Memo - DRAFT

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To: Kevin Stewart and Chad Kudym

From: Markus Ritsch

Subject: **Analysis of Large Storms in 2004**

I. ALERT Data Source

Validated ALERT data records extracted from the Urban Drainage and Flood Control District's Nova Star 4.0 base station (ALERT 2) were analyzed for several storm periods in 2004. These periods include:

- June 8, 2004
- June 27, 2004
- July 23, 2004
- August 18, 2004
- August 19, 2004

II. General System Analysis Summary

The ALERT records for complete 24-hour periods associated with each storm period were analyzed to determine the distribution of reports among the various sensor groups (Table 1).

Table 1. Distribution of Total Reports for each 24-hour Period

Group	June 8	June 27	July 23	August 18	August 19	Total	Percent
Precipitation	1,153	1,663	2,793	5,781	3,502	14,892	59.13%
Water Level	916	1,509	2,616	2,979	1,655	9,675	38.42%
Battery/Status	89	92	94	90	92	457	1.81%
Meteorological	32	17	70	27	15	161	0.64%
Total	**2,190**	**3,281**	**5,573**	**8,877**	**5,264**	**25,185**	**100%**

The total reports received ranged from 2,190 reports on June 8 to 8,877 reports on August 18. On average, during these "stormy" days, precipitation sensors account for the majority, almost 59 percent of the total reports received at the base. Water level sensors are next and account for nearly 38 percent of the total reports. Other sensors including wind, air temperature, humidity and battery account for only a small portion, less than 3 percent of the total reports received during stormy periods.

III. Radio Traffic Loading Summary

Of interest during the stormy days are those hours when radio traffic loading is high. To identify the heavy traffic periods, the number of reports received during each hour are computed (Table 2).

Table 2. Hourly Radio Traffic for Each 24-hour Storm Period

24-Hour Period (Hour)	June 8	June 27	July 23	August 18	August 19
Midnight to 0:59 AM	39	45	209	70	642
1:00 AM to 1:59 AM	23	25	140	29	492
2:00 AM to 2:59 AM	32	38	131	35	505
3:00 AM to 3:59 AM	39	28	106	27	450
4:00 AM to 4:59 AM	33	21	56	28	421
5:00 AM to 5:59 AM	26	39	52	14	396
6:00 AM to 6:59 AM	22	36	53	19	395
7:00 AM to 7:59 AM	39	34	51	12	287
8:00 AM to 8:59 AM	38	32	76	20	172
9:00 AM to 9:59 AM	41	24	64	37	167
10:00 AM to 10:59 AM	51	39	78	48	144
11:00 AM to 11:59 AM	40	26	109	39	109
12:00 PM to 12:59 PM	37	29	173	57	116
1:00 PM to 1:59 PM	36	28	321	73	110
2:00 PM to 2:59 PM	34	130	646	271	118
3:00 PM to 3:59 PM	21	363	607	528	129
4:00 PM to 4:59 PM	19	604	510	830	71
5:00 PM to 5:59 PM	23	522	484	1108	78
6:00 PM to 6:59 PM	27	412	428	1175	85
7:00 PM to 7:59 PM	69	251	351	1150	51
8:00 PM to 8:59 PM	417	210	278	1034	61
9:00 PM to 9:59 PM	572	133	209	906	75
10:00 PM to 10:59 PM	304	114	251	697	92
11:00 PM to 11:59 PM	208	98	190	670	98
Total	**2,190**	**3,281**	**5,573**	**8,877**	**5,264**

Those hours that experienced more than 500 reports are shaded in yellow. By far the biggest day in terms of radio traffic loading was August 18 which included a period from 5:00 PM to 9:00 PM where traffic loading rates greater than 1,000 reports per hour were experienced.

IV. General Rain Event Reporting Analysis

A. 24-Hour, District-Wide Total Tip/Count Statistics

The incrementing reports from all District 1-mm rain sensors were analyzed to quantify the average total 24-hour tip/count accumulation (Table 3).

Table 3. Summary of 24-Hour Total 1-mm Tip/Count

Statistic Parameter	June 8	June 27	July 23	August 18	August 19
District-Wide Mean	11.44	11.59	19.13	41.85	8.57
Median	6	8	17	41	8
Std Deviation	14.1	11.3	13.9	17.8	4.6
Min Sensor Accumulation	1	1	2	2	1
Max Sensor Accumulation	82	53	64	124	24
Max Sensor ID	1010	330	1900	1360	4290

* Denver West (ID 1010), Van Bibber (ID 330), Niver Detention (ID1900), Denver Zoo (ID 1360), Red Hill (ID 4290)

The largest event from a district-wide perspective occurred on August 18 where almost 42 mm (1.65 in) fell in a 24-hour period. This event also produced the highest single sensor accumulation which occurred at the Denver Zoo (ID 1360) which recorded 124 mm or almost 4.9 inches in a 24-hour period.

The storm of June 8 generated a lower district-wide mean of only 11.44 mm (0.45 in) but it had a high single sensor total of 82 mm or 3.22 inches at the Denver West (ID 1010) station.

B. Spatial Distribution of 24-Hour Storm Totals

The 24-hour station accumulations for each storm period are plotted using GIS to analyze the spatial extent of each storm. From the station totals a general continuous rainfall surface was determined for each storm period using an inverse distance weighting scheme with a 10-mile radius of influence for each station. The resulting rainfall maps are shown in Appendix A (note the maps are 11” by 17” format).

The rainfall maps confirm that the event of June 8 was much smaller in spatial extent but had very high localized precipitation. The events of June 27 and July 23 exhibit a larger spatial extent as shown in the higher district-wide mean but were not as locally intense as seen by the lower single sensor accumulations.

The rainfall map for August 18 shows that a fairly heavy general rainfall occurred throughout the District and embedded in the general rainfall were several cells of high intensity precipitation.

C. System-Wide Tip/Count Analysis

The sequential tip count series was analyzed for each 1-mm rain sensor to quantify the number of single tips, double tips, triple tips etc. that occurred during each 24-hour period. The incrementing tip analysis output is shown in Appendix B. The tip analysis for each sensor was used to determine the system-wide tip count summary (Table 4).

Table 4. System-Wide, 24-Hour, Tip/Count Summary

Storm Period	1-tip	2-tip	3-tip	4-tip	5-tip	6-tip	>6-tip	Received	Expected	Reception Percent
June 8	721	125	14	7	0	2	0	869	1,053	82.53%
June 27	1,223	155	17	4	0	0	3	1,402	1,623	86.38%
July 23	2,068	239	33	11	2	0	1	2,354	2,706	86.99%
August 18	3,945	747	153	37	8	4	5	4,899	6,154	79.61%
August 19	1,014	91	9	2	1	0	0	1,117	1,236	90.37%

The reception percentage experienced on August 18 when 1,255 single incrementing tip reports were not received by the base station was the worst. This would stand to reason because this was also the day that had the largest district-wide precipitation and very high radio traffic loading rates.

The second worst day in terms of reception percentage was June 8 which was not an extreme day in terms of district-wide rainfall but it was a day that experienced heavy local precipitation.

Three storm periods had sensors that experienced a jump in sequential count of more than 6 tips. The data validation process becomes difficult when large gaps exist in the sequential tip count series. The precipitation accumulations for these sensors may be inaccurate and should be double-checked in the historical archive.

- June 27: Ralston Reservoir (ID 110), Red Rocks Park (ID 2370) and Shanahan Ridge (ID 4810)
- July 23: Sable Ditch (ID 800)
- August 18: Cold Spring Gulch (ID 2240), Morrison (ID 2330), Salisbury Park (ID 2730), Castle Oaks Road (ID 2830) and Red Garden (ID 4030)

Further analysis is required to better understand the dynamics associated with data loss during periods of high radio traffic. The subsequent analysis breaks the 24-hour periods down into 1-hour periods and analyzes independently those 1-hour periods.

V. Heavy Radio Traffic Hour Rain Event Reporting Analysis

Each hour exceeding 500 messages received at the base station (Table 2 shaded in yellow) was analyzed independently to quantify the performance of each rain sensor.

A. Data Loss during Heavy Radio Traffic Hours

The following analysis seeks to establish some correlation between data loss and total hourly traffic loading.

Total actual hourly traffic loading was estimated as the number of received reports at the base station plus those incremental rain reports that were lost. The assumption made is that each incrementing report was transmitted from the remote rainfall station but due to a collision or partial collision with another data report, one or both the reports were lost. The lost reports, even though they were never received at the base station still contribute to the traffic loading. The estimated total hourly traffic loading number still underestimates the total load because there may be stage or weather reports that were also lost and these are not taken into account.

Table 5. Heavy Traffic Hour Rain Event Reporting Summary

	Total Rain Reports			Percent	Total Loading	Accurate
Heavy Traffic Hour	**Expected**	**Received**	**Missed**	**Loss**	**(reports/hr)**	**Rain Totals**
June 8, 9:00-10:00 PM	352	298	54	15.34%	572+54 = 626	Yes
June 27, 4:00-5:00 PM	418	358	60	14.35%	604+60 = 664	No (ID 4180)
June 27, 5:00-6:00 PM	246	229	17	6.91%	522+17 = 539	No (ID 4360)
July 23, 2:00-3:00 PM	411	333	78	18.98%	646+79 = 725	Yes
July 23, 3:00-4:00 PM	258	216	42	16.28%	607+42 = 649	No (ID 4290)
July 23, 4:00-5:00 PM	241	215	26	10.79%	510+26 = 536	No (ID 4240, 4250)
Aug 18, 3:00-4:00 PM	394	350	44	11.17%	528+53 = 581	No (ID 4490)
Aug 18, 4:00-5:00 PM	555	479	76	13.69%	830+76 = 906	Yes
Aug 18, 5:00-6:00 PM	741	574	167	22.54%	1,108+167 = 1,275	Yes
Aug 18, 6:00-7:00 PM	638	499	139	21.79%	1,175+139 = 1,314	No (ID 1480)
Aug 18, 7:00-8:00 PM	690	531	159	23.04%	1,150+159 = 1,309	Yes
Aug 18, 8:00-9:00 PM	539	443	96	17.81%	1,034+96 = 1,130	No (ID 1060)
Aug 18, 9:00-10:00 PM	398	346	52	13.07%	906+52 = 958	No (ID 1720, 4030)
Aug 18, 10:00-11:00 PM	254	229	25	9.84%	697+28 = 725	No (ID 4030)
Aug 18, 11:00-12:00 PM	230	216	14	6.09%	670+14 = 684	Yes
Aug 19, 12:00-1:00 AM	179	163	16	8.94%	642+16 = 658	Yes
Aug 19, 2:00-3:00 AM	90	81	9	10.00%	505+9 = 514	Yes

It can be seen that as the radio traffic loading increases, the percentage of lost reports also increases. To visually inspect this correlation, the percentage of lost rain reports (Column 5, Table 5) are plotted against the total (Column 6) loading rates and shown (Figure 1).

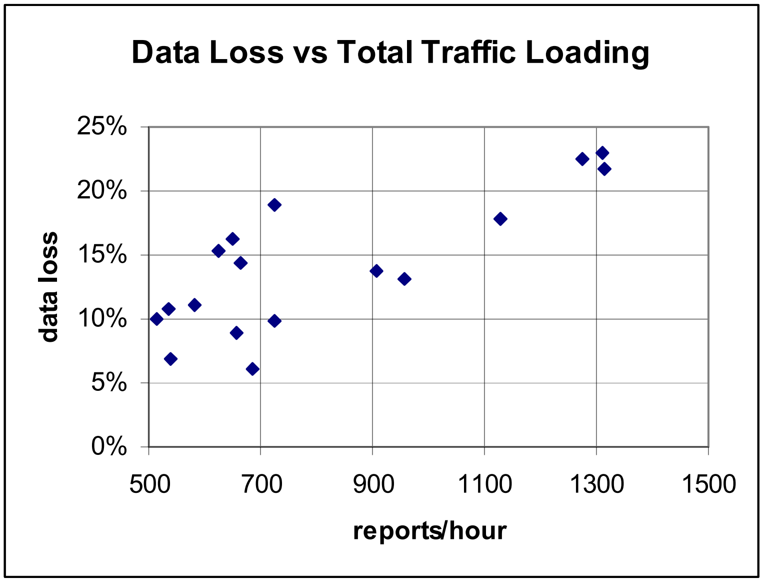

Figure 1. Rain Reports Lost versus Total Traffic Loading

A general trend can be seen on the plot (Figure 1) but there seems to be a great degree of variability in the range from 500 to 700 reports per hour. Additional insight may be gained by looking at the distribution of messages between rainfall and stage sensors during the heavy traffic hours, specifically the cluster of data points in the vicinity of 600-700 reports/hour with a loss of 15-19% (Table 6).

Table 6. Distribution of Reports during Heavy Traffic Hours

	Distribution of Total Reports				Percent of Total	
Heavy Traffic Hour	**Rain**	**Stage**	**Other**	**Total**	**Rain**	**Stage**
June 8, 9:00-10:00 PM	380	185	7	572	66%	30%
June 27, 4:00-5:00 PM	438	166	0	604	73%	27%
June 27, 5:00-6:00 PM	328	193	1	522	63%	37%
July 23, 2:00-3:00 PM	422	216	8	646	65%	32%
July 23, 3:00-4:00 PM	295	308	4	607	49%	47%
July 23, 4:00-5:00 PM	285	223	2	510	56%	40%
Aug 18, 3:00-4:00 PM	466	59	3	528	88%	11%
Aug 18, 4:00-5:00 PM	670	136	24	830	81%	16%
Aug 18, 5:00-6:00 PM	733	327	48	1,108	66%	30%
Aug 18, 6:00-7:00 PM	632	495	48	1,175	54%	42%
Aug 18, 7:00-8:00 PM	663	469	19	1,151	58%	41%
Aug 18, 8:00-9:00 PM	628	376	30	1,034	61%	36%
Aug 18, 9:00-10:00 PM	537	348	21	906	59%	38%
Aug 18, 10:00-11:00 PM	391	289	17	697	56%	41%
Aug 18, 11:00-12:00 PM	373	270	27	670	56%	40%
Aug 19, 12:00-1:00 AM	330	277	35	642	51%	43%
Aug 19, 2:00-3:00 AM	302	183	20	505	60%	36%

Generally there is approximately a 60%/30% split between data reports from rain sensors relative to stage sensors. There were several hours when the reports from rain sensors accounted for 80-90% of the total. Likewise there were also periods when the split between rain and stage sensors was about even.

The distribution of reports between rain and stage sensors does not seem to have a clear correlation with lost reports. Nothing is evident from the table that would explain why the 4 points highlighted exhibit such a high loss of rainfall data in the traffic range of 500-700 messages per hour.

B. Loss of Sequential Reports

The District (specifically the work of Mr. Don Van Wie) has proposed a measure of radio traffic loading that has direct relevance to the functionality of a flood detection system and this is the probability of losing 3 messages in a row from any single gage. At this point, the loss of data begins to pose a problem to the data validation schemes employed by typical ALERT base station software applications. When the data validation process is hampered by the loss of data, the identification of critical alarm thresholds may be delayed which may in turn cause a delay in the notification and evacuation of critical areas during flood mitigation.

To support the evaluation of system capacity as defined above, the occurrence of 2 or more lost reports in a row from a single sensor during the hours of heavy radio traffic are analyzed. A correlation may exist between the loss of sequential reports to the total traffic loading. This correlation may be useful to help establish the limit of channel capacity in terms of reports per hour. A summary of lost sequential reports is shown (Table 7).

Table 7. Loss of Sequential Reports during Heavy Traffic Hours

	Loss of Sequential Rain Tip Reports						Total Loading
Heavy Traffic Hour	**2**	**3**	**4**	**5**	**>5**	**Total**	**Reports/Hour**
June 8, 9:00-10:00 PM	4	3	0	0	0	7	626
June 27, 4:00-5:00 PM	6	1	0	0	1	8	664
June 27, 5:00-6:00 PM	0	0	0	0	1	1	539
July 23, 2:00-3:00 PM	9	3	0	0	2	14	725
July 23, 3:00-4:00 PM	6	1	0	0	0	7	649
July 23, 4:00-5:00 PM	2	0	0	0	0	2	536
Aug 18, 3:00-4:00 PM	3	0	0	0	0	3	581
Aug 18, 4:00-5:00 PM	7	0	0	0	0	7	906
Aug 18, 5:00-6:00 PM	26	6	0	0	1	33	1,275
Aug 18, 6:00-7:00 PM	17	6	1	0	0	24	1,314
Aug 18, 7:00-8:00 PM	14	9	1	2	0	26	1,309
Aug 18, 8:00-9:00 PM	9	2	0	0	0	11	1,130
Aug 18, 9:00-10:00 PM	6	0	0	0	0	6	958
Aug 18, 10:00-11:00 PM	2	0	0	0	0	2	725
Aug 18, 11:00-12:00 PM	0	0	0	0	0	0	684
Aug 19, 12:00-1:00 AM	1	0	0	0	0	1	658
Aug 19, 2:00-3:00 AM	1	0	0	0	0	1	505

Again, it is evident that some correlation exists between the occurrence of lost sequential reports and the total radio traffic loading. A plot is developed that shows the total traffic loading versus the occurrence of 3 or more lost reports "in-a-row" (Figure 2**Error! Reference source not found.**).

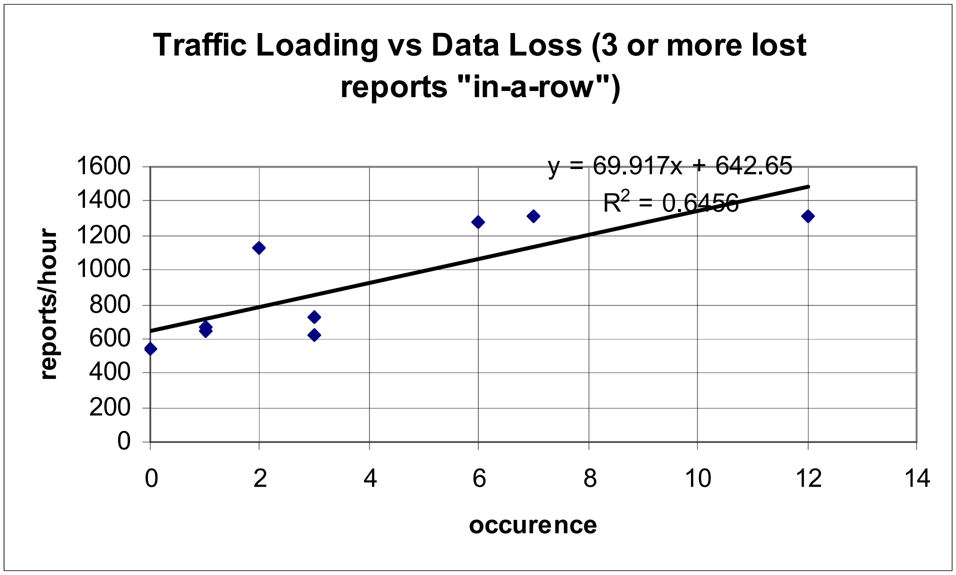

Figure 2. Plot of Total Radio Traffic Loading versus Loss of 3 or More Sequential Reports

Several general inferences can be made from the plot:

- There are too few points to develop a good statistical correlation
- At 600 reports/hour the likely hood of missing 3 reports in a row is very low
- At 1,000 reports/hour the District can expect to have 5 occurrences where 3 reports in-a-row are missing

VI. Conclusion

Four storms from 2004 were analyzed which revealed both specific and general information related to the District's ALERT-based flood detection network including:

1. During storm periods, the ALERT traffic is dominated by rain and stage sensors.
    a. On average, rain sensors account for 60% of the total traffic load.
    b. On average, stage sensors account for 40% of the total traffic load.
2. 600 reports/hour seems to be a threshold where the District network begins to experience lost reports.
    a. Below 600 reports/hour there are occurrences of missing single reports but typically no occurrences of 2 or more missing reports "in-a-row".
3. Only 4 times in all of 2004 did the District system experience radio traffic loading rates exceeding 1,000 reports/hour. These all occurred on August 18, 2004.
4. In general, as the number of reports/hour increases, so does the number of lost reports.
5. An exact single relationship between the total traffic load and lost reports does not exist.
    a. Each storm has unique characteristics in terms of its spatial extent and the occurrence of small, localized, high intensity cells. In addition to the total traffic load, the number of lost reports is also a function of these local storm characteristics.
    b. Although an exact relationship does not exist, the analysis started in this study should be supplemented with additional storm data to develop a general relationship between lost reports and total traffic loading. This study is based only on 4 storms that occurred in 2004.

VII. Appendix A – Rainfall Maps

VIII. Appendix B – General Storm Summary and Event Data Analysis Output