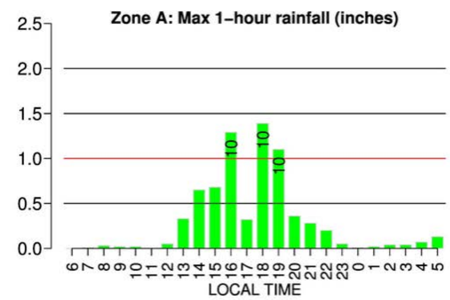

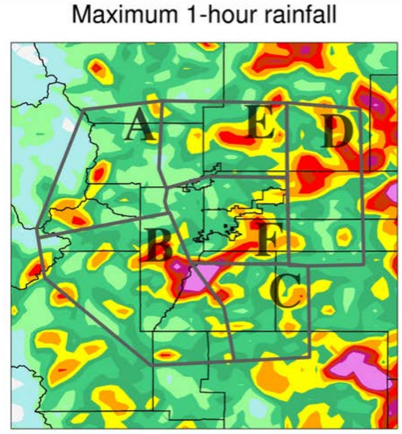

Zone	Threat	Primetime
A	HIGH	13-20Thu
B	HIGH	12-21Thu
C	HIGH	13-22Thu
D	HIGH	15-21Thu
E	HIGH	13-18Thu
F	HIGH	13-20Thu

2015 UDFCD Heavy Rainfall Guidance Tool – Performance and Validation

FINAL REPORT

November, 2, 2015

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2015 UDFCD Heavy Rainfall Guidance Tool

Validation & Final Report

OVERVIEW

In early 2015, Dewberry constructed a Heavy Rainfall Guidance (HRG) Tool (hereafter, Tool) for the Urban Drainage and Flood Control District (UDFCD). The Tool was designed to leverage the latest high resolution weather forecast models to address four crucial questions regarding the summertime daily heavy rainfall threat across the UDFCD area: (i) timing, (ii) location, (iii) intensity and (iv) confidence. The Tool's operational season spanned from May 1 through September 30. This Report provides an analysis of the Tool's performance as well as investigates the potential for future refinement.

Tool description

The UDFCD HRG Tool accesses hourly Quantitative Precipitation Forecast (QPF) data from 13 different high resolution weather models from the National Severe Storms Laboratory (NSSL) and the National Centers for Environmental Prediction (NCEP). All models have horizontal resolution of 4 km (2.4 miles) or less allowing for a more realistic representation of thunderstorm-based rainfall compared to conventional, lower-resolution weather models. QPF data from the 13-model "ensemble" is re-gridded to a common ~3.9 km grid for an area centered on the UDFCD. From there, maximum hourly QPF (QPFMAX) and exceedance probabilities (for example, chance of exceeding 1 inch per hour) are constructed for each of six forecast Zones (See Figure 1). Although UDFCD's area is about 1,600 sq. miles, the Tool covers an area of about 7,500 sq. miles to ensure that rainfall is captured within contributing watershed boundaries that extend outside of the official UDFCD boundary.

Post-processed data from the Tool is displayed on a web-based user interface. Snapshots of the "Daily Summary" and 'Zone Forecasts" sections of the Tool's web interface are shown in Figure 1 from June 3rd, when heavy rainfall was observed across the UDFCD area.

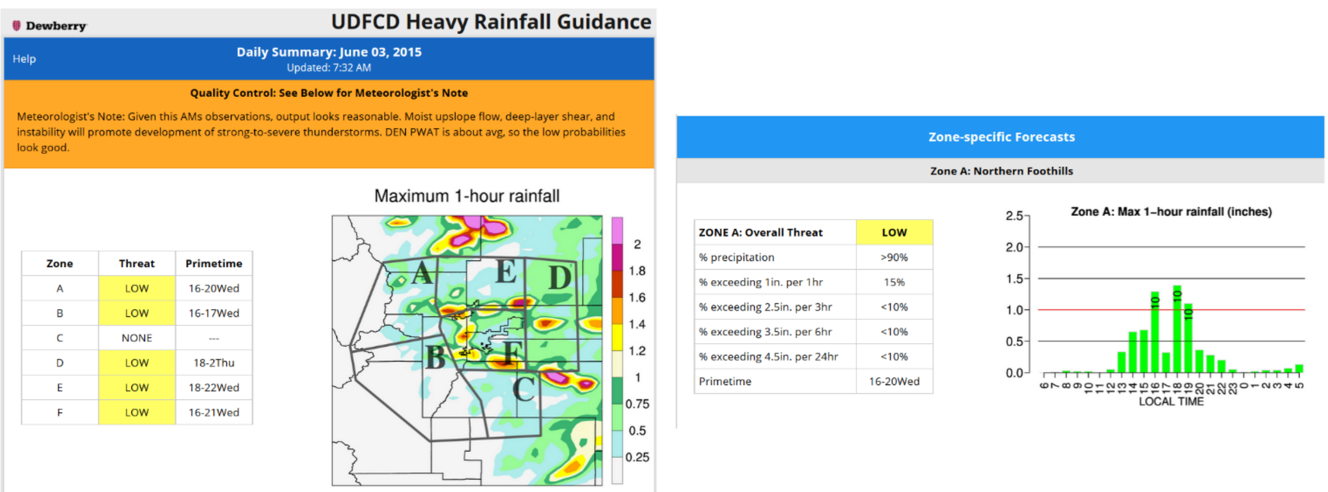

Figure 1: Snapshot of the "Daily Summary" and "Zone-Specific Forecasts" of the Tool's website for June 3, 2015.

Archives and daily validation of the Tool's output is available by clicking on the "Archives" link at the top right of the website. However, this Report represents the first comprehensive and official validation of the Tool's performance. In this report, we discuss the metrics to be analyzed for the validation effort as well as the rainfall data that is used to verify the Tool forecasts.

Next, we present key findings regarding the four questions (timing, location, intensity and confidence) that the Tool is designed to address. Finally, we provide conclusions and recommendations of how the wealth of data collected during this first operational season can be used to improve Tool performance in subsequent seasons.

METHODOLOGY

Validating the performance of rainfall forecasts is notoriously difficult due to the large spectrum of possible metrics. This is especially relevant when data from multiple weather models is involved, as is the case with the Tool. For the purposes of this report, we must recall that the UDFCD-HRG Tool was designed to detect the *maximum* rainfall amount on any given day. While it is possible and potentially useful to investigate other aspects of rainfall statistics (for example, distribution across the domain, relation to climatology, etc), the primary focus of this report will be on analyzing maximum rainfall amounts. Furthermore, since we are interested in relatively short-term rainfall capable of producing flash flooding, the focus of the validation will be on the 1-hour time period. However, we include descriptions of other durations (e.g. 3-hr, 6-hr, 24-hour) as necessary. Finally, we avoid a grid point-by-grid point comparison of the Tool's performance. This is because even the latest weather models that are used by the Tool cannot skillfully predict rainfall on a grid point-specific level (Schwartz et al. 2014). This limitation will not take away from the model's utility as long as it can come reasonably close in to predicting heavy rainfall in both space and time. To circumvent this, we perform a validation for each Zone that does not penalize the Tool output as long as it correctly forecasts rainfall anywhere within the Zone. Since the forecast zones are only about 1,000 square miles (roughly equaling to about 150 model grid points), this still represents an appropriately challenging benchmark. For example, Schwartz et al. 2014 employ a "neighborhood" validation approach characterized by a 16-mile radius circle centered on the point of interest. This equates to a square area of approximately 770 square miles, which is quite comparable with our forecast Zone areas (see Table 1).

Rainfall Observations

We used UDFCD's ALERT rainfall data at roughly 200 operating gauges across the District as one of the primary inputs to the validation. Raw tipping bucket data was processed into total hourly accumulation. To supplement the ALERT data, we use gridded 4-km gauge-adjusted radar estimates provided by the National Oceanic and Atmospheric Administration's Stage IV product. The benefit of Stage IV is that it has full coverage in space, especially due to UDFCD's proximity to the Denver NEXRAD Doppler radar. However, Stage IV's limitations are that:

(i) because it is first derived from radar reflectivity (and then gage corrected) it does not always accurately reflect the true rainfall, and

(ii) because the Stage IV product is on a 4-km grid, this may act to smooth out rainfall amounts, especially for spatially explicit storms. We note that Stage IV hourly rainfall is *lower* than corresponding ALERT data 67% of the time when rainfall occurred during our study period.

For our validation, *we use the maximum hourly rainfall from either ALERT or Stage IV*. While this doesn't represent the most ideal solution using a combination of ALERT and Stage IV data gives us the best readily attainable measurement of rainfall in the UDFCD area.

Table 1 describes the characteristics of the six forecast zones. Five of the six zones were roughly 1,000 square miles, while Zone B (Southern Foothills) was about 2,000 square miles due to its extension to the Continental Divide. Table 1 also shows that each Zone had a widely varying number of ALERT gauges within it, ranging from zero in Zone D (Plains) to 97 in Zone F (Central Metro). The right two columns of Table 1 show that 2015 rainy season was slightly above average, climatologically speaking, with 224 *hours* of the period from May 1 through September 30 exceeding 0.5 inches per hour of rainfall and 72 *hours* exceeding 1 inch per hour. On a daily aggregated level, there were 72 *days* where rainfall exceeded 0.5 per hour, and 36 *days* with rainfall exceeding 1 inch per hour.

Table 1: Summary of forecast Zones.

Forecast Zone	Area (sq. mi.)	# of ALERT gauges	# of hours >= 0.5 in/hr	# of hours >= 1.0 in/hr
(A) Northern Foothills	1,316	49	29 hours	6 hours
(B) Southern Foothills	2,029	38	57	12
(C) Palmer Divide	933	22	85	25
(D) Plains	1,283	0	47	6
(E) Northern Metro	1,053	14	34	10
(F) Central Metro	1,043	97	87	22
All Zones	**7,657**	**220**	**224**	**72**

Threat Classification System

Although the Tool outputs forecasted rainfall data, its broader purpose is to act as a decision support tool. Accordingly, we developed a classification table that translated the Tool's output into one of four Threat Levels: Low, Moderate, High and Very High. The Threat Level is based on two considerations: rainfall intensity and probability of exceedance. The following four rainfall duration thresholds are used to identify a possible threat: **1 inch per 1 hour**, **2.5 inches per 3 hours**, **3.5 inches per 6 hours** and **4.5 inches per 24 hours**. These are meant to capture the wide array of rainfall events, ranging from very intense, short-duration events to low-to-moderate intensity, but long-duration events. In addition to the threshold itself, we use the probabilistic capabilities of the Tool to quantify the confidence of a threshold being exceeded. Intuitively, a higher probability of exceedance warrants a higher threat levels. Then, the classifications are determined as follows:

Table 2: Threat classification system

Threat	Intensity	Probability of Exceedance
LOW	At least 1 threshold is broken	---
MODERATE	i) At least 1 threshold is broken AND	>50%
	ii) More than 1 threshold is broken AND	>40%
HIGH	More than 1 threshold is broken AND	>60%
VERY HIGH	More than 1 threshold is broken AND	>80%

It's important to note that this table was developed using the professional opinion of Dewberry's meteorologists and floodplain managers, and may be altered in the future to provide a refined classification of the threat/impact nexus. Table 3 shows the number of threats identified for each Zone, categorized by threat level (note that there were no "Very High" threats this season):

Table 3: 2015 Threat Level Summary, by Zone

Zone	None	Low	Mod	High
(A) Northern Foothills	115	37	1	---
(B) Southern Foothills	102	44	4	3
(C) Palmer Divide	104	43	3	3
(D) Plains	100	48	2	3
(E) Northern Metro	113	37	3	---
(F) Central Metro	110	40	2	1

Of the 153 days in the operational season, there were 77 days with at least a "Low" threat, 9 days with a "Moderate" threat and 6 days with a "High" threat in at least one of the Zones. This suggests that 2015 was quite an active season for heavy rainfall threats (see HDR, 2006). For comparison, there were 81 days when the F2P2 program issued at least a "Low" message potential. There were 61 days when the Tool identified a threat AND the F2P2 HPO had at least a "Low" message potential. A complete summary of the daily Threat Levels can be found in Appendix A.

VALIDATION

Below, we investigate four main aspects of the Tool as it relates to the heavy rainfall threat in the UDFCD area: Timing, Location, Intensity and Confidence.

Timing

By simply spending a summer in the Front Range of Colorado, it becomes obvious that rainfall (mostly from thunderstorms) occurs most frequently from early afternoon through the early to mid-evening hours. Additionally, due to the influence of the steep terrain of the Continental Divide, elevated heating causes thunderstorms to first form over the higher terrain of Zones A and B, and then propagate eastward over the lower terrain.

Figure 2 is a comparison of the daily cycle of maximum hourly rainfall in the Tool compared to observed data across the entire Tool area. Focusing on moderate to heavy rainfall intensities, panels (a), (b) and (c) show only those days when at least 0.2, 0.5 and 0.75 inches per hour were observed, respectively. The thick black line and dashed blue line show the median hourly rainfall for the ALERT/StageIV blended data and the Tool data denoted as "QPF", respectively. Since data from 13 models went into the Tool, a similar estimate was made for each model. The full range of those estimates is shown by the light green shading.

Some key points from Figure 2 are:

- Most of the models in the Tool slightly overestimate the hourly rainfall intensity over the course of a typical day , since the black line is almost always lower than even the lowest bound of the green shading. This can be seen in all panels of Figure 2, and also at various other thresholds (0.01, 0.1, and 1.00) that we do not show here. However, that overestimate is quite small, typically within 10% of observations. Given prior experience with lower resolution weather models, this was somewhat of a surprise since most lower resolution models underestimate rainfall amounts during the warm season.
- The cycle of rainfall in the Tool initiates a few hours too early compared to observations. For example, note that the biggest discrepancy between the dashed blue line and the thick black line is from about 12PM to 2PM. This finding is consistent with peer-reviewed literature on QPF, which generally suggests that models are too aggressive in generating rainfall.
- The peak of the daily rainfall cycle is very well captured by the Tool. For example, for each of the panels in Figure 2, the maximum rainfall typically occurs between 3-4 PM in both the Tool and observations.
- The Tool generally ends rainfall too soon. For example, note that all three panels have a small secondary peak in *observed* rainfall during the late evening hours between 10PM and 1AM that models do not. We speculate that this may arise from very small scale gust-front features that typically only materialize as the day progresses and are unforeseen by the weather models until very short notice.

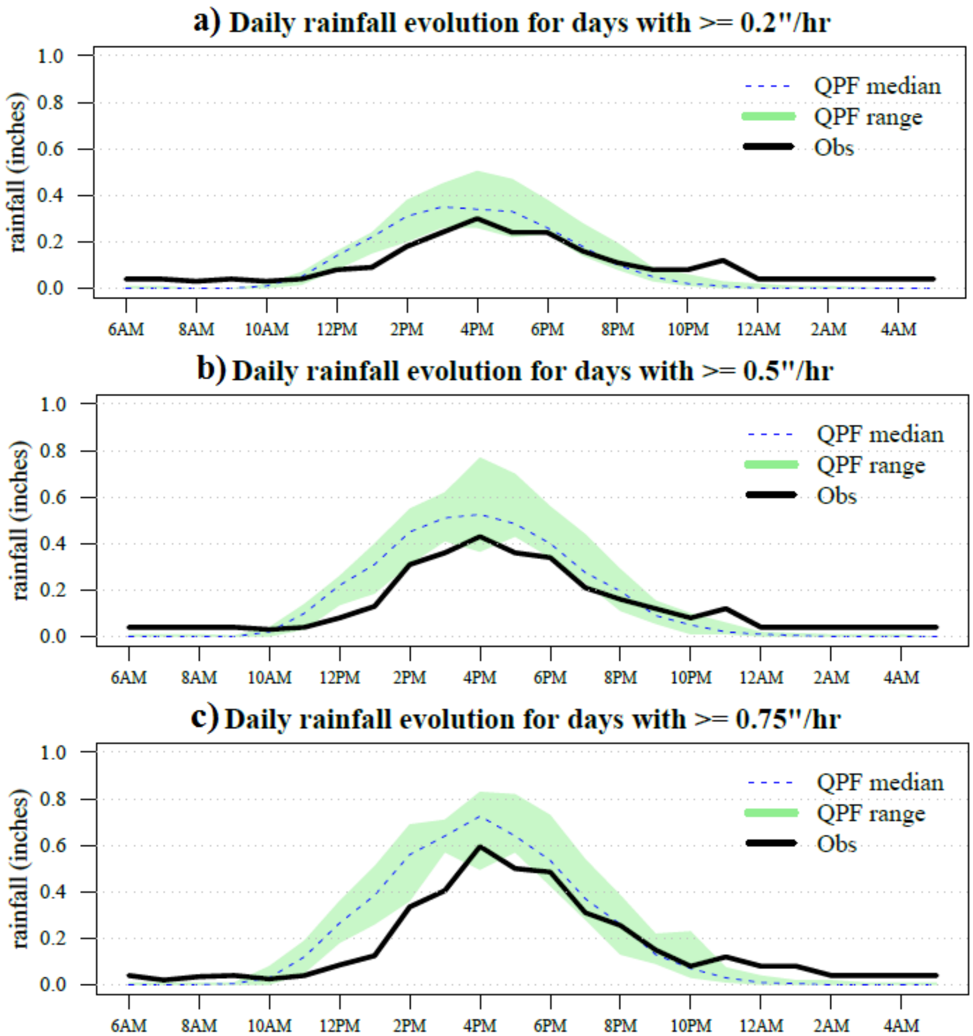

Figure 2: Comparison of the daily evolution of rainfall intensity between the Tool and observations. Median hourly values for the Tool and observations are shown by the dashed blue line and thick black line, respectively. Model spread in the Tool is shown by the light green shading.

Take-away messages:

- The Tool described a realistic daily rainfall cycle, both in the timing and magnitude of the peak rainfall intensity at a variety of rainfall thresholds.
- The Tool was too aggressive (i.e. too early) in generating rainfall, with a high bias during the early afternoon hours.
- The Tool did not have a smaller secondary peak in late evening/overnight rainfall, possibly due to the inherently low predictability of such events (especially thunderstorms spawned from gust fronts).

Location

We analyze the Tool's ability to properly place the rainfall threat using contingency tables comparing predicted and observed maximum rainfall. The contingency table has four possible outcomes as follows:

Table 4: Schematic of contingency table

		Heavy Rainfall Forecasted	
		NO	YES
Heavy Rainfall Observed	NO	HIT	FALSE ALARM
	YES	MISS	HIT

By adding up all of the total Hits and dividing by the number of total days (153), we find the "Accuracy" rate. Meanwhile, we are also interested in the quantifying the occurrence of Misses and False Alarms; these statistics are extremely useful for future refinement of the Tool. We run these calculations for each zone separately. For completeness and a reference point, we also calculate a contingency table across all zones to answer the broader question: "if a threat was forecast anywhere in the domain, did it verify anywhere in the domain?" Such a domain-wide contingency table may yield higher Accuracy numbers than each Zone since there is more leniency in the spatial dimension.

Table 5 panels (a) through (g) present contingency tables for each Zone, including one for the entire Tool domain.

Table 5: Contingency tables of the Tool's performance, by location

		Heavy Rainfall Forecasted		
	a)Zone A	NO	YES	Accuracy: 76%
Heavy Rainfall Observed	NO	114 (74.5%)	35 (22.9%)	False Alarm: 23%
	YES	1 (0.7%)	3 (2%)	Misses: 1%
	b)Zone B	NO	YES	Accuracy: 71%
Heavy Rainfall Observed	NO	100 (65.4%)	42 (27.5%)	False Alarm: 28%
	YES	2 (1.3%)	9 (5.9%)	Misses: 1%
	c)Zone C			Accuracy: 75%
Heavy Rainfall Observed	NO	99 (64.7%)	34 (22.2%)	False Alarm: 22%
	YES	5 (3.3%)	15 (9.8%)	Misses: 3%
	d)Zone D			Accuracy: 69%
Heavy Rainfall Observed	NO	100 (65.4%)	47 (30.7%)	False Alarm: 31%
	YES	0	6 (3.9%)	Misses: 0%
	e)Zone E			Accuracy: 76%
Heavy Rainfall Observed	NO	113 (73.9%)	36 (23.5%)	False Alarm: 24%
	YES	0	4 (2.6%)	Misses: 0%
	f)Zone F			Accuracy: 76%
Heavy Rainfall Observed	NO	105 (68.6%)	32 (20.9%)	False Alarm: 21%
	YES	5 (3.3%)	11 (7.2%)	Misses: 3%
	g)All zones			Accuracy: 69%
Heavy Rainfall Observed	NO	73 (47.7%)	44 (28.8%)	False Alarm: 29%
	YES	3 (2.0%)	33 (21.6%)	Miss: 2%

There are several conclusions from Table 5. First, the Tool's performance was about equal across all zones with accuracies ranging from 69-76% (this 7% range is not statistically significant given the relatively small sample size). Given this is the Tool's first operational season, we were modestly encouraged by these accuracies, which are in line or perhaps slightly lower than historical F2P2 validation statistics (see HDR, 2006). However, accuracy by itself does not tell the entire story.

Second, we are encouraged by extremely low Miss rate ranging from no misses in two zones to 5 misses in Zones C and F. Third, the False Alarm rate is high, ranging from 22-31%. Reducing this percentage should clearly be one of the main avenues of future refinement.

Collectively, we can conclude that the Tool performed reasonably well overall, but is conservative due to the identification of too many threat days. However, given the low Miss rate, this is in fact a positive finding because the Threat Level definitions can be adjusted to increase the requirements for issuing a threat.

Another benefit of the low Miss rate (and thus high probability of threat detection) is that we can decompose the False Alarm rate to determine how each threat level is performing. This yields a very interesting result, as shown in Table 6. There is a substantial drop in the False Alarm rate as we go from the Low to Moderate threat level, with a much smaller decrease from Moderate to High. Of course, we expect more False Alarms with a lower threat level since heavy rainfall occurrence is more uncertain. However, the large disparity in Table 6 suggests that most if not all future refinement of threat level classifications should be directed at the Low level, as the Moderate and High threat levels are performing well.

Table 6: False alarm rate as a function of Threat level across the entire forecast domain (compare with Table 5, panel g).

Threat Level	Hit	False Alarm
Low	42%	58%
Moderate	78%	22%
High	83%	17%

Take-away messages:

- Tool accuracy varied from 69-76% across the six Zones. This was in line with our expectations, and perhaps slightly lower than past F2P2 validation statistics. There were no significant differences noted across the Zones.
- Miss rate was low, below 3% with some Zones showing zero misses. This was above expectations, but will need to be maintained during future refinement.
- False alarm rate was relatively high, 22-31%. This was higher than expected but there appears to be some room for refinement by adjusting the threat level classifications, most notably for the "Low" threat level.

Intensity

The Tool is designed such that it focuses on the maximum realistic rainfall, or the "worst-case scenario" for any given hour for any given day. This is only possible due the probabilistic nature of the Tool: there are 13 equally realistic realizations of the rainfall evolution. Theoretically, we would expect that the Tool's maximum rainfall forecasts will always be greater than or equal to those observed. In reality, given the imperfect nature of weather models and precipitation forecasts, this will not always be the case. However, we are interested in answering this question in a quantitative fashion.

Figure 3 compares the maximum forecasted (red bars) and observed (black bars) hourly rainfall for every day of the operational season when at least 0.2 inches per hour of rain fell (i.e. the max hourly value for each day is shown only if it exceeded 0.2 inches per hour). Note that few black bars are visible: this confirms that the maximum forecasted rainfall is greater than or equal to the observed rainfall almost all of the time. Specifically, out of the 109 days where at least 0.2 inches per hour was observed, 93 of those days (85%) had higher forecasted rainfall than was observed. Focusing further on only higher rainfall intensities, out of the 36 days where observed rainfall exceeded 1 inch per hour, the Tool 1-hour QPFMAX exceeded observations on 29 (81%) of those days. Table 7 shows a comparison of the remaining seven days where QPFMAX was *lower* than observations.

Table 7: Comparison of days when rainfall was underestimated

Date	Max hourly observed	Hourly QPFMAX	# of Zones with > 1 in per hour
May 5	2.31 in/hour	1.38 in/hour	3
May 15	1.46	0.61	1
June 1	1.35	1.33	1
June 24	2.16	1.66	1
August 2	1.22	1.11	2
August 9	1.12	0.58	1
August 15	1.68	0.57	2

Despite the underestimates in Table 7, it is encouraging to see that during 4 of the 7 days, QPFMAX exceeded 1 inch/hour, and on all seven days QPFMAX exceeded 0.5 inches per hour. Thus, in the future, we need to resolve the issue of not whether rain will occur (which has conventional been a problem in forecasting thunderstorm activity), but adjusting the intensity to better reflect reality. As Table 7 also shows, it is interesting to note that on 4 of the 7 days, only 1 of the 6 forecast Zones exceeded 1 inch per hour, suggesting that storms were quite isolated. The most notable example of this is June 24th, when a heavy rainfall producing storm formed from a relatively small-scale outflow boundary over downtown Denver (Zone F). Though the rainfall was impressive, this storm dissipated within several hours without affecting any of the other Zones. Improving QPF for such isolated cases, especially during summer, is currently one of the top research topics within the atmospheric science community.

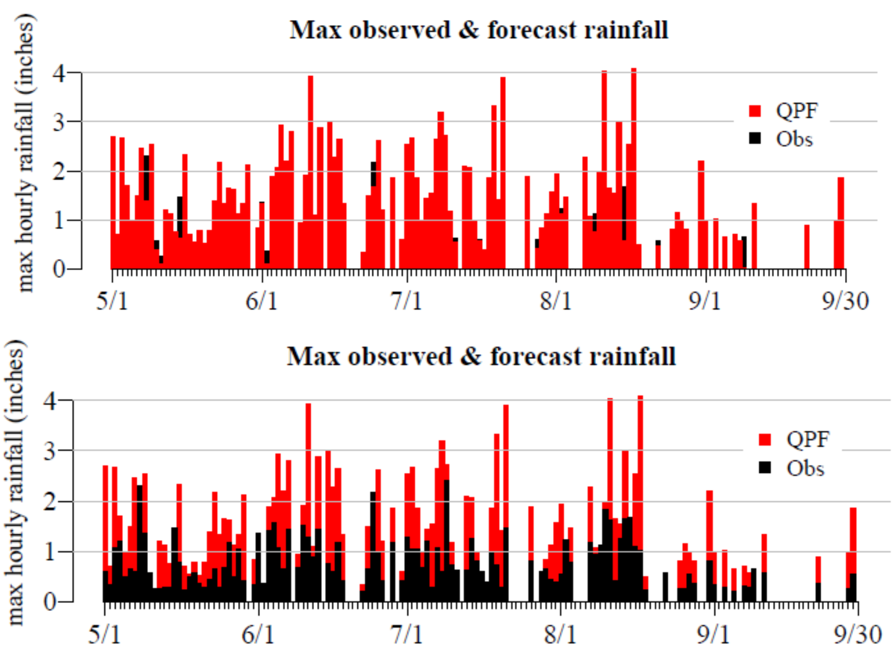

Figure 3: Top graph shows days where observations are greater than forecast (black bars are showing). Bottom graph is a comparison of maximum hourly rainfall forecast and the actual maximum rainfall observed to illustrate level of over-prediction of rainfall across all zones.

While Figure 3 presents a top-level view as to how forecasted rainfall intensities compare with observed data, this comparison (i) does not address the Zone-specific details and (ii) does not indicate the timing of when the rain fell. To probe both of these areas, we use hourly data and partition the results into each of the 6 zones as well as an aggregate across all zones. The results are shown in Table 8. We use three different thresholds: 0.2 inches per hour (as in Figure 3), and also 0.5 and 1.0 inch per hour since these are more relevant in terms of flooding impact. The "Absolute timing" column indicates an hour-by-hour comparison between observed and forecasted maximum rainfall: this is the most stringent comparison that we can make. We also show the result if we create a +/- 2 hour window on the forecast rainfall. In other words, if the forecast rainfall in a given Zone is expected to exceed 1.0 inch per hour between 3-4pm, but it is actually exceeds that amount between 4-5pm or 5-6pm, it is not unreasonable to count that as a hit (though obviously with an asterisk). In Table 8, we also show the number of hours that rainfall exceeded the indicated threshold for each Zone.

Table 8: Comparison of hourly observed and forecasted maximum rainfall across each Zone.

a) For hourly rainfall >= 0.2 inches

Zone	Absolute timing	+/- 2 hours	# of hours >= 0.2"
A	69%	96%	215
B	78%	98%	261
C	64%	93%	256
D	61%	94%	162
E	55%	93%	167
F	52%	84%	305
All Zones	76%	97%	663

b) For hourly rainfall >= 0.5 inches

Zone	Absolute timing	+/- 2 hours	# of hours >= 0.5"
A	40%	60%	30
B	74%	91%	58
C	54%	68%	85
D	58%	82%	50
E	31%	54%	35
F	38%	56%	87
All Zones	68%	85%	224

c) For hourly rainfall >= 1.0 inches

Zone	Absolute timing	+/- 2 hours	# of hours >= 1.0"
A	0%	0%	6
B	50%	75%	12
C	32%	52%	25
D	17%	67%	6
E	50%	70%	10
F	36%	50%	22
All Zones	54%	76%	72

Table 8(a) shows that using the "Absolute timing", for the >= 0.2 inch/hour threshold, the forecasted max rainfall exceeds the observed amount 52-78% of the time depending on the Zone. Highest values are found in the mountain zones, while lowest values are found in the Metro Zones (E and F). This also suggests that the Tool is performing better in the higher elevations zones, though we do not have an immediate explanation for this. On the other hand, this discrepancy could also arise from the fewer number of ALERT gauges in the higher elevation zones implying that we may be *underestimating* the rainfall intensities (refer to the Methodology section and Appendix C for more information). While the Absolute timing percentages are somewhat lower than we expected, we note a tremendous increase when including the +/- 2 hour window. In that case, forecasted rainfall exceeds observed rainfall 82-98% of time. The fact that this percentage is very high is quite encouraging and indicates that, although the Tool may not be perfect, it performed well in achieving what it was intended to do.

As we go to higher thresholds of 0.5 and 1.0 inch per hour (Table 8, panels b and c), we find that overall percentages decrease slightly. This is in agreement with peer-reviewed literature, in which there is a consensus that models skill decreases for higher and higher rainfall intensities. Nonetheless, even for the 1 inch per hour threshold, we are encouraged that the Tool is able to anticipate these heavier rainfall rates well over half of the time (if we use the +/- 2 hour window).

Take-away messages:

- The Tool's maximum rainfall is greater than observed a 52-78% of time, increasing to an impressive 82-98% of the time with a +/- 2 hour window. Note that these statistics speak to both the *intensity* and *timing* considerations of the Tool's performance.
- Timing performance decreases slightly when using progressively higher rainfall thresholds. Nonetheless, the Tool is accurately able to forecast the upper bound on intensity of rainfall *and* its timing over 68% and 54% of the time for 0.5 inch/hour and 1 inch/hour thresholds, respectively. While higher intensity rainfall is inherently more difficult to forecast, we are hopeful that this may be partially addressed from bias-correction techniques.

Confidence

Since the Tool has a significant probabilistic capability, a relevant question is "how accurate are its probability forecasts?" In other words, if the Tool forecasts a "50% chance of exceeding 0.5 inches per hour", in what fraction of the time does that forecast actually occur?

To investigate these issues, we construct "reliability diagrams" (Stanski et al. 1989; Ebert 2001). These diagrams plot the forecasted probability on the x-axis and the observed frequency on the y-axis. Figure 4 shows such a diagram across all zones for the 0.5 inch per hour threshold. The dashed line indicates a perfect relationship, while the black points show the actual relationship. We are encouraged to see that the Tool shows substantial reliability. Note that as the forecasted probability of exceeding 0.5 inches per hour increases, so does the observed frequency; *this is not a given!* For example, a forecast with no accuracy would be represented by a horizontal line with no slope equivalent to the climatological frequency of exceeding 0.5 inches per hour. However, we note that the Tool tends to be "Overconfident" because it tends to forecasts events occurring more frequently than they actually occur (this finding is also consistent with the earlier results showing that the Tool shows a relatively high False Alarm rate).

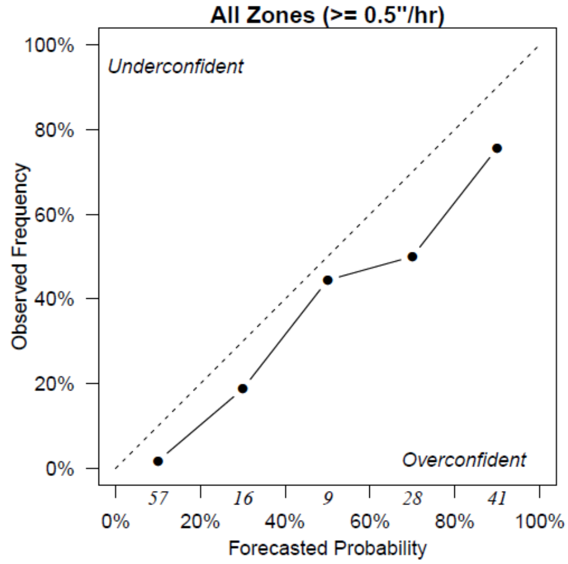

Figure 4: Reliability diagram showing how forecasted probability of rainfall exceeding 0.5 inches per hour compares with observed probabilities. The dashed line indicates a perfect relationship. Black dots show the reliability when only the indicated Zone is analyzed, while red points show the inclusion of a nearby zone. Points falling above the dashed line are "underconfident", while points falling below it are "overconfident".

While Figure 4 is for all Zones, Figure 5 presents similar reliability diagrams for each zone. Note that we use the 0.25 inch per hour threshold, due to limited sample size (the number of samples in each probability bin is shown just under the x-axis in Figures 4 and 5). As expected, we see a degradation of reliability. This occurs because we are raising the standard by focusing on a smaller region. In all zones, the Tool is largely "overconfident", but this is especially the case in the higher elevation zones (A and B). However, when we slightly relax the zone-specific constraint to include a random nearby zone, we see a marked increase in reliability. For example, focusing on Zone A, the black dots show the reliability when observed rainfall is only measure in that Zone. Meanwhile, the red dots show how reliability changes when we include Zone B into the validation. Stated differently, the red dots show how reliable the Tool is when >= 0.25 inch/hour rainfall is forecasted for Zone A, but occurs in *either* Zone A or B. Similar to the slight relaxation of the timing constraint shown in the 3rd column of Table 8, it is not unreasonable to slightly relax the spatial constraint in this manner.

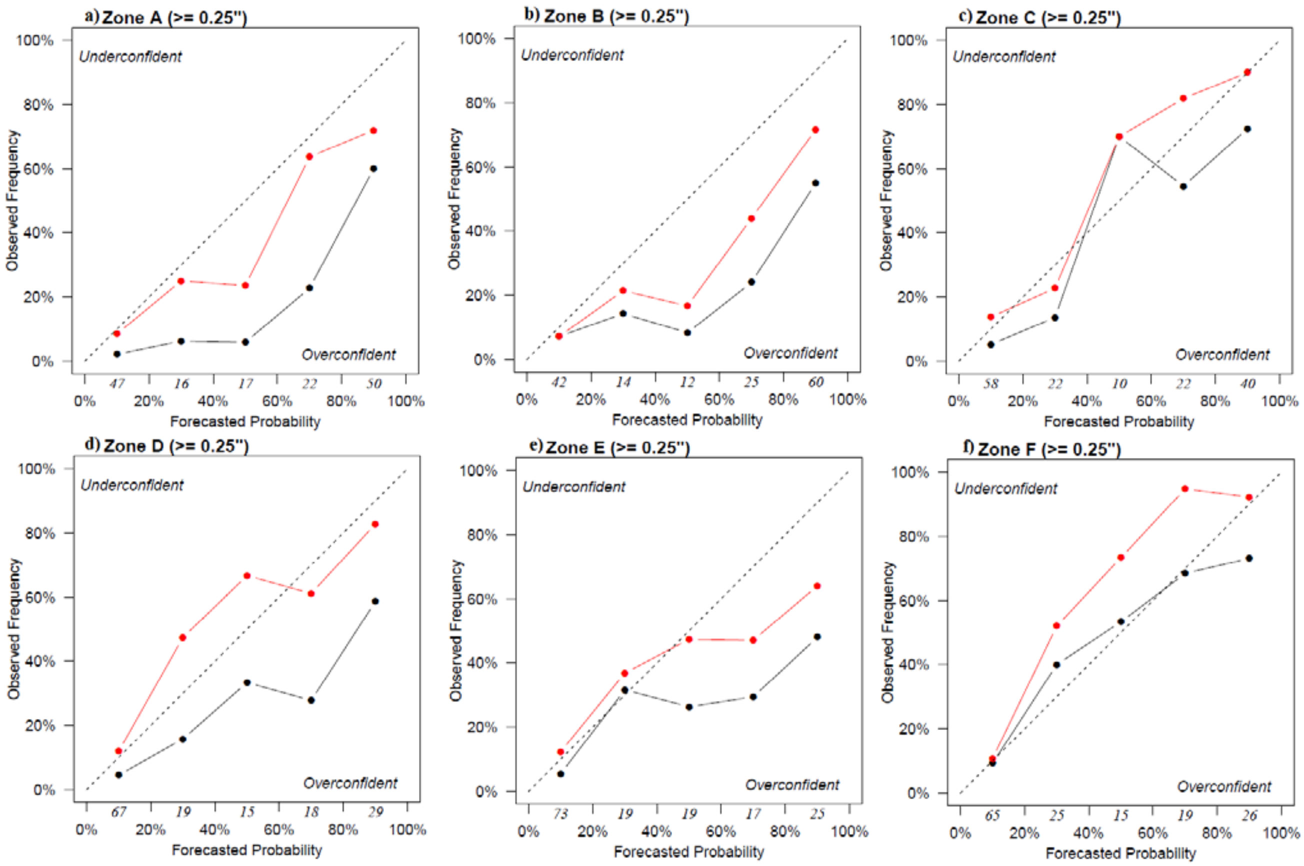

Figure 5: Same as Figure (4), except for each Zone. A lower 0.25 inch per hour threshold is used to increase sample size. Also added are red dots, which indicate the reliability if the observed frequency is measured in the indicated zone plus one additional (random) nearby zone.

Take-away messages:

- Overall, the Tool showed substantial reliability, since higher forecasted probabilities of rainfall occurrence were actually validated by higher frequencies of occurrence.
- The Tool was generally "overconfident" since it tended to forecasted events to occur more frequently than they were actually observed. We are hopeful that this may be addressed by weighting models by their performance.
- On a Zone-specific basis, the Tool has meaningful reliability. However, this reliability greatly increases when we slightly relax the validation constraint to include a random nearby Zone. For example, if heavy rainfall is forecasted for Zone A, we ideally want to see that it is actually observed in Zone A. But there is still utility in the Tool if the actual rainfall falls, for example, in nearby Zone B.

CONCLUSIONS

The UDFCD Heavy Rainfall Guidance Tool concluded its first operational season in 2015. This report investigated the Tool's performance in four categories: Timing, Location, Intensity and Confidence. Overall results are encouraging, yet we also see ample room for improvement. Here are some of the main findings that we noted:

1. The Timing of rainfall in the Tool closely matched observations, both in intensity and occurrence of peak rainfall. Yet, we noticed the Tool generated rainfall too early and also missed a secondary round of late-evening rainfall.

2. The Tool was able to place rainfall reasonably well across all of the Zones. We observed overall accuracy rates from 69-76%, with low Miss rates (0-3%), although relatively high False Alarm rates (22-31%) were also observed.
3. As the Tool was built to provide an *upper* estimate of daily rainfall, we were encouraged to see that it did provide an accurate upper bound on rainfall amounts 82-98% of the time (depending on the Zone, and with a +/- 2 hour window). However, we did notice a drop off in these statistics at higher rainfall intensities, suggesting there is still room for refinement for the heavier events.
4. Reliability diagrams showed the Tool has substantial skill in discriminating between low, medium and high probability events. However, we noted that the Tool was almost always "overconfident", implying that it generally tended to over-predict event occurrence (e.g. "probability of exceeding 1 inch per hour") compared to observations. This is, in fact, also consistent with the relatively high False Alarm rates noted in point (2) above.

Suggested Refinements

Although this Report has documented many different aspects of the Tool's performance, it has opened up a wide array of questions relating to whether or to what extent Tool forecasts can be improved in the future. Below, we list several different topics that are likely to improve the overall Tool performance (ranked in order of impact/feasibility considerations):

1. **Assess model-by-model performance.** Up to this point, it has been assumed that each of the 13 models contributing to the Tool is equally skillful. This is not necessarily the case, since model performance can vary strongly from model to model, often times even for apparently similar models. We propose investigating the data collected during the 2015 season to separate models by their performance and as necessary, weight them to use skillful models more heavily than less skillful ones.

    Benefit: We expect this to yield better reliability (see Location section), and potentially to reduce False Alarm Rates, especially if there are models that have a high bias on rainfall amounts.

2. **Historically-based bias correction.** A weather model has its own physical world, which often times does not exactly replicate the true physical world we live in. As such, many past studies have shown marked increases in model performance from bias correcting with actual observed data. In Colorado, many operational forecast agencies use **precipitable water (PW)** to evaluate the heavy rainfall threat. Higher PWs *can* result in higher rainfall rates. Using statistical relationships based on the 2015 data collected as part of the Tool, we can develop objective bias-correction techniques of how to modify Tool rainfall intensities based on knowledge of the PW measurement. Note that there are several PW measuring sites in eastern Colorado that could be used for this analysis.

    Benefit: We expect that this may lead to a potentially substantial reduction in False Alarm rates, especially for marginal threat situations.

3. **Develop sub-hourly forecasts:** While it is convenient that the Tool directly outputs hourly rainfall, sometimes sub-hourly rainfall can be more beneficial. For example, envision a situation where 0.7 inches of rainfall falls in 20 minutes, but then the storm moves off leading to a total hourly rainfall of a relatively unimpressive 0.8 inches. Using ALERT data in combination with the QPF data collected during the 2015 season, we can develop statistical relationships of how to use the Tool's output to inform on sub-hourly rainfall exceedance probabilities (for example, probability of exceeding 0.8 inches in 30 minutes, or 0.4 inches in 10 minutes, etc)

    Benefit: We anticipate that this will make the Tool's output more informative to a larger group of end-users.

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APPENDIX A – DAILY THREAT LEVELS AND OBSERVED RAINFALL

The table below shows the daily threat level at each of the 6 zones, along with the highest 1-hour rainfall observed. For reference, we also show the Flash Flood Prediction Program's Message Potential obtained from the Message Generator website. Note that there were several days when Message Potential notifications were not available (presumably because of ongoing heavy rainfall activity). For those days, we assumed that the day's Message Potential is equal to the previous days.

	Zone A		Zone B		Zone C		Zone D		Zone E		Zone F		
Date	Threat	Max-1hr	Threat	Max-1hr	Threat	Max-1hr	Threat	Max-1hr	Threat	Max-1hr	Threat	Max-1hr	F2P2-HPO
5/1	---	0.24	low	0.51	low	0.6	low	0.48	low	0.46	low	0.43	low
5/2	---	0.33	---	0.17	---	0.22	---	0.08	---	0.08	---	0.32	---
5/3	low	0.49	---	0.26	low	0.32	low	1.06	low	1.01	---	0.18	mod
5/4	low	1.04	low	0.78	low	1.19	low	0.18	---	0.36	low	1.08	high
5/5	---	0.2	---	0.28	---	0.43	---	0.28	---	0.25	---	0.48	high
5/6	---	0.35	---	0.26	low	0.66	low	0.27	low	0.32	low	0.44	high
5/7	low	0.36	low	0.28	low	0.48	low	0.53	low	0.39	low	0.6	high
5/8	---	0.36	---	0.52	low	2.31	low	1.25	low	0.44	low	1.12	high
5/9	low	0.68	low	0.51	low	1.13	low	1.36	mod	0.32	low	0.88	high
5/10	---	0.36	---	0.44	---	0.48	---	0.06	---	0.4	---	0.56	---
5/11	---	0.25	---	0.12	---	0.05	---	0	---	0	---	0.16	---
5/12	---	0.25	---	0.2	---	0.05	low	0.04	---	0.1	---	0.26	---
5/13	---	0.28	---	0.22	---	0.2	low	0.17	low	0.24	---	0.2	---
5/14	---	0.13	---	0.17	---	0.27	---	0.26	---	0.17	---	0.22	---
5/15	---	0.65	---	0.23	---	0.24	---	0.81	---	0.58	---	1.46	low
5/16	low	0.32	low	0.29	low	0.28	---	0.23	---	0.37	low	0.79	low
5/17	---	0.16	---	0.24	---	0.24	---	0.08	---	0.07	---	0.16	---
5/18	---	0.27	---	0.46	---	0.49	---	0.22	---	0.2	---	0.28	mod
5/19	---	0.32	---	0.25	---	0.57	---	0.23	---	0.24	---	0.28	mod
5/20	---	0.36	---	0.05	---	0.05	---	0	---	0.04	---	0.04	---
5/21	---	0.18	---	0.28	---	0.17	---	0.08	---	0.05	---	0.04	mod
5/22	---	0.18	---	0.22	---	0.33	---	0.08	low	0.16	low	0.44	low
5/23	low	0.2	low	0.13	---	0.32	low	0.06	low	0.2	---	0.64	high
5/24	low	0.28	low	0.12	low	0.2	low	0.03	low	0.28	low	0.2	high
5/25	---	0.68	low	0.24	low	0.4	low	0.14	low	0.56	low	0.56	low
5/26	low	0.2	low	0.44	low	1.16	low	0.14	---	0.21	low	0.36	mod
5/27	---	0.28	low	0.48	---	0.16	---	0.07	---	0.16	---	0.45	mod
5/28	low	0.28	---	0.37	---	1.05	low	0.66	low	0.36	low	0.42	high
5/29	low	0.31	low	0.23	low	0.32	low	0.11	low	0.29	low	0.4	mod
5/30	---	0.08	---	0.11	---	0.04	---	0	---	0.04	---	0.04	---
5/31	---	0.15	---	0.16	---	0.31	---	0.32	---	0.2	---	0.22	low
6/1	---	0.16	---	0.34	---	1.35	low	0.72	---	0.12	---	0.16	low
6/2	---	0.24	---	0	---	0	---	0	---	0	---	0.36	---
6/3	low	0.22	low	0.69	---	1.4	low	0.61	low	1	low	1.04	high
6/4	---	1.12	---	0.72	---	0.53	---	0.47	low	1.56	---	1.24	high
6/5	low	0.48	low	0.59	low	1.08	high	0.76	mod	0.7	mod	0.96	high
6/6	---	0.2	low	0.28	---	0.54	low	0.3	---	0.04	low	0.64	high
6/7	---	0.55	low	0.24	low	0.76	low	0.32	---	0.12	low	1.44	high

6/8	---	0.04	---	0.04	low	0.04	---	0	---	0	---	0.04	---
6/9	---	0.1	---	0.4	---	0.13	---	0.37	---	0.33	---	0.68	---
6/10	low	0.32	low	0.43	low	1.51	low	0.09	low	0.08	low	0.72	high
6/11	mod	0.6	high	0.77	high	1.04	high	0.97	mod	0.68	high	1.28	high
6/12	---	0.2	---	0.38	low	0.88	---	0.14	---	0.6	---	0.64	high
6/13	low	0.57	low	0.43	---	0.26	low	0.37	low	1.44	low	1.05	mod
6/14	low	0.1	low	0.15	low	0	---	0.08	low	0.01	low	0.04	low
6/15	low	0.3	mod	0.65	mod	0.49	mod	0.61	low	0.76	low	0.52	high
6/16	---	0.35	---	0.3	low	0.59	low	0.3	---	0.36	---	0.17	mod
6/17	low	0.09	---	0.66	low	1.18	low	0.5	low	0.03	low	0.67	mod
6/18	---	0.33	low	0.28	low	0.07	low	0.12	low	0.28	---	0.4	---
6/19	---	0	---	0.04	---	0	---	0	---	0	---	0.12	---
6/20	---	0	---	0.01	---	0	---	0.01	---	0	---	0.12	---
6/21	---	0	---	0	---	0	---	0	---	0	---	0.16	---
6/22	---	0	---	0.2	---	0	---	0	---	0	---	0.16	---
6/23	---	0.06	---	0.66	low	0.33	low	0.41	---	0.01	---	0.59	low
6/24	---	0.76	low	0.47	---	0.74	---	0.7	low	0.33	---	2.16	mod
6/25	low	0.24	---	0.3	---	1.00	low	0.59	low	0.52	low	0.44	high
6/26	---	0.08	---	0.06	---	0	low	0.01	---	0.01	---	0.4	low
6/27	---	0.08	---	0.11	---	0	---	0	---	0	---	0.12	---
6/28	low	0.09	low	0.51	low	0.78	low	1.18	---	0.91	---	0.73	---
6/29	---	0.05	low	0.15	---	0	---	0	---	0.04	---	0.12	low
6/30	---	0.28	---	0.41	---	0.12	---	0.03	---	0.06	---	0.2	low
7/1	low	0.48	high	1.28	mod	1.2	low	0.89	low	0.04	low	0.52	mod
7/2	low	0.6	low	0.33	low	0.75	low	1.03	low	0.35	low	0.76	mod
7/3	---	0.19	low	0.94	low	1.04	low	0	---	0	low	0.24	mod
7/4	---	0.36	---	0.48	---	0.36	---	0.33	---	0.13	---	0.68	low
7/5	low	0.48	low	1.2	low	0.48	low	0.05	---	0.12	---	0.24	mod
7/6	low	0.2	low	0.29	low	0.14	low	0.02	low	0.24	low	0.28	low
7/7	low	0.39	low	1.06	---	0.44	---	0.07	low	0.1	---	0.64	mod
7/8	low	0.52	mod	0.52	high	0.6	low	0.12	low	0.48	mod	0.48	mod
7/9	low	0.84	mod	1.01	low	1.76	mod	0.84	low	0.75	low	2.4	high
7/10	---	0.12	low	0.46	---	0.19	---	0.19	---	0.47	---	0.72	low
7/11	---	0.24	---	0.07	---	0.03	---	0.16	---	0.61	---	0.38	low
7/12	---	0	---	0	---	0	---	0	---	0	---	0.12	---
7/13	low	0.61	low	0.56	---	0.08	---	0.06	---	0.25	---	0.12	low
7/14	low	0.57	low	0.2	---	0.43	low	0.58	low	0.68	low	1.26	low
7/15	---	0.68	---	0.31	---	0.56	---	0.75	---	0.73	---	0.8	mod
7/16	---	0.08	---	0.2	---	0.13	---	0.48	---	0.6	---	0.44	---
7/17	---	0.39	---	0.07	---	0.11	---	0.07	---	0.06	---	0.2	---
7/18	---	0.5	low	0.25	---	0.24	low	0.49	low	0.4	low	1.00	---
7/19	---	0.05	low	0.72	low	0.42	low	0.04	---	0.04	low	0.16	mod
7/20	---	0.16	---	0.27	---	0.11	---	0.03	---	0.02	---	0.28	low
7/21	low	0.42	low	0.72	low	1.47	high	1.31	low	1.00	low	1.12	high
7/22	---	0.16	---	0.08	---	0.08	---	0.11	---	0.12	---	0.12	low
7/23	---	0.09	---	0.16	---	0	---	0	---	0	---	0.12	---

7/24	---	0.1	---	0.1	low	0.04	---	0.1	---	0.08	---	0.12	---
7/25	---	0.01	---	0.01	---	0	---	0.04	---	0	---	0.16	---
7/26	---	0.08	---	0.56	low	0.8	low	0.56	---	0.02	low	0.16	mod
7/27	---	0.01	---	0.03	---	0	---	0	---	0	---	0.12	low
7/28	---	0.02	---	0.17	---	0.08	---	0.06	---	0.18	---	0.59	---
7/29	---	0.19	---	0.64	---	0.05	---	0	---	0.17	---	0.4	---
7/30	---	0.09	---	0	---	0.43	---	0.01	---	0.01	low	0.4	---
7/31	---	0.28	low	0.23	---	0.38	---	0.01	---	0.08	---	0.08	low
8/1	---	0.06	---	0.07	low	0.37	low	0.53	---	0.03	---	0.24	---
8/2	low	0.39	low	0.5	---	1.17	---	0.18	low	1.22	---	0.96	---
8/3	---	0.21	low	0.79	low	0.77	---	0.01	---	0.03	low	0.32	---
8/4	---	0	---	0	---	0.12	---	0	---	0	---	0.08	---
8/5	---	0	---	0.03	---	0.03	---	0	---	0	---	0.16	---
8/6	---	0	---	0	---	0	---	0	---	0.08	---	0.16	---
8/7	---	0.15	---	0.1	low	1.16	low	0.75	---	0.03	---	0.32	mod
8/8	---	0.03	---	0.46	low	0.28	---	0.56	---	0.01	---	0.93	low
8/9	---	0.08	---	1.12	---	0.4	---	0.37	---	0.19	---	0.84	low
8/10	---	0.17	low	1.37	mod	1.4	low	0.44	low	0.74	low	1.82	high
8/11	low	0.67	high	1.61	high	0.17	low	0.86	---	0.14	low	1.47	high
8/12	low	0.4	low	0.34	low	0.09	---	0.05	---	0.32	---	0.22	high
8/13	---	0.36	low	1.12	low	0.38	---	0	---	0.12	---	1.25	mod
8/14	low	1.64	mod	1.42	low	0.49	low	0.45	low	0.85	---	1.04	mod
8/15	---	0.39	---	1.04	---	1.68	---	0.98	---	0.2	---	0.56	mod
8/16	low	1.1	low	1.05	low	0.61	low	0.73	low	0.2	low	0.4	high
8/17	low	0.36	low	0.67	low	1.01	low	0.43	low	0.41	low	0.54	high
8/18	---	0.12	---	0.1	---	0.24	---	0.19	---	0.13	---	0.2	low
8/19	---	0.04	---	0.04	---	0	---	0	---	0.04	---	0.08	---
8/20	---	0.04	---	0	---	0	---	0	---	0	---	0.08	---
8/21	---	0	---	0	---	0	---	0	---	0	---	0.08	---
8/22	---	0.13	---	0.1	---	0.58	---	0	---	0.05	---	0.13	---
8/23	---	0	---	0.13	---	0.02	---	0	---	0	---	0.04	---
8/24	---	0	---	0	---	0	---	0	---	0	---	0.12	---
8/25	---	0.12	---	0.25	---	0.15	---	0.06	---	0.08	---	0.17	---
8/26	low	0.26	---	0.15	---	0	---	0.05	---	0.02	---	0.12	---
8/27	---	0.14	---	0.24	---	0.53	---	0.18	---	0.33	---	0.36	---
8/28	---	0.36	---	0.16	---	0.04	---	0.02	---	0.01	---	0.14	low
8/29	---	0	low	0.03	---	0	---	0	---	0	---	0.16	---
8/30	---	0.12	---	0.03	---	0.01	---	0	---	0	---	0.08	---
8/31	---	0.56	low	0.59	low	0.59	low	0.8	---	0.38	low	0.39	low
9/1	---	0.16	---	0.19	---	0.04	---	0	---	0.2	---	0.32	low
9/2	---	0.02	---	0.12	---	0.01	---	0	---	0	---	0.08	---
9/3	low	0.28	---	0.12	---	0.2	---	0.08	---	0.09	---	0.12	low
9/4	---	0.11	---	0.09	---	0.04	---	0.06	---	0.03	---	0.08	---
9/5	---	0.11	---	0.07	---	0	---	0.08	---	0.2	---	0.12	---
9/6	---	0.04	---	0.03	---	0.01	---	0.03	---	0.1	---	0.12	---
9/7	---	0.18	---	0.11	---	0.08	---	0.19	---	0.31	---	0.25	---

9/8	---	0.01	---	0.08	---	0	---	0	---	0	---	0.28	---
9/9	---	0.02	---	0	---	0.64	---	0	---	0	---	0.12	---
9/10	---	0.01	---	0	---	0	low	0	low	0	---	0.12	---
9/11	---	0.56	---	0	---	0	low	0	---	0.2	---	0.08	---
9/12	---	0	---	0	---	0	---	0	---	0	---	0.08	---
9/13	---	0	---	0	---	0	---	0	---	0	---	0.08	---
9/14	---	0.02	---	0.01	---	0	---	0	---	0	---	0.12	---
9/15	---	0.03	---	0.02	---	0	---	0	---	0	---	0.12	---
9/16	---	0.01	---	0	---	0	---	0	---	0	---	0.08	---
9/17	---	0.04	---	0.06	---	0.05	---	0.15	---	0.07	---	0.12	---
9/18	---	0.04	---	0	---	0	---	0	---	0.03	---	0.08	---
9/19	---	0.01	---	0	---	0	---	0	---	0	---	0.08	---
9/20	---	0	---	0	---	0	---	0	---	0	---	0.12	---
9/21	---	0	---	0	---	0	---	0	---	0	---	0.12	---
9/22	---	0.01	---	0.23	---	0.08	---	0	---	0	---	0.36	---
9/23	---	0.04	---	0.04	---	0.02	---	0	---	0	---	0.12	---
9/24	---	0	---	0	---	0	---	0	---	0	---	0.12	---
9/25	---	0	---	0	---	0	---	0	---	0	---	0.12	---
9/26	---	0	---	0	---	0	---	0	---	0	---	0.12	---
9/27	---	0	---	0	---	0	---	0	---	0	---	0.12	---
9/28	---	0.08	---	0.08	---	0.15	---	0.25	---	0.16	---	0.16	low
9/29	---	0.35	low	0.49	low	0.38	---	0.05	---	0.21	low	0.53	---
9/30	---	0.06	---	0.06	---	0.05	---	0	---	0.04	---	0.16	low

Comparison with F2P2 HPOs

For future refinement of the Tool, one important benchmark is to compare its performance with human-derived forecasts. To do this, below we compare our contingency table (see Table 5, panel g) with an analogous table using the daily message potential from the Table above. **It is critical to note that this comparison is very preliminary since we do not use sub-hourly rainfall data for validation, even though that may well be relevant (e.g. 0.7 inches falling in 20 minutes but less than 1 inch in an hour, etc) from a flood risk standpoint.**

We note a very similar performance between the two products in terms of Accuracy, False Alarm and Miss statistics, leading to the ultimate question of whether this performance represents an upper-limit given the state of the science, or whether future Tool refinement can actually outperform purely human-derived forecasts.

UDFCD HRG Tool		**Heavy rainfall forecasted**		
	All zones	**NO**	**YES**	Accuracy: 69%
Heavy Rainfall Observed	**NO**	**73 (47.7%)**	**44 (28.8%)**	False Alarm: 29%
	YES	**3 (2.0%)**	**33 (21.6%)**	Miss: 2%
F2P2 HPO Message Potential		**Heavy rainfall forecasted**		
	All zones	**NO**	**YES**	Accuracy: 68%
Heavy Rainfall Observed	**NO**	**70 (45.8%)**	**47 (30.7%)**	False Alarm: 31%
	YES	**2 (1.3%)**	**34 (22.2%)**	Miss: 1%

APPENDIX B – QUANTITATIVE PRECIPITATION FORECASTS

The table below shows the daily maximum forecasted 1-hour rainfall (Max1) and probability of exceeding 1 inch per hour (POP1) for each zone. This table can be compared with the table shown in Appendix A for day by day, and zone-by-zone verification.

	Zone A		Zone B		Zone C		Zone D		Zone E		Zone F	
Date	**Max1**	**POP1**	**Max1**	**POP1**	**Max1**	**POP1**	**Max1**	**POP1**	**Max1**	**POP1**	**Max1**	**POP1**
5/1	0.83	0	2.69	31	1.31	38	1.44	38	1.58	8	1.41	8
5/2	0.64	0	0.49	0	0.7	0	0.51	0	0.23	0	0.5	0
5/3	1.09	8	0.97	0	1.03	8	2.66	23	1.51	15	0.98	0
5/4	1.23	8	1.12	17	1.69	50	1.24	17	0.96	0	1.37	17
5/5	0.9	0	0.57	0	0.68	0	0.56	0	0.88	0	0.95	0
5/6	0.6	0	0.62	0	1.48	23	1.34	15	1.14	15	1.44	23
5/7	1.25	8	2.05	15	2.32	23	2.12	38	1.86	15	2.47	23
5/8	0.68	0	0.82	0	1.3	8	1.38	8	1.17	8	1.22	15
5/9	1.66	31	2.17	15	2.55	23	1.76	23	1.7	54	2.12	15
5/10	0.17	0	0.15	0	0.07	0	0.11	0	0.09	0	0.09	0
5/11	0.08	0	0.1	0	0.04	0	0	0	0	0	0.01	0
5/12	0.92	0	0.56	0	0.4	0	1.21	8	0.72	0	0.59	0
5/13	0.72	0	0.74	0	0.71	0	1.13	8	1.02	8	0.56	0
5/14	0.42	0	0.76	0	0.44	0	0.33	0	0.47	0	0.25	0
5/15	0.61	0	0.41	0	0.28	0	0.43	0	0.41	0	0.41	0
5/16	1.03	9	1.77	18	2.33	27	0.83	0	0.84	0	1.07	9
5/17	0.27	0	0.37	0	0.69	0	0.52	0	0.38	0	0.45	0
5/18	0.47	0	0.53	0	0.54	0	0.54	0	0.39	0	0.42	0
5/19	0.78	0	0.5	0	0.38	0	0.52	0	0.45	0	0.46	0
5/20	0.33	0	0.49	0	0.51	0	0.14	0	0.23	0	0.26	0
5/21	0.6	0	0.77	0	0.58	0	0.33	0	0.46	0	0.36	0
5/22	0.49	0	0.45	0	0.75	0	0.61	0	1.38	8	1.09	8
5/23	1.66	15	1.63	8	0.97	0	2.18	15	1.92	15	0.99	0
5/24	1.34	23	1.11	15	1.06	15	1.32	23	1.05	8	1.18	15
5/25	0.54	0	1.65	18	1.5	9	1.15	9	1.17	9	1.51	9
5/26	1.23	11	1.35	11	1.61	33	1.03	11	0.88	0	1.19	11
5/27	0.82	0	1.13	8	0.84	0	0.51	0	0.71	0	0.83	0
5/28	1.26	15	0.85	0	0.79	0	1.32	15	1.16	15	1.22	15
5/29	1.46	23	1.99	15	1.69	15	2.13	15	1.72	15	1.68	15
5/30	0.35	0	0.86	0	0.22	0	0.35	0	0.07	0	0.35	0
5/31	0.5	0	0.53	0	0.75	0	0.84	0	0.76	0	0.49	0
6/1	0.61	0	0.64	0	0.92	0	1.33	8	0.51	0	0.34	0
6/2	0	0	0.09	0	0.07	0	0	0	0	0	0.01	0
6/3	1.39	15	1.17	8	0.92	0	1.73	15	1.89	15	1.75	23
6/4	0.94	0	0.48	0	0.85	0	0.84	0	2.07	15	0.85	0
6/5	1.12	8	1.5	8	1.51	8	2.93	62	1.6	54	1.98	54
6/6	0.79	0	1.21	15	0.9	0	2.19	15	0.82	0	1.17	15
6/7	0.98	0	1.2	15	1.09	23	2.81	15	0.9	0	2.02	15
6/8	0.79	0	0.77	0	1.15	8	0.66	0	0.2	0	0.85	0

6/9	0.85	0	0.78	0	0.67	0	0.71	0	0.58	0	0.93	0
6/10	1.53	50	1.29	25	1.92	75	1.86	75	1.65	50	1.63	75
6/11	1.96	54	3.93	77	3.43	69	2.36	85	1.96	54	2.45	69
6/12	0.88	0	0.95	0	1.09	8	0.88	0	0.72	0	0.86	0
6/13	2.07	15	1.23	38	0.79	0	1.05	8	2.89	15	1.69	15
6/14	1.49	17	1.39	8	1.24	8	0.88	0	1.2	17	1.58	8
6/15	1.35	8	2.99	54	1.64	54	2.07	54	2.37	38	2.45	23
6/16	0.7	0	0.53	0	2.09	10	2.29	10	0.51	0	0.68	0
6/17	1.68	8	0.83	0	1.32	15	2.63	31	2.65	15	1.63	15
6/18	0.92	0	1.04	15	1.03	8	1.32	15	1.04	15	0.91	0
6/19	0.01	0	0.07	0	0.25	0	0.03	0	0.06	0	0.18	0
6/20	0	0	0.15	0	0.26	0	0	0	0	0	0.01	0
6/21	0	0	0	0	0.02	0	0.01	0	0	0	0	0
6/22	0.03	0	0.25	0	0.12	0	0.34	0	0.14	0	0.33	0
6/23	0.02	0	0.36	0	1.06	8	1.48	8	0.3	0	0.35	0
6/24	0.71	0	1.66	15	0.78	0	0.8	0	1.41	8	0.83	0
6/25	1.44	8	0.62	0	0.98	0	2.61	8	1.84	15	1.97	8
6/26	0.79	0	0.49	0	0.34	0	1.2	8	0.48	0	0.67	0
6/27	0.41	0	0.55	0	0.01	0	0	0	0.02	0	0	0
6/28	1.49	15	1.85	15	1.17	15	1.03	8	0.77	0	0.74	0
6/29	0.91	0	1.43	8	0.22	0	0.26	0	0.22	0	0.21	0
6/30	0.56	0	0.44	0	0.59	0	0.37	0	0.44	0	0.38	0
7/1	1.18	23	2.24	62	2.54	54	1.63	15	1.44	23	1.96	23
7/2	1.54	8	1.16	8	2.57	8	2.36	8	2.66	15	2.08	8
7/3	0.86	0	1.14	15	1.4	23	1.53	8	0.94	0	1.86	15
7/4	0.64	0	0.96	0	0.75	0	0.98	0	0.69	0	0.68	0
7/5	1.08	15	1.09	15	1.11	8	1.44	8	0.57	0	0.69	0
7/6	1.05	8	1.37	31	1.08	15	1.44	8	1.54	15	1.37	15
7/7	1.77	46	2.64	23	0.47	0	0.49	0	1.71	31	0.81	0
7/8	1.77	15	1.88	54	3.2	62	1.73	38	1.66	38	1.69	46
7/9	1.49	31	2.02	46	1.3	31	2.73	46	1.26	15	2.09	38
7/10	0.82	0	1.16	8	0.66	0	0.46	0	0.88	0	0.58	0
7/11	0.55	0	0.4	0	0.27	0	0.54	0	0.21	0	0.39	0
7/12	0.17	0	0.53	0	0.41	0	0.12	0	0.05	0	0.14	0
7/13	2.09	8	1.32	8	0.55	0	0.61	0	0.74	0	0.81	0
7/14	2.06	38	1.3	38	0.94	0	1.72	15	1.12	8	1.12	15
7/15	0.84	0	0.98	0	0.85	0	0.38	0	0.82	0	0.44	0
7/16	0.43	0	0.58	0	0.29	0	0.3	0	0.42	0	0.24	0
7/17	0.19	0	0.38	0	0.19	0	0.1	0	0.15	0	0.27	0
7/18	0.71	0	1.63	8	0.47	0	1.12	8	1.85	8	1.35	8
7/19	0.94	0	1.12	8	1.81	8	1.49	8	0.52	0	3.33	8
7/20	0.83	0	0.77	0	0.65	0	0.1	0	0.44	0	0.63	0
7/21	2.5	31	2.1	23	3.91	38	2.97	77	3.7	38	1.99	38
7/22	0.78	0	0.48	0	0.36	0	0.37	0	0.26	0	0.29	0
7/23	0.04	0	0.12	0	0.18	0	0.13	0	0.08	0	0.23	0
7/24	0.73	0	0.7	0	1.14	8	0.26	0	0.05	0	0.17	0

7/25	0.14	0	0.29	0	0.1	0	0.08	0	0.1	0	0.05	0
7/26	0.32	0	0.61	0	1.89	8	1.26	8	0.55	0	1.12	15
7/27	0.7	0	0.92	0	0.95	0	0.95	0	0.5	0	0.45	0
7/28	0.12	0	0.4	0	0.39	0	0.19	0	0.03	0	0.24	0
7/29	0.38	0	0.84	0	0.7	0	0.59	0	0.5	0	0.67	0
7/30	0.86	0	0.98	0	0.99	0	0.86	0	0.81	0	1.12	8
7/31	0.75	0	1.56	8	0.98	0	0.83	0	0.28	0	0.49	0
8/1	0.49	0	0.5	0	1.31	8	1.94	8	0.31	0	0.67	0
8/2	1.06	8	1.09	8	0.72	0	0.84	0	1.11	8	0.94	0
8/3	0.83	0	1.18	15	1.45	8	0.43	0	0.36	0	1.05	8
8/4	0.07	0	0.05	0	0.06	0	0.02	0	0.03	0	0	0
8/5	0.23	0	0.14	0	0.26	0	0.08	0	0.18	0	0.18	0
8/6	0	0	0	0	0.01	0	0	0	0	0	0	0
8/7	0.75	0	0.53	0	1.09	8	2.27	23	0.54	0	0.89	0
8/8	0.41	0	0.71	0	1.07	8	0.77	0	0.48	0	0.7	0
8/9	0.1	0	0.58	0	0.55	0	0.23	0	0.05	0	0.36	0
8/10	0.64	0	1.96	38	1.76	54	1.33	23	1.36	15	1.55	23
8/11	1.02	8	1.69	62	4.04	69	1.81	23	0.94	0	1.27	23
8/12	1.36	15	1.65	23	1.29	8	0.87	0	0.78	0	0.74	0
8/13	0.95	0	1.38	31	1.54	8	0.22	0	0.72	0	0.6	0
8/14	1.62	23	2.98	46	1.44	15	1.12	8	1.03	8	0.7	0
8/15	0.51	0	0.47	0	0.48	0	0.57	0	0.14	0	0.04	0
8/16	1.11	25	1.1	25	2.3	50	2.37	50	1.81	25	2.54	50
8/17	1.43	25	2.27	50	2.88	50	4.08	25	1.08	25	3.15	25
8/18	0.4	0	0.37	0	0.36	0	0.48	0	0.43	0	0.28	0
8/19	0.03	0	0.07	0	0.09	0	0.01	0	0.02	0	0.03	0
8/20	0.22	0	0.22	0	0.17	0	0.15	0	0.13	0	0.22	0
8/21	0.22	0	0.23	0	0.1	0	0.02	0	0.05	0	0.07	0
8/22	0.09	0	0.26	0	0.23	0	0.31	0	0.02	0	0.47	0
8/23	0	0	0.24	0	0.19	0	0	0	0	0	0	0
8/24	0.1	0	0.12	0	0.02	0	0	0	0.03	0	0.01	0
8/25	0.38	0	0.81	0	0.74	0	0.16	0	0.43	0	0.06	0
8/26	1.15	8	0.62	0	0.21	0	0.34	0	0.12	0	0.27	0
8/27	0.78	0	0.96	0	0.91	0	0.67	0	0.86	0	0.56	0
8/28	0.53	0	0.57	0	0.49	0	0.15	0	0.8	0	0.41	0
8/29	0.71	0	1.01	8	0.05	0	0	0	0	0	0.01	0
8/30	0.65	0	0.4	0	0.19	0	0.04	0	0.09	0	0.09	0
8/31	0.94	0	2.19	23	2.11	15	1.13	15	0.58	0	1.26	15
9/1	0.98	0	0.89	0	0.65	0	0.3	0	0.48	0	0.39	0
9/2	0.27	0	0.42	0	0.09	0	0.07	0	0.05	0	0	0
9/3	1.02	8	0.79	0	0.45	0	0.5	0	0.84	0	0.52	0
9/4	0.46	0	0.42	0	0.23	0	0.19	0	0.21	0	0.29	0
9/5	0.64	0	0.33	0	0.15	0	0.37	0	0.35	0	0.23	0
9/6	0.23	0	0.32	0	0.14	0	0.49	0	0.72	0	0.23	0
9/7	0.58	0	0.7	0	0.46	0	0.62	0	0.57	0	0.5	0
9/8	0.09	0	0.17	0	0.17	0	0.19	0	0.1	0	0.17	0

9/9	0	0	0	0	0	0	0	0	0	0	0	0
9/10	0.75	0	0.62	0	0.55	0	1.07	9	1.37	18	0.74	0
9/11	0.13	0	0.21	0	0.71	0	1.34	9	0.77	0	0.77	0
9/12	0	0	0	0	0	0	0	0	0	0	0	0
9/13	0	0	0	0	0	0	0	0	0	0	0	0
9/14	0.42	0	0.35	0	0.34	0	0.04	0	0.29	0	0.24	0
9/15	0.14	0	0.26	0	0.15	0	0.2	0	0.03	0	0.01	0
9/16	0.21	0	0.07	0	0	0	0	0	0	0	0	0
9/17	0.14	0	0.09	0	0.05	0	0.19	0	0.17	0	0.01	0
9/18	0.12	0	0.07	0	0.02	0	0	0	0.01	0	0.02	0
9/19	0.13	0	0.09	0	0.26	0	0.05	0	0.06	0	0.07	0
9/20	0	0	0	0	0	0	0	0	0	0	0	0
9/21	0	0	0	0	0	0	0	0	0	0	0	0
9/22	0.54	0	0.51	0	0.89	0	0.68	0	0.34	0	0.41	0
9/23	0.54	0	0.49	0	0.56	0	0.08	0	0.26	0	0.1	0
9/24	0.51	0	0.21	0	0	0	0	0	0.04	0	0	0
9/25	0	0	0	0	0	0	0	0	0	0	0	0
9/26	0	0	0	0	0	0	0	0	0	0	0	0
9/27	0.16	0	0.13	0	0	0	0.05	0	0.1	0	0.02	0
9/28	0.63	0	0.67	0	0.98	0	0.46	0	0.82	0	0.59	0
9/29	0.29	0	1.01	8	1.85	8	0.97	0	0.68	0	1	8
9/30	0.3	0	0.37	0	0.32	0	0.33	0	0.41	0	0.13	0

APPENDIX C – COMPARISON OF OBSERVED RAINFALL DATA

We noted in the Report that there were substantial differencing between the gauge-based ALERT and gridded Stage IV hourly rainfall estimates. The table below quantifies these differences by showing the number of hours (out of a total of 3672) when each of the products measure rainfall exceeding 0.2 inches per hour. We calculate values for each Zone separately as well as for all zones together. Note that Zone D does not have any ALERT gauges.

Although there are sizeable disparities in all zones, we are particularly intrigued by the differences in Zone F, where ALERT data has a tremendous amount of more hours indicating rainfall exceeding 0.2 inches. We believe that it is not coincidence that these disparity is highest in the region with the most ALERT gauges (see Table 1). We also believe these differences must be pointed out to NOAA since the Stage IV product is designed to provide gauge-corrected rainfall estimates (based on radar Z-R relationships). However, we cannot pursue this topic further here since it is not directly related to the scope of this Report.

	# of hours > 0.2”		
Zone	**Both ALERT & Stage IV**	**ALERT only**	**Stage IV only**
A	56	94	65
B	74	50	137
C	109	34	113
D	N/A	N/A	162
E	29	28	110
F	126	128	52
All zones	304	150	210