Executing the Country's Largest Flow Metering Project-Evaluating the Importance of Basin Size

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Abstract

The King County Wastewater Treatment Division operates the collection trunk sewers and two wastewater treatment plants in King County to collect and treat wastewater from 34 Local Agencies in King and Snohomish Counties. The total length of all Local Agency separated sewers in the King County service area is approximately 17.5 million feet. This total does not include the combined sewer system in the City of Seattle. The system experiences significant Infiltration and Inflow (I/I) during the wet season from October to March. King County has initiated a multi-year effort to:

- Determine the wet weather performance and geographic distribution of I/I through its entire service area
- Conduct several pilot rehabilitation projects to evaluate rehabilitation effectiveness,
- Develop and calibrate an accurate hydraulic model of the system and
- Prepare an implementable Regional I/I Control Program.

This paper discusses the political and administrative actions to achieve consensus among the Local Agencies and an analysis of I/I results as a function of basin size.

Keywords: Regional Collection System, Pilot Rehabilitation projects, Basin Size, I/I, RDII, CALAMAR Rainfall

Introduction

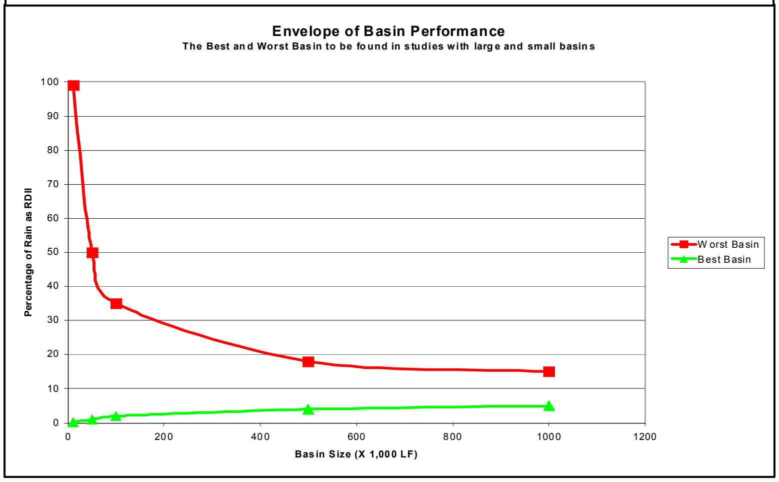
To assure that wet weather performance of all Local Agencies are measured equitably, it was determined that the entire system would be subdivided into Mini Basins of approximately 20,000 LF and that the Mini Basin monitoring in all Agencies would occur simultaneously. This metering plan resulted in the simultaneous operation of 807 flow meters. In addition, 146 of the meters were used as model calibration points and 75 of the meters were permanently installed for long-term trend analysis. Rainfall data were developed using CALAMAR radar rainfall technology and a network of 72 calibrating rain gauges supplied rainfall data. The flow metering occurred from 1 November 2000 to 15 January 2001.

The initial objectives were:

- Track long term trends on large basins
- Divide the entire system of local lines connecting to King County sewers into uniformly sized Mini Basins that average 20,000 linear feet in size.

- Isolate flows crossing agency boundaries provided the flow is from basins of 10 manholes or larger.
- Measure at least 95% of the agency's sewers with a Mini Basin meter. Local sewers not metered with a temporary meter will be considered part of the King County sewer.
- Measure excess wet weather flow as traditional I/I as well as RDII (Rainfall Dependent I/I).

Figure 1 Best and Worst Performing Basins



An important part of the metering plan called for Mini Basins that were small and uniform. Sullivan, et al., Kurz, et al. and Stevens have discussed the importance of basin size and its affect on measuring the magnitude and geographic distribution of RDII. Their work and additional results included within this paper quantifies the range of measured wet weather performance one could expect from a range of basin sizes. Figure 1 shows the relationship that would be expected between the best and worst performing basins as a function of the size of the basin.

Figure 2 Envelope of Basin Performance

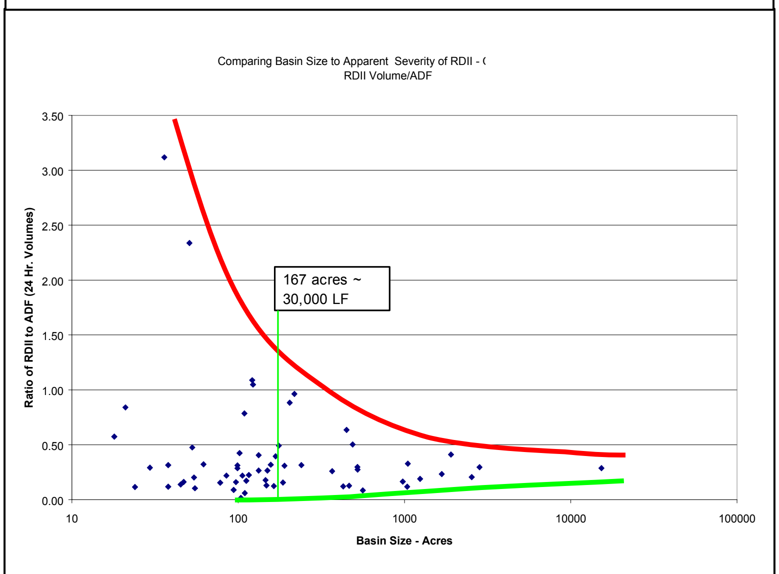


Figure 2 displays the results of wet weather data for another project for a collection of basins with sizes ranging from 20 to 10,000 acres. These data suggest that wet weather performance of larger basins fall into a much narrower range that do smaller basins. The data also suggest that it is not a valid exercise to compare or rank basins of widely varying sizes. A mistake that many municipalities make is to compare the performance of say ¼ of a city measured in a single basin to several mini-basins in another quarter. The larger basin will nearly always rank near the middle or lower half of the complete set of basins. For example, RDII measured as 5% of rainfall on a 400,000 LF may be mid-range in performance while the same 5% in a 20,000 LF may be in the lower quartile of the performance range.

Two data sets in King County– one of approximately 800 mini-basins averaging 150 acres (20,000 LF) and a second of 146 modeling basins averaging 1000 acres (113,000 LF) are used to develop the relationship shown in Figures 1 and 2. For this paper RDII is expressed as a percentage of rain falling on each basin.

Methodology

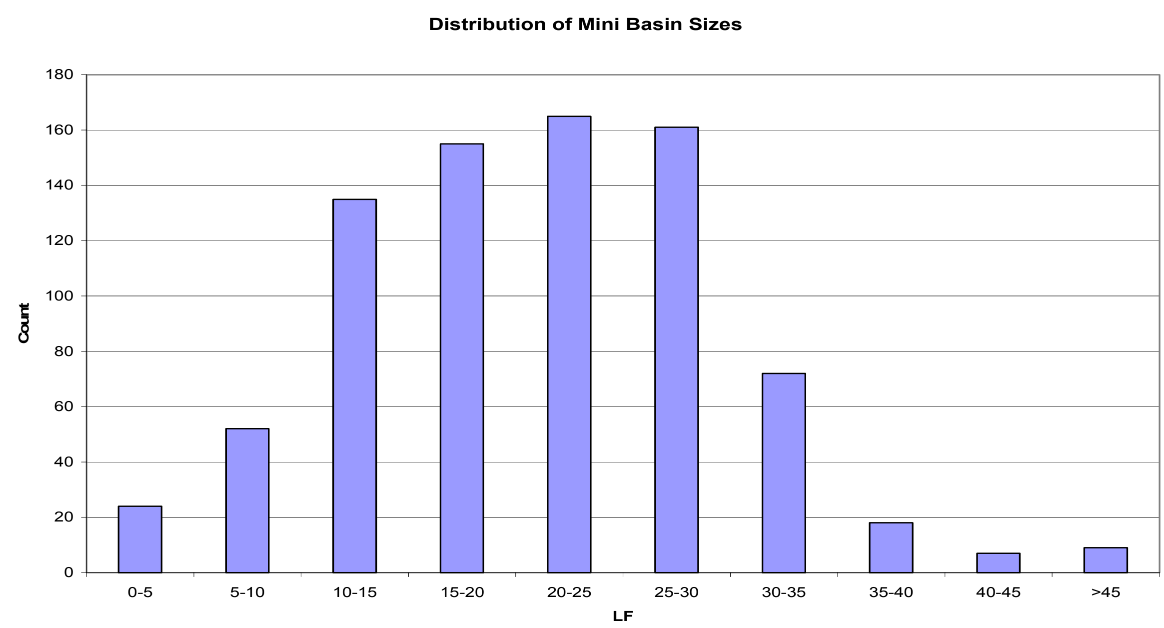
Regional Workshops

With 34 Local Agencies involved, developing a common understanding of the Program and building consensus on the tasks was achieved through a series of five (5) Regional Workshops and the use of eight (8) Local Agency Managers (LAM). The LAM was a team member tasked with maintaining direct and personal contact technical staff of their respective Local Agency. The workshops provided overview information for the program and the LAMs followed up with routine contact with each Local Agency.

Region-wide Mini Basin Layout

The Mini Basins were laid out in preliminary form on the County's GIS and each Local Agency's metering plan was delivered to the Agency by the LAM. Feedback from the Agency through the LAM was used to refine the metering plan. It was determined that the average Mini Basin size would need to be approximately 22,000 LF and that a maximum size should be approximately 32,000 LF. Smaller Mini Basins were created as meters were added to achieve 95% measurement of each Local Agency's system. Sewer networks seldom offer the opportunity for precisely breaking them into uniform basins. For example a 40,000 LF basin may be subdivided into only Mini Basins of 28,000 LF and 12,000 LF. Implementing this strategy resulted in the Mini Basin size distribution shown in Figure 3.

Figure 3 Distribution of Mini Basin Sizes



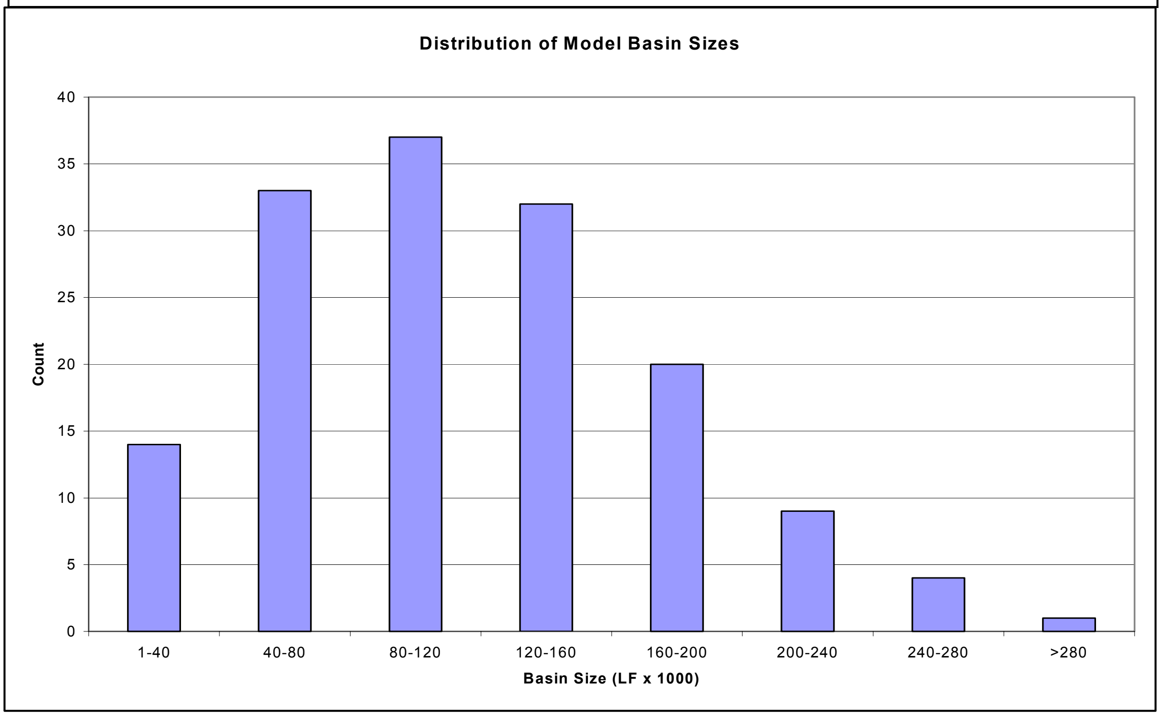
The larger Mini Basins are from two sources. One is a group of Mini Basins formed by long-term meters (LTM) after the contributing local lines have been isolated with temporary Mini Basin meters. These Mini Basins consist of mostly King County Trunk Lines with little or no contributory flow. The second source is from meters placed on lines entering the study area to isolate them for modeling purposes

Mini Basin acreage is based on Mini Basin polygons and is calculated utilizing the County's GIS. Mini Basin boundaries were established on the GIS by using sewer line and street centerline mapping for guidance. Aerial photos were occasionally used to verify land use in unclear situations, but as a general rule, any land within the interior of a logical sewer basin was included in the Mini Basin's acreage. For example the acreage of a Mini Basin with a school and soccer field in its interior will include the soccer field acreage. Conversely if a school is located at the outer edge of a Mini Basin, the Mini Basin boundary may have excluded the soccer field. The same general rule applies to small parks or any type of undeveloped land within Mini Basins. The user should be aware of this methodology in developing Mini Basin acreage when attempting to compare Mini Basins on a gallons per acre basis for either a 24-hour period or a 30-minute period.

Model Basin Size Distribution

The strategy for Model Basin layout was to breakup the system into key nodes and land use. The resulting basin sizes experienced a wider range than the Mini Basins. Figure 4 shows the distribution of Model Basin Sizes. The areas and length of sewers were derived by the same methods as Mini Basins as discussed above.

Figure 4 Distribution of Model Basin Sizes



Types of Metering

Metering for the 807 Mini Basins was accomplished with three types of metering technologies listed in Table 1. Open channel area-velocity meters function by measuring the depth (cross sectional area) and the velocity of wastewater to calculate the rate of flow. Fill and draw measurement is performed at pump station wet wells through the timing of the fill and draw cycles. No sensors are in the flow with pump station metering technology. The Time of Travel meter is a meter operated by the Sammamish Plateau District at its connection to the Issaquah Trunk Line.

Table 1	
Types of Metering	
Open Channel Area-Velocity	
LTM	75
TMP	723
Fill & Draw	8
LTM Time of Travel	1
Total	**807**

Distribution of Pipe Diameters

Meters are installed on the incoming line to a manhole. Figure 5 shows the installation in a junction structure which is more spacious than a manhole.

Figure 5 Meter Installation on Incoming Sewer

Most of the metering occurred in small to medium sized pipes within local agencies. Table 2 shows the distribution of pipe diameter at all the metering sites. The pump station meters are included in the category of 8-inch pipe. Over 69% of the meters were in pipes 15 inches and smaller. The 76 long-term meters (LTM) are measuring key nodes on large basin and consequently are located in larger pipes. Only 7 LTMs are in pipes 15 inches and smaller.

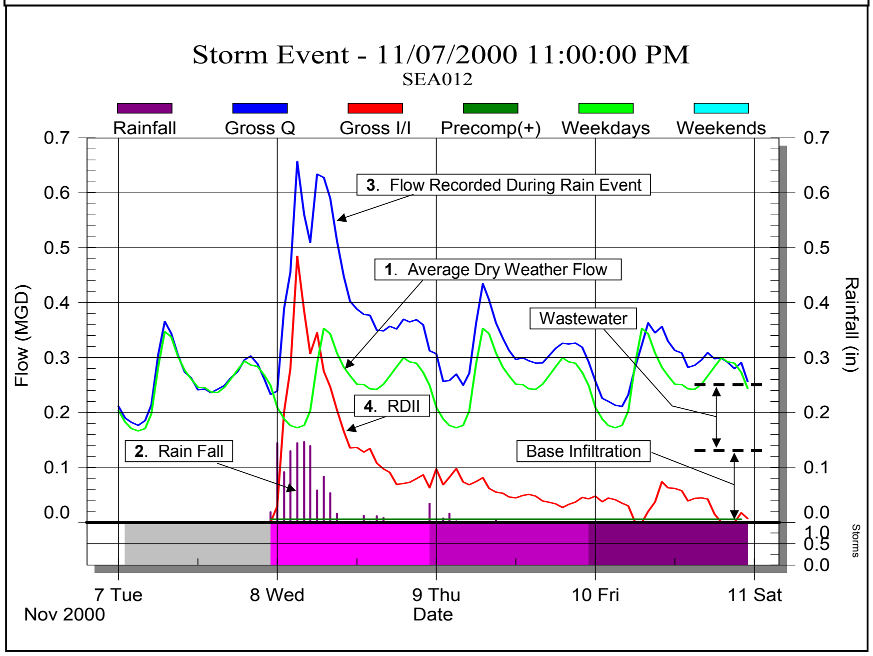
Table 2 ***Distribution of Metering Sites by Diameter***			
Diameter	Count	Percent	Cumulative %
8	200	24.8%	24.8%
10	120	14.9%	39.7%
12	142	17.6%	57.2%
14	5	0.6%	57.9%
15	93	11.5%	69.4%
18	88	10.9%	80.3%
21	33	4.1%	84.4%
24	45	5.6%	90.0%
27	11	1.4%	91.3%
30	15	1.9%	93.2%
36	19	2.4%	95.5%
42	10	1.2%	96.8%
44	1	0.1%	96.9%
48	6	0.7%	97.6%
50	1	0.1%	97.8%
52	1	0.1%	97.9%
54	1	0.1%	98.0%
60	3	0.4%	98.4%
72	8	1.0%	99.4%
84	2	0.2%	99.6%
90	1	0.1%	99.8%
108	2	0.2%	100.0%
Total	807	100.0%	

Definitions - I/I and RDII as Percentage of Rain

All I/I indicators use a measurement of "Gallons" and there are two fundamental measurements for these "Gallons": Infiltration/Inflow (I/I) and Rainfall Dependent Infiltration/Inflow (RDII). The two measurements are designed for different purposes and are discussed in this section. The King County Regional Infiltration/Inflow Program uses both measurements. However for this paper the results are expressed as RDII as a percentage of rainfall.

Traditional I/I is any excess water over and above wastewater produced in a basin. This includes all sources of clear water including base infiltration, seasonal infiltration and inflow components. King County Code specifies an I/I standard for Excess I/I as any flow other than wastewater that exceeds a 30-minute peak flow of 1,100 gpd/acre. To compare each Mini Basin to this standard, Total I/I was measured, which consists of all excess flow greater than the minimum dry weather flow Dry weather data was gathered in November and likely includes some quantity of base infiltration. An estimation of base infiltration was added to the I/I calculation to achieve Total I/I.

Figure 6 Components of RDII Calculation

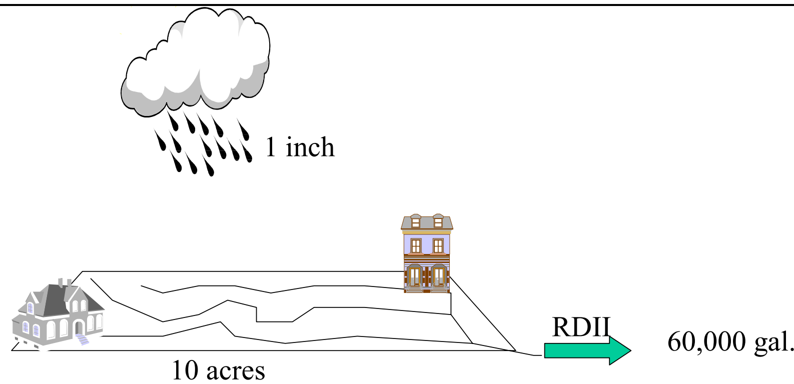


RDII as shown in Figure 6 is a measurement that specifically quantifies I/I due exclusively to a previous discrete rain event. RDII values from multiple rain events are used to develop a rainfall to RDII relationship for each Mini Basin. The rainfall to RDII relationship is in turn used to quantify the relative performance of a Mini Basin and identify improvement in I/I reduction after sewer rehabilitation. Quantifying the improvement in performance is complex and is affected by several variables. Variability includes differences in terrain, geology, ground water, method of construction, antecedent rain, season of year, age of sewers and pipe material. The techniques used to measure RDII reduce these variables by measuring the component of I/I due exclusively to a specific rain.

RDII as a Percentage of Rainfall

For this paper RDII is being expressed as a percentage of the rain volume falling on the Mini Basin. RDII volume is measured over a 24-hour period. Figure 7 illustrates how the value is obtained. Rainfall for each of the Mini Basins is calculated by CALAMAR and the RDII is measured by flow metering.

Figure 7 Calculating RDII as a Percentage of Rain



Rain volume = 1 inch of rain x 10 acres = 272,000 gal.

$$\text{Percent Rain} = \frac{\text{RDII}}{\text{Rain volume}} = \frac{60{,}000 \text{ gal}}{272{,}000 \text{ gal}} = 22\%$$

CALAMAR Rainfall Measurement

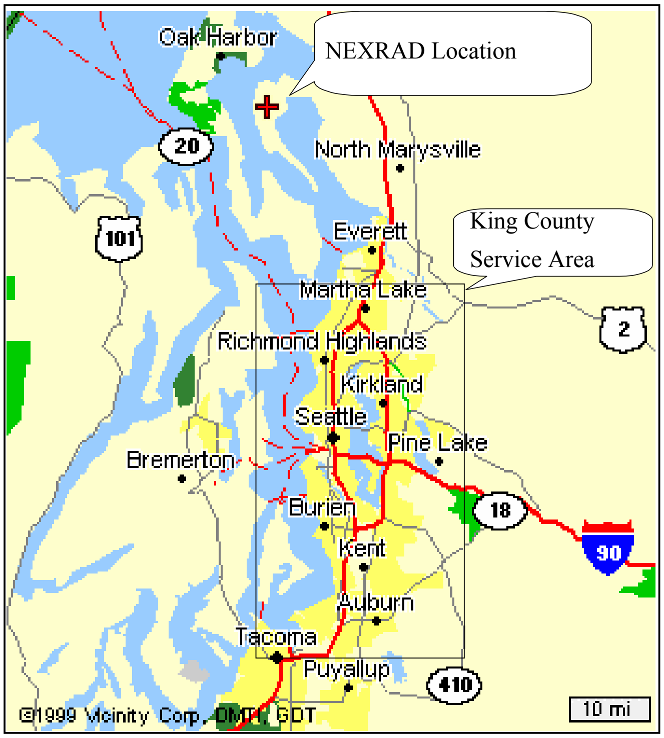
The sewer system is contained in a rectangular area of approximately 1100 square miles (2800) sq km in western King County, Washington. The area is hilly with nearly 1000 feet (300 meters) of relief in the sewered area. The cost of a conventional rain gauge network with sufficient density to assure accuracy of rainfall measurements prompted the design team to consider CALAMAR, a well-developed French technology using radar images from the National Weather Service NEXRAD Radar.

The advent of National Weather Service's NEXRAD weather radar system provides a major advance in the ability to locate and track rainfall with geographic precision. While the geographic precision of NEXRAD is very good, its ability to measure the intensity of rainfall is not precise. With the addition of CALAMAR, it is possible to have reliable, geographically precise and accurate rainfall measurements over an entire service area. CALAMAR (CAlcul de LAMes d'eau a l'Aide du Radar) translates to "Calculating Rain with the Aid of Radar". CALAMAR calibrates and processes the NEXRAD data in a unique and patented way that produces rainfall measurements with a typical accuracy of +/- 10%. This is a far higher degree of accuracy than is available from "raw" radar data, or from rain gauges alone. Accurate rainfall measurements take much of the uncertainty out of calculating relationships between rainfall and RDII whether it is by modeling or direct measurement. CALAMAR provides:

- *Geographic resolution of 1 Km^2 (0.4 square mile)*
- *Rainfall measurements between gauges with an accuracy of +/-10%.*
- *Measurements over various geographic areas in a 11,000 square mile region around the radar.*

Figure 8 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. The NEXRAD radar is located on Camano Island.

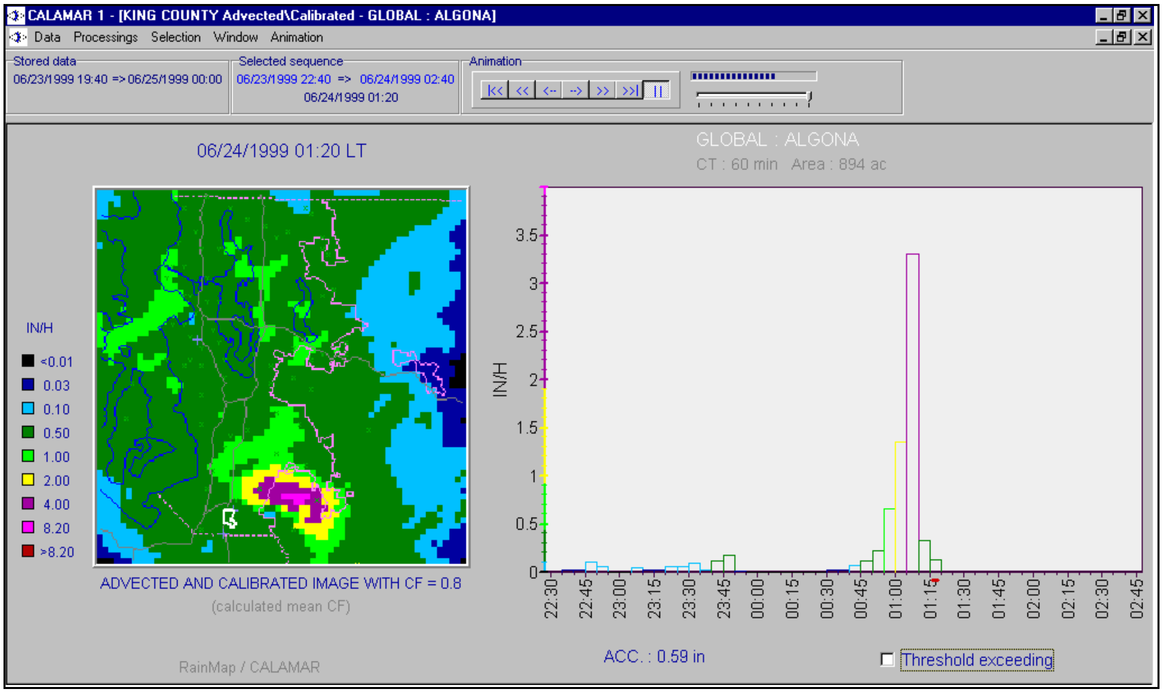
Figure 8
NEXRAD Location



CALAMAR operates by acquiring raw reflectivity images from the NEXRAD radar and processes the data with geographic resolution of 1 Km^2 pixels. Rain gauges provide "ground truth" such that, when calibrated, image pixels with rain gauges under them equal the rain gauge value. This process works well on a storm-by-storm basis since each type of storm produces a characteristically different radar image. However, such a large area provides the opportunity for multiple storms of different characteristics to occur simultaneously within the service area. To assure that only the rainfall in each region in the service area is used to calibrate the radar image for that region, the service area has been divided into eight (8) calibration zones of 200 to 500 Km^2 each.

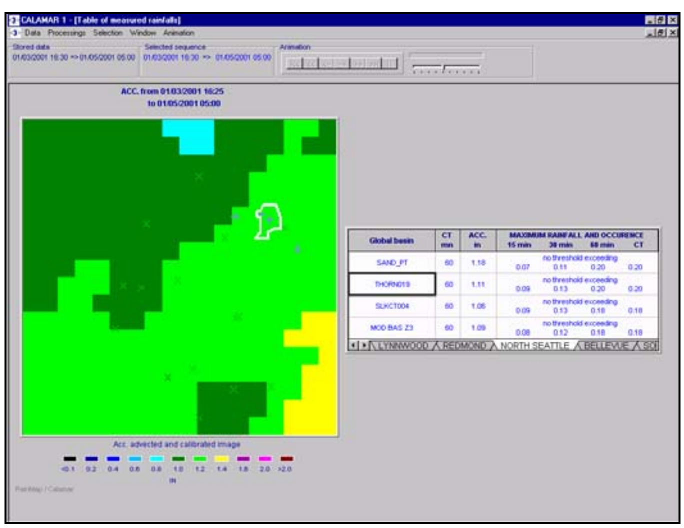
The output from CALAMAR is both graphical and tabular. Graphical views include simultaneous views of the radar image and a hyetograph. Figure 9 shows the radar image on the left and the hyetograph on the right. The image shows a red and yellow rain cell just after it passed over the City of Algona and the hyetograph shows the rainfall intensity in 5-minute steps.

Figure 9
Simultaneous views of the Radar Image and a Hyetograph in CALAMAR



A second graphical output is an image of accumulated rainfall plus a table of accumulated rainfall. Figure 10 shows the accumulated rainfall image on the left for the North Seattle calibration zone and a table of accumulated rainfall on the right. The outlined boundary on the image is the model basin above LTM Thorn019.

Figure 10
Accumulated Rainfall for Model Basin



Network of Calibrating Rain Gauges

The King County Wastewater Treatment Division (WTD) and Water and Land Resources Division (WLRD) each operate a network of rain gauges throughout King County. An additional 25 gauges were installed to create sufficient density for calibration by CALAMAR. The new gauges bring the total number of calibration gauges to 72

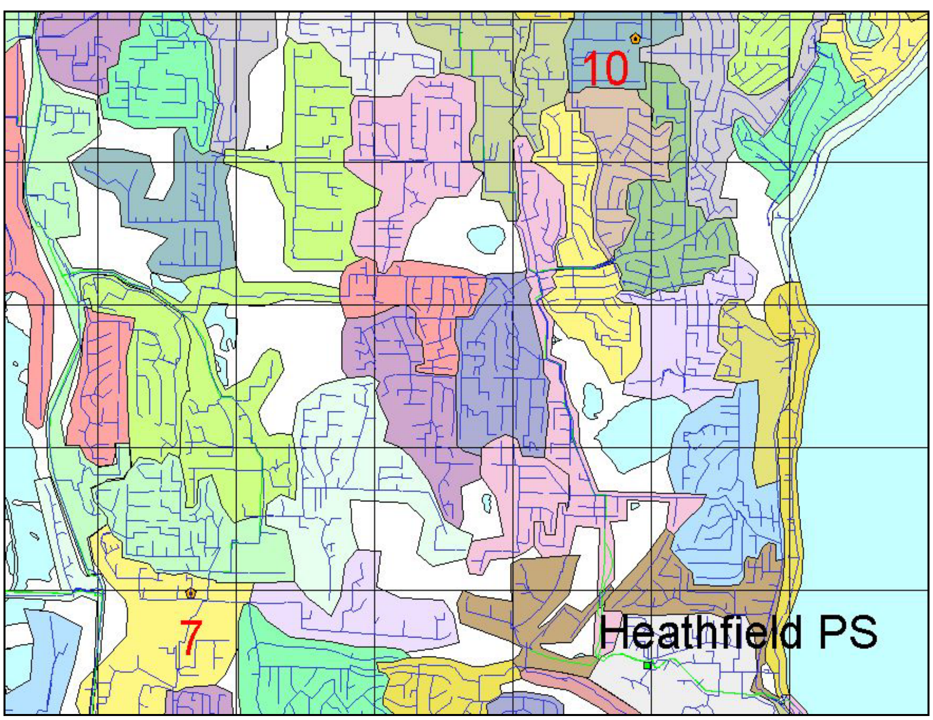
Calibration Zones

The service area has been divided into eight (8) calibration zones of 200 to 500 Km^2 each to assure that only those rains within the zone calibrate each zone. The 8 calibration zones, the 72 rain gauges together provide rainfall hyetographs for 2222 pixels of 1 Km^2 area.

Pixel Rain Data

In its most elemental form the output from CALAMAR is a series of rainfall measurements for every 1 Km^2 pixel in the service area. To provide perspective of 1 Km^2 pixels and 20,000 LF Mini Basins, Figure 11 shows a collection of Mini Basins in the City of Bellevue with 1 Km^2 pixels superimposed. Also shown are three of several rain gauges that will calibrate the Bellevue Calibration Zone. Sanitary sewer lines are shown in each colored Mini Basin. CALAMAR produces a digital hyetograph for each pixel. Pixel rain data are converted to rain data for each Mini Basin as described in the next section.

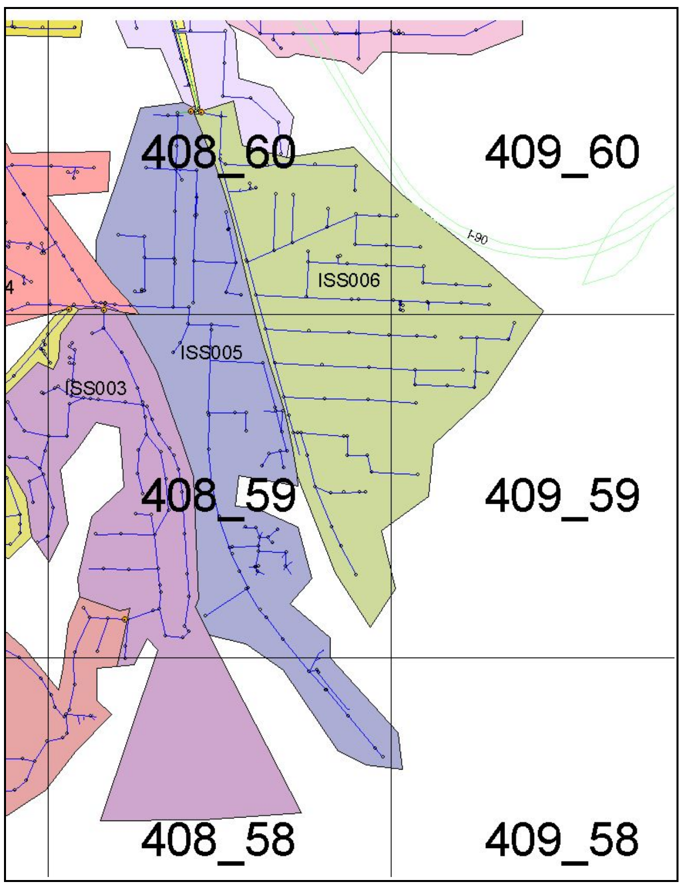
Figure 11
Bellevue Mini Basins, Three Rain Gauges and 1 Km^2 Pixels



Conversion from Pixel Data to Mini Basin Rain Data

A rainfall data file was created for each Mini Basin for each of the four storms that were analyzed. Most Mini Basins fall into more than a single pixel and a method was created to determine the average rainfall on each Mini Basin. Figure 12 shows several Mini Basins located in Issaquah and the CALAMAR pixels overlaid on the Mini Basins. The pixel numbers are derived from the approximate location, in kilometers, of the northwest corner of each pixel. The numbering system is similar to the Washington State Plane Coordinate System, but the starting coordinates are not the same. For example the pixel 408_59 is located 408 Km east and 59 Km north of the coordinate starting point.

Figure 12
Mini Basins located in Issaquah and the CALAMAR Pixels Overlaid on the Mini Basins



Many of the Mini Basins are positioned in multiple pixels. A method was developed using the GIS to determine the percent of rainfall on a Mini Basin coming from each pixel. Table 3 illustrates this method for Mini Basin ISS005. The yellow highlighting is on the 5 pixels that contribute to rainfall on Mini Basin ISS005 and the column "Percent" lists the percentage of each pixel. For example, nearly 54% of the rain on Mini Basin

ISS005 comes from pixel 408_59. This process produces both time series and accumulated rainfall data for each Mini Basin.

Table 3

Determination of Percent of Rainfall on a Mini Basin

BASIN	PERCENT	EAST	NORTH	PIXEL
ISS004	0.0002	406	60	406_60
ISS004	0.0311	407	59	407_59
ISS004	0.1228	407	59	407_59
ISS004	0.0000	408	59	408_59
ISS004	0.0000	408	59	408_59
ISS004	0.7432	407	60	407_60
ISS004	0.0357	408	60	408_60
ISS004	0.0670	408	60	408_60
ISS005	0.0052	409	58	409_58
ISS005	0.1000	408	58	408_58
ISS005	0.5397	408	59	408_59
ISS005	0.3549	408	60	408_60
ISS005	0.0001	408	60	408_60
ISS006	0.2003	409	59	409_59
ISS006	0.0006	409	59	409_59
ISS006	0.1273	409	60	409_60
ISS006	0.3393	408	59	408_59
ISS006	0.3326	408	60	408_60
ISS007	0.1790	409	60	409_60
ISS007	0.3648	409	61	409_61
ISS007	0.0389	408	61	408_61
ISS007	0.2614	408	60	408_60
ISS007	0.1560	410	61	410_61

Results

Rainfall

Rainfall through the normal wet period of November through March was 50% of normal. The average rainfall for the period is 27 inches and 17 inches fell. The rains that did fall were followed by sufficient dry periods to allow recovery to nearly dry weather I/I levels. The dry days also prevented the soil conditions from being saturated. As would be expected, the range of I/I was much less than normal.

There were four rains that caused measurable system-wide responses and they are listed in Table 4.

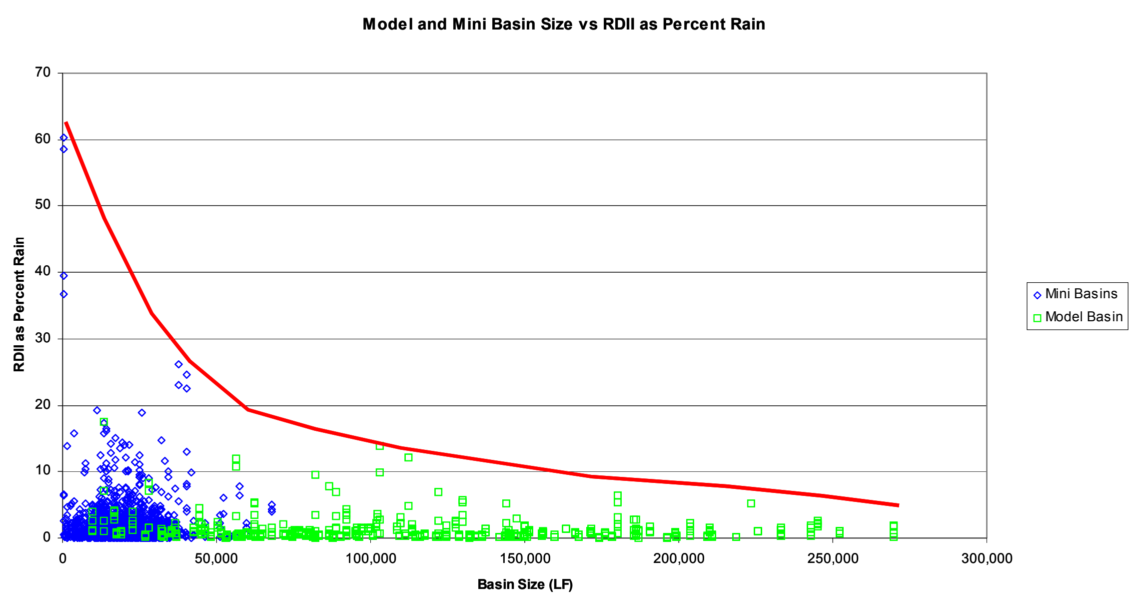
Table 4
Range of Rainfall for Four Events over Service Area

Date of Rain Event	Rainfall - Inches
7 November 2000	0.7 – 1.3
26 November 2000	0.8 – 1.4
16 December 2000	0.2 – 0.8
4 January 2001	0.4 - 0.9

RDII as a Percentage of Rainfall

Figure 13 displays RDII results for all storms for both Mini and Modeling Basins. RDII is expressed a percentage of rainfall falling on each basin. There are over 3600 data points presented in this figure. The larger modeling basins are displayed separately as green square symbols. Overlaid is a red line similar to the lines in Figures 1 and 2.

Figure 13 RDII as a Percentage of Rain v.s Basin Size



C. Conclusions

Even with the below normal rainfall during the metering period, the expected relationship between the size of a Mini Basin and its expected range of performance has been verified. With normal rains it is expected that Mini Basin RDII values will increase to approach the expected value. Based on these data it can be shown, for example, that upper range of RDII of 40,000 LF basins will be double range of 100,000 LF basins. It is improper to compare the performance of large basins directly to the performance of small basins.