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HEAVY RAINFALL THREAT ANALYSIS: 2021 FINAL REPORT

Mile High Flood District

Submitted to:
Kevin Stewart
Mile High Flood District
2480 W 26th Ave, #156B
Denver, CO 80211

Submitted by:
HydroMet Consulting, LLC
2164 Zang Street
Golden, CO 80401
HydroMetConsulting@gmail.com
303.921.5999

Table of Contents

Acronyms

ALERT	MHFD rainfall gauge network
AM	Reference to the 7AM MDT HRTA forecast
$_{BC}$QPF	Bias Corrected & Post-Processed QPF (HMC product)
CoCoRaHS	Community Collaborative RAin, Hail, and Snow Network
COOP	Cooperative Observer Program within NWS
F2P2	Flood Threat Prediction Program
FAR	False Alarm Rate
FWS	Flood Warning Services (MHFD)
HMC	HydroMet Consulting, LLC
HPO	F2P2 Heavy Precipitation Outlook product
HRTA	Heavy Rainfall Threat Analysis
MHFD	Mile High Flood District
MR	Miss Rate
MRMS	Multi-Radar Multi-Sensor, gridded QPE data set
NOAA	National Oceanic and Atmospheric Administration
NSSL	National Severe Storms Laboratory
NWS	National Weather Service
PM	Reference to the 1PM MDT HRTA forecast
POD	Probability of Detection
POE	Probability of Exceedance
POE1	Probability of Exceedance for the 1.00 inch in 1-hour threshold
POP	Probability of Precipitation
PRISM	Parameter-elevation Regressions on Independent Slopes Model, climate group from Oregon State
QPE	Quantitative Precipitation Estimation
QPE-Max	Maximum 1-hour QPE
QPF	Quantitative Precipitation Forecast
QPF-Max	Maximum 1-hour QPF
Stage IV	Gridded QPE data set
Tool	Heavy Rainfall Threat Analysis (formally known as the Heavy Rainfall Guidance Tool)
USGS	United States Geological Survey

Heavy Rainfall Threat Analysis: 2021 Upgrades and Operations

for the Mile High Flood District

Introduction

Tool History

Design of the Heavy Rainfall Threat Analysis (hereafter, HRTA or Tool; also formally known as the Heavy Rainfall Guidance) was completed for the Mile High Flood District (hereafter, District or MHFD) in 2014. From 2015 to present, the Tool has been integrated into District's Flood Warning Services (FWS) operations during Colorado's warm season, May 1st to September 30th. The main objective of the Tool has remained the same throughout the years: to inform end-users on the timing, location, intensity and confidence of heavy rainfall occurrence over the District and immediate surrounding drainage areas with at least several hours of lead time. Yearly updates have been implemented to both the scientific underpinning and presentation of the Tool to enhance the utility of its forecasts for end-users, and a full history of the Tool can be found in previous final reports (e.g. Dewberry, 2020). Prior to the start of the 2021 season, there was a major overhaul to the Tool's appearance and data structure, which will be further discussed below. Similar to years past, the Tool updates throughout the day to incorporate the latest forecast and observational data. The number of times the Tool updates this season has been increased from four to six with the first forecast beginning at 7AM and the last forecast ending at 3PM. While the Tool still aims to provide an early threat for potential heavy rainfall over the next 24-hours, the output has been tailored to what information is most useful to end-users in a new web map. Note that while the Tool provides an outlook for flood threat awareness, it does not supply real-time decision support during heavy rainfall events.

Tool Overview

As shown in Figure 1, the Tool forecast area spans the entire District, along with a buffer on the northern, western and southern sides to (i) account for forecast uncertainty, and (ii) inform of hydro-meteorological conditions upstream of the District that could carry into the District. In terms of area, Table 1 shows that the District itself, spanning an area over 1,600 square miles, is covered by the NW Metro, NE Metro, SW Metro and SE Metro zones. The North Area, North Foothills, South Foothills and Palmer Divide zones cover an additional 2,735 square miles. The elevation across the Tool ranges from over 11,000 feet in the North and South Foothills to below 5,000 feet along the South Platte River of the North Area.

The main data source for the Tool is HydroMet Consulting's (HMC) Bias-Corrected Quantitative Precipitation Forecast ($_{BC}$QPF) product. $_{BC}$QPF aggregates dozens of weather model forecasts into a single ensemble, corrects for model biases using local rainfall data and other atmospheric fields, and then outputs key parameters such as the Probability of Exceedance (POE) of a given rainfall threshold. This approach is superior to using raw QPF data alone, especially during marginal probability days where the QPF tends to be overconfident (more details below; also see Dewberry, 2016). $_{BC}$QPF outputs several key metrics used by the Tool. First, the maximum hourly QPF (hereafter, QPF-Max) provides a realistic upper-bound on a given day's rainfall potential; akin to the "worst-case scenario". Second, the POE (e.g., the chance of exceeding 1 inch in 1-hour) for each of the eight forecast zones (see Figure 1). A requested by MHFD, the Tool outputs several POE thresholds for 1, 3, 6 and 24-hour durations that are capable of causing flooding issues over the District, and each of these thresholds help determine the nature of the heavy rainfall threat. However, the Tool's output prioritizes the most common POE for warm season variety rainfall: 1 inch in 1-hour. Other POE thresholds known to cause flooding issues over the District include 2.25 inches in 3 hours, 3.5 inches in 6 hours, and 4.5 inches in 24 hours. **For the Tool's verification, a "Flood Day" will be defined when rainfall exceeds one or more of these four thresholds, which again, is most commonly the 1 inch in 1-hour threshold.**

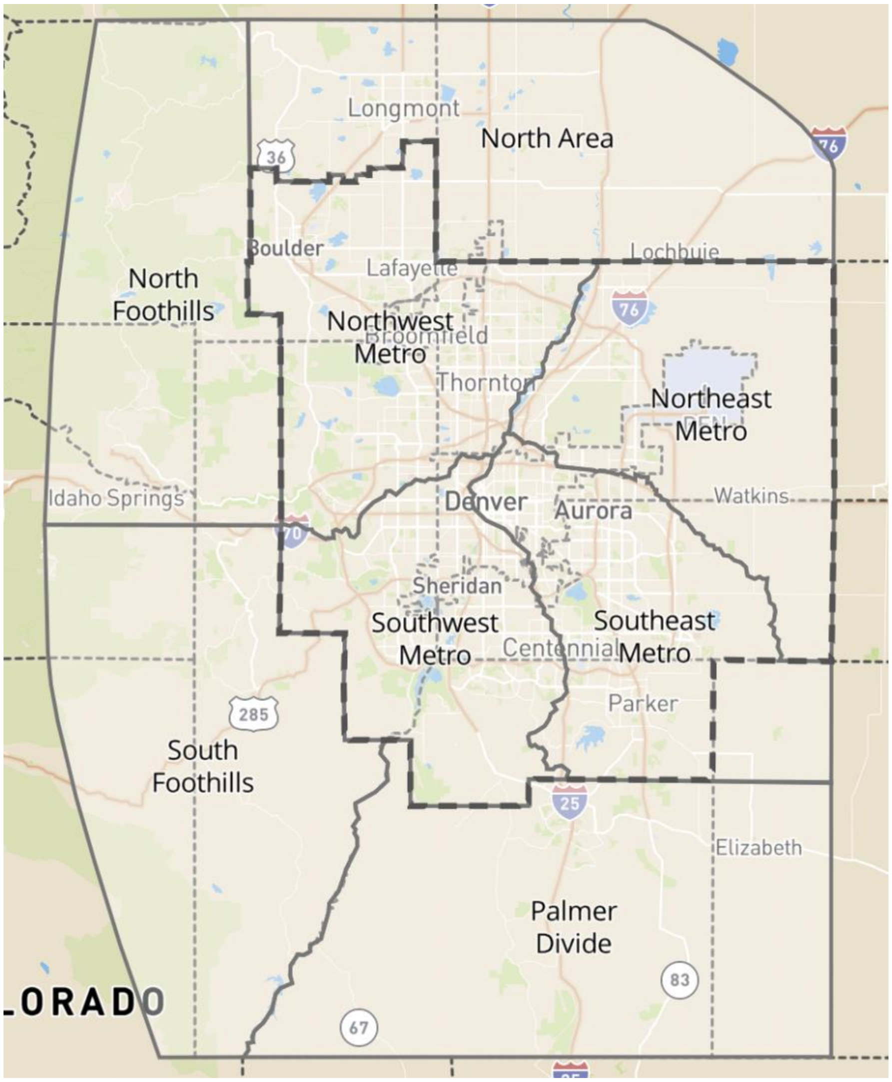

Figure 1: Forecast area of the HRTA Tool, with the "Individual Zones" labeled. The Northwest Metro, Northeast Metro, Southwest Metro and Southeast Metro zones cover the District. The North Area, North Foothills, South Foothills and Palmer Divide zones allow for a buffer to incorporate forecast uncertainty and inform of conditions upstream of the District. Note that the All Zones area is just the spatial aggregate of all eight Individual Zones.

One of the motivations for developing the Tool and POE guidelines was to capture relatively isolated and marginal heavy rainfall events that can cause runoff issues within the MHFD area. Although these account for a large portion of all heavy rainfall events within MHFD, they are typically not covered by National Weather Service (NWS) Flash Flood Watches, which are reserved for higher-end rainfall intensities that are expected to span across multiple counties. For instance, over the 2015-2020 forecast season (May to September), there were 172 days when rainfall somewhere with the MHFD area exceeded 1 inch in 1-hour, 108 days where rainfall exceeded 1.25 inches in 1- hour, and 61 days where rainfall exceeded 1.50 inches in 1hour. During that same period, there were only 17 days when a Flash Flood Watch was issued over the Tool's domain. That means that only about 1 in 10 such days had meaningful lead time in anticipating the heavy rainfall threat for the District.

Tool Upgrades

Forecast zones were redrawn this season with a noticeable increase to the Tool's resolution within the MHFD boundary (see Figure 2). The District's boundary was broken into four metro zones after the completion of a heavy rainfall climatology (Table 1). Table 1 shows noteworthy variability in Flood Day activity across the Tool's domain and within the 40 to 50 mile stretch of the MHFD boundary itself. The differences are primarily driven by the large changes within topography, especially over the Foothills and Palmer Divide. However, there are also other meteorological factors, such as the Denver Cyclone that can disproportionately affect the zones. On any given day during the warm season, Table 1 indicates a higher risk for heavy rainfall over the Palmer Divide and Southeast Metro area. This threat is almost three times as high as the occurrence of a Flood Day over the Northwest Metro zone. The frequency of Flood Days is further broken down into "pre-monsoon" and "monsoon" time periods, which represent May to June and July to September, respectively. Remarkably, during the monsoon season, the Palmer Divide has a two-fold greater chance of experiencing a heavy rainfall event. This is likely due to localized circulations induced by the change in topography. Also included in Table 1 are the number of ALERT gages per zone. These gauges are the most accurate way of estimating real-time rainfall, although a direct pass of a storm's rainfall core over a gauge is surprisingly unlikely on any given day (more details in the Methodology section).

Table 1: Forecast Zone elevation span, area, number of ALERT gages along with key Flood Day climatology statistics.

			"Flood Day" Information		
Zone	**Elev. (ft)**	**ALERT #**	**Days/Yr**	**Pre-monsoon**	**Monsoon**
N. Foothills	6.0 - 11.3k	61	4	2.7%	2.0%
S. Foothills	6.0 - 13.0k	18	6	3.8%	4.0%
Palmer Divide	6.0 - 9.3k	33	15	7.0%	13%
North Area	4.8 - 6.8k	8	8	5.4%	4.9%
NW Metro	5.0 - 7.8k	40	5	4.0%	2.7%
SW Metro	5.2 - 7.9k	36	6	4.3%	4.0%
SE Metro	5.1 - 6.6k	56	10	6.7%	6.6%
NE Metro	5.0 - 6.1k	6	7	5.4%	4.0%
All Zones	**4.8 - 13.0k**	**258**	**29**	**18.0%**	**19.0%**

While the Tool's output is predominantly built around POE, this probabilistic value is translated into a four-tier threat level for practical operations (None, Low, Moderate, High). More experienced users can also see the actual POE that is causing the threat. For example, the High threat level probability threshold of about 60% translates to the real-world application of "expect heavy rainfall for three out of the five days somewhere in the District". Since the probability of rainfall or a Flood Day is directly related to forecast confidence and area, probabilities are always higher for the All Zones forecasts when compared to the Individual Zone forecasts. For example, at the Individual Zone level, the same High threat forecast would be expected to verify roughly 1 in every 4 days it is issued. While the science at the Individual Zone scale is still evolving and may not be directly useful for an end-user, the Tool can still provide a spatial trend across the Tool's domain (e.g. Figure 2 and Figure 8). For example, there may be a lower threat over the northern portion of the Tool and higher threat over the southern portion of the Tool's domain indicating heavy rainfall is more likely to occur across the southern region. Therefore, the higher resolution zones within the District's boundary (40 to 50 mile range) can give an indication of which metro regions may see heavy rainfall during the forecast period.

Web Map

A new web map was created that helps simplify the most important details of the forecast and adds a spatial component to the Tool's output **(https://qpf.mhfd.org)**. The original website built for the Tool in 2015, albeit functional, was not designed to be mobile friendly partially due to the resource-intensive nature of developing mobile apps at that time. However, due to the "on the go" nature of Emergency Mangers and other end-users, the new interactive web map attempts to bridge that gap. An example of the new interactive web map is shown in Figure 2 from July 30th. The Tool has two main tabs related to QPF. The first is the "Threat Layer" and is akin to the "most likely" scenario, which is where the end-user can find the heavy rainfall threat level. Each Individual Zone is clickable with a drop down at the top for the All Zones QPF information. Within the clickable QPF tables are the Probability of Precipitation (POP), previously discussed POE thresholds, and QPF-Max.

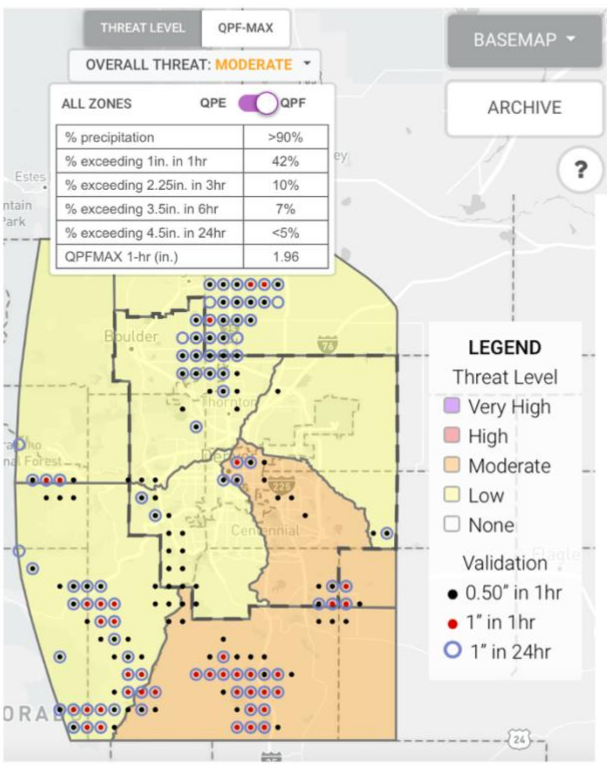

Figure 2: Snapshot of the Tool's new web map interface for the 7AM update on July 30th, 2021. Overlaid on the forecast is QPE for forecast verification.

The second tab is the "QPF-Max", which can be accessed by clicking on the button at the top of the web map (Figure 2). This overlay will show a high-resolution QPF-Max estimate across All Zones (not shown). In essence, this shows the worst-case scenario, but one with a realistic upper-bound. The Individual Zones with this feature are also clickable, and they will show not only the highest QPF-Max of the day, but also a time series aggregated in blocks of 2-hour periods. This was created to give end-users an idea of the timing of the potential heavy rainfall threat. The typical diurnal pattern for Colorado rainfall has a peak in rainfall chances during the afternoon, but this feature would also be able to capture the potential for rare, overnight heavy rainfall events.

Archive

An archive of the Tool's output is available by clicking on the "Archive" button at the top right of the web map (Figure 2). This is the exact same interface as the active Tool; however, it can be differentiated by a "Caution: Archived Forecast" note at the top (see Figure 8). All daily Tool updates can be accessed through this feature with use of the calendar and time sidebar (push "Archive"). While the archive has access to the same QPF data mentioned above, it also has an added Quantitative Precipitation Estimation (QPE) component that is updated each morning with QPE coming from three separate data sources (see Figure 2). Two of the datasets are commonly used gridded, radar-estimated, gauge-adjusted products: NOAA Stage IV (Lin and Mitchell, 2005) and NSSL MRMS (Zhang et al., 2016; Gerard et al., 2021). Gridded data has the advantage of full spatial coverage, but it can both overestimate and underestimate true rainfall depending on the atmospheric conditions. To supplement this shortcoming, the third dataset, the MHFD ALERT network, is also ingested to the verification system. This gauged data can better capture convection within a storm core (but only if the storm core directly passes over the gauge).

The archive web map has three different thresholds displayed on a high-resolution grid, to help identify the types of storm(s) that moved through the area for the selected date. Every combination of those thresholds can be seen in Figure 2. Blue circles indicates that 1 inch of rain fell in the 24-hour forecast period, which if spread over a wide area can indicate a longer-duration and stratiform (e.g. low intensity) storm type. A red dot within the center of the blue circle indicates that storms produced 1 inch of rainfall in 1-hour, which is the main type of rainfall event the Tool seeks to forecast. Finally, a black dot indicates that 0.50 inches of rain fell in 1-hour. Alone, a black dot could suggest that a small convective storm passed over the area but was not able to meet Flood Day criteria. However, a black dot located within a blue circle may indicate that the area experienced a couple rounds of storms throughout the day, but neither storm was strong enough to trigger a Flood Day. The Individual Zones are also clickable with the QPE feature. In the interactive tables are QPE stats that show the number of points or gauges that reached the particular POE thresholds. Should heavy rainfall have fallen on that day, these stats can be used to determine which dataset is causing the classification of a Flood Day. Also included in the table are the highest QPE values for the 1- and 24-hour durations. The overall goal of the Archive map is for end-users to gain more confidence in the Tool's utility by exploring how the Tool has handled past rainfall events, especially more recent ones.

Outreach

The Twitter social media platform continued to be a secondary communication outlet for HRTA forecasts this season. Without proper dissemination of a forecast, even a perfect forecast can have little value. The Twitter platform is unique in that it can quickly pass information through a headline like manner, and Tweets can be searchable by subject with the use of hashtags (e.g. #COFlood or #COwx). In order to avoid social media overload on the ALERT Flood Detection account (@mhfdfws), Tweets were only issued on two High threat days where widespread, heavy rainfall was anticipated: July 1st and July 31st. Between the two Tweets, there were 10+ "Likes" and 7 "Retweets" or shares. Both forecasts verified with hourly rain intensity exceeding 1.50 inches, which will hopefully continue to build confidence in the HRTA. Additionally, a training for the Tool and use of its new interactive web map was held on July 20th, 2021. The training had around 20 attendees from backgrounds ranging from emergency management to local on-air meteorologists. A recording of the training can be found on the FWS website. Public outreach continues to build both awareness and confidence in Tool usage by end-users, which helps increase the overall utility of the Tool.

Report Objective

This final report aims to evaluate the Tool's performance over the 2021 warm season using a variety of industry standard metrics for heavy rainfall forecasting. While there are several avenues of heavy rainfall forecasting to explore (e.g. rainfall distribution across the Tool, regional rainfall climatology, timing/duration of rainfall activity, etc.), to narrow the scope of the final report, the focus of the verification will be on the 1-hour time duration. Recall that this is the most often associated with flash flooding over the District. Since one of the main objectives of the Tool is to provide ample lead time before a heavy rainfall event, most metrics in the verification will be evaluated from the 7AM forecast (AM). The analysis will also examine the change in the Tool's output after the 1PM update (PM), albeit to a lesser degree, which is when several new weather models are added to the $_{BC}$QPF data. The purpose of this secondary PM analysis is to look at the Tool's forecast consistency and ability to take into account evolving atmospheric components (e.g. cloud cover, moisture, etc.). The analysis will focus primarily on the All Zones forecast; however, AM/PM threats for all eight Individual Zones can be found in Appendix A.

Methodology

HRTA Process Flow

Since its original design in 2014, the Tool has strived to maintain a relatively objective forecast system, which lends itself to more improvement opportunity when compared to a subjective forecast. Nonetheless, it also incorporates a significant element of physical-based "nudging" as opposed to purely using model forecasted precipitation. The overall Tool process is shown in Figure 3, and is composed of Real-Time Operations, yearly Post-Processing and the aforementioned Archive.

The **Real-Time Operations** and **Post Processing** steps are the crux of the Tool, where $_{BC}$QPF updates heavy rainfall probabilities as weather model guidance and atmospheric observations evolve throughout the day. Non-precipitation atmospheric fields such as Precipitable Water, Convective Available Potential Energy and Wind Speed are also inspected and can tweak the estimated probability of heavy rainfall up or down, depending on a variety of atmospheric circumstances. $_{BC}$QPF algorithms are updated yearly to account for the latest forecast model bias, improvements in QPE and better scientific understanding of heavy rainfall processes.

The Tool's **Archive** contains a web-map where every forecast update is saved and can be readily accessed. In addition, rainfall information from MHFD ALERT gages as well as several high-resolution QPE products are overlayed on the forecast to assess forecast performance. The Archive is updated once every morning, and accounts for the past 24 hours of forecast and QPE data.

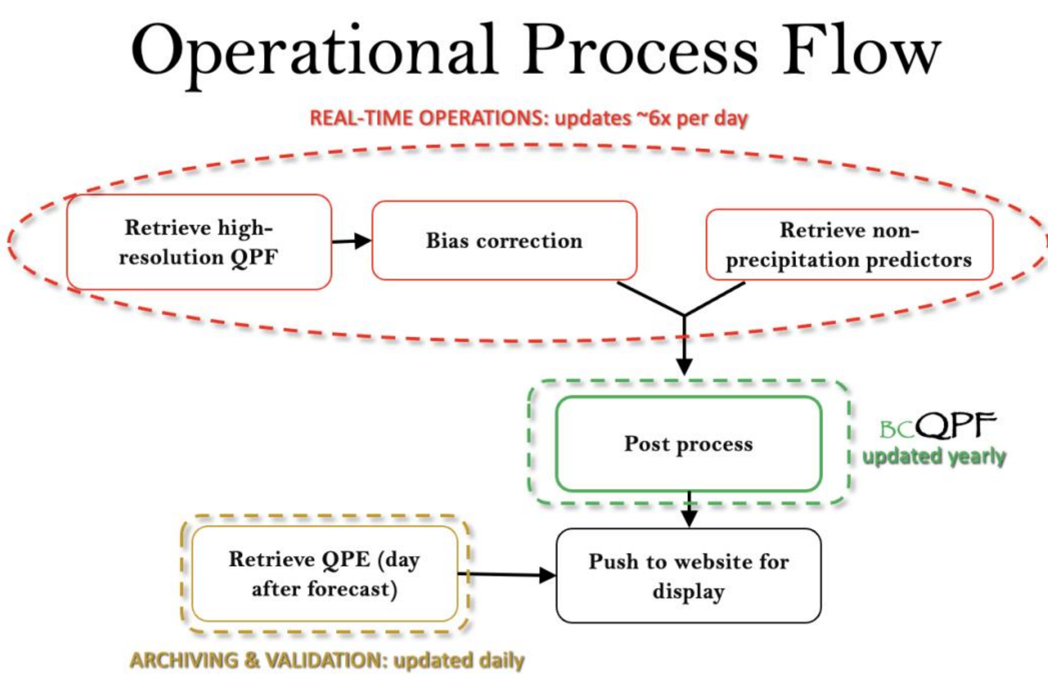

Figure 3: HRTA flow chart.

Verification Data

Forecasts

For this report, Tool forecast data is accessed through the Archive web map which has the ability to reproduce past operational forecasts. The following fields are saved for this report: Threat Level, POP, and 1, 3, 6 and 24-hour POE. In the vast majority of events, the 1 inch in 1-hour POE (POE1) is the relevant metric to the flood risk due to the region's semi-arid climatology that generally prevents longer duration heavy rainfall.

Rainfall Observations and Estimates

MHFD maintains roughly 200 ALERT rain gauges, which combined with other rain gauge networks such as CoCoRaHS, produce about 500 measurement devices across a relatively small area. However, due to (i) the often spatially-confined nature of heavy rainfall events in the MHFD area, and (ii) the limited site coverage of where gauges can be placed, the amount of "effective area" covered by the gauge network is surprisingly low. For example, Figure 4 shows that due to clustering, the effective area covered by all reliable gauges is estimated somewhere between 500-2,000 square miles, or 10-45% of the Tool's area, depending on what coverage radius one assigns to a given gauge (Figure 4 provides three radii). Isolated thunderstorm events will be characterized by the lower end of this range, while widespread, less convective events will tend to be well represented. Thus, it is somewhat surprising that the chance that an isolated, intense thunderstorm core passes directly over a rain gauge can be as low as 10%. However, even 10% is significantly higher than the ~1% coverage area estimated by all global gauges (Kidd et al., 2017).

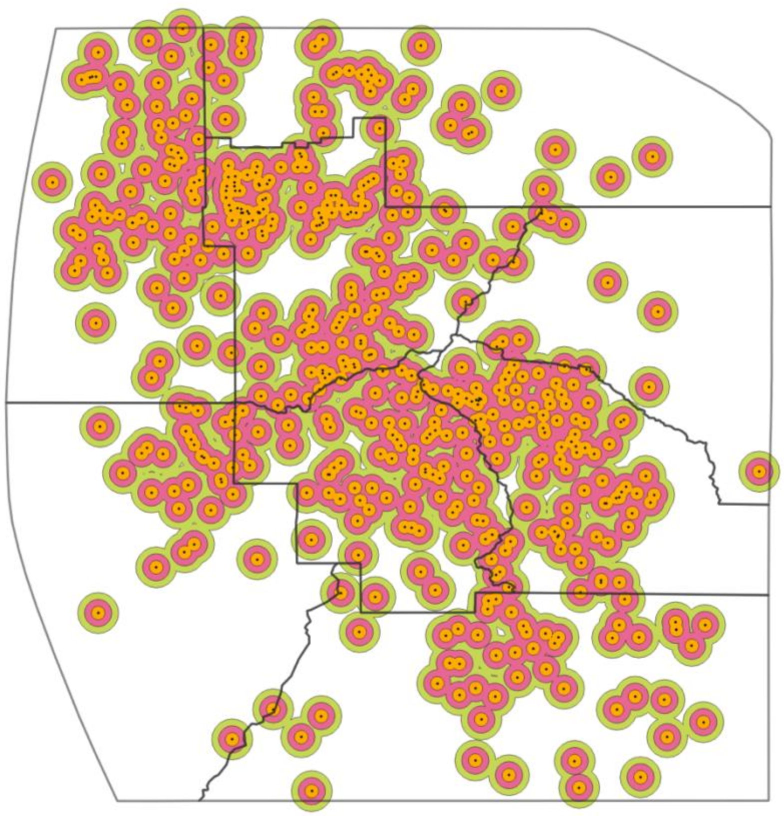

Figure 4: HRTA Tool domain overlaid with all ALERT, CoCoRaHS and NWS rain gauges (black dots). Orange, red, and green circles outline the effective coverage area of a single gauge using a radius of influence of 0.6, 1.2 and 1.8 miles, respectively.

The limitations of the gauge network density can, in theory, be mitigated by using gridded, radar and satellite-based, gauge-adjusted QPE to supplement the data. In fact, this has been done since the HRTA's inception in 2015 using the NOAA Stage IV QPE (Lin and Mitchell, 2005). However, up to this point, QPE was taken at face value under the assumption that the MHFD domain has enough gauges to provide reasonable gauge adjustment and reduce biases in the final gridded QPE product. One significant enhancement to the 2021 HRTA verification was the addition of the NSSL MRMS QPE (Zhang et al., 2016; Gerard et al., 2021), a similar product to Stage IV, but one that has higher resolution (1km versus ~4km for Stage IV) and a more sophisticated algorithm that incorporates weather modeling output into the initial QPE.

This year, for the first time since the Tool's inception, HMC completed further inspection of QPE performance revealing surprising systematic overestimates in both Stage IV and MRMS. There are many possible reasons for this from a meteorological perspective (see Zhang et al., 2016). Another possible (non-meteorological) reason is the fact that these products are national-scale and do not have explicit local-level corrections. Figure 5 compares 24-hour rainfall from gauge observations (ALERT and CoCoRaHS) with their corresponding MRMS grid points, aggregated over the 26 Flood Days during the 2021 forecast season. Only points with *at least* 0.10 inches of observed rain *or* QPE were retained. Note that multiple gauges could fall within the same MRMS grid point. In general, MRMS tended to overestimate QPE with the mean bias, as measured by a best fit line, of about 28%. Of the 6,549 data points included, 4,752 (72%) were overestimated. Stage IV had a slightly lower bias, but still tended to overestimate (not shown).

The tendency for QPE to overestimate gauges, as shown in Figure 5, may have actually been somewhat *suppressed* by the fact that many Flood Days experienced widespread rainfall, which allowed for a wide sampling of gauge observations. On the contrary, on "marginal" Flood Days, which were essentially categorized as Flood Days according to QPE, but flagged as suspicious based on manual inspection, a more significant overestimate was observed. As shown in Figure 6, a similar comparison of QPE to gauges on such days showed a very strong tendency for QPE to be overestimated. For example, at 839 gauges, MRMS overestimated 685 (82%), and the magnitude of the bias was significantly worse with numerous instances of high QPE where gauges had little to no rainfall. **This confirms that the manual inspection process completed for this analysis added value by reducing the number of false positive Flood Days identified by using QPE alone.** At this time, determining the reason for these biases is beyond our scope, but HMC will factor these findings into future $_{BC}$QPF methodology.

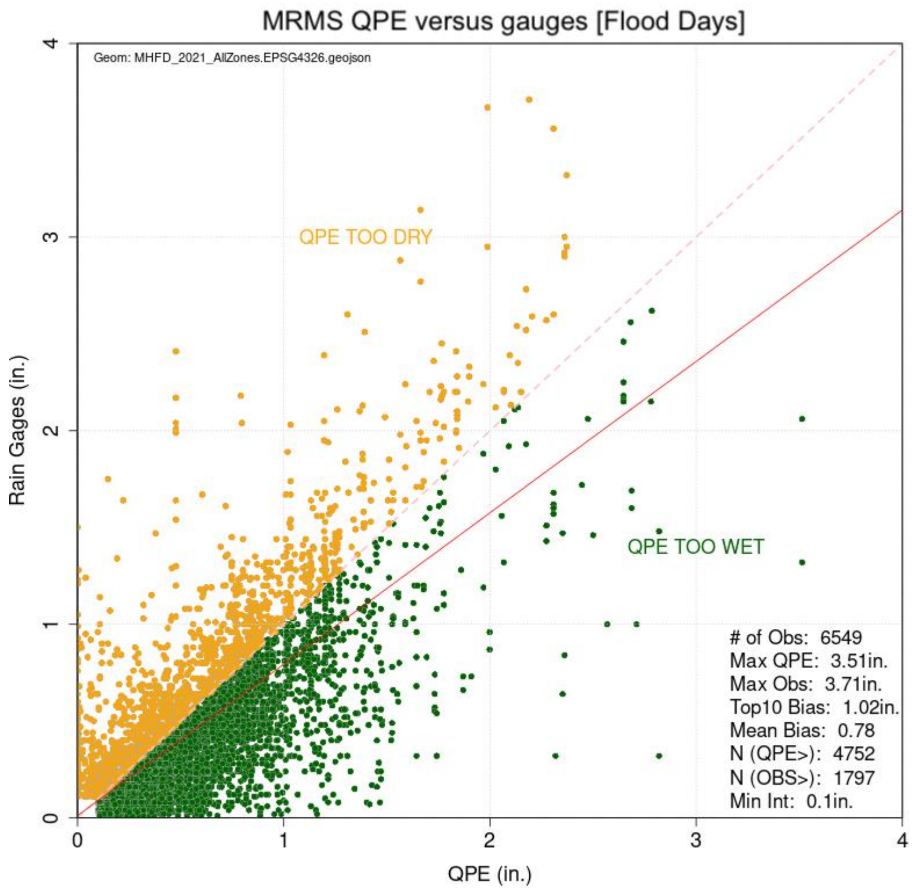

Figure 5: Comparison of MRMS QPE with gauge observations over all 26 Flood Days during the 2021 forecast season.

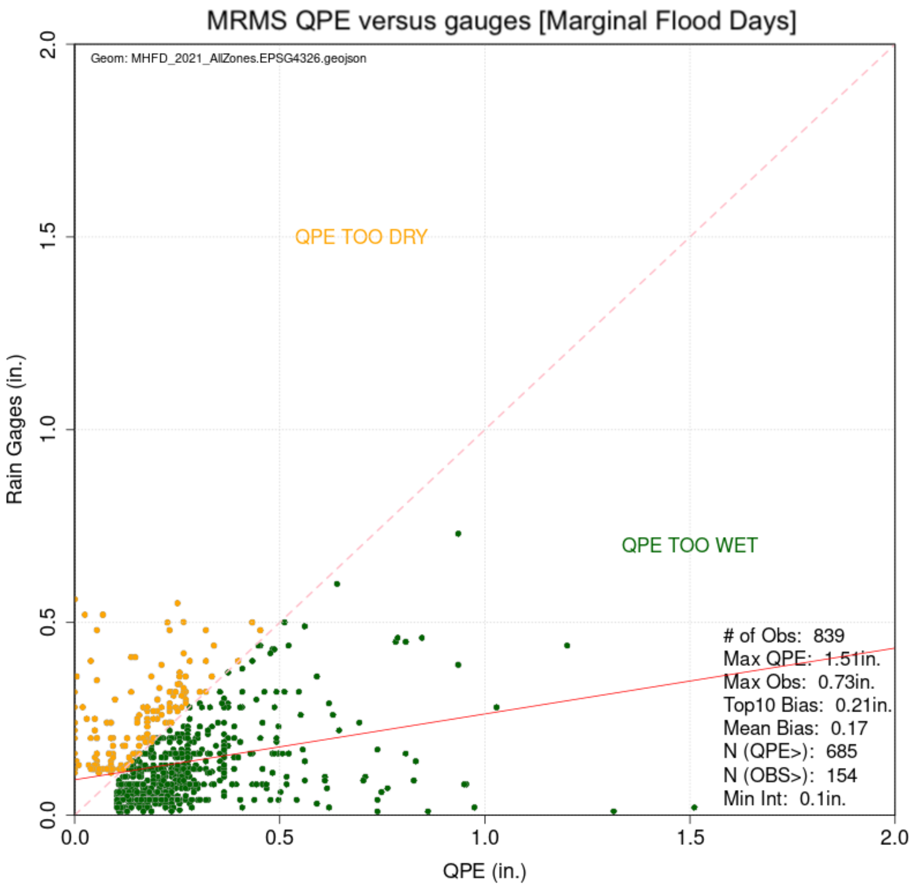

Figure 6: Same as Figure 4 except for the 11 Marginal Flood Days during the 2021 forecast season.

Flood Day Definition

A "Flood Day" is hereby defined as a 24-hour period starting at roughly 9AM during which maximum rainfall anywhere in the HRTA All Zones domain is estimated to have exceeded at least one of the following thresholds:

1.00 inch in 1-hour
2.25 inches in 3-hours
3.50 inches in 6-hours
4.50 inches in 24-hours

Maximum rainfall intensity is an estimated range of values based on a combined dataset of high-quality gauges (ALERT, CoCoRaHS, COOP), as well as the gridded Stage IV and MRMS QPE products. For each day, HMC quality controls both gauge and QPE maximum estimates, using the aforementioned scatter plots, to come up with a single value for the maximum rainfall, in 0.25 inch increments. Due to the region's climatology of favoring relatively isolated, and short-lived thunderstorms, the vast majority of Flood Days are identified by the POE1 threshold, though there are several days where multiple thresholds are exceeded.

It is important to note that a Flood Day assignment does NOT indicate that flooding was actually observed, but simply that rainfall observations and estimates were supportive of excessive runoff. **For the 2021 forecast season spanning May 1st to September 30th, HMC identified 26 Flood Days (and 127 non-Flood Days).** Table 2 shows the distribution (number of days) in maximum hourly rainfall intensity.

Table 2: Number of days during the 2021 forecast season with maximum hourly rainfall (inches) in the following bins.

None	0-0.25	0.25-0.50	0.50-0.75	0.75-1.00	1.00-1.25	1.25-1.50	1.50-1.75	>1.75
40	33	25	18	11	4	6	9	7

Verification

Forecast Period Summary

The 2021 warm season can be summarized as one with a near average number of Flood Days, but relatively spotty precipitation, and well-above average temperatures. Figure 7 shows the precipitation anomaly for the 5-month period across the Tool's full domain. For the most part, the majority of the Front Range and Urban Corridor experienced below to well-below normal precipitation. The eastern and southern regions of the Tool saw only ~33% of normal precipitation in 2021, and precipitation deficits exceeded 4 inches in the area. Only the Northwest and Southwest Metro zones received near normal to slightly above normal precipitation (though most of this fell during May and June). Both the North and South Foothills experienced a range of above and below average precipitation; however, due to an extremely dry August and September, much of the area ended up with slightly below normal rainfall.

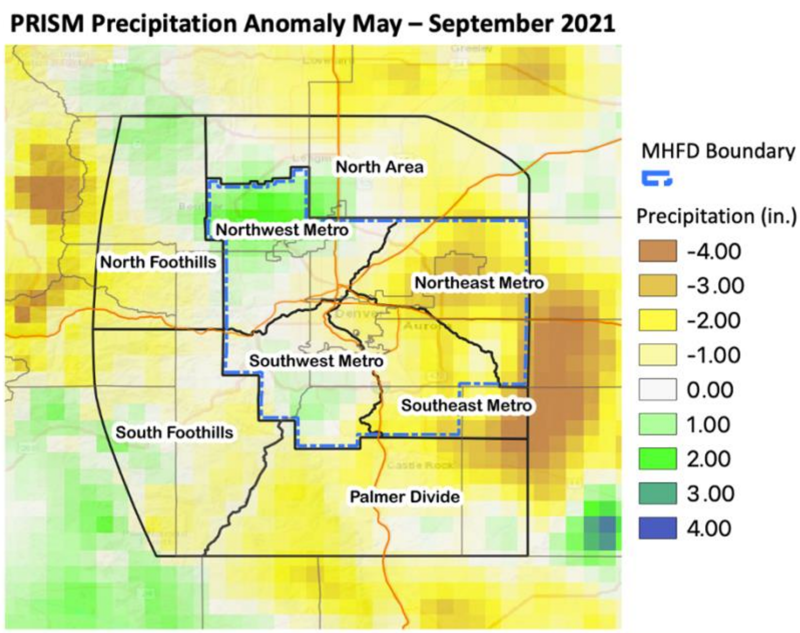

Figure 7: Precipitation anomalies (PRISM) for May through September 2021. Data source: PRISM

At the beginning of the season, the southern, eastern, and southwest portion of the Tool's domain were under D0 (Abnormally Dry) drought conditions. An abnormally wet May, thanks to a couple stratiform rain/snow events at the beginning of the month, allowed for drought conditions to recede heading into the warm season. However, compounding below average precipitation during June, July and August returned D0 (Abnormally Dry) conditions by early September. By the end of the season, and after much below normal September rainfall, D1 (Moderate Drought) conditions covered the entirety of the metro area. Temperature anomalies during the month of September also helped stoke drought conditions with the majority of the metro area averaging 5F+ above normal.

Notable Flood Events

As far as official storm reports this season, there were only two official flash flood reports: June 27th and July 4th. The June 27th event was related to flash flooding across the Calwood burn area. Just after 6PM, a storm passed directly overhead that dropped between 0.30 and 0.60 inches of rainfall on the 2020 burn area. While that is typically below flood threat criteria, hydrophobic soils, lack of vegetation and steep topography helped trigger a debris flow. Law enforcement reported a 3-to-4-foot surge of debris and water flooding down Geer Canyon at 6:18PM. Thankfully, no injuries were reported, and there were no other flash flooding incidents report this season over the burn area. During the second event, on July 4th, a strong thunderstorm passed through the Southwest and Southeast Metro during the mid-afternoon. Property flooding was reported near South Yosemite and East County Line Road. No further details were reported, but this storm went on to produce an estimated 1.50 to 1.75 inches of rainfall and penny size hail over Aurora and Parker.

In addition to the two official reports, there were two non-official flood reports that were relayed through social media from heavy rainfall events that occurred on June 25th and July 30th. On June 25th, over 2 inches of rain fell across South Denver during the evening hours with an ALERT gauge recording 2.24 inches in Parker (2.04 inches in an hour). There were several reports of elevated and overflowing streams. Images showed Cherry Creek, near Parker, was overflowing and flooding portions of the Happy Canyon bike trail. The USGS streamflow gauge at this site showed the river crested at 8.06 feet, or just below minor flooding stage, later that evening. Standing water was also reported on sports fields in the area. For the second event on July 30th, heavy rainfall and flash flooding were also reported via social media. The North Area zone (just north of Broomfield) received a couple rounds of heavy rainfall during the late afternoon and evening hours. Several CoCoRaHS stations in the area recorded over 2.50 inches of rainfall from the storms with the highest observation coming in at 3.67 inches. Although the CoCoRaHS reports specifically mention no flooding, social media indicated that folks in the area became trapped in their cars due to high waters. Thankfully, no injuries were reported.

The first Flood Day of the 2021 season occurred in mid-May with the last Flood Day occurring in early September. During that period, there were two distinct, active multi-day events. The first event occurred from June 29th to July 6th. Flood Days were recorded on 6 of the 8 days with a peak in heavy rainfall on July 1st where up to 2.50 inches of rainfall was estimated by gridded data. The second event occurred from July 21st to August 3rd. During this two-week period, there were 7 Flood Days with a streak of three Flood Days in a row from July 21st to 23rd. While it was a normal to slightly more active monsoon season across the state, the District saw a quieter monsoon during the typical peak in July. Also lacking this season were the more widespread heavy rainfall events, which tend to create the hydrological issues in local creeks and streams.

Threat Issuance Summary

Table 3 shows the number of flood threats issued, by threat level, in 2021 as well as historical forecasts since 2016 for reference. Note that the HRTA Tool has evolved almost yearly in terms of its domain and underlying science. Thus, a comparison of Tool forecast frequency and performance across years should be done with caution. **In 2021, there were 37 days with a threat issued, though the majority of threats (22) were categorized as Low.** For reference, the F2P2 (Flood Threat Prediction Program) HPO (Heavy Precipitation Outlook) saw 54 days with an early threat issued. Compared to an extremely quiet 2020, it is safe to say that 2021 saw a rebound in heavy rainfall activity. However, overall, 2021 added to the streak of three consecutive years (beginning in 2018) of below normal heavy rainfall activity.

Table 3: Threats issued over the forecast season, by category. F2P2 HPO is included for comparison. Note that the HRTA has evolved almost yearly since 2016 so drawing conclusions based on comparison across years should be done with caution.

All Zones	None	Low	Moderate	High	Very High	Threats Days
2021	116	22	8	5	2	37
2021 F2P2 HPO	99	22	19	13	--	54
2020	125	13	15	0	0	28
2020 F2P2 HPO	130	6	7	10	--	23
2019	120	13	19	1	0	33
2019 F2P2 HPO	76	39	21	17	--	77
2018	115	15	9	0	1	25
2018 F2P2 HPO	87	18	23	12	--	53
2017	87	13	28	24	1	66
2016	92	35	19	7	--	61

Table 4 breaks down HRTA threat issuance by month and by Individual Zones. The 2021 season saw a climatologically consistent pattern with July seeing the greatest number of threats issued, by far, with 14 threats issued for All Zones. August also had a few periods of active weather with a total of 8 threats issued, 7 of which included the climatologically favored Palmer Divide zone. May and June also saw pulses of heavy rainfall potential with 4 and 8 threats issued, respectively.

Table 4: Number of threats issued, by month, by forecast zone.

Zone	May	Jun	Jul	Aug	Sep	Total
N. Foothills	3	4	10	6	1	24
S. Foothills	1	6	11	6	1	25
Palmer Divide	5	5	11	7	1	29
North Area	2	2	7	4	1	16
NW Metro	1	1	9	4	0	15
SW Metro	2	2	8	4	0	16
SE Metro	1	3	9	6	1	20
NE Metro	2	2	8	5	1	18
All Zones	4	8	14	8	3	37

An interesting takeaway from Table 4 is the variation in threats issued across the Individual Zones. Recall from Table 1 that the HRTA domain experiences strong seasonality that generally favors the northern areas in May and June, followed by a distinct preference towards the southeast and southern zones in July and throughout the monsoon season. Interestingly, Table 4 was consistent with this climatology with (i) the Palmer Divide experiencing the highest number of threats issued at 29 (climatological average Flood Day count for Palmer Divide is about 15), and (ii) the Northwest Metro experiencing the lowest at 15 threats (average Flood Days here is about 5). Another interesting takeaway is that the North and South Foothills zones likely experienced a much above normal season (in terms of heavy rainfall potential). Typically, these zones only have ~5 Flood Days, but with over 20 threats issued for each zone during 2021, it is likely this number of Flood Days was exceeded. Day to day forecast experience suggests this was due to persistently above normal monsoonal moisture that favored the very highest elevations of the North and South Foothills for storm activity.

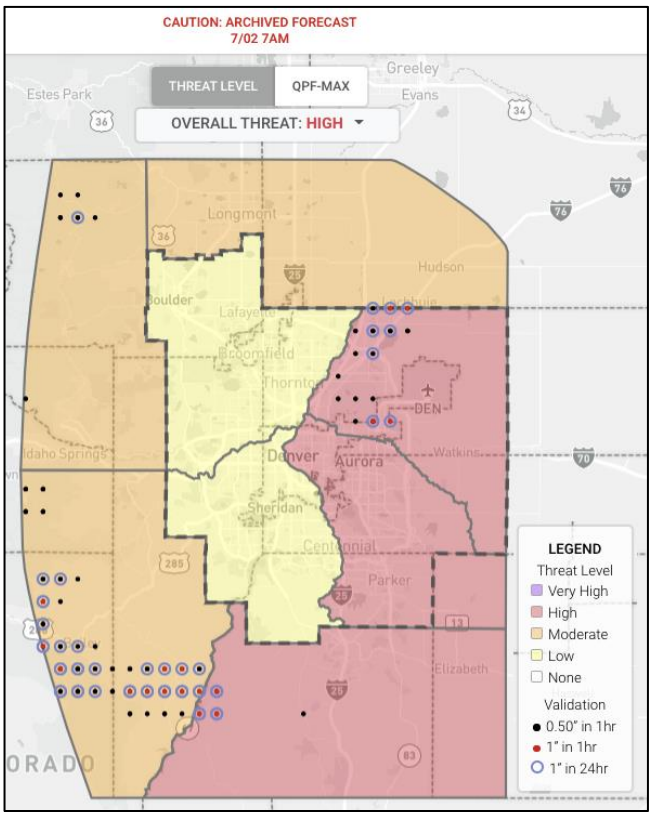

Figure 8: An example of a forecast from July 2nd with a sharp threat gradient. In this case the forecast verified in both the higher elevations of the South Foothills as well as in parts of the Northeast Metro. Note that the Northeast Metro and especially Southeast Metro are more prone to heavy rainfall from a climatological perspective (see Table 1).

To further highlight the Tool's ability to distinguish threat location, Figure 8 shows the archived AM forecast from July 2nd, 2021. On this day, monsoonal moisture was present across Colorado, though weak steering flow suggested only scattered heavy rainfall potential. The HRTA AM forecast showed an overall High threat, though this was limited to the three southern and eastern zones. The North and South Foothills, as well as North Area, were under a Moderate threat. Meanwhile, the Northwest and Southwest Metro zones were under a Low threat, as a Denver Cyclone type circulation was expected to induce subsidence over these areas (a common occurrence during summer). During the afternoon and evening, several pockets of heavy rainfall occurred. One, over the South Foothills zone as slow-moving storms were anchored over the higher terrain. Another over the Northeast Metro zone were outflow boundaries collided with higher moisture content to spark relatively short but heavy rainfall. In both locations, over 1 inch in 1-hour of rainfall resulted, and the daily verification was quite encouraging regarding the HRTA forecast.

Worst Case Scenario

An important objective of the Tool is to provide a realistic upper-bound on a day's heavy rainfall, known as QPF-Max (1-hour duration). For example, even if the Tool does not issue a threat on a given day (low POE), the QPF-Max could still produce a high value. This may occur, for example, during monsoon season when an atmospheric warm air "cap" can be in place and it is unlikely that storms will fire; yet, if they could "break the cap", very heavy rainfall is a possibility. Figure 9 shows the QPF-Max along with the maximum 1-hour QPE (QPE-Max) for all 26 Flood Days during the 2021 forecast season. **On 18 of 26 Flood Days, the AM update QPF-Max exceeded QPE-Max, which denotes a successful forecast as the worst-case scenario was not realized. There were eight days where the QPE-Max exceeded AM QPF-Max, but only three days where QPF-Max underestimated by more than 0.25 inches per hour. When using the updated PM QPF-Max, there were only two days where QPF-Max underestimated QPE by more than 0.25 inches.** And of these two days, Figure 9 shows that one day stands out as irregular, July 25th.

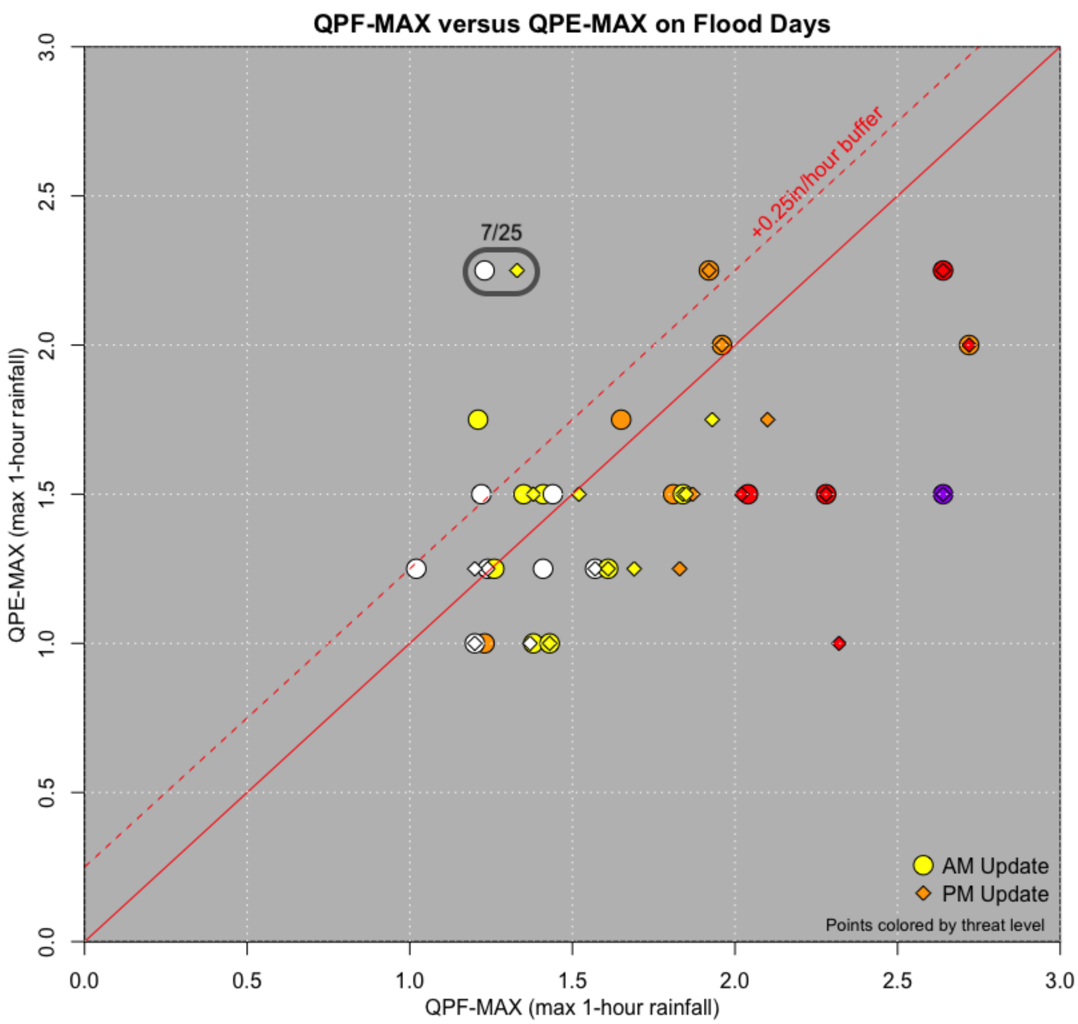

Figure 9: 1-hour QPF-Max versus 1-hour QPE-Max on all Flood Days. The large circle represents the AM forecast, while the smaller rhombus denotes the PM forecast. Color fill denotes the threat at the time of the forecast. The solid red line denotes a perfect 1:1

On this day, plentiful monsoon moisture was observed over most of Colorado, but a strong atmospheric cap was also in place. This suggested that rainfall would be limited to the highest elevations of the Tool's domain. With weak steering winds intact, storm longevity was expected to stay on the brief side, and the AM QPF-Max of 1.23 inches appeared reasonable (in addition to the "No threat" issued by the Tool). By the 9AM Tool update, a Low threat was posted, though QPF-Max was essentially unchanged. This indicated a higher potential for outflow boundaries to ignite lower-elevation storms (break the cap) within the MHFD area. Two such storms did manage to form later in the afternoon with this lifting mechanism, causing very heavy, but fortunately, isolated rainfall. The following summary was taken from the Colorado Flood Threat Bulletin's July 26th State Precipitation Map discussion:

"*Outflow boundaries from the storms further east* [e.g. east of the Continental Divide] *ignited a somewhat surprising set of new storms along parts of the I-25 corridor, both north and south of the Palmer Divide. To the north, Mile High Flood District gages observed two separate very heavy rainfall cores near Boulder and Morrison. At the Boulder gage, about 1.70 inches was recorded in only 20 minutes, making this a 100-200 year event. A CoCoRaHS gage from the area observed 2.41 inches this morning. Fortunately, the very limited spatial extent of the rainfall did not translate to a riverine flooding threat with Boulder Creek only rising a few hundred c.f.s."*

Thus, while the July 25th QPF-Max undoubtedly underestimated the QPE-Max, the issuance of a mid-morning Low threat at least provided a relatively long amount of lead-time to anticipate the incoming rainfall threat.

To summarize, the QPF-Max continues to provide a realistic, upper-bound to the daily heavy rainfall potential. Of the eight days where the AM QPF-Max underestimated QPE-Max, the PM updated QPF-Max provided a notably better forecast on five of the eight days. Only July 25th stood out as an instance where QPE-Max was substantially underestimated, and even on that day, the Tool issued a Low threat by mid-morning providing at least some guidance for the potential of heavy rainfall.

Forecast Performance

This section breaks down the HRTA forecast performance from a variety of statistical standpoints. For categorical forecasts such as the HRTA, the contingency table shown below is a convenient method of assessing forecast quality. For each forecast, for each day, a Flood Day is either forecasted to occur, or not. Similarly, a Flood Day is then either observed to occur, or not. This sets up four possible forecast-observed combinations: a Hit (Flood Day is forecasted and observed), a Miss (Flood Day is NOT forecasted, but is observed), a False Alarm (Flood Day is forecasted, but does NOT occur) and a Dry Hit (Flood Day is NOT forecasted and does NOT occur).

		Flood Day Forecasted?	
		YES	**NO**
Flood Day Observed?	**YES**	**HIT (a)**	**MISS (b)**
	NO	**FALSE ALARM (c)**	**DRY HIT (d)**

From these four combinations, a wealth of statistical performance measures can be calculated, though here we only focus on six of the most commonly used ones as shown in Table 5. Where appropriate, targets are set for each metric based on generally accepted standards set forth by the meteorological community. However, it should be acknowledged that there is no specific guide as to what targets should be. For example, the False Alarm Rate target is here set to 0.50 with anything less being considered satisfactory and anything below 0.25 considered very good (also see FCMDC, 2020). However, note that for the statewide Colorado Flood Threat Bulletin, the target is set to 0.20 (Dewberry, 2020a). The difference in the target is based on the forecast spatial scale. The HRTA covers only about 4,400 square miles, while the Flood Threat Bulletin covers about 100,000 square miles with individual threats often on the order of 20,000-40,000 square miles (see Dewberry, 2020a). Intuitively, as spatial scale increases, the chance of verifying a threat also increases and the False Alarm Rate generally decreases.

Table 5: Description of statistical metrics used for verifying forecasts.

Metric / Abbreviation		Formula	Summary	Target
Overall Accuracy	(OA)	$\frac{a+d}{a+b+c+d}$	Measures probability that all Flood Days and non-Flood Days are accurately forecast. Perfect forecast value is 1.0.	>0.75
Threat Score	(TS)	$\frac{a}{a+b+c}$	Measures the probability in successfully forecasting Flood Day, including Misses and False Alarm. Perfect forecast value is 1.0.	---
False Alarm Rate	(FAR)	$\frac{c}{c+a}$	Measures probability that a Flood Day (Hit) is forecast but a non-Flood Day is observed. Perfect forecast value is 1.0.	<0.50
Probability of Detection	(POD)	$\frac{a}{a+b}$	Measures probability of accurately forecasting Flood Days. Perfect forecast value is 1.0.	>0.75
Miss Rate	(MR)	$\frac{b}{a+b}$	Measure probability that a non-Flood Day is forecast but a Flood Day is observed. Perfect forecast value is 0. Note the sum of the MR and POD equals 1.	<0.20
Bias	(BIAS)	$\frac{a+c}{a+b}$	A ratio of total number of Flood Days forecast compared to those observed. Perfect forecast value is 1.0.	---

Table 6 shows the populated contingency tables for the HRTA AM forecast, PM forecast, as well as the F2P2 HPO (morning forecast plus any updates, if applicable). From these numbers, we observed that there were 26 Flood Days (sum of Hit and Miss) and 127 non-Flood Days (sum of Dry Hit and False Alarm) during the 2021 season. See Appendix A for a daily breakdown of rainfall estimates and forecasted threat.

Table 6: Number of Hits, Misses, False Alarms and Dry Hits for HRTA AM and PM forecasts. Also shown are results for F2P2 Heavy Precipitation Outlooks, for comparison.

	Hit	Miss	False Alarm	Dry Hit
HRTA AM	18	8	19	108
HRTA PM	21	5	18	109
F2P2 AM	24	2	31	96
F2P2 Update	24	2	31	96

Next, Table 7 shows the performance metrics for the HRTA. The OA of the HRTA AM forecast was 0.82, implying that 82% of days had a correct forecast. However, given that the MHFD is only expected to experience ~29 Flood Days per year (and 124 non-Flood Days; see Table 1), the OA is significantly affected by the non-Flood Day performance, and thus is considered to have limited utility. On the other hand, the TS metric *only* focuses on Flood Days making it the more useful metric. **The HRTA AM forecast TS was 0.40, and it increased to 0.47 by the PM update suggesting that forecast performance does get better as the Tool is updated.** The F2P2 HPO had a comparable TS of 0.42.

Table 7: Forecast performance metrics (see Table 5) for HRTA AM and PM forecasts, along with F2P2 Heavy Precipitation Outlooks, for comparison.

	OA	TS	FAR	POD	MR	BIAS
HRTA AM	0.82	0.40	0.51	0.69	0.31	1.4
HRTA PM	0.84	0.47	0.46	0.81	0.19	1.5
F2P2 AM	0.78	0.42	0.56	0.92	0.08	2.1
F2P2 Update	0.78	0.42	0.56	0.92	0.08	2.1

The next three metrics in Table 7 (FAR, POD and MR) provide complementary pieces of information. **Starting with POD, the AM HRTA showed a rate of 0.69, implying that 69% of Flood Days were "detected" by that forecast. This** increased **to 0.81 by the PM update.** The goal for POD is 0.75 so it was slightly missed in the morning forecast but was achieved during the later update. **The Miss Rate for the AM HRTA was 0.31, which is higher than the 0.20 goal, though it dropped to 0.19 by the afternoon update. The False Alarm Rate in the AM forecast was 0.51 and dropped to 0.46 by the afternoon update. Finally, the BIAS in both the AM and PM HRTA forecasts was 1.4-1.5, implying that there were about 3 days with a threat issued for every 2 actual Flood Days. The overall takeaway from Table 7 is that the morning HRTA forecast generally achieved its target performance, although the Miss Rate was higher than desired. However, the afternoon HRTA update showed notably better performance across all metrics, including a substantial drop from 0.31 to 0.19 in the Miss Rate.**

Table 8 shows the probability of correctly forecasting a Flood Day, based on the forecast threat level. Intuitively, a higher threat should carry with it a higher probability of occurrence (otherwise, there is no justification for issuing threat levels!). **As seen in Table 8, there is a clear tendency for higher forecast threats to be correct more frequently.** However, with relatively few Moderate and High threat forecasts, there are some issues with low sample size leading to noisy data. Instead, it is more meaningful to provide a range using the HRTA AM and PM updates. The Low threat range was 36-41%, the Moderate threat range was 56-75% and the High/Very High threat range was 60-88%.

Table 8: Hit rate for forecasting a Flood Day, conditioned on forecast threat level. For each threat, the number in parenthesis shows the number of days with that threat level.

	Threat Level		
Product	**Low**	**Moderate**	**High/Very High**
HRTA AM	36% (22)	75% (8)	60% (7)
HRTA PM	41% (22)	56% (9)	88% (8)
F2P2 AM	27% (22)	35% (20)	85% (13)
F2P2 Update	23% (21)	40% (20)	79% (14)

It is interesting to compare the HRTA performance with the F2P2 HPO, as seen in Table 6 and Table 7. While the Overall Accuracy and Threat Score are similar between the two, the HRTA has a tendency to be conservative compared to the F2P2 HPO. In fact, this has generally been the case since the HRTA's inception (see Table 3). This results in a *lower* False Alarm Rate (e.g. 19 False Alarms by HRTA versus 30 by F2P2 HPO), but also a *lower* Probability of Detection and *higher* Miss Rate.

Given the focus of operational forecasts of heavy rainfall is to generally minimize the Miss Rate, Table 9 shows a strategy for decreasing the HRTA Miss Rate. Recall that although the threat level is arguably the most commonly discussed end-product of the HRTA, threats are assigned rather subjectively, and almost always stem from the POE1 value. For example, in 2021, this value was 20%. A POE1 above 20% resulted in at least a Low threat, while a POE1 below 20% resulted in no threat being assigned. **As shown in Table 9, nudging the POE1 down by only 3%, to 17%, resulted in a significant improvement in performance across all metrics. The Threat Score improved from 0.40 to 0.53, the Probability of Detection increased from 0.69 to 0.96, the Miss Rate dropped substantially from 0.31 to only 0.04 and the False Alarm Rate actually *decreased* from 0.51 to 0.46 despite the issuance of more threats.** Although some caution is warranted here given the limited sample size, solid evidence justifies increasing the HRTA's sensitivity by *lowering* the thresholds that trigger a threat.

Table 9 shows two additional forecast metric comparisons, for reference. First, if the HRTA POE1 threshold is lowered further, to 10%, we see a general degradation in performance suggesting that this low of a threshold introduces too many False Alarms with little improvement of Misses. Lastly, shown for reference is the performance metrics using National Weather Service Flash Flood Watches as an analogy to an HRTA threat. Typically, NWS is very cautious in FF Watch issuance: the result is an extremely low False Alarm rate (in fact, it was zero in 2021), but also a very high Miss Rate of 0.88 for POE1. Interestingly, the Overall Accuracy for NWS FF Watches was 0.85, comparable to the HRTA, owing to the minimal false alarms and thus, correct forecasting of non-Flood Days. Overall, Table 9 shows that a variety of approaches are possible when forecasting heavy rainfall, and to some extent, it is the end-user preference that dictates which approach is best.

Table 9: Similar to Table 7 except including two variations of the HRTA, and days with a NWS Flash Flood Watch issued.

Product	OA	TS	FAR	POD	MR	BIAS
HRTA AM	0.82	0.40	0.51	0.69	0.31	1.4
HRTA [17% POE1]	0.86	0.53	0.46	0.96	0.04	1.8
HRTA [10% POE1]	0.80	0.43	0.56	0.96	0.04	2.2
F2P2 AM	0.78	0.42	0.56	0.92	0.08	2.1
NWS FF Watch	0.85	0.12	0	0.12	0.88	0.1

Table 10 performs a final sensitivity test by re-calculating metrics but using two lower rainfall intensity thresholds to define a Flood Day: 0.75 inch and 0.50 inch in 1-hour. Both the HRTA and F2P2 HPO are shown for comparison's sake. Interestingly, despite the fact that the $_{BC}$QPF used by HRTA was specifically tailored to the 1 inch in 1-hour intensity, the best forecast performance actually occurs when using the 0.75 inch in 1-hour intensity. One possible reason for this could be that the necessary ingredients to achieve a 0.75 inch hourly intensity are very likely to produce more than that (i.e. storm climatology). However, this will need to be further investigated. When the Flood Day intensity is lowered to 0.50 inches, HRTA performance declines due to a much lower Probability of Detection and higher Miss Rate. Interestingly, for the F2P2 HPO, the performance metrics are actually *best* for the 0.50 inch hourly intensity, implying that those forecasts take an overall cautious approach.

Table 10: Forecast performance measures when the threshold for Flood Day is reduced from 1.00 inch per hour, to 0.75 and 0.50 inches. Note that the HRTA performance is based on the updated 17% POE as shown in Table 9. Highlighted rows represent the best overall performance for each product.

	Threshold	OA	TS	FAR	POD	MR	BIAS
HRTA	> 1.00 in/hr	0.86	0.53	0.46	0.96	0.04	1.8
	> 0.75 in/hr	0.88	0.63	0.30	0.86	0.14	1.2
	> 0.50 in/hr	0.86	0.66	0.13	0.73	0.27	0.9
F2P2 HPO	> 1.00 in/hr	0.78	0.42	0.56	0.92	0.08	2.1
	> 0.75 in/hr	0.83	0.56	0.40	0.89	0.11	1.5
	> 0.50 in/hr	0.86	0.67	0.20	0.80	0.20	1.0

Summary

- The HRTA Tool underwent significant upgrades in 2021:
    i. The creation of four smaller metro-area zones within the District with the aim of improving forecast location,
    ii. Forecast updates throughout the day increased from four to six,
    iii. A new interactive web map,
    iv. A more comprehensive, easily accessible archive and verification web map with estimated rainfall based on ALERT gauge and gridded QPE data,
    v. The incorporation of a second source of gridded QPE to better inform end-users on heavy rainfall events that occur between rainfall gauges.

- The 2021 season was much more active than 2020, but still on the quieter side overall. This is the fourth consecutive year of below average Flood Days (beginning in 2018). There were 37 days with an HRTA threat, 22 of which were Low threats. The HRTA domain experienced 26 Flood Days, 11 of which occurred in July. There were 16 days where at least a 1.50 inch hourly rainfall rate occurred within the HRTA All Zones area.

- Assessment of the worst-case scenario rain rate (QPF-Max) showed solid performance in the morning HRTA forecast, with a noticeable improvement by the early afternoon update. There was only one day (7/25) when the rain rate was underestimated by more than 0.50 inches, though a Low threat was issued providing at least some early guidance on the situation.

- Forecast performance metrics using the AM HRTA threat met targets for all measures except the Miss Rate, which was 0.31 and considered too high. Noticeable improvement in the Miss Rate (down to 0.19) occurred by the PM HRTA update.

- Sensitivity analysis of the underlying HRTA guidance revealed a tendency for it to be overly *conservative* with threat issuance. Relaxing the threshold for issuing a threat resulted in a tremendous boost in all forecast performance metrics. This includes the substantial reduction of the Miss Rate to only 0.04.

Recommendations

⇒ HMC does not recommend changing HRTA forecast zones for 2022 operations. The current zones finally appear to appropriately balance reasonable spatial precision with the uncertainties constrained by our meteorological understanding of heavy rainfall forecasting.

⇒ A thorough investigation of historical QPE bias is recommended by directly comparing high-quality rainfall gauge observations with the Stage IV and MRMS QPE products used within the HRTA. The propensity for gridded QPE to overestimate rainfall implies that Flood Day climatology may also be overestimated.

⇒ Decreasing the lower Probability of Exceedance bound that triggers a Low threat is advised, which is expected to decrease the Miss Rate, possibly significantly.

⇒ Investigate Tool update methods to see if more improvement can be achieved from the initial AM forecast by more heavily incorporating newer guidance and observations.

⇒ Add a later afternoon/evening Tool update to capture evolving overnight threats more clearly.

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Appendix A

Table 11 below shows a daily summary of observations and forecasts for All Zones. Column names are described below:

Column	Units	Description
A	N/A	Date
B	Inches	Max 1-hour QPE from ALERT gages
C	Inches	Max 1-hour QPE from average Stage IV and MRMS
D	Inches	Max 24-hour QPE from ALERT gages
E	Inches	Max 24-hour QPE from average Stage IV and MRMS
F	Inches	Manual max 1-hour QPE estimation range (intervals of 0.25 inches)
G	Inches	Max 1-hour QPF 7AM Update
H	Inches	Max 1-hour QPF 1PM Update
I	Category	HRTA threat level (color) and outcome of POE1 7AM update
J	Category	HRTA threat level (color) and outcome of POE1 1PM update
K	Category	HPO threat level (color) and outcome of POE1 AM update
L	Category	HPO threat level (color) and outcome of POE1 PM update (issued only occasionally)

Table 11: Verification Table for All Zones.

*NWS FF Watches: 7/1, 7/30, 7/31

	QPE					QPF		HRTA Threat		HPO Threat	
Date	Max 1-hr ALERT	Max 1-hr MRMS/ST4	Max 24-hr ALERT	Max 24-hr MRMS/ST4	Max 1-hr estimate	Max 1-hr QPF AM	Max 1-hr QPF PM	Threat AM	Threat PM	Threat AM	Threat PM
Units	inches	inches	inches	inches	inches	inches	inches	category	category	category	category
1-May	0.04	0.04	0.04	0.03	0-0.25	0.16	0.28				
2-May	0.56	0.92	1.96	2.00	0.75-1.00	1.26	1.34				
3-May	0.32	0.40	0.84	1.85	0.25-0.50	0.34	0.35				
4-May	0.44	0.39	1	0.44	0.25-0.50	0.24	0.71				
5-May	0.20	0.37	0.36	0.48	0.25-0.50	0.39	0.45				
6-May	0.00	0.00	0	0.00	0	0.01	0.01				
7-May	0.12	0.01	0.12	0.02	0	0.19	0.19				
8-May	0.24	0.86	0.48	1.11	0.50-0.75	0.97	1.18				
9-May	0.24	0.24	0.4	0.54	0.25-0.50	0.52	0.52				
10-May	0.33	0.36	1.03	1.42	0.25-0.50	0.52	0.63				
11-May	0.32	0.27	0.68	0.53	0.25-0.50	0.46	0.55				
12-May	0.01	0.01	0.005	0.01	0	0.06	0.08				
13-May	0.02	0.02	0.14	0.03	0-0.25	0.11	0.16				
14-May	0.08	0.67	0.08	0.74	0.50-0.75	0.73	0.73				
15-May	1.28	1.40	1.4	1.79	1.25-1.50	1.41	1.69	Miss	Hit		
16-May	0.12	0.46	0.16	0.67	0.25-0.50	1.99	1.99	False Alarm	False Alarm		
17-May	0.96	0.86	1.4	1.71	1.00-1.25	1.23	2.32	Hit	Hit		
18-May	0.28	0.38	0.6	0.77	0.25-0.50	0.57	0.57				
19-May	0.24	1.07	0.28	1.13	0.50-0.75	0.79	1.52				
20-May	0.08	0.27	0.08	0.29	0-0.25	0.47	0.47				
21-May	0.12	0.09	0.12	0.13	0-0.25	0.15	0.16				
22-May	0.84	1.14	0.92	1.88	1.00-1.25	1.2	1.2	Miss	Miss		
23-May	0.24	0.55	0.36	0.60	0.25-0.50	0.55	0.57				
24-May	0.28	0.41	0.32	0.45	0.25-0.50	0	0.01				

*NWS FF Watches: 7/1, 7/30, 7/31

	QPE					QPF		HRTA Threat		HPO Threat	
Date	Max 1-hr ALERT	Max 1-hr MRMS/ST4	Max 24-hr ALERT	Max 24-hr MRMS/ST4	Max 1-hr estimate	Max 1-hr QPF AM	Max 1-hr QPF PM	Threat AM	Threat PM	Threat AM	Threat PM
Units	inches	inches	inches	inches	inches	inches	inches	category	category	category	category
25-May	0.04	0.35	0.04	0.37	0.25-0.50	0.45	0.88				
26-May	0.48	0.16	0.48	0.22	0-0.25	0.17	0.17				
27-May	0.01	0.01	0.005	0.01	0	0.43	0.43				
28-May	0.04	1.13	0.04	1.17	0.75-1.00	0.69	0.69				
29-May	0.72	1.21	0.8	2.28	1.00-1.25	1.38	1.37	Hit	Miss		
30-May	0.88	1.61	1.44	1.92	1.50-1.75	1.41	1.87	Hit	Hit		
31-May	0.24	0.15	0.44	0.43	0-0.25	0.8	1.59				
1-Jun	0.16	0.66	0.32	0.76	0.50-0.75	0.67	0.67				
2-Jun	0.12	0.05	0.12	0.09	0-0.25	0.65	0.65				
3-Jun	0.28	0.03	0.48	0.06	0-0.25	0.16	0.28				
4-Jun	0.00	0.01	0	0.01	0	0.2	0.22				
5-Jun	0.96	1.06	0.96	1.34	1.25-1.50	1.24	1.24	Miss	Miss		
6-Jun	0.24	1.20	0.32	1.23	0.75-1.00	1.47	1.47				
7-Jun	0.24	1.61	0.44	1.76	1.25-1.50	1.57	1.57	Miss	Miss		
8-Jun	0.04	0.04	0.04	0.04	0-0.25	0.32	0.32				
9-Jun	0.01	0.01	0.005	0.01	0	0.12	0.54				
10-Jun	0.01	0.01	0.005	0.01	0	0.12	0.12				
11-Jun	0.12	0.01	0.12	0.01	0	0	0				
12-Jun	0.01	0.01	0.01	0.01	0	0.32	0.45				
13-Jun	1.04	1.72	1.08	2.50	1.25-1.50	1.02	1.2	Miss	Miss		
14-Jun	0.24	0.11	0.32	0.16	0-0.25	0.28	0.31				
15-Jun	0.04	0.04	0.035	0.04	0-0.25	0.77	0.77				
16-Jun	0.24	0.12	0.44	0.17	0-0.25	0.39	0.39				
17-Jun	0.32	0.39	0.44	0.59	0-0.25	0.28	0.31				
18-Jun	0.16	0.09	0.16	0.15	0-0.25	1.14	1.14	False Alarm	False Alarm		

*NWS FF Watches: 7/1, 7/30, 7/31

	QPE					QPF		HRTA Threat		HPO Threat	
Date	Max 1-hr ALERT	Max 1-hr MRMS/ST4	Max 24-hr ALERT	Max 24-hr MRMS/ST4	Max 1-hr estimate	Max 1-hr QPF AM	Max 1-hr QPF PM	Threat AM	Threat PM	Threat AM	Threat PM
Units	inches	inches	inches	inches	inches	inches	inches	category	category	category	category
19-Jun	0.32	1.03	0.52	1.07	0.50-0.75	1.3	1.3		False Alarm		
20-Jun	0.28	0.21	0.6	0.38	0-0.25	0.89	0.89				
21-Jun	0.01	0.01	0.005	0.01	0	0.13	0.13				
22-Jun	0.20	0.06	0.48	0.08	0-0.25	0.29	0.29				
23-Jun	0.28	0.21	0.48	0.32	0-0.25	0.14	0.14				
24-Jun	0.60	1.02	0.68	1.11	0.75-1.00	1	1	False Alarm	False Alarm		
25-Jun	2.04	1.89	2.92	2.96	2.00-2.25	2.72	2.72	Hit	Hit		
26-Jun	0.76	0.67	0.8	0.98	0.75-1.00	1.06	1.32	False Alarm	False Alarm		
27-Jun	0.76	0.82	1.28	1.33	0.75-1.00	1.5	1.5	False Alarm	False Alarm		
28-Jun	0.48	0.42	0.56	0.56	0.25-0.50	1.36	1.36	False Alarm	False Alarm		
29-Jun	1.72	1.06	2.36	1.58	1.75-2.00	1.21	1.93	Hit	Hit		
30-Jun	0.44	0.74	0.52	1.58	0.50-0.75	2.1	2.1	False Alarm	False Alarm		
1-Jul*	1.92	1.95	2.04	3.01	2.25-2.50	2.64	2.64	Hit	Hit		
2-Jul	0.28	2.13	0.32	2.50	1.50-1.75	2.28	2.28	Hit	Hit		
3-Jul	0.44	1.16	0.44	1.34	0.75-1.00	1.27	1.57		False Alarm		
4-Jul	0.76	1.95	0.76	2.59	1.50-1.75	1.22	1.52	Miss	Hit		
5-Jul	1.20	1.86	1.2	2.26	1.50-1.75	2.04	2.28	Hit	Hit		
6-Jul	0.88	1.55	1	1.81	1.50-1.75	1.81	2.02	Hit	Hit		
7-Jul	0.02	0.02	0.015	0.02	0-0.25	1.27	1.27				
8-Jul	0.28	0.26	0.44	0.34	0.25-0.50	1.06	1.06				
9-Jul	0.08	0.49	0.08	0.51	0.25-0.50	0.67	0.98				
10-Jul	0.00	0.00	0	0.00	0	0.86	0.86				
11-Jul	0.01	0.01	0.005	0.01	0	0.16	0.2				
12-Jul	0.05	0.05	0.045	0.05	0-0.25	0.72	0.84				
13-Jul	0.28	0.68	0.44	0.78	0.50-0.75	0.98	1.28				

*NWS FF Watches: 7/1, 7/30, 7/31

	QPE					QPF		HRTA Threat		HPO Threat	
Date	Max 1-hr ALERT	Max 1-hr MRMS/ST4	Max 24-hr ALERT	Max 24-hr MRMS/ST4	Max 1-hr estimate	Max 1-hr QPF AM	Max 1-hr QPF PM	Threat AM	Threat PM	Threat AM	Threat PM
Units	inches	inches	inches	inches	inches	inches	inches	category	category	category	category
14-Jul	0.52	0.62	0.52	0.80	0.50-0.75	2.27	2.27	False Alarm	False Alarm		
15-Jul	0.32	1.24	0.48	1.29	0.75-1.00	1.23	1.23				
16-Jul	0.12	0.31	0.12	0.34	0-0.25	0.88	1.06	False Alarm			
17-Jul	0.44	0.95	0.48	1.06	0.75-1.00	1.19	1.27	False Alarm	False Alarm		
18-Jul	0.01	0.01	0.005	0.01	0	1.3	1.3				
19-Jul	0.00	0.00	0	0.00	0	0.75	0.75				
20-Jul	0.24	0.12	0.44	0.14	0-0.25	0.83	1.32				
21-Jul	2.32	2.01	2.56	3.80	2.25-2.50	1.92	1.92	Hit	Hit		
22-Jul	1.24	1.59	1.28	2.44	1.50-1.75	1.35	1.38	Hit	Hit		
23-Jul	0.48	2.67	0.52	3.61	1.75-2.00	1.65	2.1	Hit	Hit		
24-Jul	0.28	0.21	0.48	0.33	0.25-0.50	1.48	1.48	False Alarm	False Alarm		
25-Jul	2.00	2.34	2.04	2.41	2.25-2.50	1.23	1.33	Miss	Hit		
26-Jul	0.00	0.00	0	0.00	0	0.87	0.87				
27-Jul	0.32	0.10	0.56	0.10	0-0.25	0.43	0.63				
28-Jul	0.28	0.08	0.48	0.16	0-0.25	0.43	0.43				
29-Jul	0.28	0.88	0.44	1.00	0.50-0.75	1.83	1.83	False Alarm	False Alarm		
30-Jul*	1.94	2.00	1.94	3.41	2.00-2.25	1.96	1.96	Hit	Hit		
31-Jul*	1.32	1.14	1.92	1.97	1.50-1.75	2.64	2.64	Hit	Hit		
1-Aug	0.03	0.02	0.03	0.03	0	0.88	2.07				
2-Aug	0.28	0.61	0.48	0.83	0.50-0.75	1.76	1.76	False Alarm	False Alarm		
3-Aug	1.16	1.30	1.56	1.90	1.25-1.50	1.26	1.83	Hit	Hit		
4-Aug	0.24	0.11	0.44	0.11	0-0.25	1.3	1.3				
5-Aug	0.32	0.21	0.48	0.21	0.25-0.50	0.29	0.29				
6-Aug	0.16	0.53	0.24	0.53	0.25-0.50	0.59	0.94				
7-Aug	0.01	0.01	0.005	0.01	0	0.55	0.74				

*NWS FF Watches: 7/1, 7/30, 7/31

	QPE					QPF		HRTA Threat		HPO Threat	
Date	Max 1-hr ALERT	Max 1-hr MRMS/ST4	Max 24-hr ALERT	Max 24-hr MRMS/ST4	Max 1-hr estimate	Max 1-hr QPF AM	Max 1-hr QPF PM	Threat AM	Threat PM	Threat AM	Threat PM
Units	inches	inches	inches	inches	inches	inches	inches	category	category	category	category
8-Aug	0.00	0.00	0	0.00	0	0.32	0.6				
9-Aug	0.04	0.02	0.035	0.04	0-0.25	0.16	0.2				
10-Aug	0.32	0.04	0.4	0.07	0-0.25	0.28	0.47				
11-Aug	0.01	0.01	0.005	0.01	0	0.12	0.16				
12-Aug	0.68	1.87	0.68	2.04	1.50-1.75	1.44	1.84	Miss	Hit		
13-Aug	0.08	1.17	0.12	1.34	0.75-1.00	1.38	1.38	False Alarm	False Alarm		
14-Aug	0.72	0.75	0.72	0.65	0.50-0.75	1.3	1.41	False Alarm	False Alarm		
15-Aug	0.24	0.86	0.48	1.13	0.50-0.75	1.5	1.5	False Alarm	False Alarm		
16-Aug	0.28	0.05	0.48	0.05	0-0.25	1.3	0.19	False Alarm			
17-Aug	0.32	1.12	0.56	1.29	0.75-1.00	0.87	1.18				
18-Aug	0.28	0.12	0.48	0.24	0.25-0.50	0.88	0.88				
19-Aug	1.08	1.26	1.16	2.13	1.25-1.50	1.61	1.61	Hit	Hit		
20-Aug	0.04	0.01	0.04	0.04	0	0.28	0.94				
21-Aug	0.36	0.50	0.48	0.58	0.25-0.50	1.02	1.02				
22-Aug	0.00	0.00	0	0.00	0	0.16	0.16				
23-Aug	0.24	0.14	0.48	0.16	0-0.25	0.39	0.59				
24-Aug	0.02	0.02	0.02	0.02	0	0.2	0.2				
25-Aug	0.24	0.93	0.44	1.09	0.50-0.75	1.43	1.61				
26-Aug	0.28	0.33	0.44	0.43	0.25-0.50	1.22	1.22				
27-Aug	0.20	0.17	0.24	0.19	0-0.25	0.44	0.44				
28-Aug	0.24	0.12	0.4	0.15	0-0.25	0.74	0.74				
29-Aug	0.24	1.47	0.48	1.73	1.00-1.25	1.43	1.43	Hit	Hit		
30-Aug	0.00	0.00	0	0.00	0	0.2	0.2				
31-Aug	0.00	0.00	0	0.00	0	0.28	0.28				
1-Sep	0.28	0.28	0.56	0.38	0.25-0.50	1.02	1.02				

*NWS FF Watches: 7/1, 7/30, 7/31

	QPE					QPF		HRTA Threat		HPO Threat	
Date	Max 1-hr ALERT	Max 1-hr MRMS/ST4	Max 24-hr ALERT	Max 24-hr MRMS/ST4	Max 1-hr estimate	Max 1-hr QPF AM	Max 1-hr QPF PM	Threat AM	Threat PM	Threat AM	Threat PM
Units	inches	inches	inches	inches	inches	inches	inches	category	category	category	category
2-Sep	0.48	0.60	0.92	1.32	0.50-0.75	1.27	1.35				
3-Sep	1.39	1.46	1.39	1.70	1.50-1.75	1.84	1.85	Hit	Hit		
4-Sep	0.24	1.02	0.44	1.18	0.50-0.75	1.06	1.06				
5-Sep	0.00	0.00	0	0.00	0	0.04	0.04				
6-Sep	0.00	0.00	0	0.00	0	0.04	0.04				
7-Sep	0.00	0.00	0	0.00	0	0.04	0.04				
8-Sep	0.00	0.00	0	0.00	0	0.04	0.04				
9-Sep	0.00	0.00	0	0.00	0	0.04	0.04				
10-Sep	0.08	0.00	0.08	0.00	0	0.04	0.04				
11-Sep	0.16	0.64	0.24	0.68	0.50-0.75	0.4	0.4				
12-Sep	0.28	0.60	0.48	0.69	0.25-0.50	1.06	1.18				
13-Sep	0.24	0.40	0.4	0.47	0.25-0.50	0.69	0.69				
14-Sep	0.48	1.07	0.48	1.13	0.50-0.75	1.53	1.53				
15-Sep	0.00	0.00	0	0.00	0	0	0				
16-Sep	0.00	0.00	0	0.00	0	0.23	0.23				
17-Sep	0.02	0.02	0.02	0.02	0	0.12	0.2				
18-Sep	0.03	0.03	0.025	0.03	0	0.41	0.41				
19-Sep	0.28	0.13	0.44	0.27	0-0.25	0.32	0.4				
20-Sep	0.24	0.37	0.44	0.74	0.25-0.50	0.36	0.36				
21-Sep	0.01	0.01	0.005	0.01	0	0.16	0.16				
22-Sep	0.00	0.00	0	0.00	0	0.04	0.04				
23-Sep	0.28	0.02	0.44	0.06	0	0.16	0.24				
24-Sep	0.00	0.00	0	0.00	0	0	0				
25-Sep	0.00	0.00	0	0.00	0	0.04	0.04				
26-Sep	0.01	0.01	0.005	0.01	0	0.04	0.04				

*NWS FF Watches: 7/1, 7/30, 7/31

	QPE					QPF		HRTA Threat		HPO Threat	
Date	Max 1-hr ALERT	Max 1-hr MRMS/ST4	Max 24-hr ALERT	Max 24-hr MRMS/ST4	Max 1-hr estimate	Max 1-hr QPF AM	Max 1-hr QPF PM	Threat AM	Threat PM	Threat AM	Threat PM
Units	inches	inches	inches	inches	inches	inches	inches	category	category	category	category
27-Sep	0.20	0.05	0.28	0.07	0-0.25	0.36	0.36				
28-Sep	0.16	0.45	0.32	0.50	0.25-0.50	1.3	1.3	False Alarm			
29-Sep	0.52	0.61	0.52	0.80	0.50-0.75	1.44	1.44	False Alarm	False Alarm		
30-Sep	0.04	0.10	0.08	0.12	0-0.25	0.48	0.49				

Table 12 (below) shows the Tool's AM and PM threats issued for Individual Zones. Colors are related to the three-tier threat system: Low (yellow), Moderate (orange), High/Very High (red). The last column has whether or not a Food Day occurred in All Zones.

Table 12: AM and PM threats issued for Individual Zones.

*NWS FF Watches: 7/1, 7/30, 7/31

Date	North Foothills		South Foothills		Palmer Divide		North Area		Northeast Metro		Northwest Metro		Southeast Metro		Southwest Metro		Flood Day (All Zones)
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	
1-May																	
2-May																	
3-May																	
4-May																	
5-May																	
6-May																	
7-May																	
8-May																	
9-May																	
10-May																	
11-May																	
12-May																	
13-May																	
14-May																	
15-May																	Yes
16-May																	
17-May																	Yes
18-May																	
19-May																	
20-May																	
21-May																	
22-May																	Yes
23-May																	

*NWS FF Watches: 7/1, 7/30, 7/31

Date	North Foothills		South Foothills		Palmer Divide		North Area		Northeast Metro		Northwest Metro		Southeast Metro		Southwest Metro		Flood Day (All Zones)
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	
24-May																	
25-May																	
26-May																	
27-May																	
28-May																	
29-May																	Yes
30-May																	Yes
31-May																	
1-Jun																	
2-Jun																	
3-Jun																	
4-Jun																	
5-Jun																	Yes
6-Jun																	
7-Jun																	Yes
8-Jun																	
9-Jun																	
10-Jun																	
11-Jun																	
12-Jun																	
13-Jun																	Yes
14-Jun																	
15-Jun																	
16-Jun																	
17-Jun																	
18-Jun																	
19-Jun																	
20-Jun																	

*NWS FF Watches: 7/1, 7/30, 7/31

Date	North Foothills		South Foothills		Palmer Divide		North Area		Northeast Metro		Northwest Metro		Southeast Metro		Southwest Metro		Flood Day (All Zones)
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	
21-Jun																	
22-Jun																	
23-Jun																	
24-Jun																	
25-Jun																	Yes
26-Jun																	
27-Jun																	
28-Jun																	
29-Jun																	Yes
30-Jun																	
1-Jul*																	Yes
2-Jul																	Yes
3-Jul																	
4-Jul																	Yes
5-Jul																	Yes
6-Jul																	Yes
7-Jul																	
8-Jul																	
9-Jul																	
10-Jul																	
11-Jul																	
12-Jul																	
13-Jul																	
14-Jul																	
15-Jul																	
16-Jul																	
17-Jul																	
18-Jul																	

*NWS FF Watches: 7/1, 7/30, 7/31

Date	North Foothills		South Foothills		Palmer Divide		North Area		Northeast Metro		Northwest Metro		Southeast Metro		Southwest Metro		Flood Day (All Zones)
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	
19-Jul																	
20-Jul																	
21-Jul																	Yes
22-Jul																	Yes
23-Jul																	Yes
24-Jul																	
25-Jul																	Yes
26-Jul																	
27-Jul																	
28-Jul																	
29-Jul																	
30-Jul*																	Yes
31-Jul*																	Yes
1-Aug																	
2-Aug																	
3-Aug																	Yes
4-Aug																	
5-Aug																	
6-Aug																	
7-Aug																	
8-Aug																	
9-Aug																	
10-Aug																	
11-Aug																	
12-Aug																	Yes
13-Aug																	
14-Aug																	
15-Aug																	

*NWS FF Watches: 7/1, 7/30, 7/31

Date	North Foothills		South Foothills		Palmer Divide		North Area		Northeast Metro		Northwest Metro		Southeast Metro		Southwest Metro		Flood Day (All Zones)
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	
16-Aug																	
17-Aug																	
18-Aug																	
19-Aug																	Yes
20-Aug																	
21-Aug																	
22-Aug																	
23-Aug																	
24-Aug																	
25-Aug																	
26-Aug																	
27-Aug																	
28-Aug																	
29-Aug																	Yes
30-Aug																	
31-Aug																	
1-Sep																	
2-Sep																	
3-Sep																	Yes
4-Sep																	
5-Sep																	
6-Sep																	
7-Sep																	
8-Sep																	
9-Sep																	
10-Sep																	
11-Sep																	
12-Sep																	

*NWS FF Watches: 7/1, 7/30, 7/31

Date	North Foothills		South Foothills		Palmer Divide		North Area		Northeast Metro		Northwest Metro		Southeast Metro		Southwest Metro		Flood Day (All Zones)
	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	AM	PM	
13-Sep																	
14-Sep																	
15-Sep																	
16-Sep																	
17-Sep																	
18-Sep																	
19-Sep																	
20-Sep																	
21-Sep																	
22-Sep																	
23-Sep																	
24-Sep																	
25-Sep																	
26-Sep																	
27-Sep																	
28-Sep																	
29-Sep																	
30-Sep																	
Total Threats	**24**	**28**	**25**	**27**	**29**	**29**	**16**	**19**	**18**	**22**	**15**	**18**	**20**	**24**	**16**	**20**	**26**