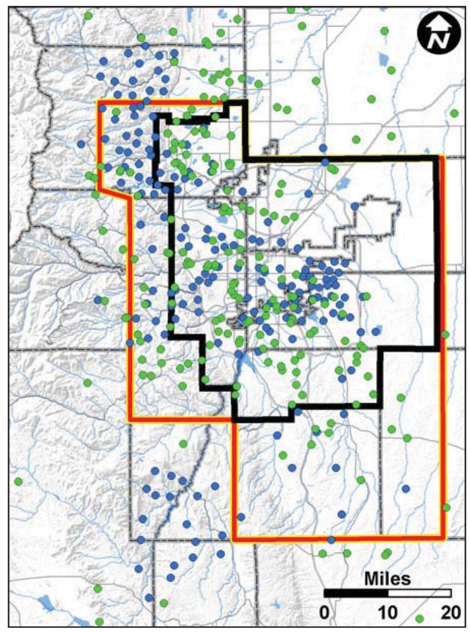

Figure 7. Map to show location of CoCoRaHS rain gauges (green) and UDFCD rain gauges (blue).

	Gauge	QPE	QPE_GC	NWS
# of Obs	218	218	218	218
MAX (in)	2.19	1.52	1.42	1.13
MEAN (in)	0.52	0.35	0.49	0.31
STD DEV	0.30	0.21	0.22	0.16
CORR		0.76	0.79	0.72
BIAS (G/R)		1.50	1.06	1.70
MAE (in)		0.19	0.10	0.23

Table 2. Statistics for 24-hour event valid from 06/12/07 at 12 UTC to 06/13/07 at 12 UTC. 'Gauge' refers to the CoCoRaHS rain gauges, 'QPE' refers to the WDT radar-only QPE, the 'QPE_GC' refers to the WDT gauge-adjusted QPE and 'NWS' refers to the NWS precipitation analysis product.

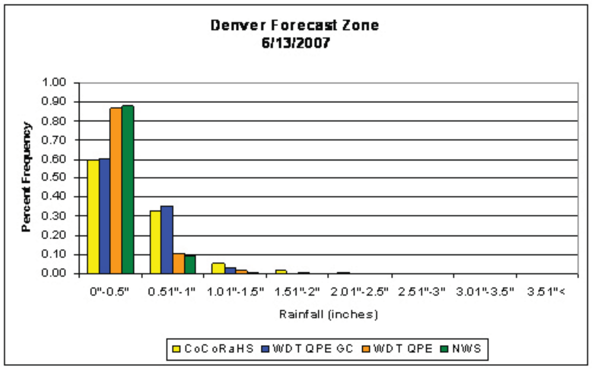

Figure 8. Histogram of rainfall distribution for 24-hour event ending 06/13/07 at 12 UTC.

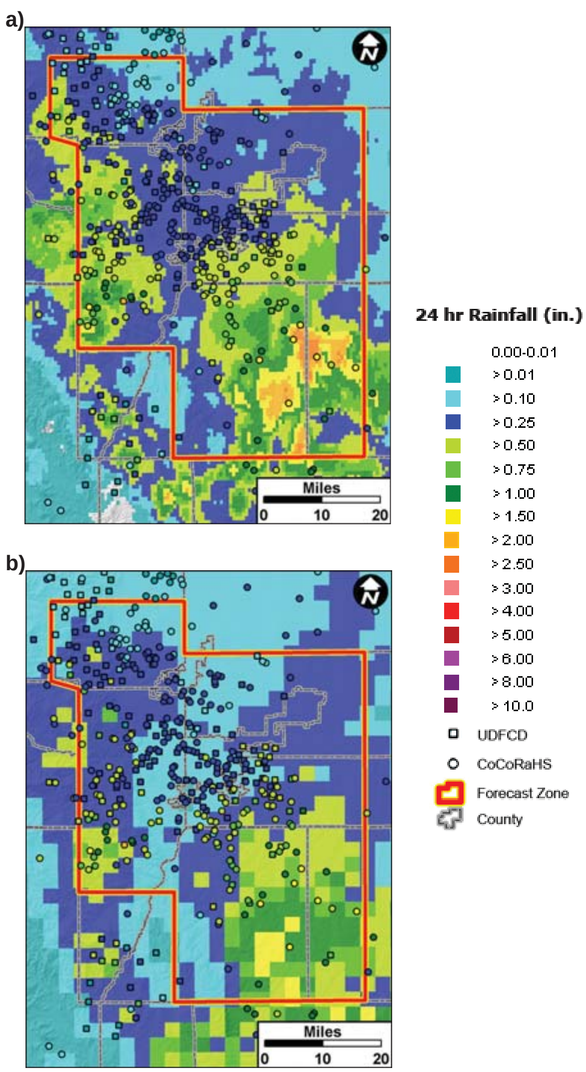

Figure 9. a) WDT QPE_GC rainfall map at 1km resolution and b) NWS precipitation analysis map at 4km resolution for the 24-hour rainfall accumulation valid on 06/13/07 at 12 UTC. Gauge reports are shown for UDFCD rain gauges (black squares) and CoCoRaHS rain gauges (black circles).

Scatter plots show that the WDT QPE_GC correlated well with CoCoRaHS rain gauge reports (Figure 10). The bias of the WDT QPE_GC estimate is 1.06 and the NWS bias is 1.70, showing that on average the NWS product underestimated rainfall by 70%. The MAE for this case was 0.22 inches for NWS and 0.09 inches for the WDT QPE_GC product. The WDT QPE_GC product performed better than the NWS product for this event, indicating that the inclusion of UDFCD rain gauges improves radar estimates of precipitation.

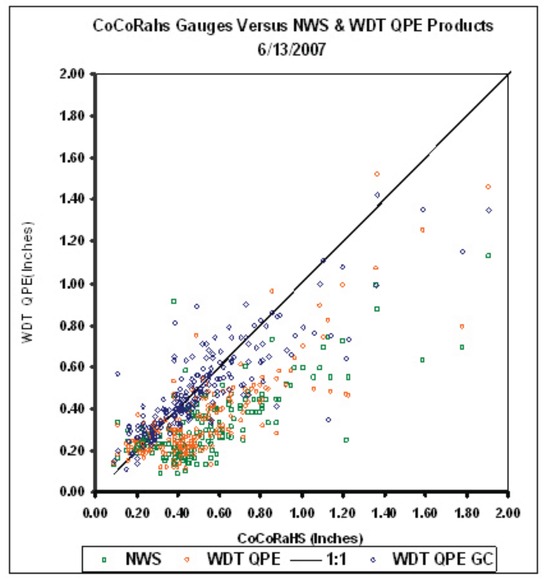

Figure 10. Scatter plot to show 24-hour gauge reports from CoCoRaHS versus QPE products valid on 06/13/07 at 12 UTC.

b. Case Study 07/28/07

The passage of a cold front early morning on Friday, July 27th resulted in a moist air mass in place over the UDFCD. An outflow boundary from storms northeast of the District initiated slow moving storms late into Friday afternoon. The FFP program meteorologist predicted rainfall amounts to vary from 0.5 inches to a maximum of 2.75 inches in 45 minutes during this event.

	Gauge	QPE	QPE_GC	NWS
# of Obs	203	203	203	203
MAX (in)	2.23	2.57	2.41	1.57
MEAN (in)	0.54	0.78	0.57	0.38
STD DEV	0.44	0.61	0.38	0.38
CORR		0.87	0.77	0.65
BIAS (G/R)		0.68	0.94	1.41
MAE (in)		0.28	0.20	0.25

Table 3. Statistics for 24-hour event valid from 07/27/07 at 12 UTC to 07/28/07 at 12 UTC. 'Gauge' refers to the CoCoRaHS rain gauges, 'QPE' refers to the WDT radar-only QPE, the 'QPE_GC' refers to the WDT gauge-adjusted QPE and 'NWS' refers to the NWS precipitation analysis product.

For the 24-hour rainfall event ending 07/28/07 at 12 UTC, the average rainfall in the forecast zone, reported by CoCoRaHS rain gauges, was 0.54 inches and the maximum rainfall reported was 2.23 inches (Table 3). The histogram shows that 20% of rain gauges reported over 1.0 inch of rainfall in the 24-hour period (Figure 11).

Rainfall maps show that the higher rainfall amounts occurred within or around the Denver Metropolitan Area (Figure 12).

In this case, the WDT QPE_GC product was better correlated to rain gauges than the NWS precipitation product, with a correlation coefficient of 0.72 compared to 0.65 for the NWS product (Figure 13). The bias for the WDT QPE_GC estimate was 0.94 compared to 1.4 for the NWS estimate showing that the NWS QPE underestimated by 40%.

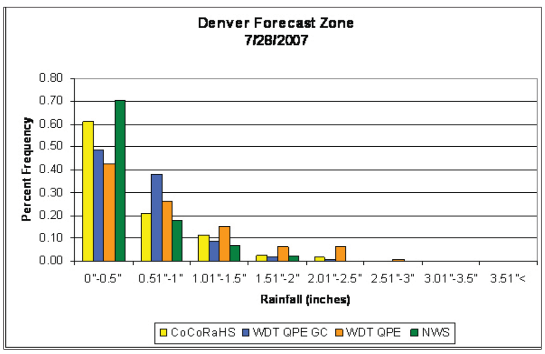

Figure 11. Histogram of rainfall distribution for 24-hour event ending 07/28/07 at 12 UTC.

c. Case Study 08/4/07

Deep moisture combined with high temperatures (in the lower 90's) resulted in the development of showers and thunderstorms over the UDFCD. This event produced locally heavy storms with hail and lightning. FFP program meteorologists predicted storm precipitation totals between 0.7 inches and 4.0 inches in 90 minutes.

	Gauge	QPE	QPE_GC	NWS
# of Obs	178	178	178	178
MAX (in)	1.00	3.05	3.29	0.86
MEAN (in)	0.13	0.37	0.35	0.08
STD DEV	0.19	0.58	0.62	0.13
CORR		0.75	0.71	0.59
BIAS (G/R)		0.35	0.35	1.74
MAE (in)		0.22	0.2	0.08

Table 4. Statistics for 24-hour event valid from 08/03/07 at 12 UTC to 08/04/07 at 12 UTC. 'Gauge' refers to the CoCoRaHS rain gauges, 'QPE' refers to the WDT radar-only QPE, the 'QPE_GC' refers to the WDT gauge-adjusted QPE and 'NWS' refers to the NWS precipitation analysis product.

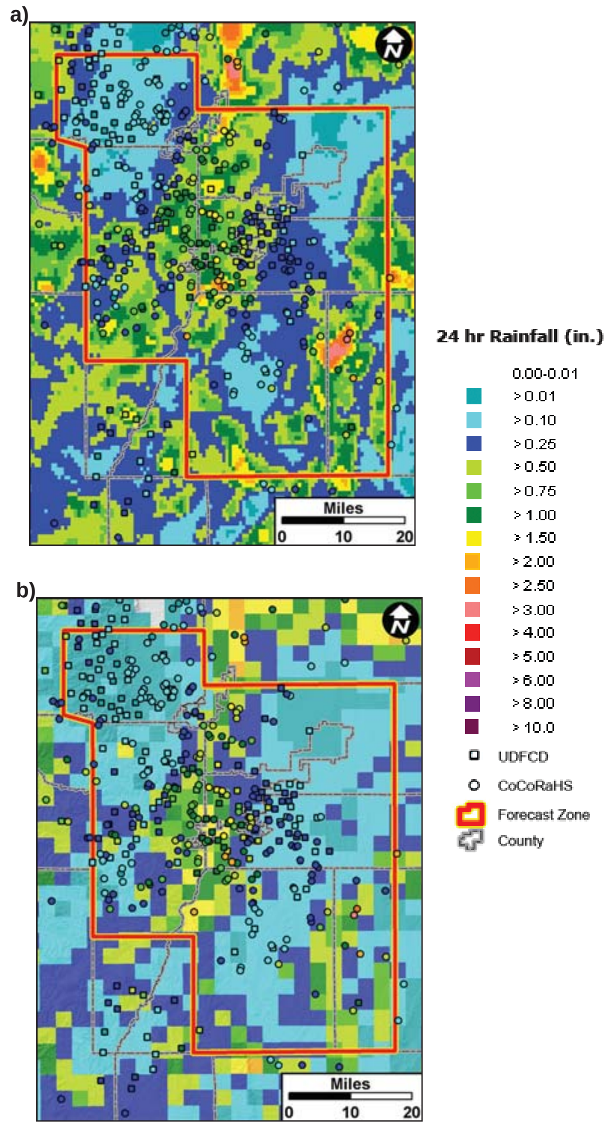

Figure 12. a) WDT QPE_GC rainfall map at 1km resolution and b) NWS precipitation analysis map at 4km resolution for the 24-hour rainfall accumulation valid on 07/28/07 at 12 UTC. Gauge reports are shown for UDFCD rain gauges (black squares) and CoCoRaHS rain gauges (black circles).

The maximum rainfall reported by CoCoRaHS gauges for this event was 1.0 inch and the mean rainfall was 0.13 inches (Table 4). The histogram shows that 80% of rain gauge reports were less than 0.5 inches (Figure 14). It is clear that the WDT QPE_GC overestimated precipitation with a maximum of 3.29 inches.

During this event, rainfall was concentrated in a few small areas, associated with convective cells, with less than 0.1 inches of rainfall in the surrounding areas. Overestimation of rainfall by WDT QPE_GC corresponded with hail-contaminated storms, with reports of ¼ inch hail (shown as triangles in Figure 15).

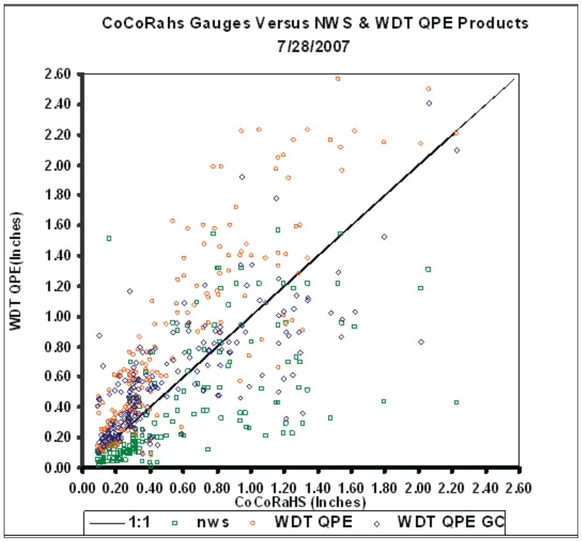

Figure 13. Scatter plot to show 24-hour gauge reports from CoCoRaHS versus QPE products valid on 07/28/07 at 12 UTC.

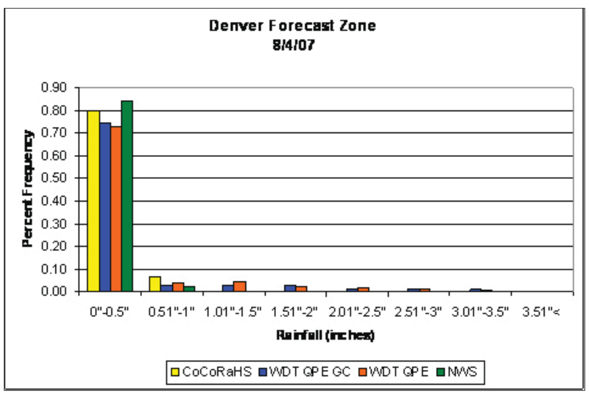

Figure 14. Histogram of rainfall distribution for 24-hour event ending 08/04/07 at 12 UTC.

The weak correlation shown in the scatter plot reflects the impact of hail contamination on the WDT QPE_GC estimation. Overestimation is not evident in the NWS estimation of precipitation, likely due to the implementation of a hail cap.

6. Summary

WDT provides rainfall estimates in real-time to the UDFCD in shapefile format for their FFP program. WDT derives rainfall from multiple NEXRAD Level-II radar, utilizing the UDFCD rain gauge reports every 15 minutes to correct the radar rainfall estimates.

Numerous case studies over the 2007 season show that the accuracy of WDT radar rainfall is greatly improved when rain gauges are used. The quality of WDT rainfall estimates of rainfall was compared to the NWS precipitation analysis. Results show that WDT rainfall estimates are statistically better than NWS, providing more accurate rainfall data to the Denver Metropolitan Area.

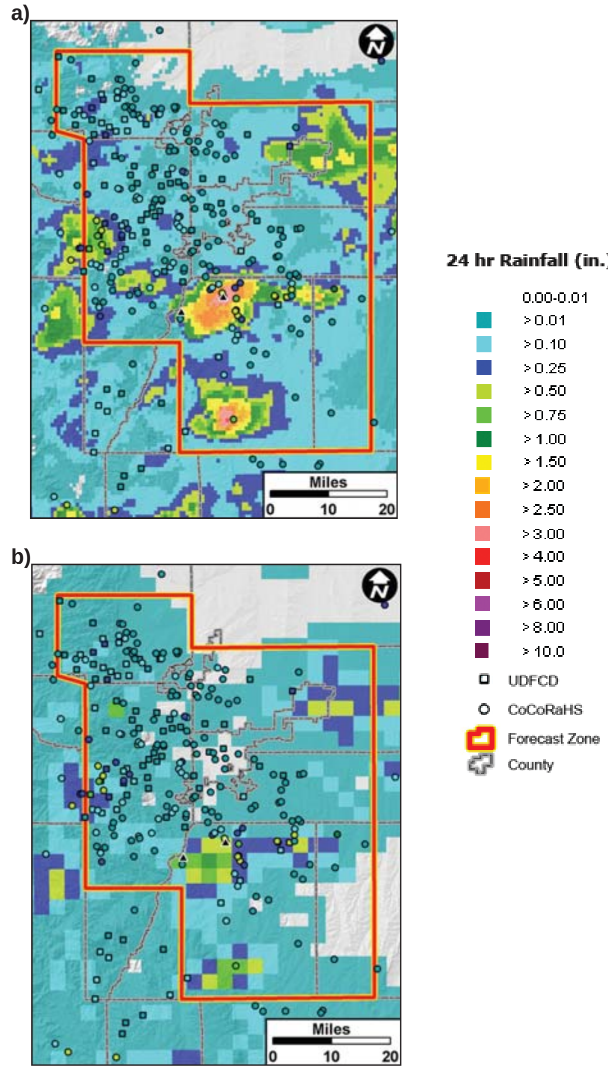

Figure 15. a) WDT QPE_GC Rainfall map at 1km resolution and b) NWS precipitation analysis map at 4km resolution for the 24-hour accumulation valid on 08/04/07 at 12 UTC. Gauge reports are shown for UDFCD rain gauges (black squares) and CoCoRaHS rain gauges (black circles). Black triangles show the location of Hail reports during this time period.

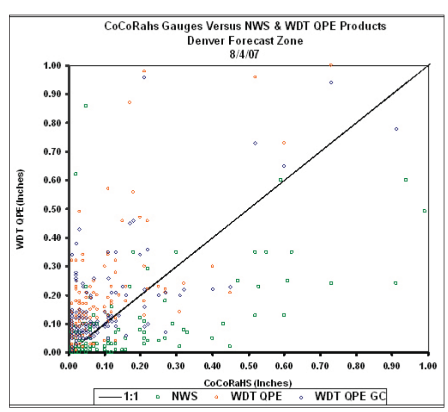

Figure 16. Scatterplot to show 24-hour gauge reports from CoCoRaHS versus QPE products valid on 08/04/07 at 12 UTC.

7. Future Work

It was noted that the accuracy of WDT Rainfall estimates is reduced when there was hail present in the storm. The detrimental impact of hail contamination will be addressed in 2008 by the introduction of a hail cap using VIL density as a hail indicator (Stumpf, 2004).

Future work will also include providing basin-averaged rainfall data for UDFCD in 2008.

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