10.2 AUTOMATIC GAGE-ADJUSTED RADAR RAINFALL ESTIMATION FOR REAL-TIME STORM WATER CONTROL

Leiji Liu*, Brian Hoblit, Rick Jensen, and David Curtis
OneRain Inc., Orangevale, CA

1. Introduction

Accurate rainfall estimation is an important issue in research and engineering fields. The traditional approach is to use a number of rain gages to create the spatial and temporal rainfall distribution by using Thiessen polygons, inverse distance squared weighting, or statistical Kriging techniques. The rainfall estimates are marred by the sparse distribution of rain gages in the network, and the events that occurred between gages are often not captured by gages. Since the release of the WSR-88D (NEXRAD) radar in the early 1990s, attempts to accurately estimate rainfall by radar have been made, but radar rainfall estimates, by themselves, are not always consistent with rainfall estimates made by ground-based rain gages.

Gage-adjusted radar rainfall estimates combine the advantages of both radar and gages. The radar captures the temporal and spatial characteristics of rainfall and the gages measure the actual rain falling on the ground. Different gage adjustment techniques are available such as single parameter adjustment, distance-related adjustment (i.e., Brandes 1975), and statistical approaches. Each technique has its own advantages and disadvantages. For smaller area with fewer gages, single parameter adjustment often produces satisfactory results.

2. Project Background

Jefferson County, located in north central Kentucky along the Ohio River, covers an area of approximately 1,010 km^2 (390 mi^2). The City of Louisville covers 162 km^2 (62.5 mi^2) and is located in Jefferson County. The City of Louisville/Jefferson County Metropolitan Sewer District (MSD) contracted NEXRAIN Corp. (now OneRain Inc.) to build a radar rainfall data system that is integrated with MSD's existing rain gage network, computer network, telemetry system, web page, combined sewer overflow (CSO) program and emergency response initiatives. The CSO program includes an innovative real-time control (RTC) system to automatically manage sewer flows. The radar rainfall system is a hardware/software package designed to ingest gage and radar data, adjust the radar data with the local gage data, serve rainfall images to the Internet and Intranet, and create output data files. These output data files seamlessly integrate with MSD's geographic information system (GIS), the RTC system, and with MSD's Oracle database for future use. The system also includes a radar rainfall forecast feature that provides predicted rainfall over the next 60 minutes.

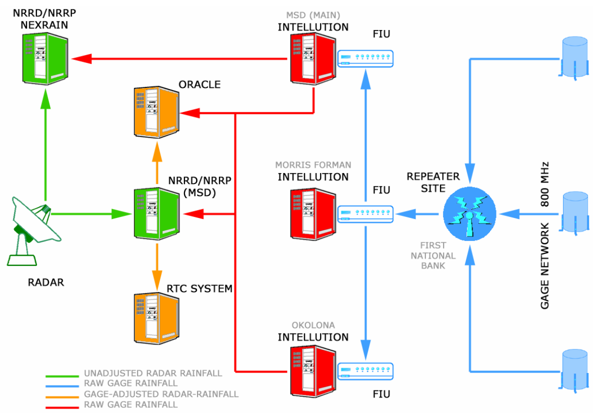

Figure 1: NEXRAIN Radar Rainfall Data System

Figure 1 shows a schematic of how the NEXRAIN Radar Rainfall Data System works. Starting on the right of the figure, data from MSD's telemetry gage network is sent (blue line) to a repeater, where it is then sent (blue line) to three base stations: MSD's main office, Morris Forman, and Okolona. Each of these locations temporarily stores the data in a SCADA (Supervisory Control And Data Acquisition). The rain gage data are then sent (red line) to three locations: to the NEXRAIN Radar Rainfall Processing (NRRP) machine at MSD's main office, to the redundant NRRP at OneRain's office in Orangevale, California, and to MSD's Oracle database. OneRain has established two radar feeds from its radar provider and each of these feeds sends (green line) raw radar rainfall data to the NRRP in the MSD's main office and to the NRRP in Orangevale, California.

Each NRRP independently calculates the gage-adjusted radar rainfall estimates. The NRRP at MSD's main office sends the gage-adjusted data to an FTP site where it can be ingested into the RTC and into the Oracle database and serves images of the gage-adjusted radar rainfall estimates to the MSD Intranet through NEXRAIN Radar Rainfall Display (NRRD) machine. The NRRP in Orangevale, California, currently serves data to the Internet and can be configured to deliver data to the RTC and to the MSD Oracle

* *Corresponding author address*: Leiji Liu, OneRain Inc., 9267 Greenback Lane, Suite C4, Orangevale, CA 95662. Email: leiji.liu@onerain.com.

database if one of the processes goes down. Thus, the NRRP/NRRD System is a completely redundant system that allows for the continuous processing of gage-adjusted radar rainfall data.

3. Data

The raw radar data is supplied from Baron Services Inc. The raw radar data covers entire continental United States (national mosaic data set) with spatial resolution of approximately 1km by 1km and temporal resolution of 5 minutes. OneRain processes the data and saves the data into its own data format and algorithms are used to extract the specified study area. A predictive data feed from local radar site KLVX is also used to predict the rainfall out to 60 minutes.

The study area covering City of Louisville/Jefferson County is a rectangle with longitudes between -86.214 and -84.845 and latitudes between 37.717 and 38.786 (133 column by 120 rows of radar pixels). The total number of radar pixels is 15960.

Gage data are obtained from 15 gages operated by MSD. The gage data are QA/QC'ed in real-time. Gage data not satisfying QA/QC criteria are removed from the processing. There is also a configuration file to manually remove problematic gages. Other QA/QC methods, such as dynamic updating of the configuration file by using correlation coefficients, are in development.

The output files are gage-adjusted radar rainfall estimates in ASCII format in 10-minute intervals, as specified by MSD. Notes files are also created at each time step to indicate the quality of the adjusted radar data.

4. Radar Adjustment Methodology

Currently, a simple uniform adjustment algorithm is used for the study. The procedure determines a ratio based on hourly radar and gage data by dividing the average rainfall measured at all of the valid rain gages by the average radar rainfall estimates at the radar pixels over the valid rain gages.

$$\text{Ratio} = \Sigma R_g / \Sigma R_r \qquad (1)$$

This gage-radar ratio is then multiplied by the radar fields for each time period (10 minute) and the result is a gage-adjusted radar rainfall dataset that maintains the spatial signature of the radar data while incorporating the volume estimates from the rain gage network. Hourly data are used for gage-radar ratio computation to eliminate the timing mismatch between radar and gage datasets. This procedure has been successfully employed in numerous studies (Hoblit and Curtis 2000, Hoblit and Curtis 2001).

5. Hardware

The hardware for radar rainfall processing includes two parts: the processor (NRRP) and the display (NRRD). The NRRP is a SUN FIRE V100 server with OS Solaris 8 and the NRRD is a Dell Pentium 4 machine with OS Windows 2000 professional. NRRP is used for processing gage and radar data and NRRD is for image display. Samba was installed on the NRRP to communicate with the Windows-based NRRD. The two machines are attached into local network so the output files can be transferred to other locations easily.

6. Software Development

ksh script and C language are used to develop the codes. Each module accomplishes specific tasks so maximum flexibility can be achieved (Figure 2). Figure 2 shows the process flow chart. The blue boxes are the program modules. There are three FTP processes running simultaneously to deal with data feeds (national mosaic radar rainfall estimates from Barons and local radar predictive data feed from Barons, and the gage data feed from MSD). Once the data arrives, other processes run sequentially to reformat or reproject the data, extract the study area, and do the adjustment. The standard output are CSV files where only non-zero values are stored to save storage space. GIF image files and customized files are created based on the standardized CSV files. The customized files are transferred to other locations for RTC (Real Time Control) and to the Oracle database.

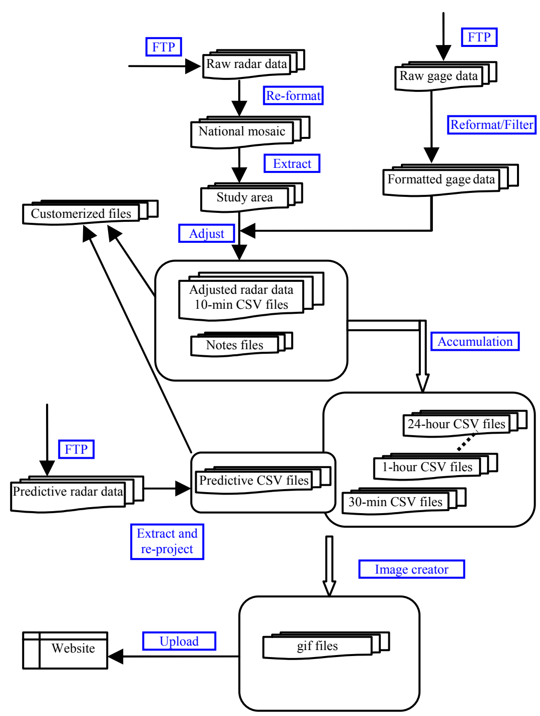

Figure 2: Process Flowchart

The adjustment process is the main module of the NRRP software package. The process takes the raw radar data and gage data, computes the gage-radar ratio, applies the ratio to the entire radar field, and outputs the CSV files data to indicate the quality and status of the output files. Maximum and minimum values are set for the gage-radar ratios to prevent wildly varying adjustments from time step to time step. If the gage data are not available, the final estimates are unadjusted; if the radar data are not available, the gage data are interpolated; if both are not available, -9s are filled in to indicate missing data.

A "Notes" file which is associated with the output CSV file indicates the file creation date and time, the gage-radar ratio, and the quality of the data. The quality flag is a one-character indication as follows.

A Current and predicted rainfall values calibrated with gages.

B Radar data not available; current rainfall estimates based on gage readings; predicted rainfall not available.

C Gage data unavailable; estimates from radar and predicted estimates not calibrated.

D Predicted data not available; current radar rainfall data calibrated with gages. Note that predictive rainfall is not available when there is no rainfall, thus the NRRP will operate under the D status for the majority of the time.

E Gage and predicted rainfall data not available; current radar data not calibrated with rain gages.

F Radar, rain gage, and predicted rainfall data all unavailable. This level would only be reached when all data sources are unavailable which would probably only occur during a major communication failure.

At each time step, the CSV files are reformatted to a customized format for delivery to MSD. These deliverable files can be directly ingested into MSD GIS system. The customized file is in ASCII format with the first line as:

Pixel,TYYYYMMDD_hhmm_flag,T10,T20,T30,T40,T50,T60,T70,T80,T90,T100,T110,T120

Where the **Pixel** is the pixel list of the study area pre-defined as the starting point from the lower left corner, **YYYYMMDD** is the date of the data; **hhmm** is the hour and minute of the current data, **flag** is to indicate the data quality (from the Notes file). **T10**, **T20**, …, **T120** indicate the predictive rainfall estimates of time periods 0-10 minute, 10-20 minute, …, 110-120 minute ahead of current time.

The images created are stored in local machine for NRRD display and FTP'ed to the website as well. Figure 3 shows a snapshot of the web site display.

There are also other processes running to backup gage data, radar data, output rainfall estimates, and clean up excess image files and intermediate files.

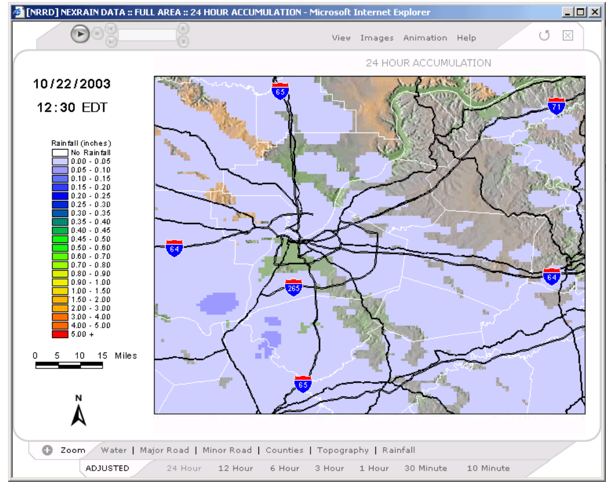

Figure 3: NRRD rainfall display

Most processes are started from cron table periodically. Each time the processes start, they will check to make sure the proper files are available. If there are any files missing, appropriate actions will be taken to handle the missing data. Thus, the system is robust enough to handle most conditions and runs continuously.

7. Conclusion

The NEXRAIN Radar Rainfall Data System has performed very well since it was installed in MSD in October 2002. A comprehensive comparison and study of radar rainfall estimates and gage data is under way.

9. References

Brandes, E.A., 1975, "Optimizing Rainfall Estimates with the Aid of Radar", *J. of Applied Meteorology*, 14(7): 1339 – 1345.

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