9.1 GAUGE-ADJUSTED RADAR RAINFALL ESTIMATION AND BASIN AVERAGED RAINFALL FOR USE IN LOCAL FLASH FLOOD PREDICTION AND RUNOFF MODELING

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1. INTRODUCTION

The Urban Drainage and Flood Control District (UDFCD) maintains an ALERT gauging network, for real-time monitoring of rainfall, and operates a Flash Flood Prediction (FFP) Program, to forecast rainfall events up to 24 hours in advance, within the Denver metropolitan area. The Program Meteorologists communicate directly with area emergency management and public works agencies to prepare for and assess flash flood events. Spatially comprehensive rainfall estimates that are both timely and accurate are critical in this mission, to determine the level of threat in real-time. UDFCD is contracting with Leonard Rice Engineers, Inc to evaluate the use of rainfall data in real-time runoff models, simplified versions of the UDFCD master plan models.

Weather Decision Technologies (WDT) Inc. provides UDFCD rainfall estimates that are automatically derived from NEXRAD Level II mosaicked radar data and adjusted using the ALERT rain gauge data. These data are provided in Geographic Information System (GIS) format in real-time on a high-resolution 1 km grid (**Figure 1**). Traditionally FFP Program Meteorologists have used NWS single site radar data in conjunction with point ALERT data to estimate basin rainfall and communicate the potential flash flood threat with local agencies. During the 2007 FFP Program, WDT integrated the ALERT rain gauge data into their high resolution gridded radar rainfall mosaics, updated every 15 minutes. Both the radar-only Quantitative Precipitation Estimates (QPE) using multiple radars and the gauge-adjusted QPE products were provided. In 2008, WDT introduced a basin averaged product using delineated basins provided by the UDFCD.

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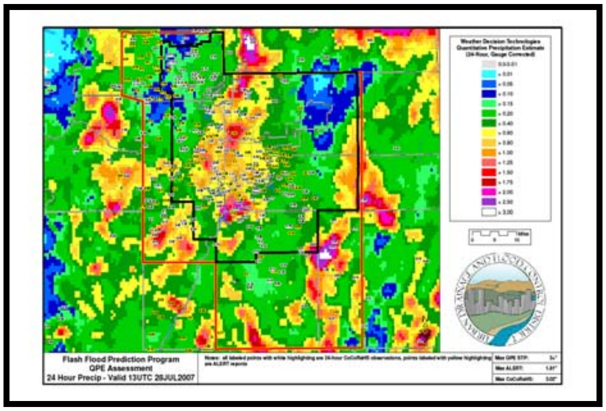


Figure 1. Sample of the daily QPE assessment map created at UDFCD using the 24 hour gauge-adjusted radar rainfall accumulation product provided by WDT.

Leonard Rice Engineers, Inc hosts real-time runoff models for select basins within the UDFCD area. In the past, these models were completely driven by ALERT rainfall data. The output of the models included web-based tables and graphs. During 2008, the models were also tested using the WDT basin averaged QPE products.

2. RAINFALL DATA

2.1. Radar derived rainfall

Radar based precipitation estimates provide critical information in regions where rain gauge reports are sparse or unavailable. 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 and single radar rainfall estimation techniques (Figure 2). 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.

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 polar 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 (Laksmanan, 2004, 2004, 2006). In areas of radar coverage overlap, a distance weighting scheme is applied to assign reflectivity to each 1km 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. A hail cap is applied using maximum reflectivity thresholds in a vertical column and VIL Density as a hail indicator. The hail cap mitigates over-estimation of rainfall caused by the presence of hail. The Low Altitude mosaic is used to derive precipitation rates and accumulated over time intervals ranging from 5 minutes to 72 hours.

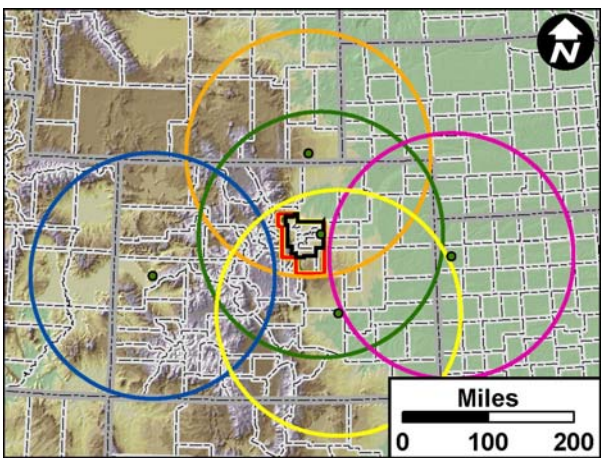


Figure 2. Multiple radar coverage of the Denver Metropoliton Area. Circles show the 230 km range rings.

The NQPE-II technique segregates snow ($Z=75S^2$) and rain areas and determines convective ($Z=300\ R^{1.4}$) versus stratiform ($Z=200R^{1.6}$) precipitation regions, applying the appropriate Z-R relationship (widely implemented by the National Weather Service) to each 1 km grid in the reflectivity field. 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 10km resolution WRF numerical model forecasts, which are updated every 15 minutes and blended with observed precipitation type whenever reports are available (Bourgouin, 2000, Wandishin, 2005).

2.2. Gauge-adjusted radar rainfall

It is 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.

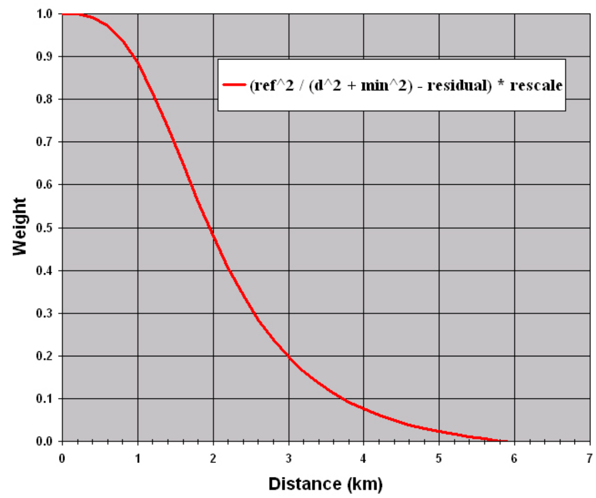


Figure 3. Graph to show the weighting function used in the WDT gauge correction algorithm.

To overcome some of these inadequacies, WDT uses UDFCD rain gauge data obtained via HTTP 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 3).

In real-time the WDT hourly and 3 hourly local gauge-adjusted radar QPE product (QPE_GC) is provided every 15 minutes. Multi-hour products, up to 24h hour accumulations, are updated every hour. Both the radar QPE and the QPE_GC products are provided in real-time in shapefile format. The QPE products are also basin averaged and provided to UDFCD (Fig. 4).

For testing purposes during this project WDT gauge-adjusted the 5 minute radar rainfall accumulations using

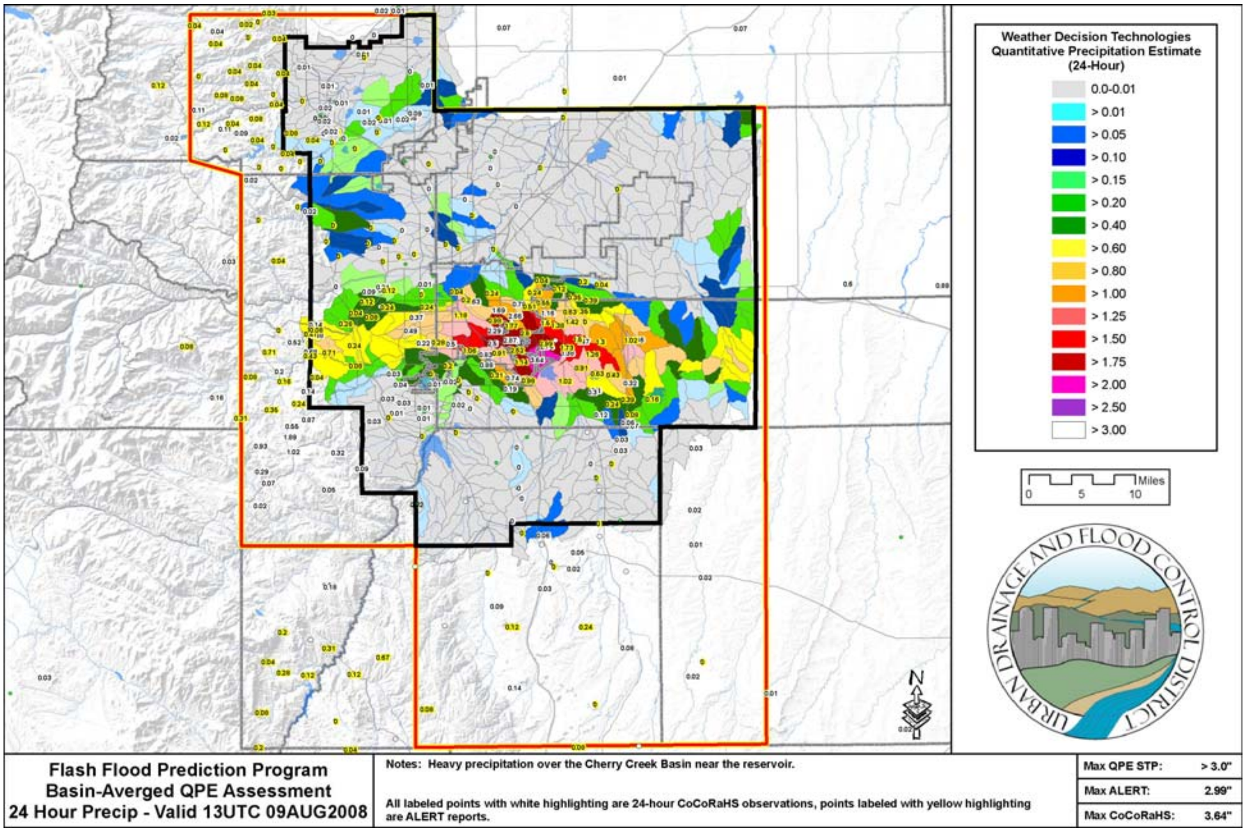


Figure 4. Sample Basin Averaged gauge adjusted radar rainfall product.

5 minute ALERT rain gauge reports. UDFCD provided individually delineated basin in GIS shape file format and WDT computed the basin averaged rainfall for each basin in 5 minute intervals.

2.3. Interactive Rainfall Display

WDT provide an interactive web-based display for their radar mosaics, rainfall maps and the UDFCD rain gauges. The display is integrated into Google Earth providing all the capabilities including various background maps, zoom controls and a transparency slider (**Figure 5**). WDT have also built in the capability to loop data; all data shown updates automatically in real-time. The UDFCD rain gauges change color corresponding to different rainfall thresholds. The user can click on each gauge to display the most recent rain gauge amounts over various time intervals and toggle on and off the radar rainfall maps. This display allows the user to see how much rainfall is occurring between rain gauges and monitor the evolution of the storm.

3. HYDRO MODELING

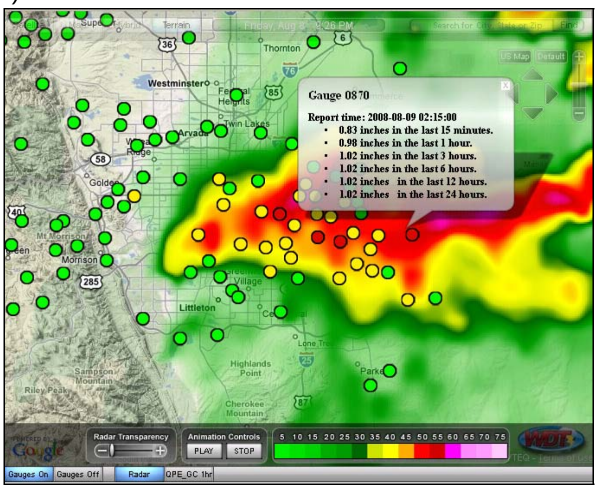
Intense, localized thunderstorms are a common occurrence in the Denver metropolitan area. As part of the Flash Flood Prediction Program, UDFCD call for a runoff model that produces results in a timely manner. The model should automatically acquire real-time rainfall estimates or forecasts as input and produce results that are comprehensive and easily interpreted.

In 2006, UDFCD began investigating the use of simplified hydrologic modeling techniques from Leonard Rice Engineers for use in real-time flood prediction. These automated modeling techniques utilized spreadsheets and the District's ALERT rainfall data as the real-time input. In 2008, the District embarked on a project to test the use of gauge-adjusted radar rainfall as input to the models.

3.1. Modeling Approach

A spreadsheet template was created in Excel to compute basin runoff for each basin of interest based on the current design standards of the District's Drainage Criteria Manual. Basin averaged ALERT rain gauge data was used as the input to the models in 5 minute time steps, obtained using Excel's built-in Web Query capability that allows the user to manually specify a time to automatically refresh the data, assuring that the model is reflecting current rainfall estimates. A fully networked model was created by using additional templates to simplify channel routing by approximating more detailed routing techniques that were linked to basin runoff worksheets.

a)



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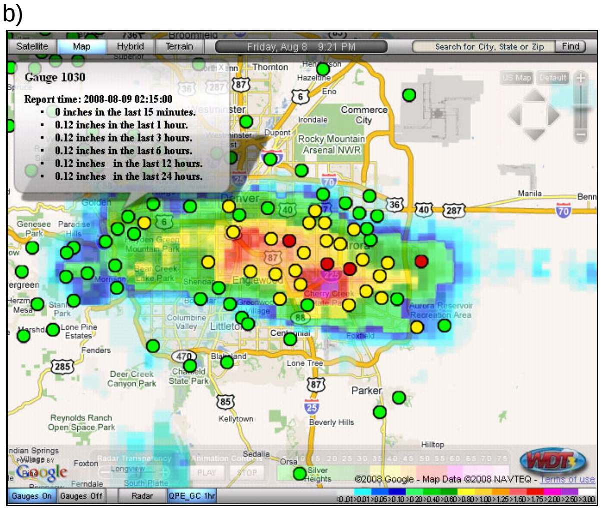

Figure 5. Imap Interactive display of a) Radar reflectivity and b) 1hr gauge-adjusted radar rainfall accumulation with overlay of ALERT rain gauges. Gauge colors correspond to 15 minute rainfall thresholds.

A number of basins were tested as a proof of concept at UDFCD using various models such as the Hydrologic Engineering Center's (HEC-1) model and the Colorado Urban Hydrograph Procedure (CUHP) integrated with the Environment Protection Agencies Storm Water Management Model (SWMM). The goal of Leonard Rice Engineers was to investigate how detailed of a model is really necessary for real-time flood warning. Results from the HEC-1 model for Boulder Creek were replicated using the simplified Excel spreadsheets. Simplification of the Harvard Gulch SWMM model that originally used a large number of sub-basins (59) also proved to be successful (**Figure 6**).

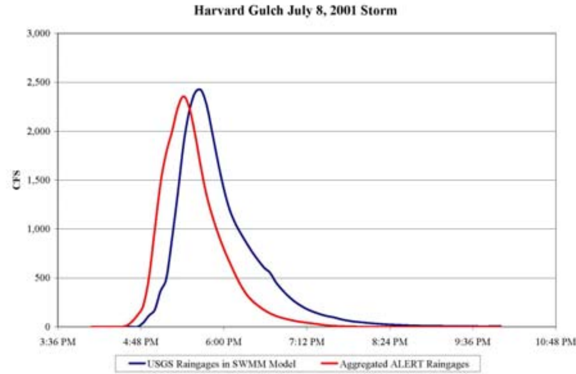

Figure 6. Hydrograph for Harvard Gulch Basin for July 8, 2001 Storm.

To create the simplified model, three design points were selected at critical locations and tributary sub-basins were assigned a single rain gauge for analysis, which resulted in just three aggregated sub-basins.

The unit hydrographs for each sub-basin were developed by modifying the rain gauge data in the first time step to produce exactly one inch of runoff volume for the entire aggregated sub-basin. The model computed run-off from this rainfall for each individual sub-basin and routed it through the model to the selected design points and the results became the unit hydrograph for that basin. The routing worksheet used Muskingum routing techniques to route the runoff hydrographs downstream. Calibration was performed by comparing the results of the detailed SWMM model at downstream design points. The Muskingum parameters were then optimized in excel worksheet to match the SWMM output so that the simplified excel model mirrored the results of the SWMM model.

These results were tested and measured peak flows compared favorably showing that the simplified spreadsheet approach shows promise as a tool to accurately predict potential flooding in real-time and results can be displayed via a web interface. Irrespective of the complexity of the model used, it can be imitated using simplified spreadsheet techniques by retrieving results at selected design points.

4. CASE STUDY

The goal of this project was to assess the utility of rain gauge-adjusted radar rainfall estimates for flash flood prediction in the UDFCD forecast zone during the 2008 storm season, where historically only rain gauges had been used (**Figure 7**). If this study proved successful, the gauge-adjusted radar rainfall could be used as input to hydrologic models in real-time.

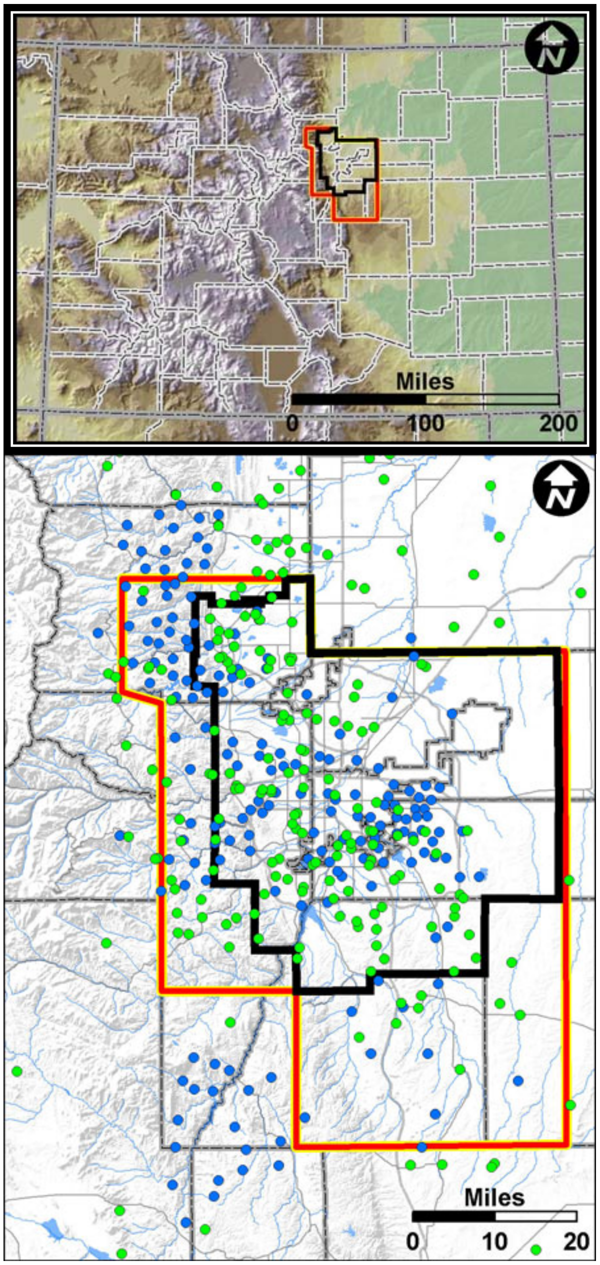

Figure 7. Location of Denver Urban Drainage Flood Control District (Black outline) and Forecast zone (Red outline). Circles show the location of show location of CoCoRaHS rain gauges (green) and UDFCD rain gauges.

For this case study, WDT's basin averaged gauge-adjusted radar rainfall was used as input to the simplified hydrologic model described in Section 2. The gauge-adjusted radar rainfall data was provided on a 1km grid and in basin averaged amounts for each sub-basin on 5 minute time steps. The hypothesis was that the gridded radar rainfall would provide vital information regarding the spatial variability of the storm and data for basins where rain gauges either did not exist or were not reporting during a rainfall event, thus improving the accuracy of hydrologic models.

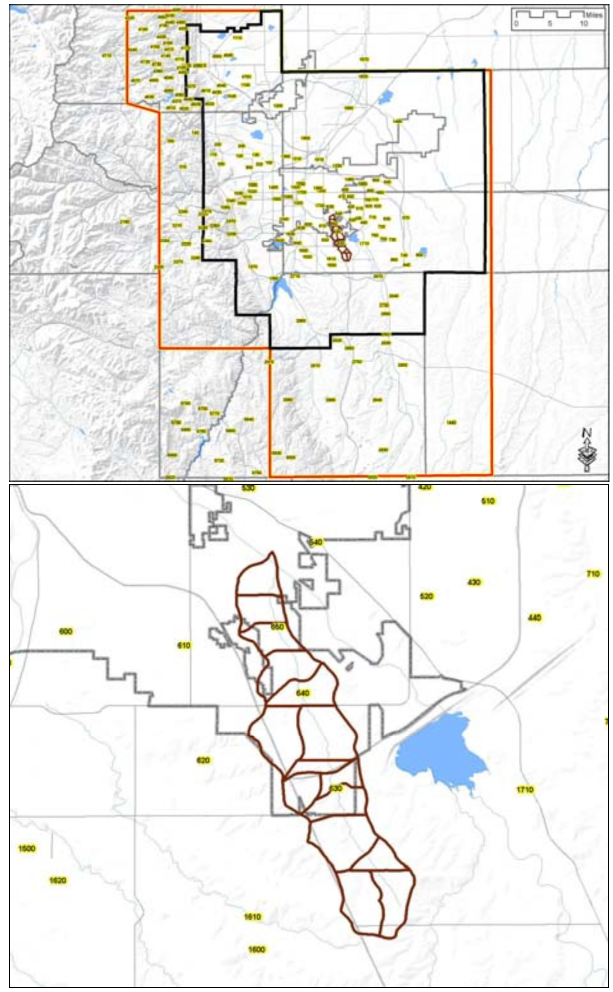

Figure 8. Location of Goldsmith Gulch basin and ALERT rain gauges.

The rain gauge data were provided by UDFCD from their ALERT network consisting of over 200 stations. These gauges were ingested by algorithms at WDT to adjust the radar derived rainfall estimates every 5 minutes. WDT then produced basin averaged estimates of rainfall using the GIS shapefiles of each sub-basin provided by UDFCD.

4.1. Case 08/08/08

The 2008 season did not result in significant flash flood events within the UDFCD modeling basins. One event of interest occurred within the Denver Metropolitan area on August 8th 2008 between 18:45 and 21:15 MST. During this storm an intense cell affected the Goldsmith Gulch basin where 3 rain gauges exist within the basin and 12 sub-basins remain ungauged.

4.2. Results

Hydrographs were produced by Leonard Rice Engineers for models run using both the ALERT rain gauges as input and the gauge-adjusted radar rainfall as input. Rainfall data from these sources were provided as basin averaged rainfall in 5 minute time steps. The results were similar but the hydrograph using only the ALERT gauges as input showed a lower total volume of water, which was less realistic than the gauge-adjusted radar rainfall hydrograph. The only stream flow report available for verification in this study was from Temple pond, which experienced less stream flow than lower parts of the basin. The peak stream flow measured at Temple pond was 180 cfs. The model using ALERT gauges as input estimated a lower peak flow of approximately 80 cfs but the gauge-adjusted hydro model produced a peak flow of 205 cfs, which was closer to the observed value.

4.3. Discussion

During this storm event there were often time increments with missing rain gauge reports from the UDFCD ALERT network (**Figure 10**). This could have occurred for two reasons. Firstly, the rainfall amount during the 5 minute interval may have been less than the minimum gauge tip (1mm). Secondly, the tip report may have been missed due to radio collisions or timed hold offs. In either instance the result was a gap in the data reported from rain gauges, meaning that frequently there was no rain gauge value available to adjust the radar rainfall grid. An investigation into the gauge performance during this event revealed that all gauges in the vicinity reported less than 100 percent of the time, typical for ALERT data, and a gauge in the basin of interest reported only 65 percent of the time. For these reasons the comparison of hydrologic modeling using rain gauge as input versus using gauge-adjusted radar as input remains ambiguous for this case study.

Implementation of the ALERT2 protocol should alleviate the issue of missing rain gauge reports during

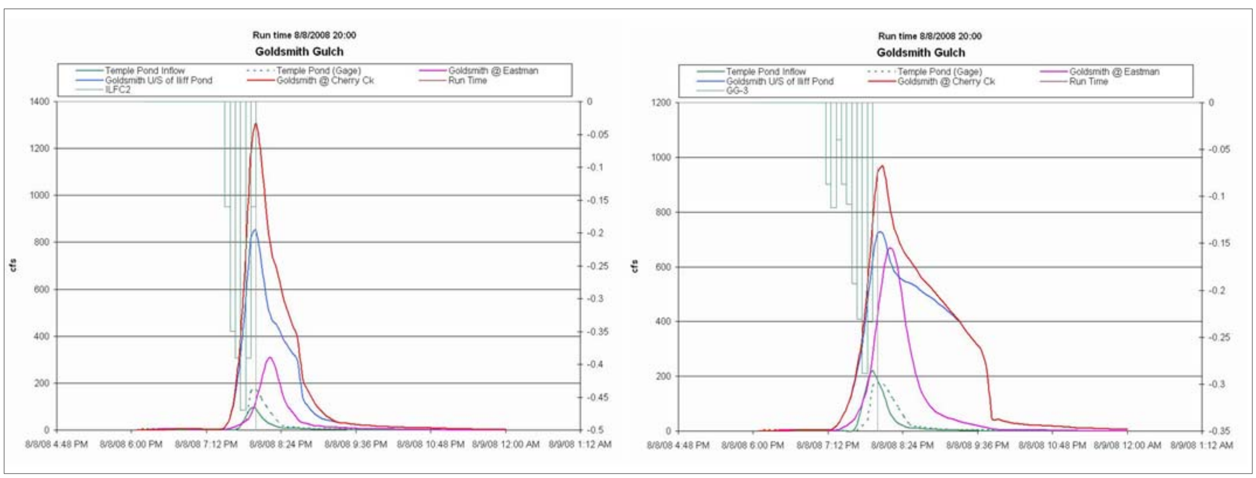

Figure 9. Hydrographs and hyetographs for the Godsmith Gulch on August 8, 2008 produced using (left) Alert rain gauges as input and (right) gauge-adjusted radar rainfall as input.

The hyetographs showed that the radar based rainfall reported rainfall starting earlier than the rain gauge reported (Figure 9). A closer study into the time series of 5 minute rain gauge reports and 5 minutes radar rainfall reports at each rain gauge location revealed that rainfall reports were often missing from the UDFCD ALERT rain gauges during an event. The missing data could have lead to erroneous gauge adjustment and potentially had a detrimental impact on the hydrologic modeling results. More details on the performance of the ALERT rain gauges during this event are found in the next section.

events. Testing of the new protocol will take place at UDFCD during winter 2008/09.

4.4. Summary

This case study yielded inconclusive results due to inconsistencies in gauge reporting and lack of available stream flow data to verify the performance of hydrologic models. Using rainfall amounts on short time intervals of 5 minutes requires a reliable rain gauge network with few missing reports. In turn, the quality of gauge-adjusted radar rainfall relies on accurate and timely rain gauge reporting.

This study did prove that rain-gauge adjusted radar rainfall can be computed efficiently and easily input into the simplified hydrologic models running at UDFCD when provided in basin averaged format. Clearly more case studies are needed to compare the results of using the gauge-adjusted radar rainfall as input to the models versus rain gauges alone.

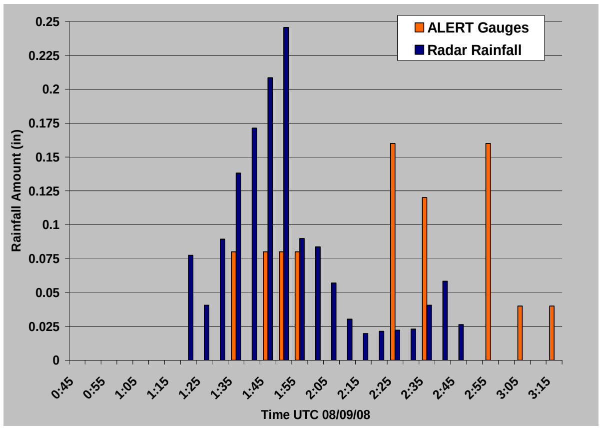

Figure 10. Graph to show a time series of ALERT Rain gauge reports (orange) and radar rainfall (blue) on 5 minute intervals for August 9, 2008.

Other studies completed at the Flood Control District of Maricopa County have been successful in using WDT 5 minute gauge-adjusted radar rainfall data to remove much of the model uncertainty in the most important hydrologic parameter. The gauge-adjusted radar rainfall was used to accurately calibrate parameters for floodplain delineation models.

There is certainly a need for accurate 5 minute rain gauge-adjusted radar rainfall so work will continue to further prove its utility and introduce it as a real-time input to hydrologic modeling.

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