Evaluation of Gauge Adjusted Radar for Rainfall Measurement in RDII Programs

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ABSTRACT

The use of Gauge-Adjusted Radar (GAR) for rainfall measurement is a recent innovation in Urban Hydrology in the United States for measuring rainfall between rain gauges. Gauge Adjusted Radar is the result of calibrating a radar image with ground truth rain gauges. This technology is particularly useful for Rainfall Dependent Infiltration Inflow (RDII) programs in which the relationship between rainfall and RDII is critical to defining sewer basin performance and directing rehabilitation programs. The rainfall and RDII relationship is equally dependent on quality of both flow measurement and rainfall measurement.

Users of this technology generally have demonstrated its effectiveness in one of four ways; 1) Comparing the results of hydraulic model prediction and RDII calculations using GAR and conventional rain gauges as input, 2) Determining the accuracy of the image calibration by comparing the closeness of rain gauge accumulation to the accumulation of the radar pixel containing the rain gauge, 3) Comparing the closeness of a “test” rain gauge, which was not used in the calibration process, to the radar pixel containing the test rain gauge and 4) Observing the measurement of localized rain events that would have gone undetected by a rain gauge network.

This paper evaluates the technology by investigating two projects performed by the author and reviewing results reported by others. Some users consider it almost self evident that the use of Gauge Adjusted Radar will result in better rainfall measurements and consequently yield better wet weather analyses. However, the magnitudes of improvement from the use of GAR reported by authors have varied from no improvement in hydraulic model prediction to the discovery and elimination of an over-prediction of RDII by over 50%. Key variables contributing to the wide variation of results appear to be to differences in temporal and geographic resolution of GAR system being used. Rainfall measurements can vary as much as 14% between geographic resolution of 1 Km^2 and 4 Km^2.

Key Words

Calibration, Gauge Adjusted Radar, Geographic Resolution, Hydraulic Model, Rainfall Accuracy, NEXRAD, Rain Gauge, RDII and Temporal Resolution

Introduction

This paper looks at the results from two sewer agencies that have conducted RDII analyses using Gauge Adjusted Radar. One is the City of Indianapolis Department of Public Works in Indiana and the second is King County Wastewater Treatment Division Resources in the state of Washington. Both agencies used temporary and permanent flow meters from ADS Environmental Services for RDII measurement and Gauge Adjusted Radar technology from RHEA in France for rainfall measurement. In addition the paper addresses:

1. Principles of Gauge Adjusted Radar Technology
2. Transforming Gauge Adjusted Radar Pixels to Sewer Basin Rainfall.
3. Evaluating Accuracy of the Image Calibration Process in King County.
4. High Variability of Rainfall Captured by 1 Km^2 Pixels
5. Modeling Improvements and Calibration Accuracy Reported by Others.

The King county system consists of approximately 17 million linear feet (5.2 million meters) of sanitary sewer operated by King County and 34 local agencies in a service area of approximately 1100 square miles (2800) sq km. The King County terrain is hilly with nearly 1000 feet (300 meters) of relief in the sewered area.

The Indianapolis system consists of approximately 13 million linear feet (4 million meters) of sewer in a service area of approximately 400 square miles. The Indianapolis terrain is flat with approximately 200 feet of relief within the service area. The rain gauge density in both agencies is approximately 1 gauge per 10 to 15 square miles (26 to 39 Km^2).

1. Principles of Gauge Adjusted Radar Technology

There are several systems for delivering Gauge Adjusted Radar data and they all operate on similar principles. King County and Indianapolis both selected the RHEA system called CALAMAR (CAlcul de LAMes d'eau a l'Aide du Radar), which translates, to "Calculating Rain with the Aid of Radar". CALAMAR calibrates and processes the NEXRAD data in a unique way that overcomes many of the obstacles such as ground clutter that creates uncertainty with the use of radar images produced by NEXRAD radar. Jacquet (2002) discusses several of the unique methods used to transform radar images to rainfall.

Figure 1 shows the location of the NEXRAD radar in relation to the King County Service Area. The sewer service area is contained in a rectangular area approximately 25 miles (40 Km) wide and 45 miles (73 Km) long.

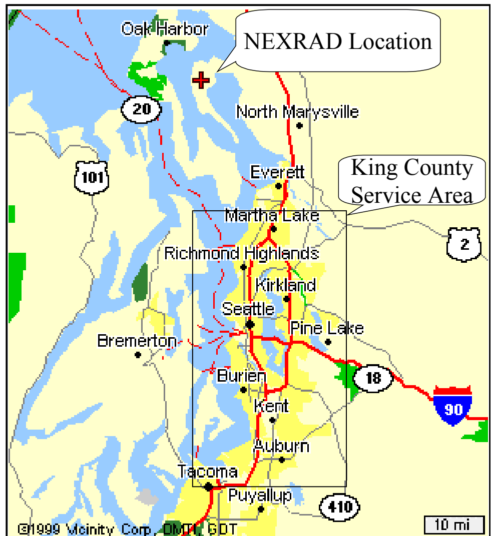

Figure 1** NEXRAD **location in King County

Gauge Adjusted Radar systems operate by acquiring reflectivity images from the NEXRAD radar and processing the data with a geographic resolution of either 1 or 4 Km^2 pixels and temporal resolution of either 5 or 15-minute time steps. The CALAMAR system operates at a 1 Km^2 geographic resolution and a 5-minute temporal resolution.

Rain gauges provide "ground truth" for image calibration such that a pixel containing a rain gauge will show approximately the same rainfall value as a rain gauge within that pixel. This process works well on a storm-by-storm basis since each type of storm cell produces a characteristically similar radar image. However, employing the technology over a large area provides the opportunity for multiple storms of different characteristics to occur simultaneously within the service area. The calibration factor needed for one storm may be inappropriate for a second, but more distant, storm in the service area. To avoid this problem several calibration zones should be developed over a large area.

The King County service area has been divided into eight (8) calibration zones of 200 Km^2 to 500 Km^2. There are a total of 2222 pixels of 1 Km^2 and 72 calibrating rain gauges in this system.

2. Transforming Gauge Adjusted Radar to Sewer Basin rainfall values

To provide perspective of 1 Km^2 pixels and 20,000 LF mini-basins, Figure 2 shows a collection of sewer basins in the city of Bellevue with 1 Km^2 pixels superimposed. Also shown are three (XRDS, FACT and HEAT) of the 15 rain gauges that were used to calibrate this Zone. Sanitary sewer lines are shown in each colored sewer basin. A digital time series hyetograph is produced for each pixel.

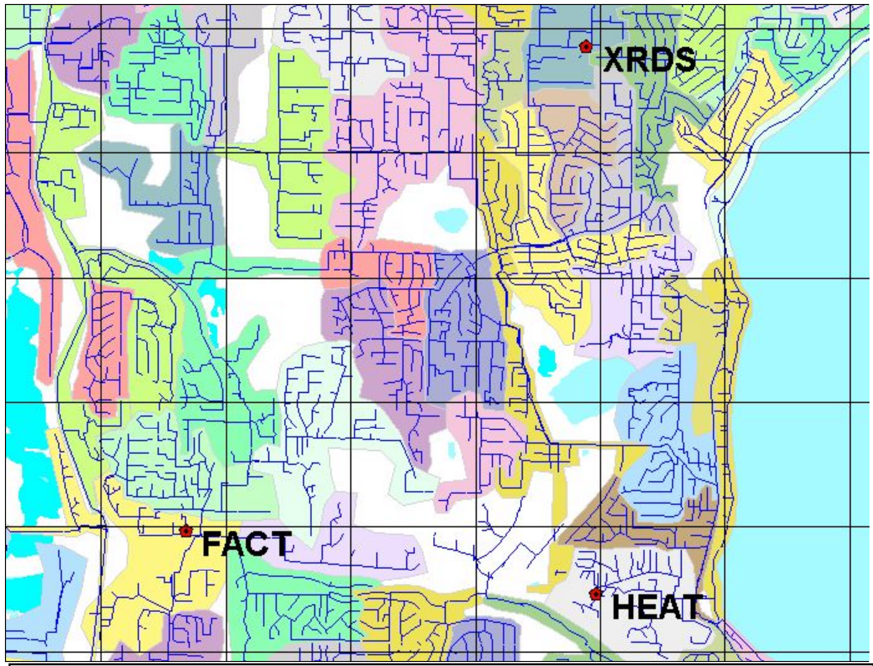

Figure 2 Sewer Basins shown with 1 Km2 rainfall Pixels

Most sewer basins span across more than a single pixel and a method was created to determine the average rainfall on each sewer basin. Figure 3 shows several sewer basins located in city of Issaquah and the gauge adjusted radar pixels overlaid. The pixel numbers are derived from the approximate location in kilometers of the northwest corner of each pixel. The numbering system is based on the Washington State Plane Coordinate System. For example the pixel 408_59 is located 408 Km east and 59 Km north of the coordinate starting point.

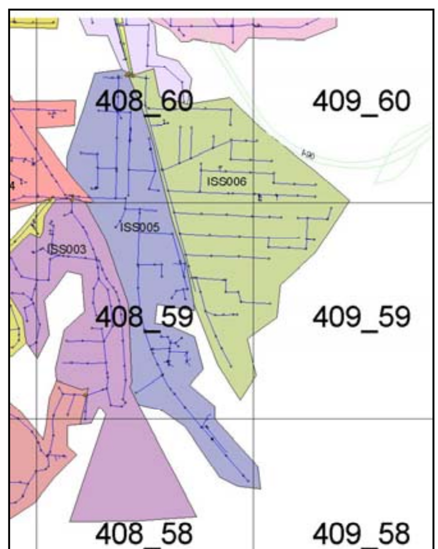

Figure 3 Sewer Basins span multiple pixels.

A method was developed using the GIS to determine the percent of rainfall on a sewer basin coming from each pixel. Table 1 illustrates this method for sewer basin ISS005. The yellow highlighting is on the 4 pixels that contribute to rainfall on sewer basin ISS005 and the column "Percent" lists the percentage of each pixel. For example, nearly 54% of the rain on sewer basin ISS005 comes from pixel 408_59. This process produces both time series and accumulated rainfall data for each sewer basin.

BASIN	PERCENT		PIXEL
ISS004	0.0002		406_60
ISS004	0.0311		407_59
ISS004	0.1228		407_59
ISS004	0.0000		408_59
ISS004	0.0000		408_59
ISS004	0.7432		407_60
ISS004	0.0357		408_60
ISS004	0.0670		408_60
ISS005	0.0052		409_58
ISS005	0.1000		408_58
ISS005	0.5397		408_59
ISS005	0.3549		408_60
ISS005	0.0001		408_60
ISS006	0.2003		409_59
ISS006	0.0006		409_59
ISS006	0.1273		409_60
ISS006	0.3393		408_59
ISS006	0.3326		408_60
ISS007	0.1790		409_60
ISS007	0.3648		409_61
ISS007	0.0389		408_61
ISS007	0.2614		408_60
ISS007	0.1560		410_61

Table 1 GIS table of weightings on each sewer basin.

3. Evaluating Accuracy of the Image Calibration Process

The basic tool for determining the accuracy achieved by the radar measurement is to compare rainfall accumulation measured by a rain gauge to the accumulation measured by the pixel containing the gauge. A scatter plot as shown in Figure 4 is an easy way to visualize the comparison. Such a scatter plot is prepared for each calibration zone for each rain event.

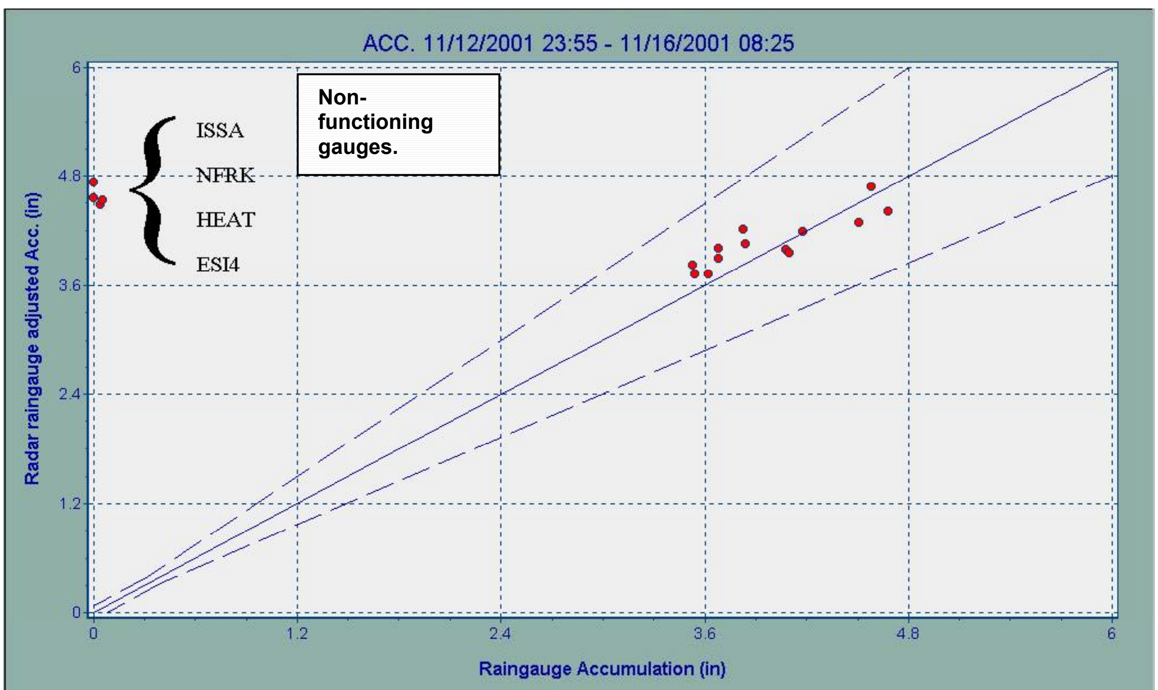

Figure 4 Scatter plot of rain gauge accumulation and radar pixel accumulation.

Figure 4 shows rain gauge accumulation on the X-axis and Radar accumulation on the Y-axis. In an ideal situation the data points in this display would lie on a 45-degree line, however there is a natural variability between a point reading and an areal reading of rainfall. The variation is a function of the type and intensity of precipitation. More uniform frontal precipitation will produce better correlations than less uniform convective precipitation. Also within each type of precipitation more intense rainfall will produce better correlations than lighter precipitation. A variation of 20% is used in this analysis as the normal statistical difference between a point reading and an areal reading of 1 Km^2 and the dashed lines indicate this 20% range.

Figure 4 shows that 13 of 17 data points lay on or near the 45-degree line and none of the functioning gauges differ from its pixel by more than 10%. These conditions indicate that the radar image is well calibrated. The four gauges along the Y-axis are not functioning and were not be used in the calibration process. This comparison should be the first quality control step applied to gauge adjusted radar data. Several authors use this type of pixel/rain gauge comparison to quantify the accuracy achieved by a Gauge Adjusted Radar system and their findings follow later in this paper.

Accuracy of Calibrations in King County

The King County service area was divided into 8 calibration zones to assure that only those rain gauges in each area were used to calibrate the radar images of the rain cells in that area. The service area is 45 miles in one dimension and without this division a rain gauge at the south end of service area could be used to calibrate a rain cell image at the north end of the service area. Table 7 lists, for each calibration zone, the percentage of pixels with an accumulation within 20% of the accumulation of the associated rain gauge. These data are for all 10 rain events analyzed, including those with less than 1 inch accumulation. For all zones and all rain events 76% of the valid rain gauges were within 20% of the accumulation of its associated pixel. Storm 2 produced the heaviest rain and 100% of the pixels in all eight calibration zones were within 20% of the associated rain gauge. Storms 1, 8 and 10 all produced less than 1-inch accumulation over the entire service area and these events tended to result in less precise calibrations.

Table 2

Accuracy of Radar Calibration in King County

Percentage of Gauge Adjusted Radar Rainfall Values that are Within 20% of Rain Gauge Value									
Storm	**Range of Rainfall**	**King County Calibration Zone** (671 Total Data Comparisons)							
	(Inches)	Auburn	Bellevue	Lynnwood	Maple Valley	North Seattle	Redmond	SEATAC	South Seattle
1	0.1 - 0.62	100%	58%	58%	20%	100%	100%	100%	100%
2	1.36 - 5.74	100%	100%	100%	100%	100%	100%	100%	100%
3	0.92 - 2.39	71%	86%	93%	20%	100%	82%	29%	100%
4	0.64 - 2.86	56%	77%	86%	60%	100%	100%	0%	45%
5	1.77 - 3.97	78%	50%	93%	20%	100%	100%	50%	82%
6	0.64 - 2.32	88%	92%	62%	100%	100%	83%	100%	91%
7	1.38 - 2.9	57%	93%	71%	60%	100%	83%	88%	75%
8	0.38 - 0.95	89%	36%	47%	20%	100%	42%	38%	75%
9	1.03 - 2.6	50%	93%	79%	60%	Missing RG data	82%	88%	100%
10	0.12 - 0.97	78%	80%	60%	60%	83%	67%	100%	50%
Average % Within 20%		**77%**	**77%**	**75%**	**52%**	**98%**	**84%**	**69%**	**82%**

4. **High Variability of Rainfall Captured by 1 Km^2 Pixels**

The geographic variability of rainfall is nearly invisible with a conventional network of rain gauges at a density of 10 to 20 miles^2 per gauge. Figure 5 is rainfall map of King County sewer basins with pixel outlines superimposed for perspective. Each sewer basin contains approximately 22,000 LF of sewer. The area is in the North Seattle calibration zone and sewer basins are colored according the radar rain accumulation for the 28 November 2001 rain event. Two rain gauges, LYON and BOEN are approximately 5 Km (3 miles) apart were unable to capture either the heavier rain at the northwest in basin RON011 or the lighter rain in the north center in basin RON014.

The magnitude of the localized rain event would have been significantly lessened if the measurements had been at a pixel resolution of 4 Km^2 as opposed to this pixel resolution of 1 Km^2. The average of the 4 pixels (4 Km^2) surrounding sewer basin RON011 results in a rainfall 14% less than the rainfall calculated with 1 Km^2 pixels. Experience with 1 Km^2 rainfall mapping reveals that there is far more variability in rainfall than is commonly suspected.

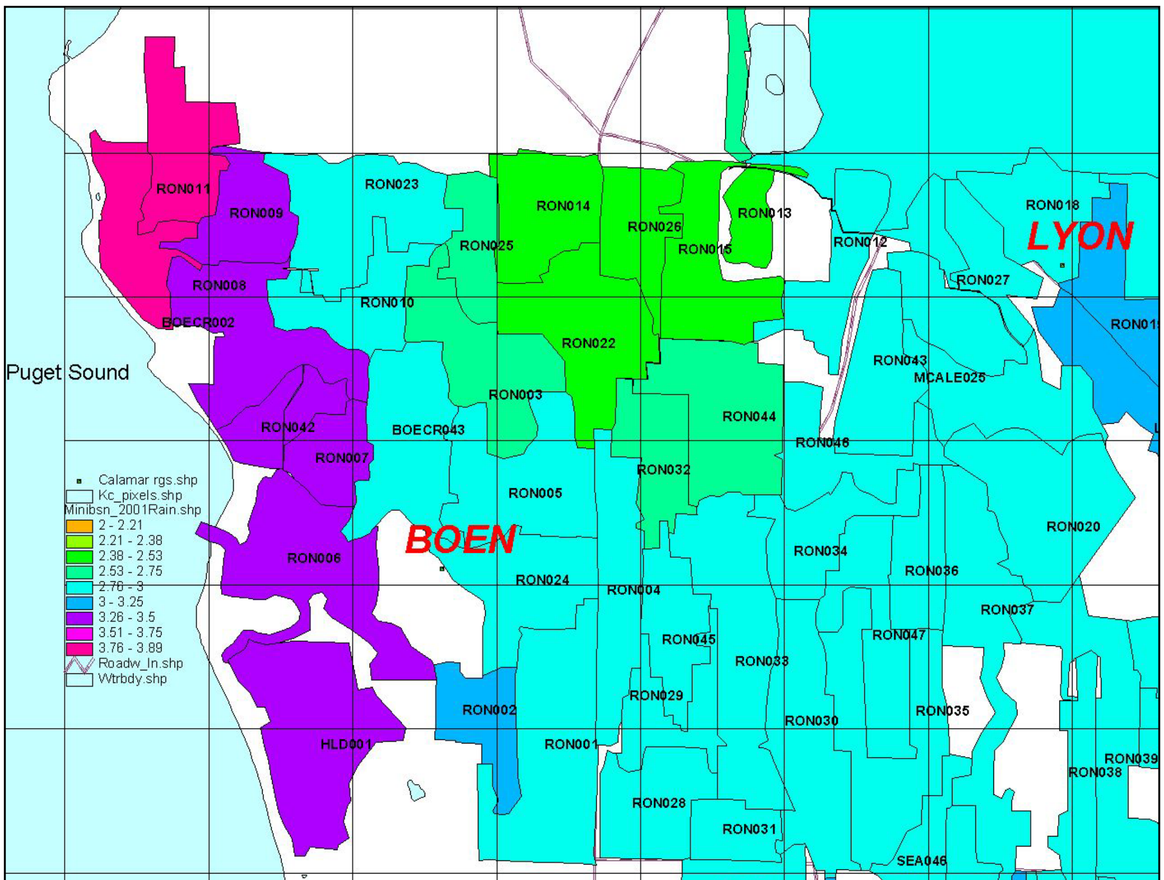

Figure 5 Map of radar rainfall accumulation at a resolution of 1 Km^2 per pixel. Pixel outlines are superimposed for perspective.

Localized heavy rainfall, as shown in Figure 5, can have a major impact on sewer overflows and backups. Figure 6 shows an Intensity Duration Frequency (IDF) curve for sewer basin RON011 and rain gauge BOEN. Rain gauge BOEN is approximately 2 miles (3 Km) from the sewer basin RON011. Sewer basin RON011 experienced a 50-year, 6-hour event while the BOEN rain gauge experienced less than a 1-year event. Had sewer basin RON011 experienced an overflow or backup, the operator would have been perplexed as to how an apparent 1-year rain event could have been the cause.

A poor rainfall-RDII relationships (Q to i diagram) at sewer basin would also have resulted if the gauge adjusted radar not been in place.

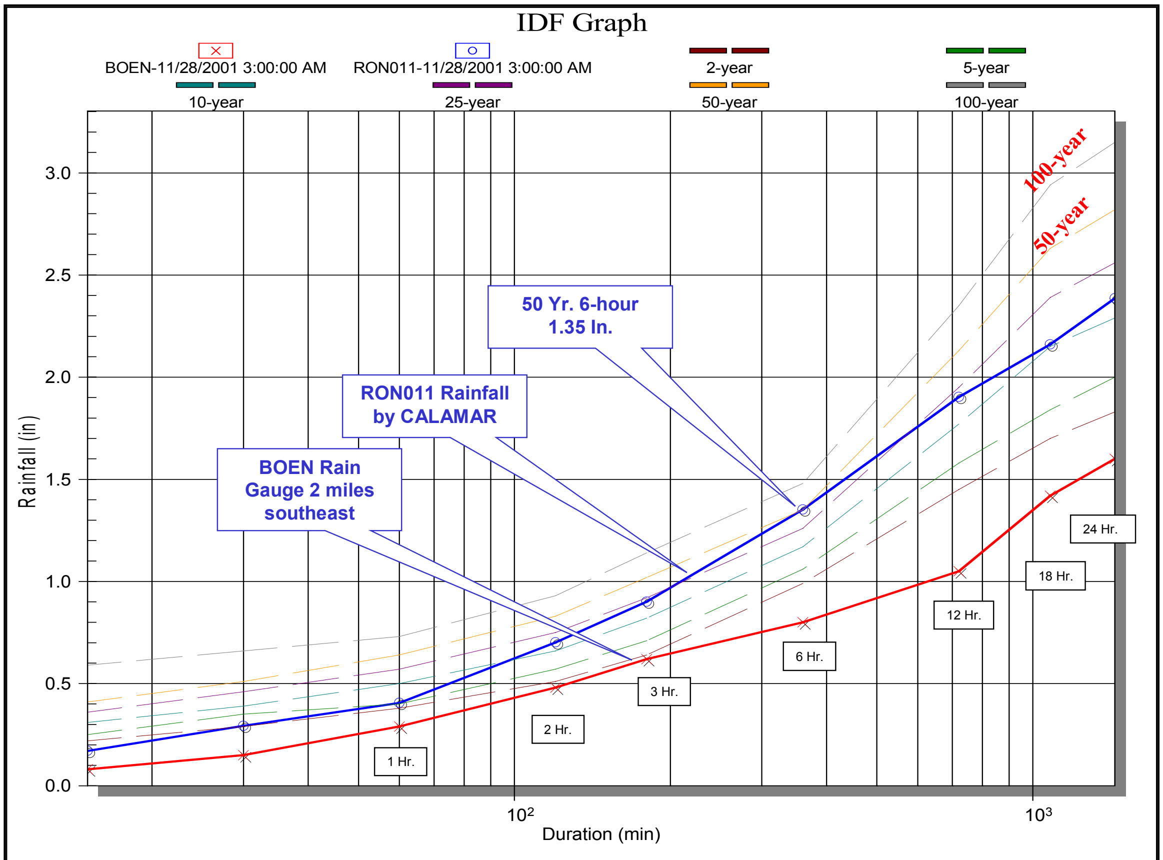

Figure 6 Intensity Duration Frequency (IDF) curve showing the dramatic difference in rain intensity over a distance of less than 2 miles (3 Km).

Improvements to RDII Relationships in Indianapolis

The Q to i diagram is a simple, but significant tool for evaluating the wet weather performance of sewer basins. They are used in selecting basins for rehabilitation and for quantifying the I/I reduction after work has been completed. The amount of rain (i) is plotted on the X-axis and the response (Q) in Rainfall Dependent Infiltration and Inflow (RDII) is plotted on the Y-axis. Normally a best-fit regression line is fit to the data to represent the Q-to-i relationship and the slope of this line is an indicator of the volume of I/I generated per inch of rainfall in each sewer basin. The quality of the best-fit regression is indicated by the statistical R^2 value.

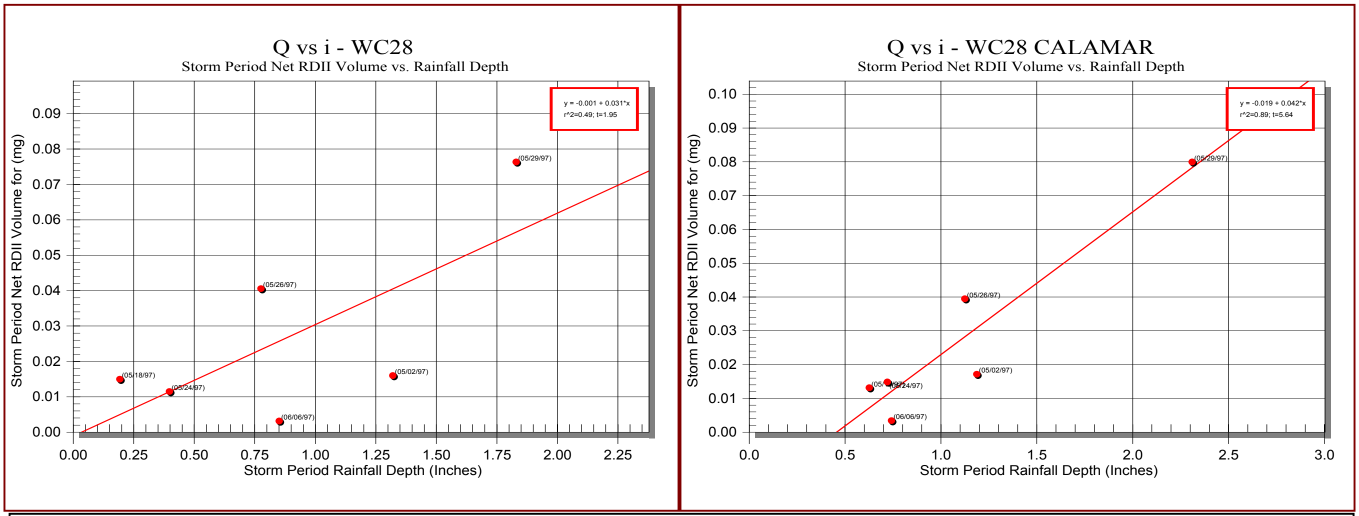

Figure 7 An example of the improvement in a Q vs i relationship with gauge adjusted radar. The statistical R^2 value of the fit with rain gauge data is 0.49 and the fit for the gauge-adjusted data is 0.89. The average of 30 basins in Indianapolis improved from 0.74 to 0.89 with the use of gauge adjusted radar rainfall.

Figure 7 shows an example the improvement in a Q vs. i relationship from a sewer basin in Indianapolis between the use of nearby rain gauges and gauge adjusted radar. The quality of flow data is just as important as the quality of rainfall data in determining the quality of the best-fit line. In the project the RDII data was developed by ADS using very accurate ultrasonic metering technology. In this example the R^2 value increased from 0.49 to 0.89 with use of gauge adjusted radar.

Of the 30 sewer basins in the Indianapolis project, 17 were independent basins with no upstream basins, which require a meter subtraction. Only the 17 basins were used to evaluate the two rainfall measurements to avoid any uncertainty that could be attributed to meter subtraction. Table 3 lists the best-fit line equation as well as the statistical R^2 for each regression line for each sewer basin. For the 17 independent basins the R^2 value averaged 0.74 using nearby rain gauges and 0.87 with gauge adjusted radar. The rain gauge density for the Indianapolis network is approximately one gauge per 10 square miles (26 Km^2).

Comparison of Statistical R Squared Values for Indianapolis Q-to-i Relationships

	Sewer Flow	CALAMAR			Nearby Rain Gauges		
Basin	Average Dry Flow (MGD)	Y Intercept MGD	Q to i Slope (MGD/Inch)	R Squared	Y Intercept MG	Q to i Slope (MGD/Inch)	R Squared
WC02	0.427	-0.04	0.067	0.97	-0.02	0.058	0.79
WC03	0.022	0.00	0.002	0.16	0.00	0.002	0.12
WC05	0.042	-0.03	0.060	0.88	-0.02	0.058	0.79
WC08	0.044	-0.02	0.040	0.92	-0.01	0.034	0.81
WC09	0.026	-0.02	0.031	0.94	-0.01	0.030	0.91
WC12	2.300	-0.38	0.601	0.93	-0.22	0.646	0.96
WC13	5.244	-1.51	2.751	0.95	-0.80	2.811	0.89
WC14	0.068	-0.05	0.087	0.96	-0.03	0.077	0.83
WC15	0.085	-0.03	0.069	0.96	-0.02	0.064	0.95
WC17	0.055	-0.04	0.064	0.89	0.02	0.051	0.73
WC19	0.048	-0.02	0.033	0.95	-0.01	0.027	0.75
WC22	0.056	-0.02	0.034	0.96	-0.01	0.030	0.77
WC24	0.058	-0.02	0.038	0.97	-0.01	0.033	0.77
WC26	0.029	-0.02	0.023	0.95	-0.01	0.019	0.79
WC28	0.109	-0.02	0.042	0.89	0.00	0.031	0.49
WC29	0.074	0.00	0.010	0.57	0.00	0.008	0.33
WC30	0.034	0.00	0.008	0.99	0.00	0.007	0.90
Average				**0.87**			**0.74**

5. Modeling Improvements and Calibration Accuracy Reported by Others

Burgess (1996), Orie (2002) and Gurlaskie (2001) each separately evaluated the effectiveness of a Gauge Adjusted Radar system by comparing the output of a hydraulic model to measured flow data. Gauge adjusted radar and rain gauge data are used as model input. In all three analyses the output takes the form shown in Figure 8. Model predictions using both Gauge Adjusted Radar and rain gauge data are plotted along with actual flow measured following a rain event.

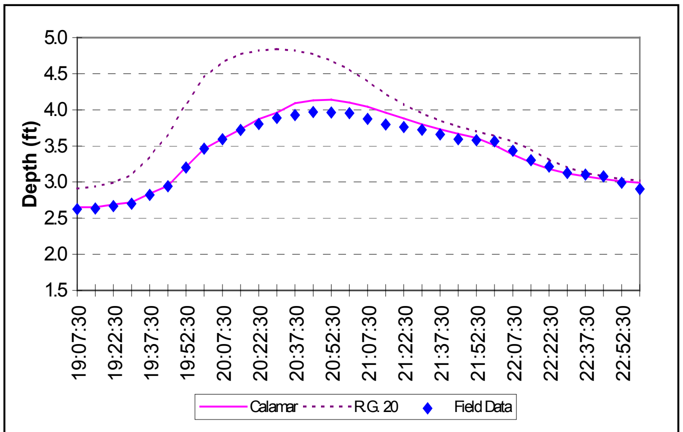

Figure 8 Comparing measured flow to model output from rain gauges and gauge adjusted radar.

Burgess (1996) reported that two of three tested basins showed significantly improved agreement with observed data. Figure 8 shows the comparison of one of the three CSO basins. Table 4 displays the results for all basins. For each site a difference in percentage is calculated by dividing the simulated value by the measured value. Differences are calculated for total flow volume, peak flow rate and maximum hydraulic grade line (HGL). Rain gauge data caused an over prediction in all cases by as much as ten fold in site AM-1.

Table 4

Difference (%) in Simulated vs. Observed Values						
	Site PL-2		Site AM-1		Site WI-1	
	CALAMAR	RG	CALAMAR	RG	CALAMAR	RG
Flow Volume	-10	10	24	208	-2	52
Peak Flow Rate	-1	37	24	264	21	23
Maximum HGL	4	22	-19	50	31	26

Orie conducted a similar analysis in ALCOSAN as part of the 3 Rivers Wet Weather Demonstration Program. He generated scatter plots of simulated vs observed response volumes using three types of rainfall input; one nearby rain gauge, Inverse Distance Squared and CALAMAR. Describing the slope, intercept and R^2 of the best-fit regression line as shown in Table 5 summarized his demonstrated improvements. Also included are ratios of peak flow and time to peak expressed as the simulated value over the observed value.

Table 5

Summary Statistics for Event Volume Regression					
Rain Input	Slope	Intercept	R-Squared	Peak Ratio	TP Ratio
One RG	0.28 +/- 0.15	0.16 +/- 0.09	0.54	0.43 +/- 0.21	1.27 +/- 0.40
IDS	0.86 +/- 0.24	0.04 +/- 0.15	0.84	0.83 +/- 0.16	1.14 +/- 0.13
Radar	0.87 +/- 0.18	0.06 +/- 0.11	0.89	0.94 +/- 0.13	1.09 +/- 0.09

Gurlaskie compared model outputs for seven basins using Theissan polygon distribution and gauge adjusted radar. He found "*no dramatic difference in the rainfall-RDII relationships obtained using Theissan Polygons and the relationships obtained by using gage adjusted radar*".

Meeneghan compared the measurement of R, the fraction of rainfall entering sewers, in the Saw Mill Run Basin using four types of rainfall measurement:

- The regional long-term gauge, located at the Pittsburgh International Airport, approximately 12 miles (19 km) away from the Saw Mill Run basin
- The nearest short- term gauge, located within the Saw Mill Run basin
- A dense network of 5 gauges, located within and around the study basin
- A calibrated radar-rainfall system, with a pixel resolution of 1 Km^2

His demonstrated improvements are shown in Table 6, which compares three types of rain gauge input to gauge adjusted radar.

Table 6

Change in R Calculated with Calibrated Radar vs. Conventional Rain Gauge Measurements			
	Regional RG	**Nearest RG**	**IDS Weighting**
% Change in R	-16.30%	-11%	-7.20%
% Change in Standard Deviation	-45.30%	-32.70%	-10.30%

Although other variables may be affecting the results, Burgess, Meeneghan and Orie each demonstrated improved results using gauge adjusted radar operating with geographical resolution of 1 Km^2 and temporal resolution of 5 minutes. Gurlaskie found no dramatic improvement using a gauge adjusted radar system operating with geographical resolution of 4 Km^2 and temporal resolution of 15 minutes.

Evaluating the Accuracy of Calibration.

Walch, Jacquet and this author each reported on the accuracy of radar calibration by comparing rain gauge accumulation to the accumulation of the radar pixel containing the rain gauge. This analysis of gauge adjusted radar should be the first quality assurance step and is probably the most important indicator of the reliability of rainfall values between rain gauges. Results from three analyses are summarized in Table 7.

Table 7

Comparing Accumulation of Rain Gauge with Radar Pixel			
Within % of RG	**Miami-Dade Co.**	**Allegheny Co.**	**King Co.**
within +/- 10%	10%	54%	
within +/- 20%			76%
within +/- 25%	26%	88%	
within +/- 50%	57%	98%	

There is a clear difference in the apparent precision with which these three gauge adjusted radar systems operate. Although several features are different, key differences between the systems are geographic and temporal resolution. The Miami-Dade County system operates with a geographical resolution of 4 Km^2 and a temporal resolution of 15 minutes while the Allegheny and King County systems operate with resolution of 1 Km^2 and a temporal resolution of 5 minutes.

Conclusion.

Gauge adjusted radar is a significant improvement over rain gauges at a density of 1 gauge per 10 square miles (26 Km^2). Clear improvements can be demonstrated in the output of hydraulic models and in rainfall to RDII (Q-to-i) relationships. Gauge adjusted radar systems that operate with geographic resolution of 1 Km^2 and 5 minute temporal resolution appear to produce more accurately calibrated radar images than systems with less geographic and temporal resolution. Experience with rainfall analysis at 1 Km^2 resolution in King County suggests that variability in rainfall is greater that most users and this author believed. Several situations were found in which significant rainfall occurred between gauges and that the amount of measured rainfall between gauges would have been as much as 14% less if measured in 4 Km^2 pixels.

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