## J2.7 Using Multiple-Sensor Quantitative Precipitation Estimation for Flood Forecasting in the Lower Colorado River Basin

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### 1. Introduction

The Lower Colorado River Authority (LCRA) utilizes flood forecasting models for the management of water systems in the lower Colorado River basin. The task of managing flood releases from the six Highland Lakes is of vital importance for the mitigation of risk to human life and property (Fig. 1.).

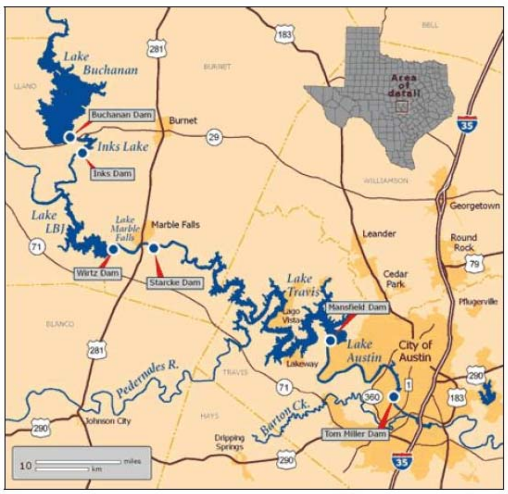



**Figure 1- Lower Colorado River Authority Highland Lakes and Dams**

The accuracy of flood forecasting is dependent on the precision of the estimated precipitation inputs and the modeled streamflow information. The goal of flood forecasting is to efficiently evaluate hydrologic information to determine the potential outcomes of release decisions in a timely manner. Further more, it is imperative that flood information is promptly and concisely disseminated.

After an evaluation of various flood forecasting models, the LCRA recommended the US Army Corps of Engineer's Hydrologic Engineering Center's (HEC's) Corps Water Management System (CWMS) as the best software package to assist in the operation of the Highland Lakes and dams (USACE, 2002a). The data acquisition module of CWMS provides access to the real-time multiple sensor gridded rainfall data provided by Weather Decision Technologies INC (WDT) through a custom Hydromet Decision Support System (HDSS), developed in collaboration with the National Severe Storms laboratory (NSSL) and deployed specifically to support operations at the LCRA.

This paper will describe the multiple sensor quantitative precipitation estimation (QPE) component of the HDSS and provide an overview of the CWMS flood forecast decision support system that utilizes the QPE. A rainfall event from 2005 will be used to demonstrate the flood forecasting procedure at LCRA.

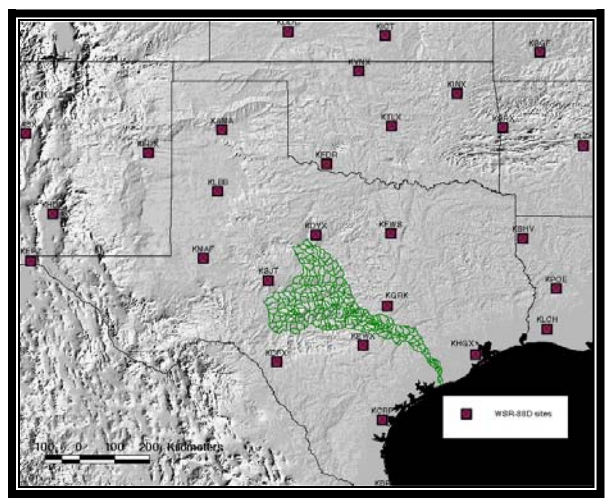


**Figure 2-The LCRA-defined domain for HDSS showing the location of the 24 WSR-88D radars used for QPE. The LCRA basin is delineated in green.**

### 2.HDSS data sources

The HDSS accesses NEXRAD Level II base radar data in real time from 24 radars in Oklahoma and Texas providing complete and redundant coverage of the LCRA river basins and the larger LCRA-defined domain (Fig. 2). The HDSS utilizes a variety of other meteorological data from multiple sensors such as Gauge, Satellite and numerical model data to produce a full suite of multiple-sensor QPE on high temporal and spatial scales .The Level II radar data are accessed from the nationwide NEXRAD network and collected in full volume scans every 4-6 minutes dependent upon VCP. The NEXRAD Level II reflectivity data has a resolution of 1 degree (azimuth) by 1km (gate-spacing) with a data precision of 0.5 dBZ and velocity data have a resolution of 1 degree by 250 meters with 0.5 m/s precision.

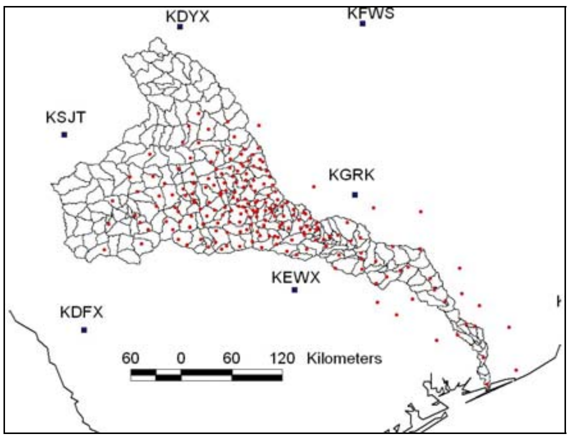



**Figure 3 - LCRA's 201 automated gauge locations (red dot).**

The HDSS ingests 201 rain gauges from an automated gauge network operated by the LCRA (Fig. 3). The LCRA real-time data collection system provides rainfall amounts at critical points in the basins main drainage areas. The rain gauge data are used to produce gridded gauge-only products using a Barnes interpolation schemes, to remove biases from radar derived precipitation and as ground truth to verify the full suite of quantitative precipitation products.

Other data ingested by the HDSS includes GOES satellite IR data that is available every 15 minutes at a 4km resolution and RUC numerical model data available hourly at a 20 km resolution.

2.1 HDSS algorithms

The HDSS comprises of a collection of algorithms that are either licensed from leading research organization subsequently enhanced and tuned by WDT or proprietary technologies developed at WDT. The HDSS 3D radar Level II mosaic algorithm, licensed from the NSSL, applies an automated quality control to remove non-meteorological artifacts, re-samples data to a 3D Cartesian grid and then mosaics data from individual radars using a distance weighting scheme plus interpolation. The HDSS future radar algorithm was licensed from McGill University as a software system known as MAPLE that predicts the evolution and movement of storms out to 4 hours. Finally the HDSS uses the Quantitative Precipitation Estimation Using Multiple Sensors (QPESUMS) algorithm to provide widespread precipitation estimates at a high spatial and temporal resolution in real time, overcoming limitations associated with the use of point rain gauge data alone.

This paper will focus on the QPESUMS aspect of the HDSS system and its utility in flood forecasting at the LCRA.

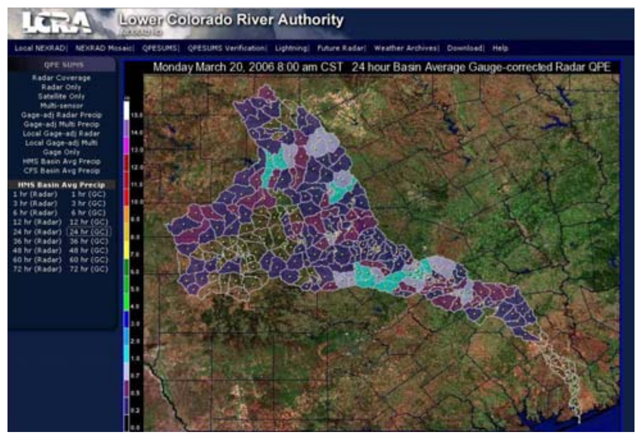



**Figure 4 - Sample Local gauge corrected basin average from QPESUMS.**

2.2 QPESUMS

The QPESUMS algorithm was developed at the NSSL and provides precipitation estimates for multi-hour precipitation accumulations using sophisticated algorithms. For the LCRA, precipitation estimates are provided on a 1 by 1 km grid with 5 minute updates. The precipitation rates are accumulated using hybrid-scan reflectivity fields to provide estimates of rainfall over the past 1, 3, 6, 24 and 72 hrs. In addition, basin average amounts are computed using the gridded output (Fig. 4). QPESUMS automatically integrates data from multiple sensors and applies techniques to overcome deficiencies associated with the use of radar data such as terrain blockages, limited coverage, beam geometry, bright band contamination, frozen hydrometeors and errors in Z-R relationships. The QPESUMS comprises of numerous components including an automated removal non-meteorological radar artifacts through quality control (QC) , application of differential Z-R based on precipitation type and phase, delineation between bright band or frozen precipitation and good radar sampling regions, application of satellite derived precipitation rates and bias adjustment using hourly rain gauge data . Details of these sub algorithms are provided below.

a) Bright Band Detection

The presence of a Bright band (BB) in radar data occurs due to the sampling of melting snow or ice and the result is an enhanced radar echo that leads to gross over-estimation of precipitation. This algorithm detects BB occurrences by searching for a horizontally homogeneous layer of strong reflectivity near to the radar. The height of BB is then indicative of the melting layer and this information is used in other algorithms within QPESUMS. Radar sampling within the melting layer is considered contaminated and efforts are made to reduce the potentially negative impact on QPE.

b) Convective versus stratiform segregation

Convective grid cells are flagged using this algorithm by searching the 3D reflectivity fields for reflectivity's greater than 40 dBZ or greater than 30dBZ above the -10 C isotherm. Studies have shown that different precipitation rates are associated with deep convective systems versus shallower stratiform situations. This algorithm applies differential Z-R relationships according to the stratiform /convective identification. This algorithm is executed for both radar-only (RAD) and Multi-sensor (MS) QPE products.

c) Satellite regression

For stratiform regions, the height of the freezing Level (determined by either RUC model data or the BB detection algorithm) infers the maximum sampling height for radar grid cells that are expected to result in "good" (higher quality) rainfall estimation and "good" snowfall estimation. For those grid cells containing "good" rainfall and "good" snowfall echoes, the appropriate Z-R and Z-S relationships are applied. These precipitation rates are plotted versus cloud top temperature and a regression is fit to the data. If a good relationship exists, this regression equation is used to apply rates to "bad" (poor quality) grid cells that are either contaminated by the BB or where frozen hydrometeors exist. This algorithm is only executed for the MS QPE precipitation products.

d) Rain Gauge-Only Estimates

A Barnes analysis technique is used to analyze the LCRA point gauge data on a 1 by 1 km grid. This technique uses a distance weighting scheme with an exponential weighting function. The gauge-only grid can ingest hourly gauge data and accumulates gauge data over multiple hours, updating all rainfall amounts when new data becomes available.

e) Rain gauge adjusted estimates

QPESUMS produces two key estimates of precipitation called Radar-Only (RAD) and Multiple-Sensor (MS). These products are corrected on an hourly basis using a spatially non-uniform bias adjustment technique called local gauge correction (LGC) and a mean field (domain-wide) adjustment procedure called gauge correction (GC). For LGC the difference between the gauge and QPE rainfall amount is computed at each gauge location and the results are analyzed to a 1 by 1 km common grid. The local bias field is added to the RAD/MS QPE field at each grid cell to yield the LGC QPE. For GC the sum of all point gauge amounts is divided by the sum of the QPE grid at each gauge location, the resulting mean bias is applied to the entire domain at every grid cell. Both GC and LGC products aim to remove inaccuracies that may occur due to inappropriate Z-R relationships and bright band contamination.

## 3. Corps Water Management System (CWMS)

The total surface area of the LCRA basin is 18,400 square miles draining to 481 miles of the Colorado River. The basin lies in a region of Texas that has come to be known as Flash Flood Alley. Over the years, flood forecasting computer models have become vital components of the operation of the six Highland Lakes and dams.

Historically, the LCRA staff relied on observer networks for information on real-time rainfall and stream flow data. However, since 1957, the evolution of weather radar detailing the areal extent and magnitude of storms combined with enhanced computing power has enabled the LCRA to increase response time in providing critical warnings to the public.

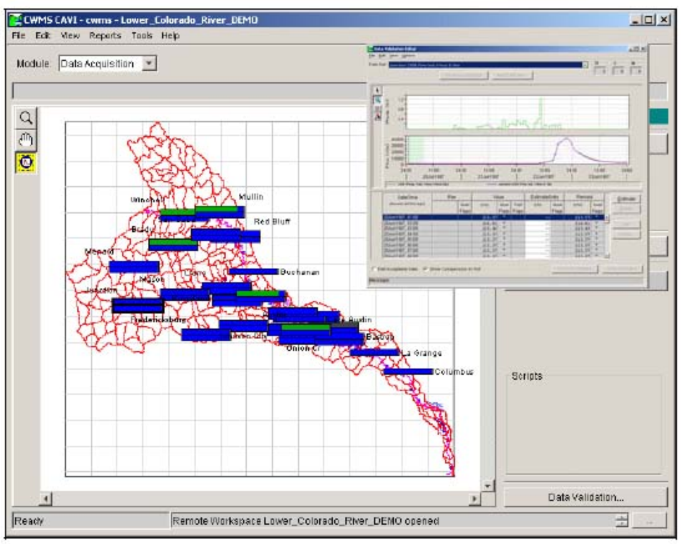



**Figure 5 - Sample CAVI data acquisition module at LCRA**

In the early 1980's, the LCRA began implementation of a real-time automated data collection system comprised of rain and stream gauges installed strategically in the basin's main drainage areas. These gauges were the primary input for the first real time flood forecast model in 1998, which simulated rainfall-runoff, reservoir operations and dynamic hydraulic routing. Since then, a number of flash flood models have been developed and tested. This has lead to great advancements in flood forecast capabilities that capitalize on new meteorological technologies.

The LCRA has implemented the HEC's CWMS to provide a comprehensive flood forecast decision support system that through the utilization of QPESUMS gridded rainfall enables the analysis and dissemination of real-time hydrologic and hydraulic information. CWMS consists of an integrated system of hardware, software and communications resources enabling data acquisition from a variety of sources, data storage in a relational database, model execution and data visualization. The control and visualization interface (CAVI) allows the user to set up watersheds, view data and run models in a client-server environment (Fig. 5).

Flood forecasting with CWMS is organized into four modules under the CAVI. Initially, the watershed is set up including details of sub-basins and routing reaches. The QPESUMS gridded rainfall products and point gauge data are acquired by and visualized in CWMS map-based environment. Next, the gridded rainfall or mean areal precipitation product from QPESUMS is fed into the hydrologic model to produce runoff hydrographs. Following this, predicted lake levels are computed by feeding the hydrographs into the reservoir operation model. Lastly, the lake levels and hydrographs are input to hydraulic models to produce water surface elevation profiles for the main stem of the Colorado River. Each of the modeling components are built in their respective applications first and then integrated within CWMS. Each modeling component will be discussed in the following section.

### 3.1 Hydrologic Modeling System

HEC's Hydrologic Modeling System (HEC-HMS) computes rainfall-runoff and is organized into the following two components within CWMS: the Meteorological Forecast Processor (MFP) which creates, manipulates, and organizes rainfall grids, and the Hydrologic Forecast Processor (HFP) which executes hydrologic calculations. Inputs to the model for the purpose of this simulation include gridded precipitation provided by QPESUMS and hydrologic parameterization the basin model. The model utilizes the ModClark unit hydrograph to simulate the storage and translation of runoff, the Initial and Constant-rate model to simulate abstractions and baseflow is calculated as a ratio of drainage area. HEC-HMS produces runoff time series hydrographs accessible through the CAVI that then provide input to the reservoir simulation component (USACE, 2001).

3.2 Reservoir Simulation System

HEC's Reservoir Evaluation System (HEC-ResSim) simulates reservoir regulation. HEC-ResSim utilizes inflow hydrographs in reservoir operation modeling for a variety of operational goals and constraints. Other inputs include reservoir characteristics, dam physical properties and regulation rule curves. Outputs provide information regarding reservoir storage, release and spillway flow and produce downstream hydrographs. The CAVI provides access to graphs and tables of reservoir elevation, inflow and outflow from HEC-ResSim (USACE, 2003).

3.3 River Analysis System

HEC's River Analysis System (HEC-RAS) calculates water surface profiles for the main stem of the Colorado River. HEC-RAS allows the LCRA to perform one-dimensional steady and un-steady flow calculations. The CWMS model interface module graphs and tabulates water surface profiles (USACE, 2002b).

## 4.0 Case Study : August 7-12, 2005

Since implementation of CWMS at the LCRA in 2005 there has been insignificant rainfall reported in the LCRA basins, with minimal stream response. Therefore, at the time of writing this paper, a case on August 2005 provided the best opportunity to date for investigation into the utility of the WDT HDSS system for flood forecasting at the LCRA.

**Table 1- LCRA 24 h rain gauge accumulations in inches**

| Date (end 12 UTC) 2006 | 08/08 | 08/09 | 08/10 | 08/11 | 08/12 |
|---|---|---|---|---|---|
| Max rainfall (in) | 0.63 | 1.00 | 0.8 | 1.72 | 0.00 |

4.1 Synoptic overview

A near stationary upper level trough was located over North Texas, positioned between a ridge of high pressure over Southwest and Southeast US. The middle to upper level low remained stalled allowing the continuous development of widespread showers and thunderstorms. By late afternoon on August 11th the trough of low pressure that persisted over south central Texas for the past 4 days, weakened significantly. A ridge of high pressure gradually spread south west from the Tennessee valley, strengthening as it moved into Texas. A drier, more stable atmosphere resulted and brought the end to this precipitation event. Table 1 shows the 24h maximum point rainfall measured by LCRA rain gauges during this event.

a) b)

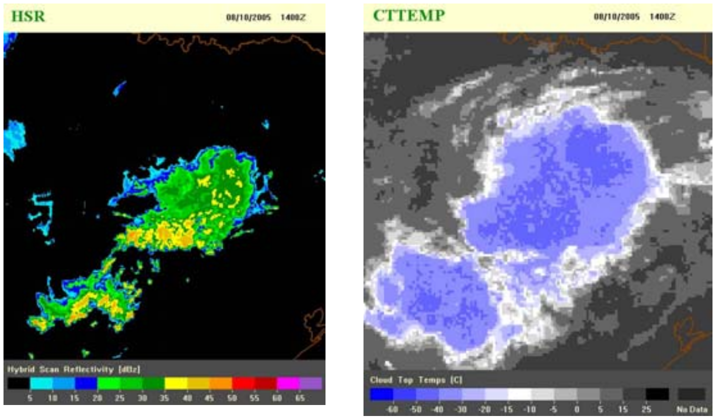



**Figure 6 - Snapshot of a) Hybrid scan reflectivity and b) Satellite IR cloud at on 08/10/05 at 1400 UTC.**

4.2 HDSS QPESUMS rainfall verification

Between August 7th and August 12th, 2005 a series of widespread storms developed over central and south central Texas (Fig.6). Light steering winds resulted in slow-moving storms with locally heavy rainfall, impacting the upper reaches of the

Lower Colorado River Basin. The maximum 24 hour point rainfall measured by gauges approached 2 inches during this event.

For brevity only the highest 24h rainfall period ending at 12 UTC on 08/11/05 will be discussed in detail (Fig. 7). The maximum gauge amount over the LCRA basins for this 24h period was 1.72 inches. The QPESUMS Radar Only product estimated a 24 rainfall amount of 1.8 inches. The maximum QPESUMS Local Gauge corrected product indicated a maximum rainfall amount of 1.68 inches.

a) b)

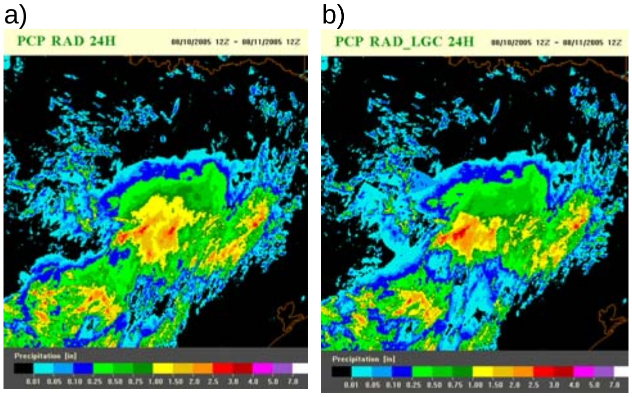


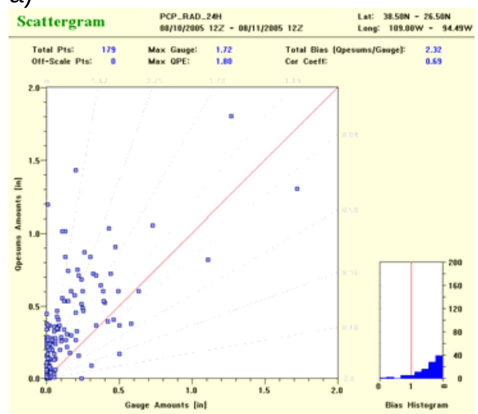

**Figure 7 - QPESUMS 24 h rainfall estimate ending 08/11/05 at 1200 UTC for a) RAD and b) LGC_RAD**

The bias (QPESUMS/GAG) was computed to show how the sum of all 24 h QPESUMS rainfall accumulations compared with the sum of collocated 24 h gauge reports. The RAD and LGC 24h data pairs are visualized via scatter plots shown in Figure 8. These scatter plots are created in real-time as tools for the LCRA for a quick-look at the QPESUMS data to assess their performance. In this case the scatter plots showed that the QPESUMS RAD estimate had a moderately strong correlation coefficient of 0.69 but a poor bias of 2.32, indicating overestimation. The QPESUMS LGC product shows a significant improvement with a stronger correlation coefficient (0.82) and a Bias closer to 1 (1.23). Overall the LGC provided the best QPE, showing a marked improvement over RAD.

4.3 CWMS Flood forecasting

Both RAD and LGC QPESUMS products were used as input for the CWMS system for the entire duration of this event, August 7 – 12, 2005. A time of forecast (TOF) of August 12, 2005, 7:00 PM CST was chosen to ensure that all rainfall would be included in the hydrological analysis. The HEC-HMS model was calibrated to peak flow at the Colorado River near San Saba, TX gauge (USGS 08147000) for the LGC simulation**.** Observed streamflows were not blended to simulated flows in this calibration

a)




b)

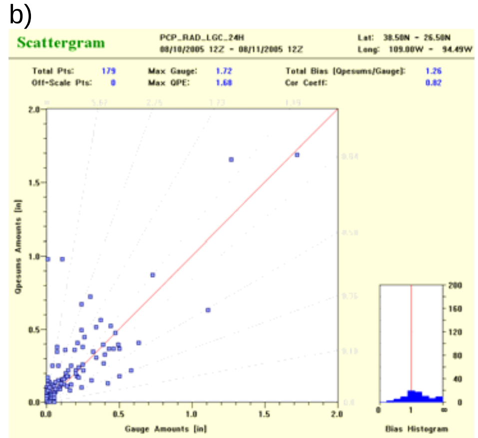



**Figure 8 - 24 h Scatter plots of gauge amount (x axis) versus QPESUMS estimate (y axis) in inches for a) RAD and b) LGC_RAD**

in an effort to concentrate the analysis on the precipitation input. Initial losses for one zone of subbasins were increased by 50% and constant-rate losses for three zones of subbasins were also increased by 50%. These changes are summarized in Table 2.

**Table 2 – Calibration Values for CWMS**

| Zone | Area (sq. mi.) | Initial Losses (in) | | Constant – Rate Losses (in/hr) | |
|---|---|---|---|---|---|
| | | Initial | Modified | Initial | Modified |
| Mullin | 2,074 | 0.86 | 1.29 | 0.19 | 0.29 |
| Menard | 1,137 | 2.3 | No Change | 0.12 | 0.18 |
| Winchell | 1,140 | 1.76 | No Change | 0.23 | 0.35 |
| Brady | 499 | 2.81 | No Change | 0.24 | No Change |
| San Saba | 1,411 | 2.1 | No Change | 0.29 | No Change |
| Red Bluff | 920 | 1.53 | No Change | 0.17 | No Change |

Figure 10 shows the hydrologic sub-basins outlined in red. Adjustments made to the model are applied to strategically grouped zones of sub-basins. The zones associated with this simulation are those colored in the graphic. This zonal arrangement expedites the real-time calibration process while maintaining the hydrologic model's finer detail.

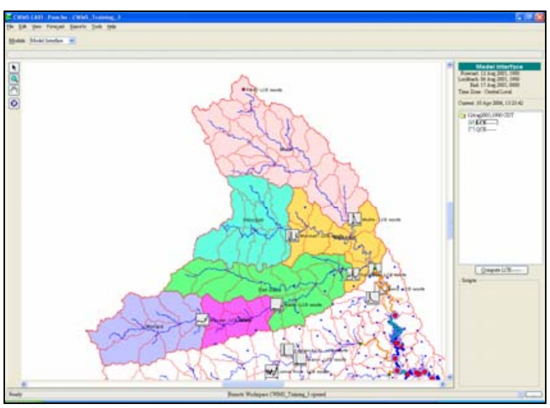


**Figure 10– Precipitation and Hydrologic Zones Draining to the Colorado River near San Saba, TX streamflow Gauge.**

This calibration process brought the simulated peak flow to within 7% of observed. The resulting sub-basin mean areal precipitation and streamflow hydrograph for the LGC QPESUMS product is presented in Figure 11.

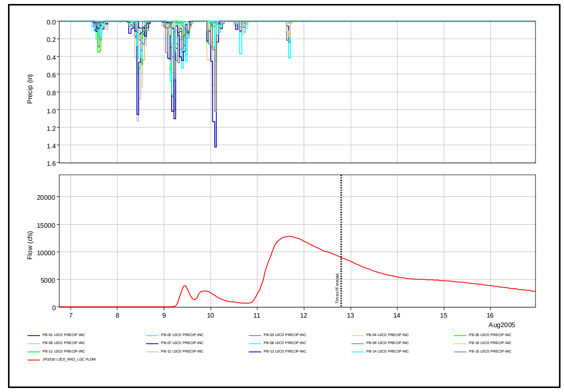


**Figure 11 – LGC Mean Areal Precipitation and Streamflow Hydrograph For Colorado River near San Saba Gage**

The RAD data was then run on this same calibration for comparison. Figure 11 presents the resulting RAD hydrograph compared with LGC and observed. The RAD hydrograph has a peak flow of 22,808 cfs compared with 12,805 cfs for LGC and 12,051 cfs observed. These results concur with the discussion in section 4.3 that the RAD is indicating higher values than LGC.

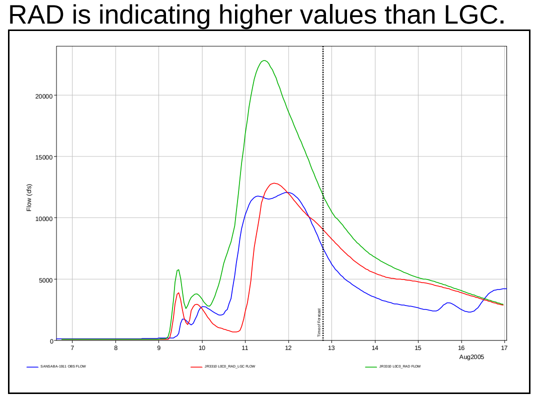


**Figure 12 – LGC (in red), RAD (in green) and Observed (in blue) Streamflow Hydrographs For Colorado River near San Saba Gage, August 2005**

A summary of peak flow and total volume shown in Table 3.

**Table 3 – Peak Flow and Total Volume, Simulated and Observed at Colorado River near San Saba, TX Gage**

| | RAD | LGC | Observed |
|---|---|---|---|
| Peak Flow (cfs) | 22,808 | 12,805 | 12,051 |
| Volume (acre-ft) | 134,213 | 89,475 | 79,056 |

The flows generated by the hydrologic component, HFP, are routed through the CWMS ResSim model to calculate projected reservoir elevations. Figure 13 is a chart for Lake Buchanan the uppermost reservoir in the Highland Lakes. The upper portion of the chart displays the climb in the reservoir's water surface elevation in ft NAVD88 and the lower portion displays inflow and outflow in cfs. This minor event required extended generation time through Buchanan Dam's turbines as shown by the green line in the lower portion of the chart. The reservoir remained below its normal pool elevation of 1020 ft. The HEC-RAS model was not executed for this forecast as flows were not high enough to necessitate a calculation of water surface profile for Lake Buchanan.

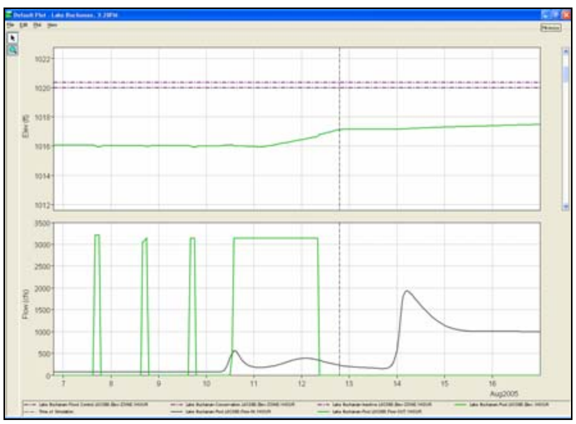


**Figure 13 – HEC ResSim Output for August, 2005**

## 5. Summary

Real-time Quantitative precipitation estimates are provided to the LCRA through a Hydromet Decision Support System customized and supported operationally by WDT. The suite of precipitation estimates are produced by the QPESUMS algorithm, developed at the National Severe Storms Laboratory. The local gauge corrected radar-only (RAD-LGC) QPESUMS product is used by the LCRA in real-time as input into the Hydrologic Engineering Center's (HEC's) Corps Water Management System (CWMS), a software package to aid the operation of lakes and dams and for flood forecasting in Lower Colorado River basin. The case study discussed in this paper shows that using RAD-LGC QPESUMS rainfall, peak streamflow can be estimated to within 7 % of observed streamflow. The RAD-LGC QPESUMS input produces stream flow estimates more accurately than the radar-only (RAD) QPESUMS. A multiple sensor approach to QPE, in which gauges are used to correct the gridded radar rainfall, consistently produces more accurate rainfall estimates than using radar alone and enhances the performance of flood forecasting at the LCRA. However the RAD estimates are suitable for use as a redundancy measure if problems occur in the receipt of rain gauges due to technical failures.

Since writing this paper, the LCRA have learned that in recent convective storms where large hail occurred, the RAD-LGC may not be preferable in some circumstances. The presence of small scale convective cores lead to local overestimation of RAD rainfall and if they were not exactly co-located with gauge locations, corrections by gauge were not large enough to match true rainfall. In this situation the RAD-GC QPESUMS product (mean field gauge corrections) performed very well.

The LCRA has plans to continue studying events as they arise to evaluate QPESUMS further and determine which type of QPE product performs best under various weather regimes influences over the LCRA basins. This includes study of stratiform, convective and tropical systems.

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