Radar-Rainfall Estimates in Florida During the 1999 Hurricane Season

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Abstract

An active 1999 hurricane season brought several significant hurricanes, tropical storms, and other heavy rainfall events to the Florida Peninsula. During this period, high-resolution gage-adjusted radar-rainfall estimates were developed for the entire state. Radar-rainfall estimates from a mosaic of overlapping radar coverages in Florida were combined with local rain gages from northeastern Florida to create a composite data set of gage-adjusted radar-rainfall estimates on a 2 km x 2 km grid every 15 minutes.

This paper presents comparisons between gage measurements and the resulting radar estimates. The results will focus on a 12,400 square mile area in northeastern Florida containing 97 rain gages.

The results are quite promising. For example, the R-squared correlation coefficient for storm totals (gage & gage-adjusted radar) from Hurricane Floyd was 0.87. Example gage-radar scatter grams, gage-radar rainfall accumulation charts, and maps will be presented.

Perhaps the most important result from radar-rainfall estimates is the improvement in the spatial definition of rainfall when compared to the spatial definitions derived from rain gages alone. Conventional techniques for distributing rainfall such as inverse distance-squared, Kriging, or Thiessen polygons often severely distort our understanding of the true rainfall distribution. Conventional techniques are also geometrically static and fail to convey storm dynamics to hydrologic models. High resolution radar-rainfall estimates not only provide a better definition of the volumetric distribution of rainfall at each time step, the high resolution data also better communicates storm dynamics to hydrologic models, which leads to more consistent model results.

Introduction

The inability of rain gages to adequately resolve the spatial distribution of rainfall volume entering a watershed is why meteorologists, hydrologists, and engineers have looked to radar as an alternative tool to measure rainfall. Ever since rainstorms were first observed with early military radars in England during World War II (Atlas, 1990), hydrologists have held out hope that radar could reliably estimate rainfall accumulation.

The idea is compelling. Raindrops falling through the atmosphere reflect radar signals. The strength of the reflected signal provides an estimate of the rainfall rate and integrating the rainfall rates over time yields accumulated rainfall. Since radars scan regions continuously, radars, in theory, can provide a continuous estimate of the spatial variability of rainfall - the perfect solution to the problem of defining total rainfall volume.

Unfortunately, for most of the 50 years since rain storms were first observed by radar, radar-rainfall estimates have not be accurate enough nor consistent enough to be useful to hydrologists. In the 1980’s, as the National Weather Service planned to deploy the WSR-88D radars (Hudlow, 1989), it was expected that reliable radar-rainfall estimation was possible. The new radars were

Figure 1: SJRWMD area of responsibility

more powerful and more sensitive than their predecessors. In addition, the new radar network was more dense with many parts of the eastern United States covered by 2, 3, 4 or even 5 radars simultaneously.

While the WSR-88D radars represent a great meteorological success story, they have not provided the final solution to the rainfall estimation problem. It is now generally accepted that rain gages, despite their deficiencies, remain an important part of the rainfall estimation solution (Fulton, 1997).

What exists today are two different measurement tools, each with its own strengths and weaknesses. The strength of a rain gage is its ability to measure rainfall at a point. Its weakness is the lack of insight to what is happening in the vast areas between gages. The strength of radar is its ability to define the spatial variability of rainfall. Its weakness is still its relative inability to consistently describe the absolute depth of rainfall at a given location.

The task at hand is to determine how to maximize the strengths of each measurement system while minimizing their individual weaknesses. The desired result is a merged data set that is consistent with the desirable and familiar characteristics of a rain gage network while preserving the valuable spatial information available from radar.

Project Description

The St. Johns River Water Management District in northeastern Florida (Figure 1) maintains an extensive monitoring program that includes instrumentation to measure the quantity and quality of the District's water resources. Rainfall measurement is one of the District's key water resource monitoring activities and is currently accomplished by a network of 113 automatic telemetered rainfall measurement stations, 16 recording rain gages, and 99 manually observed gages.

The District covers approximately 12,400 square miles. The District's average telemetered rain gage density is one gage per 110 square miles, which means that the average distance between telemetered gages is on the order of 10-11 miles.

Florida's rainfall is highly variable, with extreme differences in rainfall totals frequently observed over relatively short distances. An accurate understanding of the true spatial distribution of rainfall is vital to an accurate accounting of the volume of water entering the District. While it is possible to deploy more rain gages, it is not economically feasible to install enough to gages to achieve the level of accuracy needed to meet the District's needs. Therefore, the District has chosen to explore new technologies to more completely and accurately define the spatial and temporal distribution of rainfall entering the District's water resource systems.

During the period from December 1, 1998, to Septembert 30, 1999, the District conducted a pilot project to evaluate gage-adjusted radar-rainfall estimates. The District provided 15-minute rainfall data from a network of 97 rain gages for comparison with radar-rainfall and for use in preparing the gage-adjusted radar-rainfall estimates. The gage locations are shown in Figure 2.

Figure 2: Pilot project gage locations (97)

Radar-Rainfall Estimation

With approximately 160 WSR-88D radars currently deployed by the National Weather Service, the Federal Aviation Agency, and the Department of Defense, the national radar network is nearly complete.

Eleven overlapping WSR-88D radars provide coverage of the Florida peninsula,of which, six cover the District (See Figure 3). Half of the District receives coverage from at least three different radars. The six radars covering the District include:

- Jacksonville,
- Tampa Bay,
- Melbourne,
- Miami,
- Tallahassee, and
- Moody AFB, GA.

Raw radar-rainfall estimates obtained from WSI Corporation were used in the project. In the late 1980's, WSI developed a mosaiced radar product that seamlessly integrated radar reflectivities for all US radars into one national image called NowRAD™. The system was designed to handle the older National Weather Service WSR-57 and WSR-74 radars as well as the new WSR-88D radars, enabling a smooth transition to the NEXRAD era.

Radar reflectivity at WSI is processed through two rigorous machine QA/QC procedures and one human quality control process performed by an experienced operational meteorologist. Ground clutter, test patterns, speckles, spikes, false echoes, and other anomalous features are addressed. One example of the human input is at the QA/QC workstation. The meteorologist compares the latest radar images with the latest satellite image. If radar echoes appear where satellite images show cloud-free conditions, the meteorologist can assume that the radar returns are false and remove them from the radar data set. This aggressive three-phase QA/QC procedure helps provide clean high quality data to the precipitation processing algorithms.

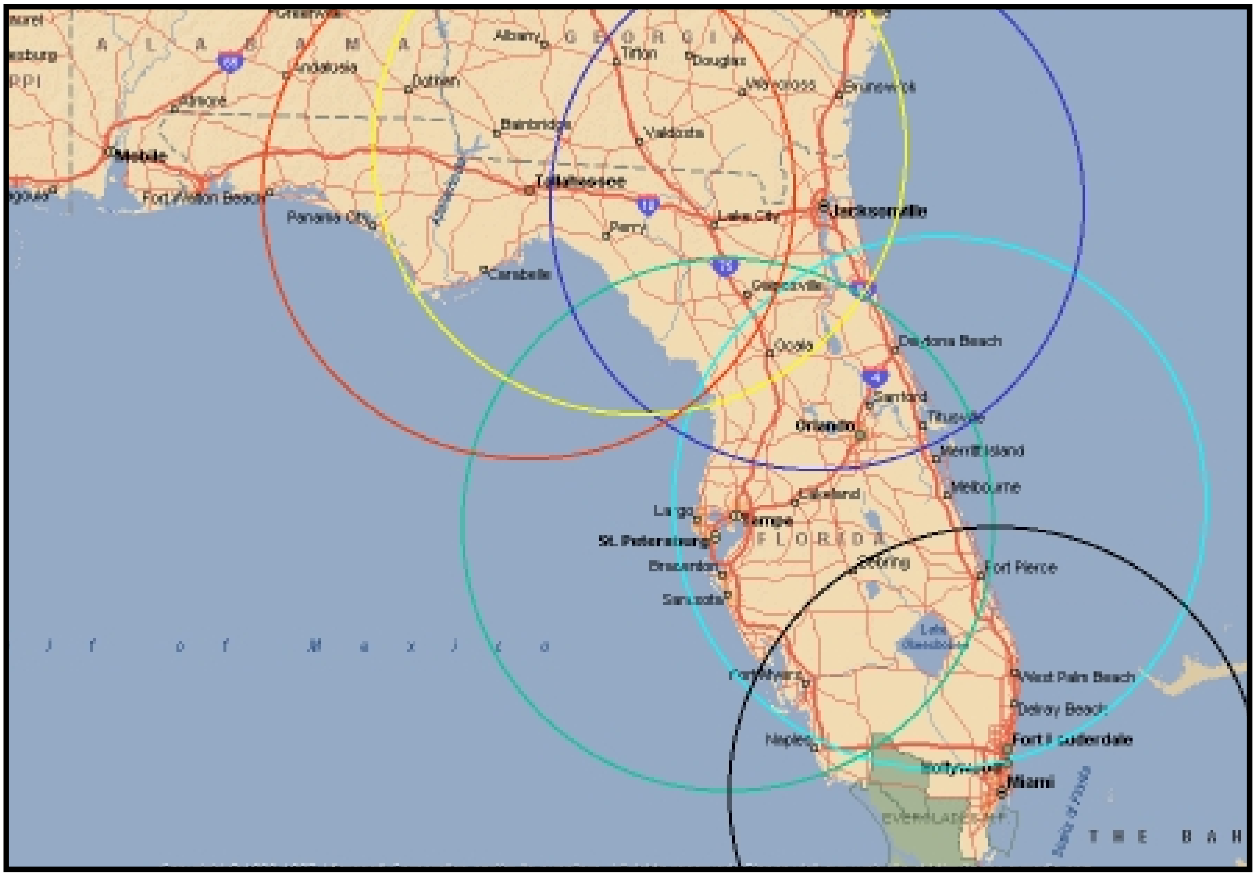

Figure 3: Radar coverage areas for the St. Johns River Water Management District

Shortly after introducing NowRAD, WSI began development of a rainfall accumulation product. WSI's early research confirmed that a precipitation algorithm based on a single radar reflectivety to rainfall intensity relationship was inadequate to account for the varied meteorological conditions producing rain. This conclusion led WSI to develop a new approach to rainfall estimation based on two key features:

1. Using mosaiced radar reflectivities as input to the precipitation estimation routine process, and
2. Using a dynamic weather-condition-based rainfall estimation algorithm.

WSI introduced their rainfall accumulation product called PRECIP in 1992. PRECIP is a nationwide data set of 15-minute rainfall accumulations produced on a 2-km x 2-km grid.

Many of the problems associated with single site radar-rainfall estimation are eliminated or, at the very least, minimized when using a multi-radar or mosaiced approach. For example, path attenuation and wet radome can cause lower than expected reflectivities. If several radars are available to look at the same location, there's a good chance that one of the radars will have a viewing angle that produces a better image of the target rain cell. Ground clutter effects near radar towers can also be overcome by overlapping radar coverages. Using data from overlapping radars also reduces range effects, beam blockage, and partial beam filling problems associated with single site radar-rainfall estimation.

Gage-Adjusted Radar-Rainfall Estimates

Rain gages and radars are difficult to compare directly because they measure the same physical process in two fundamentally different ways. Radar estimates the ***average*** rainfall over an entire 2 km x 2 km radar pixel. Rain gages essentially sample rainfall at a *point* often measuring less than 0.000000028 square miles (e.g. a 12 in. diameter rain gage). Within a given radar pixel, the rain gage observation is a function of the gage's location within the pixel. Figure 4 shows a hypothetical example of the *true* distribution of rainfall along one slice through a radar pixel. The radar estimate is the average across the entire pixel but the rain gage measurement depends upon the gage's location along the slice. Both observations can be exactly correct yet both observations can be significantly different.

If there is just one pixel-gage pair of rainfall estimates, there is no way of knowing which measurement is *correct*. But, if there's no way to determine which estimate is correct, how can one determine that the radar estimates need adjustment, as is commonly assumed?

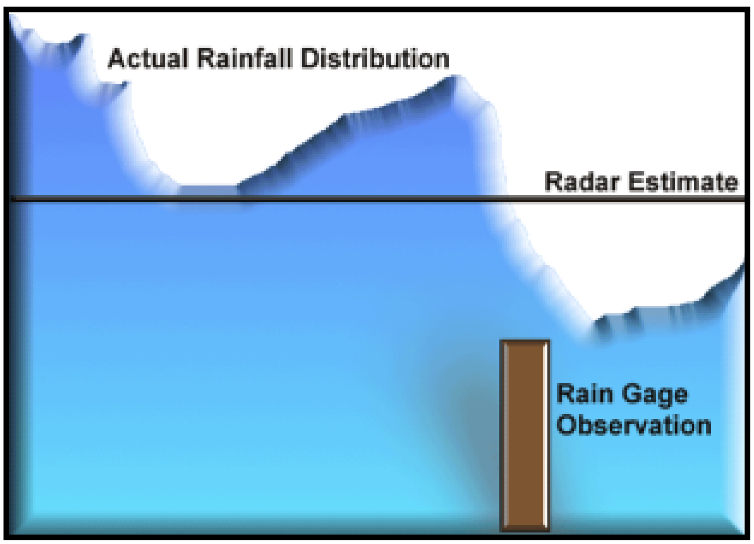

Figure 4: hypothetical example of the true *distribution of rainfall along one slice through a radar pixel*

Now consider the case where several gage-pixel pairs are available. With several gage-pixel pairs to evaluate, some statistical inferences can be drawn regarding radar performance. In each pixel where a gage is randomly located, it is expected that sometimes a gage will sample a low spot in the intra-pixel rainfall distribution and sometimes a gage will sample a high spot. If the average of the gage observations is about equal to the average of the associated radar pixel observations, then the radar data field is said to be unbiased relative to the rain gage observations. However, if the average of the gage observations is different than the average of the radar pixel observations, the radar data field is said to be biased.

If a bias between the radar and gage observations is found, the natural inclination is to eliminate the bias by correcting the radar estimates to the gage estimates. However, the bias computation only reveals the differences between the average gage and average pixel. It doesn't say anything about the direction of the correction, which data field needs correction or if both fields need correction. The inclination to correct the radar data to the rain gage data comes from hydrologists' long standing familiarity with rain gages, the relative lack of confidence in radar data, and the convenient assumption that rain gages are correct in the first place.

Precipitation adjustments may be made if a bias between rain gage observations and radar-rainfall estimates is detected. One common approach is to assume that if a bias detected between radar and rain gage estimates, it is the radar estimates that need adjusting. A uniform multiplier based on gage-radar differences is used to scale the entire data field. The simplest multiplier is formed as the ratio of the average gage observation and the average associated radar-rainfall estimate for each time period. This ratio is known as the Gage/Radar ratio, or the G/R ratio. The technique is also called the *mean-field adjustment* as the entire data field is scaled by the same amount.

The G/R ratio has three important features:

1. It is simple and computationally efficient,
2. It exactly preserves the areal characteristics of the radar estimates,
3. The average of the rain gage observations is exactly equal to the average of the adjusted radar-rainfall estimates at the pixel where gages are located.

The simple G/R ratio technique is intuitively robust and optimal in the sense that the technique exactly preserves the areal information content of the radar observations and it exactly preserves the volumetric information represented by the rain gages. In this context, the radar data field is simply used as a template to describe the areal distribution of rainfall at each time period. Scaling is done to make the radar data consistent on average with gage observations.

September 1999 Results

For each month from December 1998 to September 1999, NEXRAIN reviewed the data from the 97 District rain gages used in the study. Missing data periods were identified for each gage. Any gages with irregularities, unreasonable data values, or other discrepancies were flagged and the data for these gages were removed from the analysis, either all or in part depending on the nature of the problem.

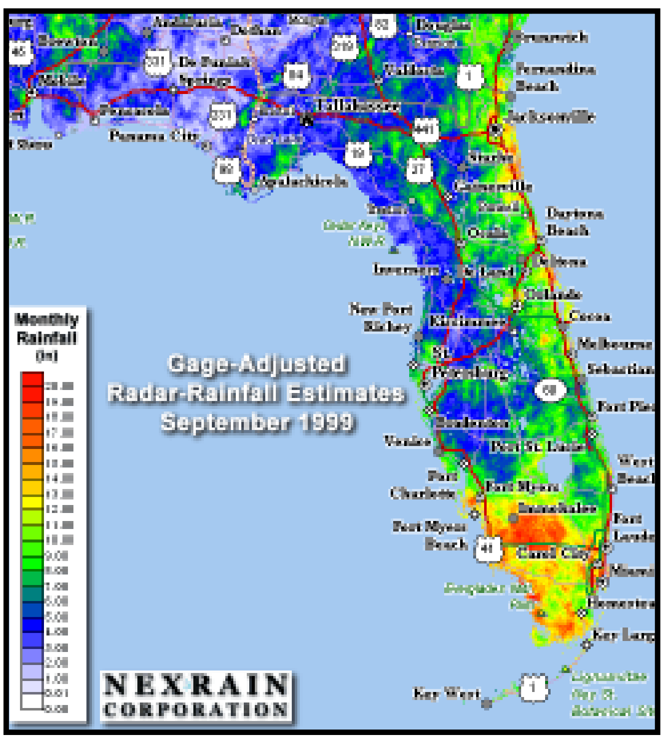

Figure 5: Gage-adjusted radar-rainfall estimates for September 1999

Next, the 15-minute data for the individual radar pixels associated with each rain gage location were extracted from the master radar data set and compared to gage data. The master radar data set for this project covered an area bounded on the west by 88° 27’04” West longitude, on the east by 79° 24’ 26” West longitude, on the south by 24° 15’ 27” North latitude and on the north 31° 33’ 03” North latitude, which covers the entire State of Florida (See Figure 5)

If any unreasonable differences were identified between the gage and radar rainfall accumulations during the month (i.e. volume, timing, etc.), the individual gage-radar data pairs were excluded from the analysis. This prevented unreasonable individual differences between the gage and radar observations from dominating the analysis. Considering data excluded for various reasons,inimum gage availability during any one 15-minute period ranged from a 64% June 99 to 96% in April 99.

After the gage data were quality checked, gage/radar ratios were computed for each 15-minute time step using average rainfall estimates for the previous hour. Hourly volumes were used in the gage/ratio computations to smooth the 15-minute adjustments and to help account for any timing mismatches between gage and radar observations. A default gage/radar ratio was computed using the monthly totals. The default value was used for any time step when the average radar value dropped below a threshold value to prevent unreasonably large adjustments during periods when the average radar value was very small. Typically, the threshold for average radar was set to 0.02 inches. The gage/radar ratios were also constrained between 0.3 and 3.0 to prevent unreasonable large adjustments to the radar data set. If the computed gage/radar ratio was outside these constraints, the monthly default was used. The constraints were also used to prevent unreasonable adjustments during times when rainfall was in the area but not falling on any of the gage/pixel locations. The resulting gage/radar ratio was applied to each radar-rainfall estimate in each 15-minute period for the month.

After adjusting the 15-minute radar data for each month, the gage-adjusted radar-rainfall estimates were compared to both the unadjusted radar estimates and the gage observations. If any additional data anomalies were found, these gage-radar pairs were removed from the analysis, the adjustment values were recomputed, and the radar data were readjusted.

Figure 5 shows the gage-adjusted radar-rainfall estimates for September 1999. Figure 6 shows the average accumulated rainfall estimates during the month and Figure 7 shows the

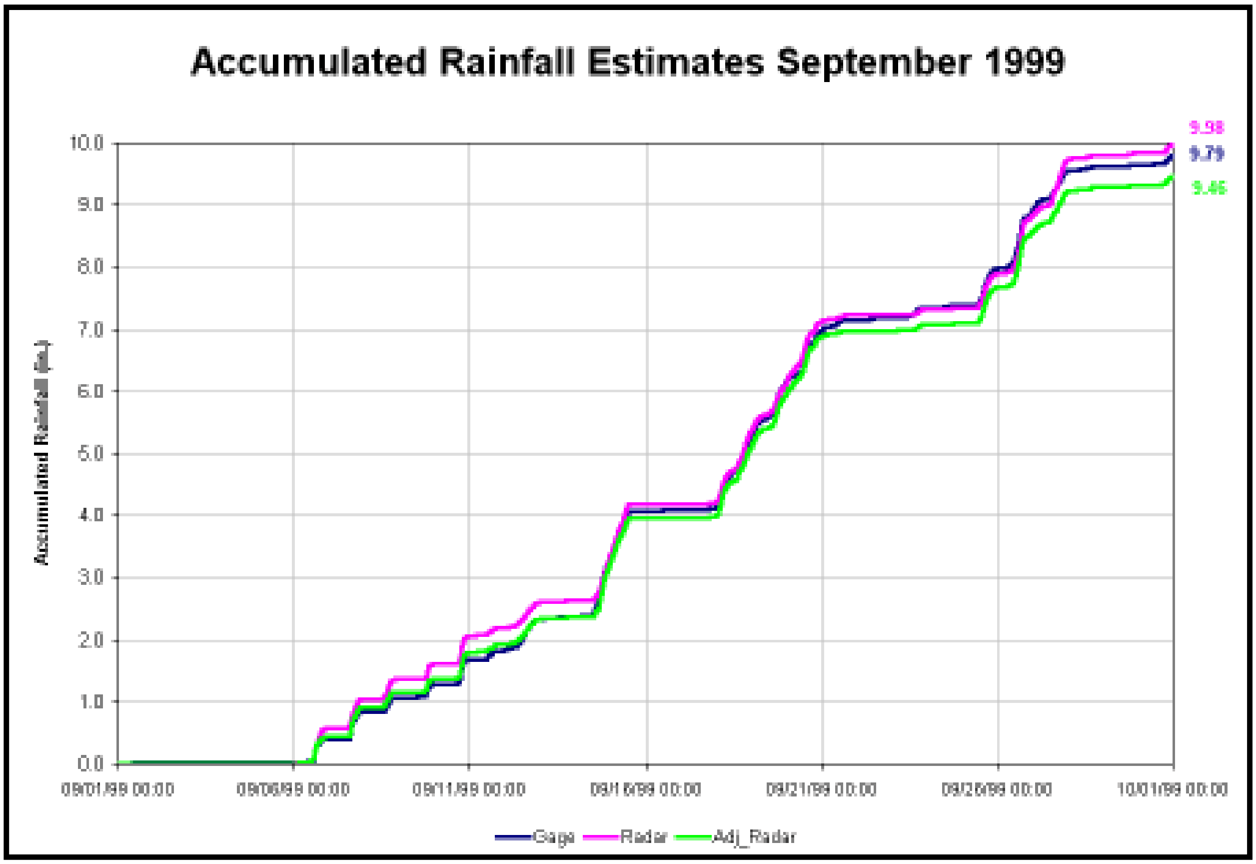

Figure 6: Average accumulated 15-minute rainfall estimates for September 1999

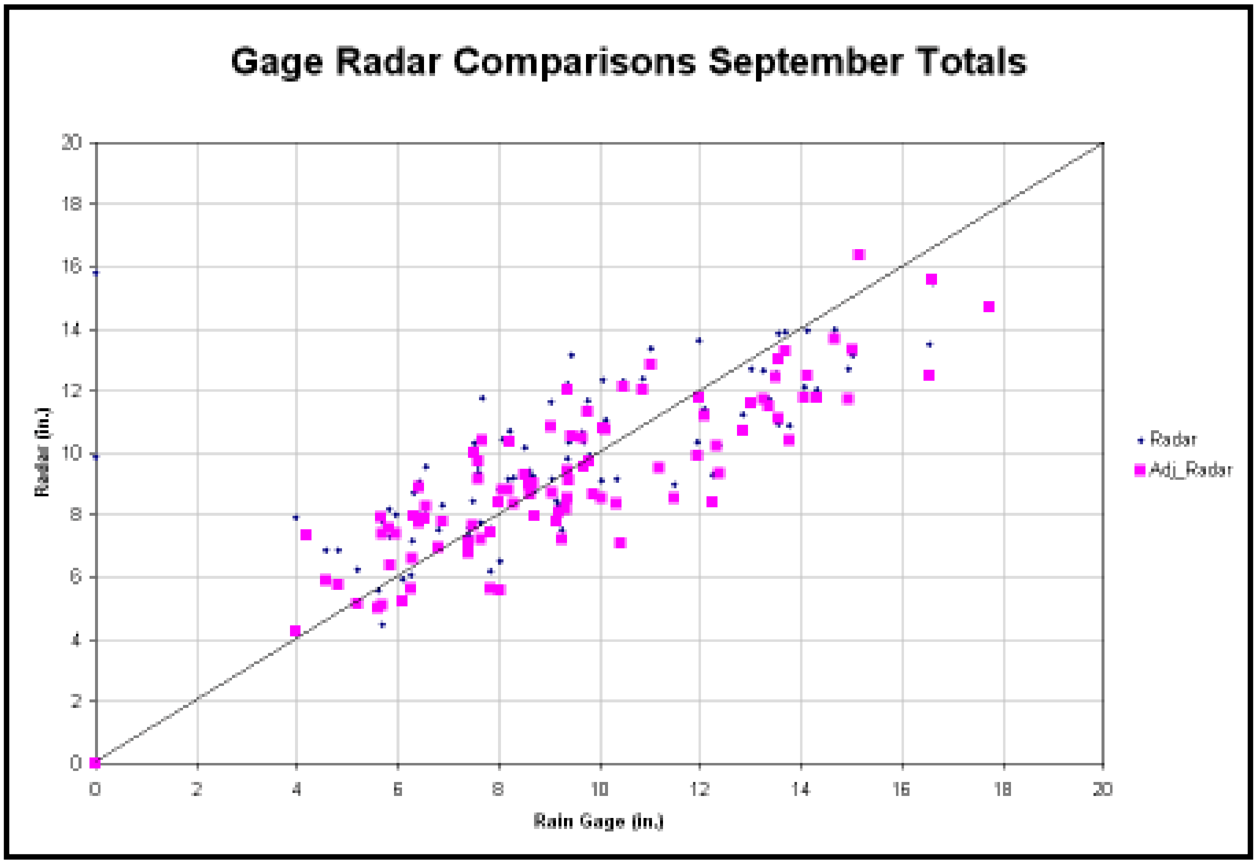

Figure 7: Scatter plot of individual gage vs. radar-rainfall estimates of monthly totals for September 1999

scatter plot of monthly totals comparing gage, radar, and adjusted radar-rainfall estimates. September was a busy month for hurricanes and tropical storms. Average rainfall was for the month was approximately 10 inches with heavier amounts along the east coast approaching 18 inches. Since most of the tropical events tracked along the coastline just offshore, some interior sections of the District only received 2-3 inches for the month.

No obvious spatial discontinuities were readily apparent on the map of monthly totals. The average accumulations tracked well for the entire month and the agreement between unadjusted radar and the gage amounts was excellent, which resulted in very small adjustment factors overall.

Hurricane Floyd. Hurricane Floyd was a category 5 storm headed for Florida in mid-September. As Floyd approached the Florida coastline, the storm turned north, delivering only a glancing blow to the state. Figure 8 shows the storm totals for Hurricane Floyd for the 48-hour period September 14-15, 1999. Rainfall over the District ranged from less than 0.5 inches to more than eight inches near Flagler Beach. The heaviest rainfall was confined to a fairly small area that stretched from the coast inland to Ocala. It's interesting to see the banded structure of the rainfall distribution corresponding to the persistent tracks of the Floyd's rain bands as the storm slowly moved northward along the Florida coast. These features would not be observable with a gage-only analysis. Figure 9 shows that the accumulations tracked extremely well during the event and Figure 10 shows shows that the gage and gage-adjusted radar-rainfall estimates were highly correlated, with $\mathbf{R^2}$ = of 0.87.

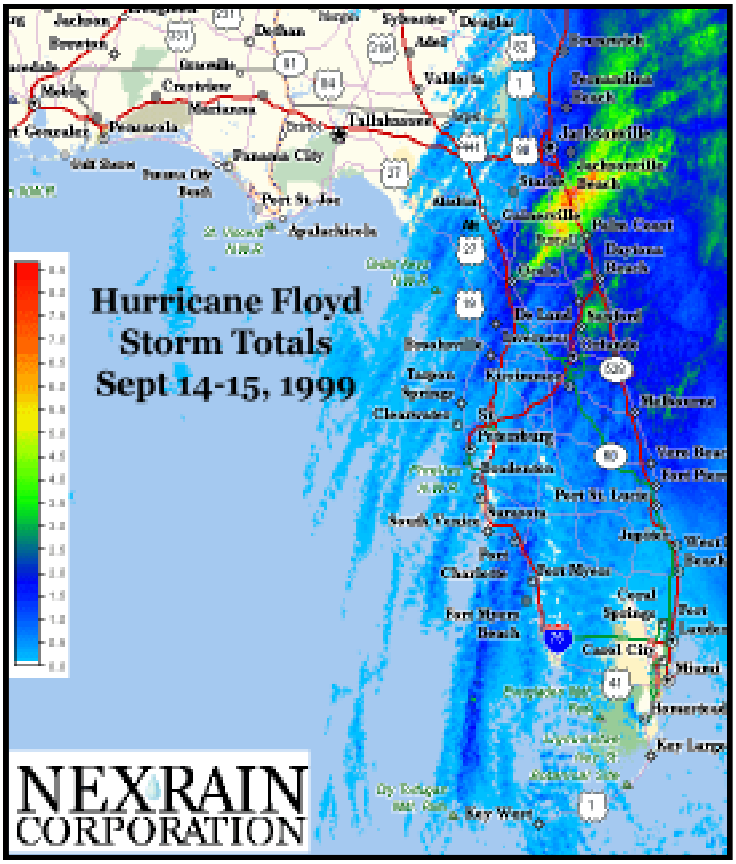

Figure 8: Gage-adjusted radar-rainfall estimates for Hurricane Floyd

Summary and Conclusions

Gage-adjusted radar-rainfall data were developed for a 10-month period from December 1, 1998, to September 30, 1999. The data were provided with 2 km x 2 km spatial resolution in several time increments including: 15-minute, hourly, daily, and monthly totals. The spatial coverage of the rainfall data set included the entire St. Johns Water Management District, the remaining area of the state of Florida, and near shore portions of the Atlantic Ocean and the Gulf of Mexico. More than 250,000 square miles are included in the coverage area.

The 10-month pilot project demonstrated the successful creation of gage-adjusted radar-rainfall estimates that provide highly resolved depictions of the rainfall surface over the entire Florida peninsula region.

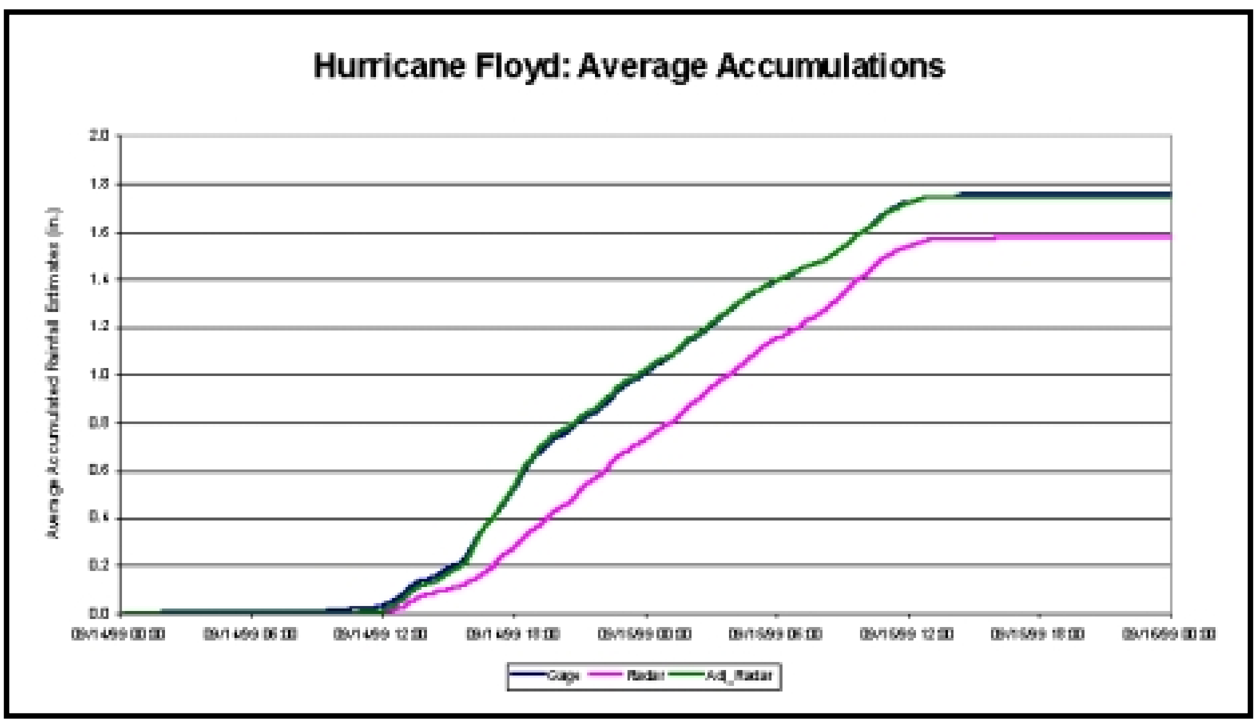

Figure 9: Average rainfall accumulations for Hurricane Floyd

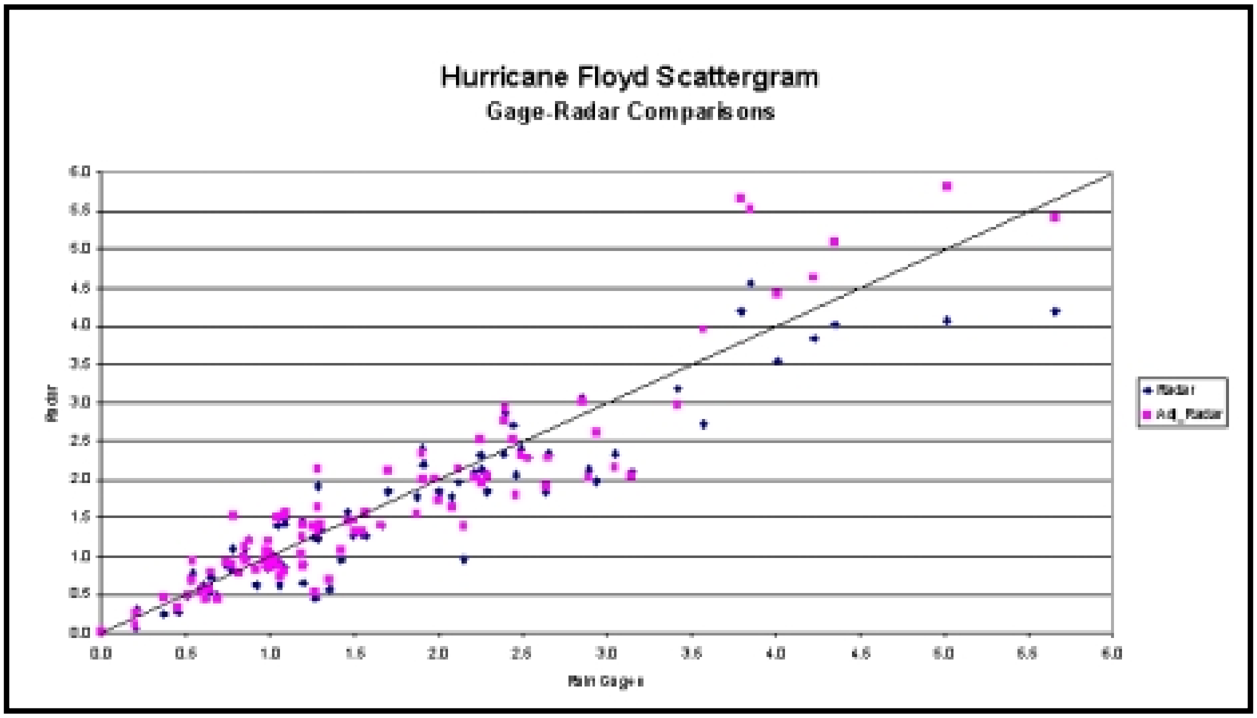

Figure 10: Scatter plot of gage, radar, and gage-adjusted radar-rainfall estimates for Hurricane Floyd

Specifically, the results for the entire month of September 1999 and for Hurricane Floyd showed that the average gage-adjusted radar-rainfall estimates tracked the average gage estimates very well. In addition, the scatter plots showed that the gage-adjusted radar-rainfall estimates were highly correlated.

This new data set provides the opportunity to view the District's rainfall patterns in unprecedented detail. Previously, the District had just 100-200 rain gage observations to monitor rain falling over 12,400 square miles. The gage-adjusted radar-rainfall data set includes more than 8,200 estimates of rainfall every 15-minutes covering the same 12,400 square miles.

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