Colorado Flood Threat Bulletin – 2023 Final Report

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ACRONYMS

AEP.................................. Annual Exceedance Probabilities
CDOT................................ Colorado Department of Transportation
CoCoRaHS........................ Community Collaborative Rain, Hail, and Snow Network
COOP................................ Cooperative Observer Program
CWCB............................... Colorado Water Conservation Board
FAR.................................. False Alarm Rate
FBF .... Fire Burn Forecast
FEMA................................ Federal Emergency Management Agency
FFG ....Flash Flood Guidance
FTB.................................. Flood Threat Bulletin
FTO.................................. Flood Threat Outlook
HMC................................ HydroMet Consulting, LLC
IEM.................................. Iowa Environmental Mesonet
LSR .... Local Storm Reports
mPING .... Meteorological Phenomena Identification Near the Ground
MRMS .... Multi-Radar Multi-Sensor
NAM .... North American Monsoon
NDMC .... National Drought Mitigation Center
NOAA .... National Oceanic and Atmospheric Administration
NRCS................................ Natural Resources Conservation Services
NSSL .... National Severe Storms Laboratory
NWS .... National Weather Service
PM Update .... Update to FTB product during the afternoon hours
POD.................................. Probability of Detection
QPE .... Quantitative Precipitation Estimate
SNOTEL........................... Snow Telemetry
SPM.................................. State Precipitation Map
SQL .... Standard Query Language
SWE.................................. Snow Water Equivalence
USGS................................ United States Geological Survey

2023 Colorado Flood Threat Bulletin

Final Report

1) INTRODUCTION

The 2023 forecast season (May 1st to September 30th) was the second year of a 5-year contract awarded to Dewberry and HydroMet Consulting, LLC (HMC) to produce the Colorado Flood Threat Bulletin (hereafter, Program) on behalf of the Colorado Water Conservation Board (CWCB). Since work began on the Program in 2006, it has maintained the double objective of 1) producing and disseminating reliable heavy rainfall and flood forecasts, and 2) incorporating the frontier of hydro-meteorological research into operations for more accurate forecasts, along with a transparent verification process. Numerous Program upgrades have been made since the Program's inception (see previous season's final reports, e.g., Dewberry and HMC, 2022) and the five main products of the Program in 2023 are:

1. the daily Flood Threat Bulletin (FTB) that both describes and visualizes the flood threat across the state of Colorado;
2. the bi-weekly (Monday/Thursday) 15-day Flood Threat Outlook (FTO) that highlights the upcoming possible flood threat from rapid snowmelt and local heavy rainfall, or conversely, the development of drought conditions;
3. the daily State Precipitation Map (SPM) that recaps the past 24- to 72-hours of hydrometeorological conditions and includes flood reports;
4. the daily Fire Burn Forecast (FBF) that is a standalone forecast system that assigns a daily flood threat to the most impactful wildfire burn areas, including yesterday's precipitation on burns areas and burn-specific flood/debris flow reports;
5. the monthly Streamflow Tracker that shows recent and Water Year to-date adjusted (i.e., naturalized) streamflow conditions across most of the largest river basins within Colorado.

For the 2023 operational season, Dewberry continued to operate as the Program's Project Manager with subconsultant HMC in charge of forecast operations (together, hereafter referred to as Team). Dewberry meteorologists Alyssa Hendricks Dietrich and Stevenray Janke, and hydrologist Cara Williams produced the SPM and identified flood events for archiving within FBF. The Programs' forecasts (FTB/FTO/FBF), supplemental in-season FBF analyses and Streamflow Tracker tables were developed by HMC meteorologists Dana McGlone, Julie Gaddy, Dmitry Smirnov, and Kevin Goebbert. Archived forecasts continue to be available through the Program's website www.coloradofloodthreat.com. David Sutley served as the Project Manager for Dewberry, and Mat Mampara served as Principle-in-Charge.

This Final Report was created to provide verification metrics for the daily flood forecasts, summarize the hydro-meteorological weather conditions over the 2023 forecast season, evaluate Program viewership, and to document any upgrades made to the Program.

Website Upgrade

New to the 2023 season was a redesigned website, utilizing a custom-built and hosted react application and underlying Standard Query Language (SQL) database. The addition of a homepage allows end-users to gather the day's crucial forecast information in one place (Figure 1). The homepage features individual tiles for many of the Program's products, along with the daily FTB flood map. In addition to the headlines, the FTB, FBF and FTO tiles are color-coded to match each of their (maximum) flood threat level, and the SPM tiles (far right) turn red on days when there are any flood or heavy rainfall reports. Finally, with a simple click of a tile, the end-user is redirected to the respective product page for the full forecast.

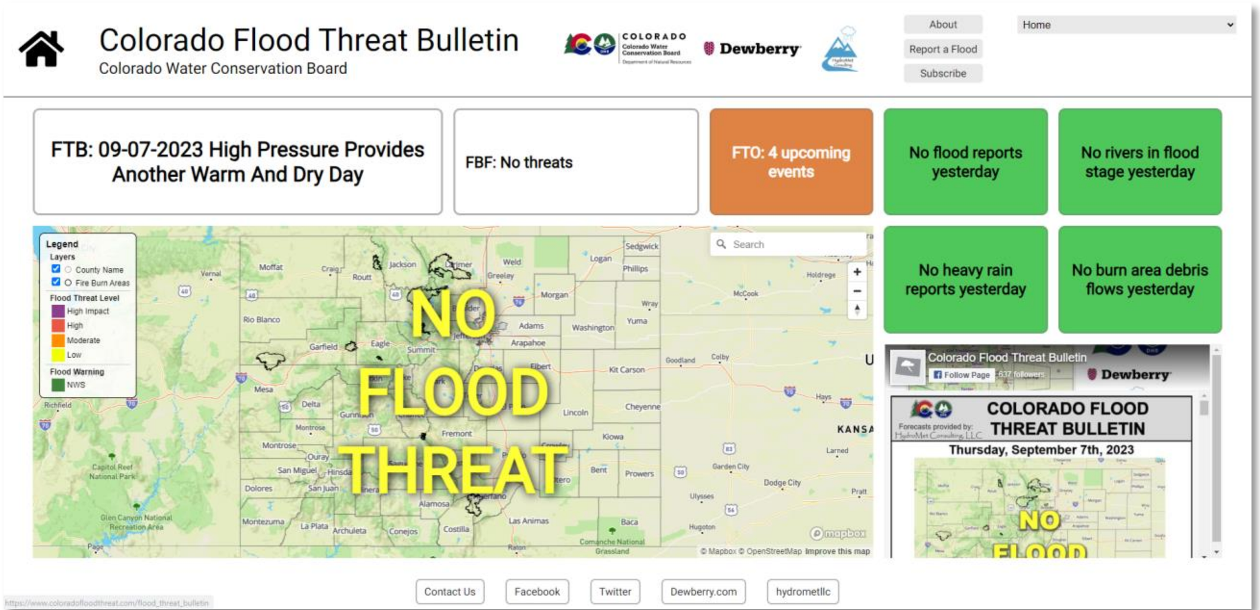

Figure 1: Screenshot of the newly designed homepage for the Program from September 7, 2023.

Each of these Program products, including the Streamflow Tracker, have a dedicated, interactive map that shows various layers of relevant data and a clickable and/or hover feature for extra product or map information. All products also have a calendar-based archive at the bottom to efficiently access older posts. Finally, on the top right-hand corner of the site, there is a drop-down menu that allows for quick navigation to other product pages along with three stationary buttons that navigate to important Program information.

Daily Flood Threat Bulletin (FTB)

FTB daily issuance occurs by 11:00 AM within the forecast season. Often, FTB forecasts are issued earlier to provide increased lead time to end-users, which is especially important on days when there is an elevated flood threat. The FTB highlights the daily threat level of flooding across the state, describes the nature of the threat, and notes the time period in which the threat of flooding would be the greatest in a zone-specific manner (14 climate-defined Forecast Zones, see Figure 5). The beginning of each FTB discussion also highlights any threats issued for the FBF and provides a direct link to that forecast page for more information. Additional information provided by the FTB includes the probability and maximum intensity of thunderstorm rainfall rates, expected storm totals and a characterization of the threat of severe weather (tornadoes, high winds, hail, etc.). Table 1 summarizes the six-tier category system that is used to characterize the daily flood threat. The first five tiers indicate the day's flood threat: None, Low, Moderate, High, and High Impact. The last tier, National Weather Service (NWS) Warning, specifies if there are any active NWS Flood Warnings (riverine flood threat) at the time of the FTB post. During situations with a particularly threatening and/or rapidly evolving flood threat, the FTB and associated map can be updated during the afternoon hours (PM Update). Updates to social media posts are also provided to notify end-users about the evolving flood threat.

Table 1: Description of the six-tier category threat system.

Threat	EXPECTED PROBABILITY OF FLOODING WITHIN A GIVEN COUNTY
NONE	Less than 10%
LOW	10-30%
MODERATE	30-60%
HIGH	Greater than 60%
HIGH IMPACT	Greater than 60% along with a particularly severe threat to life & property
NWS WARNING	Active NWS (riverine) Flood Warning(s)

The threat of daily flooding is conveyed to the end-user using graphics and text. The graphical component of the product includes a map of the state of Colorado with county boundaries and a color-coded flood threat to succinctly illustrate the probability of flooding (Figure 2). Scroll over features on the maps will pop up relevant maximum rain rates and potential hazards by threat level for each of the threat areas drawn (not shown). All FTB forecasts issued for the season are available at the bottom of the product's page using a calendar search, and past forecasts (prior to 2023) are available through the Team.

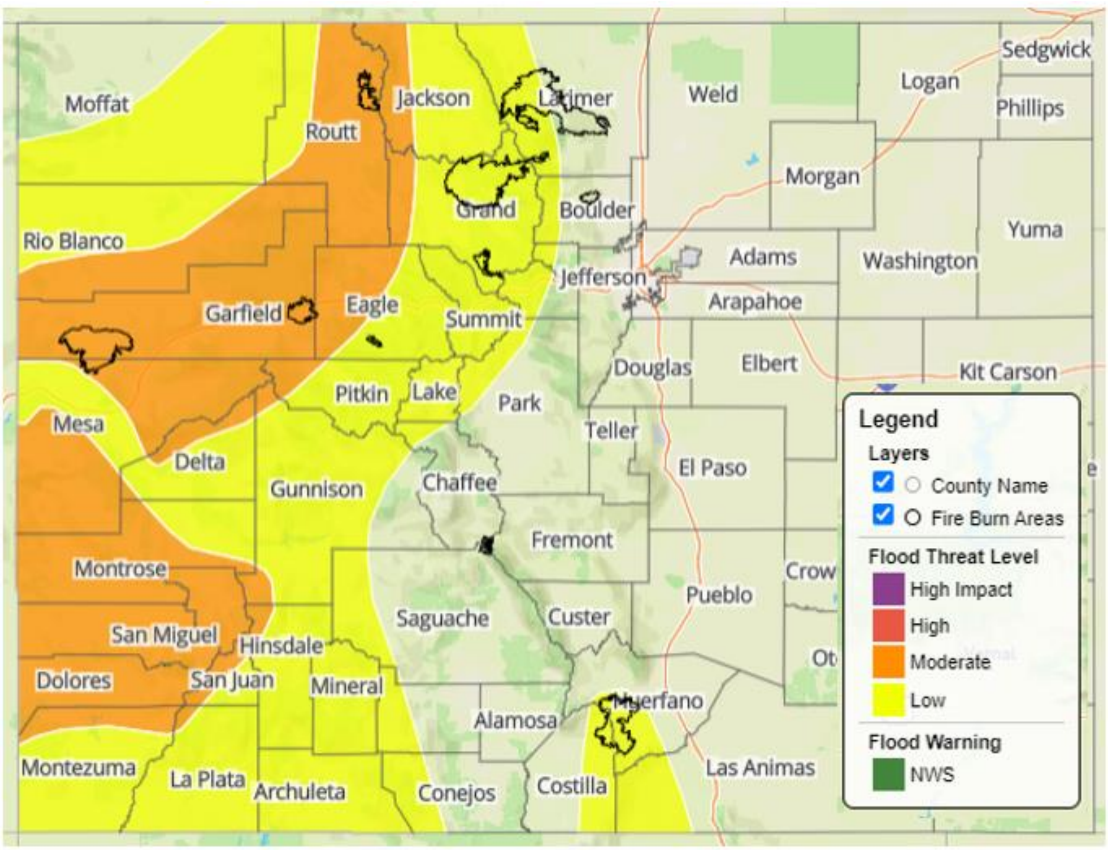

Figure 2: Example of the FTB map from August 24, 2023. The Low and Moderate threats are highlighted in yellow and orange, respectively.

Flood Threat Outlook (FTO)

The FTO is a bi-weekly product issued on Mondays and Thursdays by 3PM to address the expected flood threat across the state over the next 15 days. This product addresses both the snowmelt (May to early June) and precipitation-driven flood threat, and it provides a precipitation forecast map, by event, for the entire state when meaningful precipitation is expected. Each event's precipitation map is available via a drop-down menu as a visual aid to the forecast discussion. The FTO continues to be structured in an event-based manner, where rainfall is partitioned by its forcing features and presented in a timeline at the top of the product's page.

An example of a threat "timeline" is shown below in Figure 3 from May 18th. This FTO includes a snowmelt riverine flood threat forecast, which typically peaks at the beginning of the warm season as temperatures rise and snowmelt begins. Occasionally, additional climate-related analyses that are relative to the precipitation season are provided within the FTO such as Snow Water Equivalence (SWE) percent of normal, changing drought conditions, and rainfall anomalies. All forecasts are available at the bottom of the page by use of a calendar, and past forecasts (prior to 2023) are available through the Team.

Next 15 Days	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri
	19-May	20-May	21-May	22-May	23-May	24-May	25-May	26-May	27-May	28-May	29-May	30-May	31-May	01-Jun	02-Jun
Precipitation	Event 1	Event 1	Event 1	Event 1	Event 1	Event 2	Event 2	Event 2	Event 3	Event 3	Event 3	Event 3			
Snowmelt															

No Apparent Threat | Elevated Threat | High Threat

Figure 3: Example of an FTO "timeline" from May 18, 2023, illustrating the flood threat and a snowmelt outlook.

State Precipitation Map (SPM)

The State Precipitation Map (SPM) includes gridded Quantitative Precipitation Estimates (QPE) of 24-, 48- and 72-hour accumulations, as well as maximum 1-, 3- and 6-hour precipitation over the past 24-hour period at 250-meter resolution. The QPE product, MetStorm Live version 2.0, was obtained from sub-consultant DTN as hourly grids, and durational accumulations and maximum precipitation were computed for data visualization through the website.

Making sure the Program has the highest quality QPE is essential for post-storm assessment, tracking flood events, and assessing antecedent soil conditions that can influence the FTB forecast. It should be noted that the objective of the SPM is to provide a near real-time (i.e., very short lag time) look at precipitation accumulation. This comes at the cost of introducing a possible QPE bias, compared to rain gauge data, that is difficult to fully resolve by the SPM's noon issuance deadline (see APPENDIX E – FLOOD THREATS ISSUED). To account for this complication, the data shown by the SPM was NOT used in the verification procedures outlined in Appendix A.

In addition to QPE, automated data pipelines pull daily flood and heavy rain reports from the National Weather Service, through the Iowa Environmental Mesonet (IEM), to be stored in a SQL database and displayed on the SPM page. Manually identified flood reports, for example those from CDOT or social media, were also stored in the SQL database. Having this database is a drastic improvement over previous seasons, where flood reports were only discussed in the precipitation summary and were not archived or displayed on the web map. The final SQL database acts as a complete archive of all flood season reports and will continue to grow each season. Lastly, meteorologists and hydrologists provided text-based summaries of recent hydrometeorological conditions including contextualizing extreme rainfall totals, severe weather, and wildfire activity. Discussions are also supplemented with gauge data from CoCoRaHS, COOP/ASOS, Mile High Flood District's ALERT, and SNOTEL networks. The "Report a Flood" tool on the website brought in only one report this season, however, it was a debris flow report over the Cameron Peak burn area and added value to the FBF.

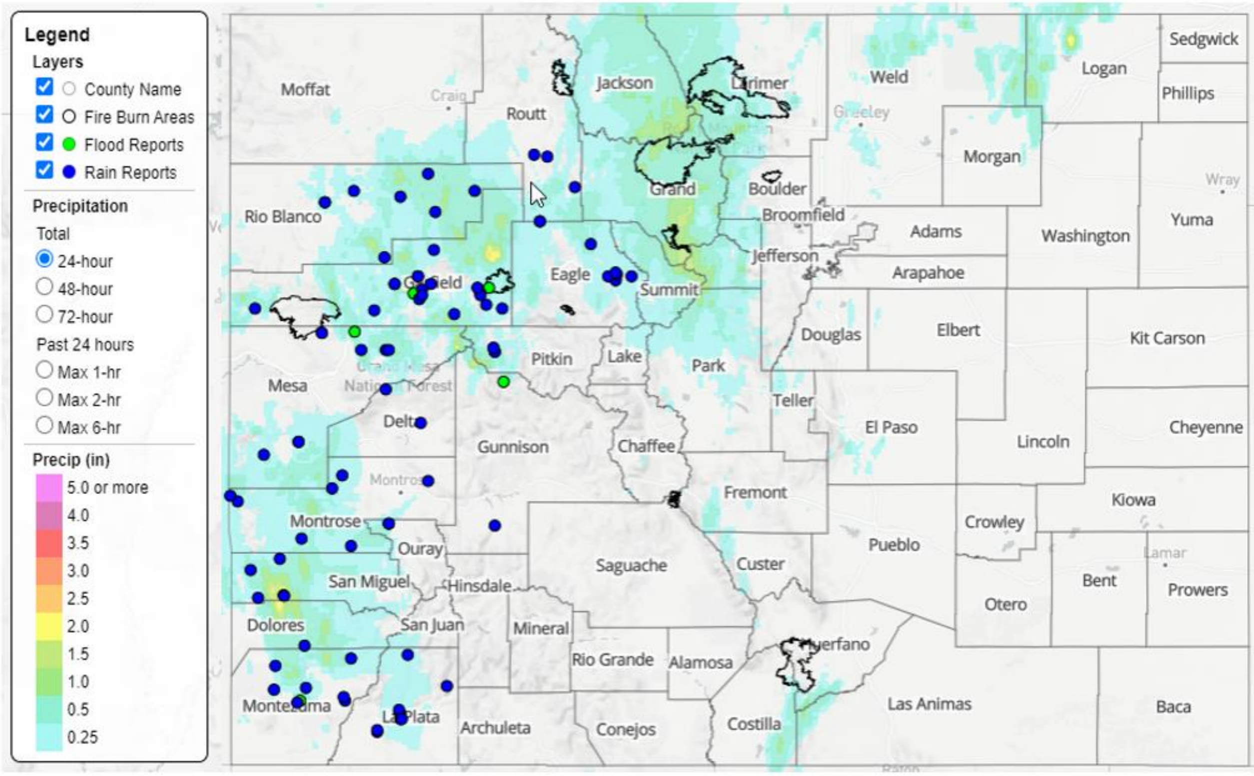

Figure 4: Example of SPM from August 25th, 2023, showing the previous day's precipitation, flood reports (green) and heavy rainfall reports (blue).

Fire Burn Forecast (FBF)

There is concern for extremely dangerous runoff, mud flows, and debris slides over recent wildfire burn areas located over steep terrain, especially those near population centers and highly traveled roads. Since roughly 1980, Colorado has experienced an increasing trend in wildfires exceeding 10,000 acres (HMC and Dewberry, 2022). During the 2020 wildfire season alone, Colorado experienced three of its largest fires on record with a total of seven fires exceeding 10,000 acres in size. While burn areas continue to recover each season, they still produce enhanced flooding hazards during heavy rainfall events. Due to the stark difference between runoff sensitivity over burn areas compared to nearby unscarred areas, the FBF product was created in 2021. The FBF is a standalone wildfire forecast system meant to complement the overall goals of the Program and remove burn areas from the daily FTB discussions (as was done from 2017 to 2020). The main objective of the product is to create a concise, easily accessible tool that (i) helps assess and prepare for the flood threat specifically focusing on the most vulnerable burn areas, and (ii) archives recent conditions for an enhanced perspective of multi-day rainfall events. Similar to the FTB, the FBF provides an early outlook for threat awareness, and it is not to be used for real-time flood warning and monitoring.

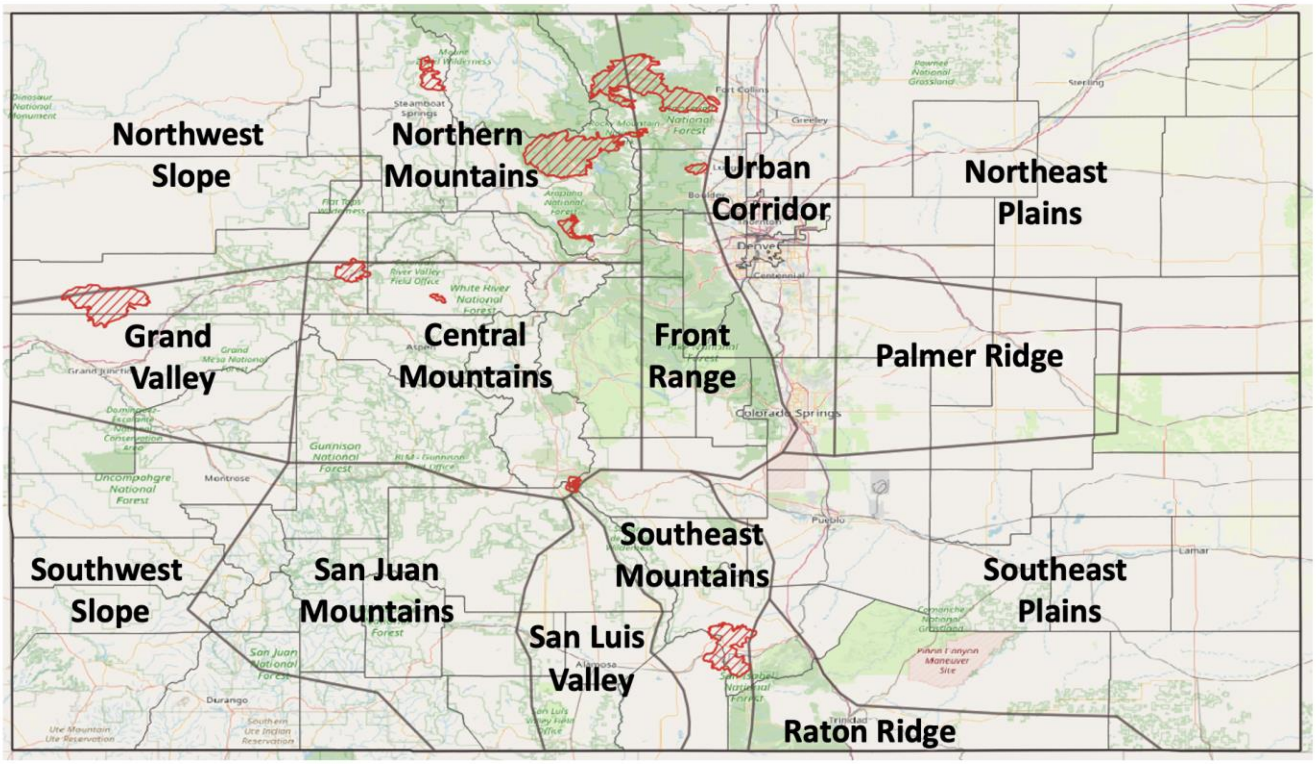

Figure 5: Forecast zones and wildfire burn areas (red hatch) that were featured on the daily FTB maps for 2023. Source: National Interagency Fire Center

This forecast season, the Team and CWCB Program Manager identified and monitored the same 11 potentially dangerous burn areas in the FBF from 2022 (Figure 5): Calwood (year of fire: 2020), Cameron Peak (2020), Decker (2019), East Troublesome (2020), Grizzly Creek (2020), Middle Fork (2020), Morgan Creek (2021), Pine Gulch (2020), Spring Creek (2018), Sylvan (2021) and Williams Fork (2020). Ideally, every recent wildfire burn area would be the subject of a dedicated flood threat, but in practice limited resources imply the need to focus on the most impactful burn areas for the daily FBF: those which are relatively large in scale (corresponds to a higher runoff threat) and those that are near high population density and/or major roads. Similar to the FTB and FTO maps, the burn areas are interactive on every Program map, and clicking on a burn area shows the fire's name, year of occurrence, and the number of acres burned.

An example of data displayed in the daily FBF is shown in Figure 6. The product contains both the daily forecast as well as rainfall statistics over each burn area from the prior day. The "Fire Burn Forecast" threat level (Figure 6, left) uses the same five-tiered threat system as the FTB (None, Low, Moderate, High and High Impact) with the threat level representing the likelihood for excessive runoff, flash flooding, mud flows, and/or debris slides over the given burn area within the next 24 hours. Burn area rainfall thresholds are set at the beginning of each season and are adjusted prior to the start of the monsoon season, as necessary. More information about the "Post-Season Fire Burn Forecast Threshold Assessment" can be found below.

The "Fire Burn Info" (Figure 6, right) shows three measures of antecedent rainfall for the prior 24 hours to assess the current soil conditions over the given burn area. The measures are: (1) maximum 3-hour and (2) average 24-hour rainfall over any portion of the burn area, and (3) the percentage of the burn area that received precipitation. The estimates in 2023 are derived from MetStorm Live and manually quality controlled by the Team, if necessary. The last column shows an evaluation of whether flooding was reported in the past 24 hours, which is determined from news reports, social media reports, storm reports and personal contacts. Three specific contacts for burn area flooding were established this season, two for the Cameron Peak burn area and one for the Spring Creek burn area. For the Cameron Peak burn area, the Program communicated with Eric Tracy (Larimer County civil engineer) and the Larimer County Sheriff's office after rain events to determine if there was flooding. For the Spring Creek burn area, the program would reach out to local resident Cyndee Blenkush who lives on the burn area. The Team has also completed a high-level verification for burn area threats once again this season. More information and methodology can be found in Appendix B of this report.

Fire Burn Forecast 8-24-2023		Fire Burn Info 8-23-2023			
Fire Name	Today's Threat	Max 3hr (in)	Avg 24 hr (in)	Burn Area Coverage	Flooding Reported
Calwood	NONE	0.0	0.0	0 %	NO
Cameron Peak	MODERATE	0.6	0.2	70 %	NO
Decker	NONE	0.0	0.0	0 %	NO
East Troublesome	HIGH	0.4	0.1	> 90 %	NO
Grizzly Creek	MODERATE	0.4	0.2	> 90 %	NO
Middle Fork	MODERATE	0.1	0.1	75 %	NO
Morgan Creek	MODERATE	0.1	0.1	55 %	NO
Pine Gulch	MODERATE	0.0	0.0	0 %	NO
Spring Creek	LOW	0.0	0.0	0 %	NO
Sylvan	LOW	0.3	0.2	> 90 %	NO
Williams Fork	MODERATE	0.3	0.2	> 90 %	NO

Figure 6: An example of data shown in the daily FBF post from August 24, 2023.

Streamflow Tracker

To expand the Program's reach to a more diverse group of end-users, a streamflow table that tracks naturalized flow across 14 sites representative of Colorado's largest river basins continued to be provided this season after implementation in 2022. Historically, these sites produce large flows (combined average yearly flow close to 10 million acre-feet), have long periods of record, and represent key sites at their headwaters. The table is updated mid-month during the forecast season, and it uses "adjusted" observed streamflow from National Resources Conservation Services (NRCS), which estimates the volume of streamflow that would occur without the influences of major upstream reservoirs or diversions. In addition to tracking monthly flow and Water Year to-date flows at each site, the table tracks the average and percentile values relative to normal. While average flow can be a useful metric, it does not do well at capturing the extremes of high and low flows at a site. For this reason, the percentile of normal flow was added which better captures the potentially non-Gaussian distribution of flow relative to the site's history. This metric can be especially helpful when the site has a long period of record.

Figure 7 below illustrates the tracker table from May 2023 (updated mid-June). Blue shades indicate values above normal whereas red shades indicate values below normal. Missing data continues to present a challenge for the product as sites are updated with a varying degree of latency or are sometimes backfilled only once a year. For example, monthly statistics available by mid-month at each site ranged from 86% (May) to 64% (June through August). The Team will continue to work with NRCS and its partners (e.g., Northern Water) during the off season to work through such data complications.

COLORADO STREAMFLOW TRACKER [MAY 2023]

Location	Latest Month Data (May)				Water Year To-Date Data (Oct-May)			
	Value	Normal	% of Average	Percentile	Value	Normal	% of Average	Percentile
SOUTH PLATTE RIVER basin								
South Platte	52.3	49.8	105%	71	94.6	123.5	77%	38
Cache la Poudre at Canyon Mouth		69.5				113.1		
ARKANSAS RIVER basin								
Arkansas River above Pueblo	78.7	67.9	116%	71		262.7		
RIO GRANDE basin								
Rio Grande River at Del Norte	273.5	156.2	175%	97		308.3		
NORTH PLATTE RIVER basin								
North Platte near Northgate		64.4				155.3		
COLORADO RIVER basin (NORTH)								
Little Snake River near Lily	306.0	154.3	198%	98		271.6		
Yampa River near Maybell	749.9	379.3	198%	99	1071.4	675.1	159%	96
White River near Meeker	160.1	94.2	170%	98	296.4	250.6	118%	89
COLORADO RIVER basin (CENTRAL)								
Colorado River near Cameo	1195.9	663.2	180%	97		1469.2		
Gunnison River near Grand Junction	1044.9	528.2	198%	97	1721.1	1177.2	146%	92
COLORADO RIVER basin (SOUTH)								
Dolores River at Dolores	203.7	102.4	199%	97	295.2	176.6	167%	97
Animas River near Durango	218.1	137.9	158%	92	353.8	284.2	124%	79
Los Pinos River near Bayfield	119.0	65.8	181%	99	197.9	129.5	153%	93
San Juan River near Carracas	255.7	129.2	198%	100		298.7		
TOTAL	**4657.7**	**2528.4**	**184%**			**2374.8**		

All Units are x1000 acre-feet; Updated: June 16, 2023; Next Scheduled Update: July 17, 2023

Figure 7: An example of the Streamflow Tracker from May 2023. The middle column shows monthly data, while the right column shows Water Year to-date data.

Performance Metrics

Table 2 shows the final year-to-date number of all products provided and the percent provided on time. Out of 503 total products delivered, the Team delivered 499 on time or ahead of time. Of the four late products, three were FTBs and one was a FTO. Three of the four late products this season were posted within 30 minutes of their deadline with the final late product being posted with 1.5 hours of the deadline. Note that Table 2 also shows September performance, since there was no monthly Progress Report prepared. All necessary information for the September Progress Report is contained within this Final Report. Other monthly Progress Reports were prepared for May through August and sent to the CWCB Project Manager no later than 3 weeks after the end of the month.

Table 2: On-Time performance metrics for all issued products in 2023 (SPM, FTB, FTO and FBF).

		Products to Date	Products on Time	Products Late	Percent on Time			Products to Date	Products on Time	Products Late	Percent on Time
September	SPM	30	30	0	100%	YTD	SPM	153	153	0	100%
	FTB	30	30	0	100%		FTB	153	150	3	98%
	FTO	8	8	0	100%		FTO	44	43	1	98%
	FBF	30	30	0	100%		FBF	153	153	0	100%
	TOTAL	**98**	**98**	**0**	**100%**		**TOTAL**	**503**	**499**	**4**	**99%**

In-Season Analysis of Flash Flood Events

In an effort to supply rainfall related data after a noteworthy flash flood event, the Team produces in-season, event-based analyses at the request of the Program Manager. Near real-time reanalysis work, which can be helpful for end-users, particularly emergency management teams, has been lacking for flood events across Colorado. By providing information about the timing of rainfall, magnitude of rainfall, and corresponding peak flows on nearby rivers and creeks, responders can not only better assess similar, future situations, but it may provide helpful insight about other potential flood events across an area. Also, by disseminating these analyses through social media, the Program can engage more end-users, boosting Program viewership and conveying that the Program is not just about providing forecasts.

For the 2023 season, an in-depth analysis was provided for an unanticipated flood event over the Grizzly Creek burn area on August 16th. Regrettably, there was no threat issued in the FBF that morning. Fairly unusual for that day, storm motion was from north to south. Around 4PM small storm cores started to develop over the high terrain in and around the burn area. By 4:30PM, the cores became larger and stronger. With storm cores remaining nearly stationary due to training from northerly flow, the continuous rainfall eventually caused a debris flow onto the highway just after 5PM. This led to the closure of I-70 until 9PM that night.

The Team completed a rainfall reconstruction of the event and overlaid nearby USGS observations and the debris flow report (pink starburst; Figure 8, top). Various Annual Exceedance Probabilities (AEP) were also calculated at the max observed gauge site (No Name Creek) on the western portion of the burn area along with incremental and accumulating rainfall (Figure 8, bottom). The max observed point rainfall of 2.03 inches in 60 minutes was estimated to have a 0.1% AEP using the Colorado-New Mexico Regional Extreme Precipitation Study (CO-NM REPS). Interestingly, this is the third event for the burn area that the Team has analyzed since 2021 that has reached a 60-minute 0.1% AEP.

There were two other mud flow events this season over the burn area on August 24th and August 26th (not analyzed), which had a Moderate and Low threat issued, respectively. During August 24th event, rainfall lasted for 3 to 4 hours over the burn area in the evening. A gauge measure 0.91 inches in 30 minutes, which is about a 4% AEP. For the August 26th event, 1.66 inches was measured in 2 hours, which is equivalent to a 0.2% AEP. Under normal circumstances, it would be hard for any steep terrain to withstand these types of rainfall rates, let alone over a recovering burn area in a steep canyon. So, it's hard to understand the burn area recovery from these three events alone. However, the lack of flooding incidents at lower thresholds this season does imply a continued recovery over the area. Mitigation efforts also appear to be successful with reduced debris flow volume and areal coverage when events do occur, especially when compared to prior years.

The full analysis and images for this flood was posted to X (formerly known as Twitter) on the morning of August 18th. The social media post garnered more than 2,700 “Impressions”, was “Liked” 5 times, and was Retweeted 3 times. These statistics were on par from last season’s in-season flood analysis, so these posts continue to help Program viewership. Off-season work is being completed about the optimal time to post and best practices for a multi-thread post.

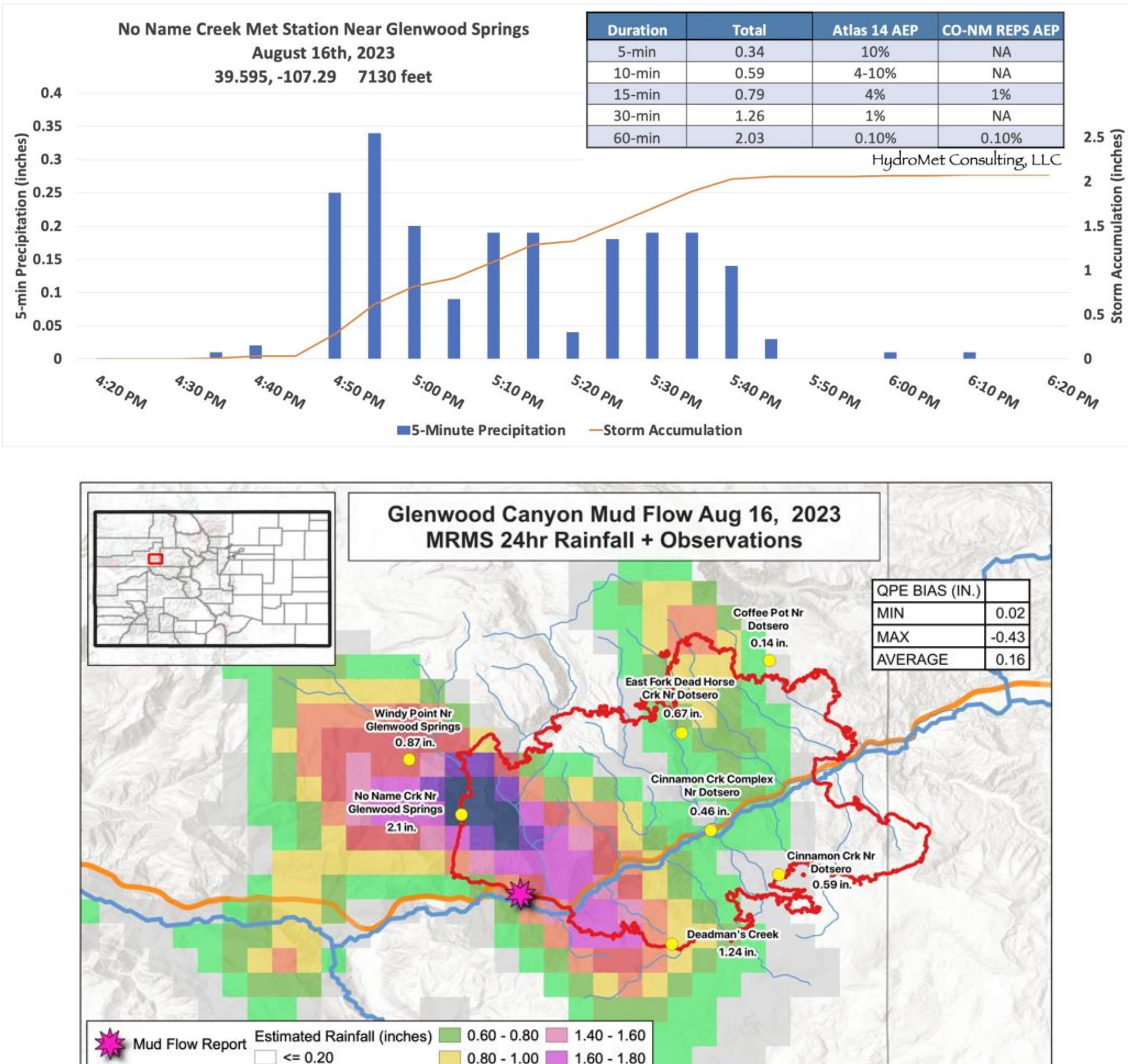

Figure 8. Top panel: Rainfall analysis of the August 16, 2023, mud flow event within the Grizzly Creek burn area. Overlaid are rainfall gauges (yellow circles) and the debris flow location (pink starburst). Bottom panel: Incremental and accumulated precipitation time series from the event. Data for the AEP come from the USGS No Name Creek rainfall gauge.

Post-Season Fire Burn Forecast Threshold Assessment

As an effort to keep track of the recovery over each burn area and adjust rainfall intensity thresholds prior to the start of the season, the Team produces a yearly Technical Memo during the off season addressing the FBF thresholds (HMC, 2022). The procedure for the Post-Season Fire Burn Forecast Threshold Assessment uses the same general methodology for post-wildfire burn debris flow forecasting from the latest peer-reviewed literature (e.g., Hoch et al., 2021). The methodology follows that burn areas have high initial sensitivity (<= 1 year after the burn occurred) and over a 3-5 year period after, this threshold begins to recover to the "normal" value. In this case, it's the Program's 1.0 inch per hour threshold over mountainous terrain.

For each burn area, a two-part analysis is completed. The first part of the analysis is to inform of the long-term net precipitation deficit/surplus over the burn, which serves as a proxy for the vegetative recovery process. For this analysis, a time series of net warm season precipitation accumulation (from the year of the burn) is compared to climatology. An example of this for Spring Creek is shown in Figure 9. Cumulative anomaly, percent of normal and maximum 24-hour totals over the period are also collected (top left). The second part of the analysis (not shown) informs on the number of hours during the warm season (since the year *after* the burn occurred) where greater than 0.25 inches of rain was estimated using Multi-Radar Multi-Sensor (MRMS) data. This also helps inform on the vegetation's recovery, but this analysis includes a spatial component.

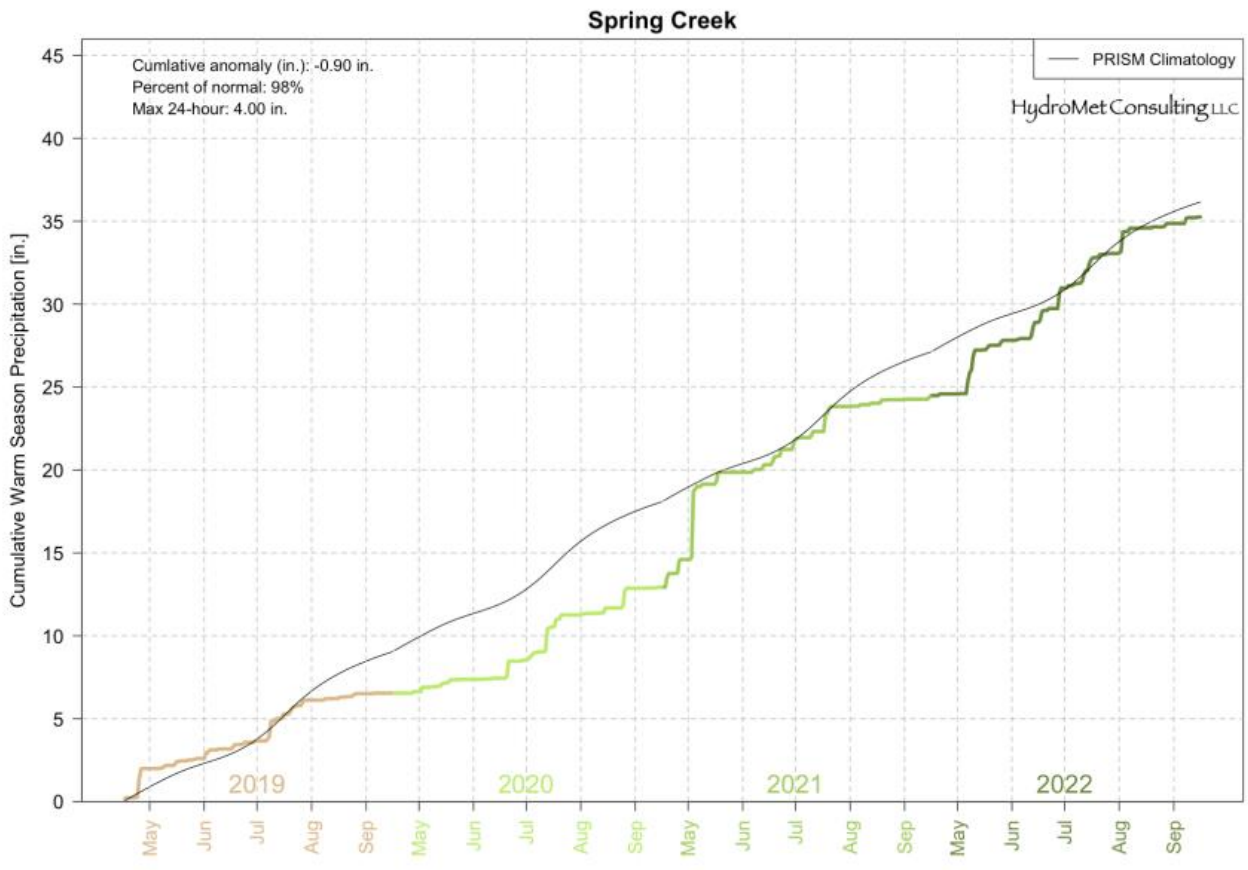

Figure 9: Cumulative warm season rainfall (2019 orange, 2020 light green, 2021 green and 2022 dark green) over the Spring Creek Burn area as compared to normal (black line).

Assessments and recommendations are then presented in the preseason to the CWCB Program Manager. Adjustments to thresholds are finalized with input also received from Emergency Managers. As expected, the rainfall intensity thresholds utilized in the FBF product either stay the same or increase each season. Table 3 shows the 2023 forecast thresholds for each of the 11 burn areas. While the thresholds listed are in inches per hour (to match the Team's internal guidance as well as gridded rainfall estimates), the assumption is that most rainfall accumulation occurs in a 15 to 45-minute period. For the thresholds given below, the bottom four burn areas (green) match the Program's 1.0 inch per hour threshold over mountainous terrain. However, unlike FTB, there is no areal coverage of rainfall rates that need to be met to issue a FBF threat. Additionally, if one of these four burn areas is included in the FTB threat map, the FBF forecast threat level is raised one category (e.g., Low up to Moderate). As previously mentioned, forecast thresholds may be adjusted prior to the onset of the monsoon, but only with CWCB Program Manager approval and after being tested by several rainfall events.

Table 3: Fire burn area thresholds used for 2023 forecast operations.

Burn Area Name	Year of Fire	Acres Burned	Forecast threshold (inches/hour)
Cameron Peak	2020	208,912	0.50
East Troublesome	2020	193,811	0.50
Grizzly Creek	2020	32,431	0.75
Morgan Creek	2021	7,586	0.75
Sylvan	2021	3,792	0.75
Pine Gulch	2020	138,803	0.75
Williams Fork	2020	14,833	0.75
Calwood	2020	10,114	1.00
Decker	2019	8,886	1.00
Middle Fork	2020	20,433	1.00
Spring Creek	2018	108,131	1.00

2) CHARACTERIZATION OF FORECAST PERIOD WEATHER

Overview

The 2023 operational season saw no shortage of record-breaking rainfall, significant flood events, and severe weather. The season began with much of eastern Colorado in some level of drought, ranging from D0-Abnormally Dry conditions along the Front Range, Central, and Southeast Mountains, to D4-Exceptional Drought in the extreme southeast corner of the state (Figure 10, left). Conversely, western Colorado began the season largely drought-free thanks to an above average snowpack following a wet winter (Figure 11).

This early season period was packed with significant flood events and severe weather, including several large hail events, which is fairly unusual for the early portion of the warm season. Not surprisingly, drought conditions across eastern Colorado quickly receded as portions the Urban Corridor and Eastern Plains saw their record wettest May and June (Figure 12), resulting in statewide drought-free conditions on July 4 - the first time since 2019.

By mid-season, the North American Monsoon (NAM) kicked in but was relatively uneventful, especially compared to last year's monsoon season. Though portions of the eastern plains again saw above average precipitation for July, many typical areas of monsoon rain (mountains and adjacent ridges) received little to no rain. This caused drought conditions to return to the San Juan Mountains, Southwest Slope and San Luis Valley by early August, expanding in spatial extent and severity throughout August and September.

By the end of the season, drought conditions had flipped from May, with large portions of western Colorado under D0-Abnormally Dry to D2-Severe Drought conditions, while eastern Colorado was mostly drought-free (Figure 10, right).

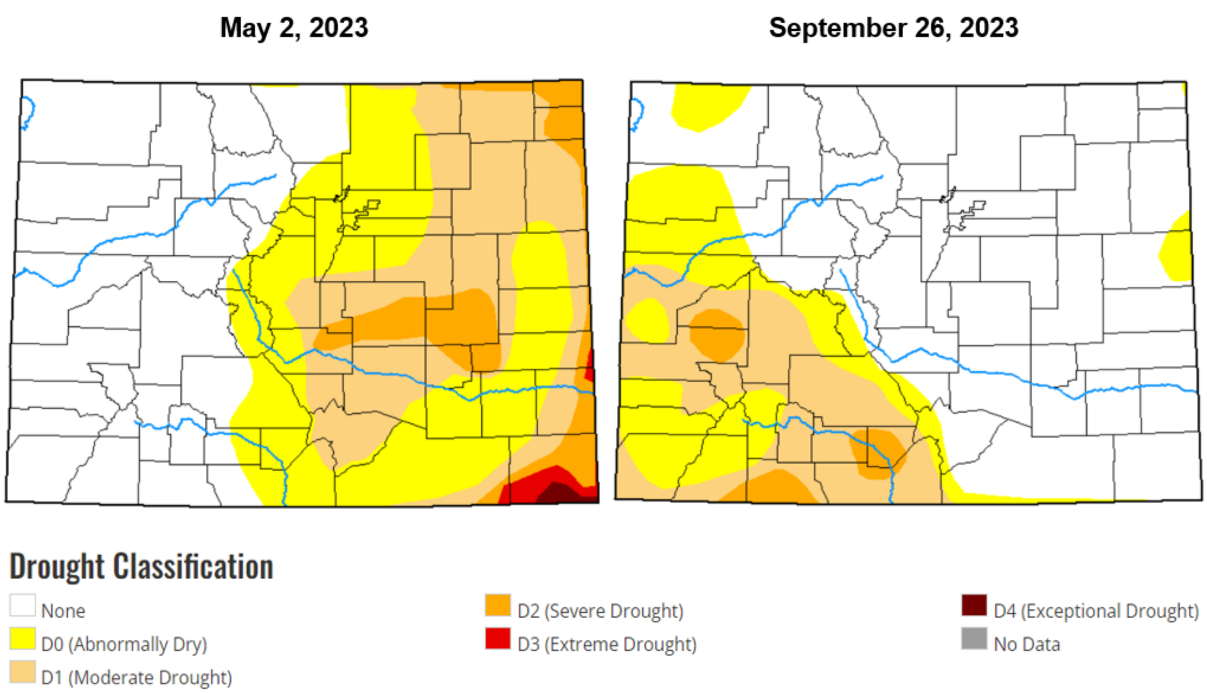

Figure 10: US Drought Monitor update valid on May 2, 2023 (left) and September 26, 2023 (right), showing the drought conditions at roughly the start and end of the 2023 season. Source: The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center (NDMC) and the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Maps courtesy of NDMC.

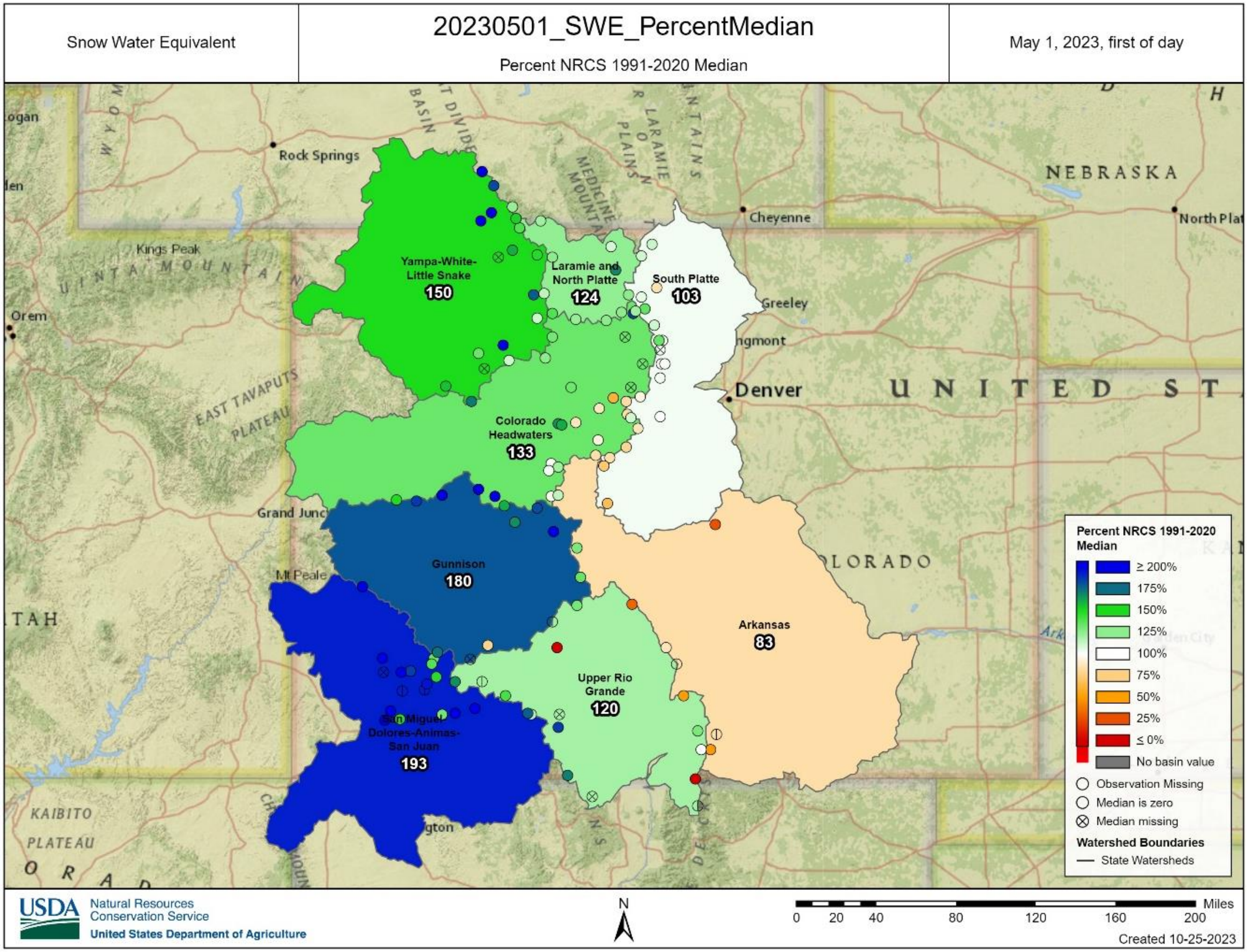

Figure 11: Percent of Median Snow Water Equivalent on May 1, 2023. Source: NRCS

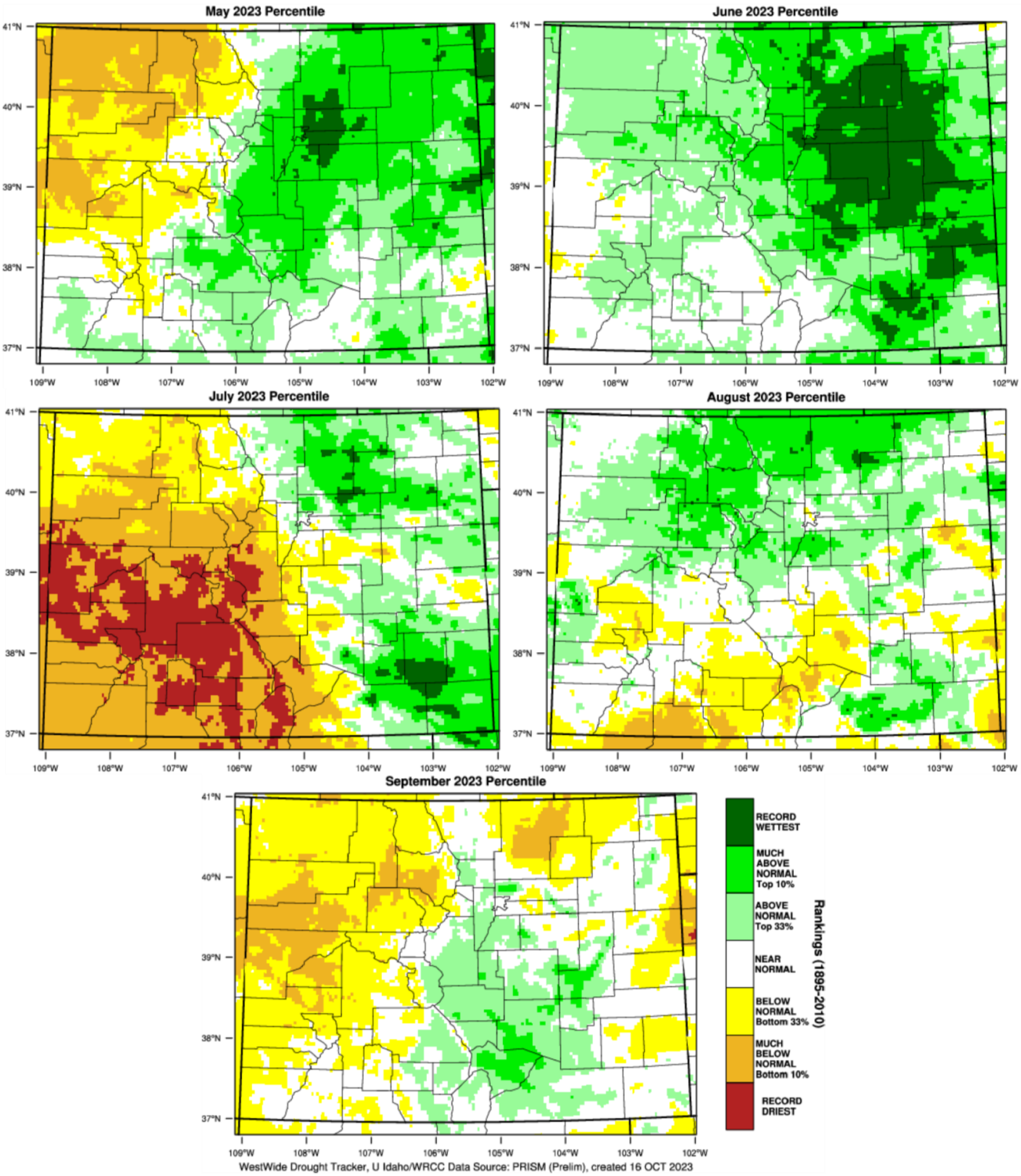

Figure 12: Monthly precipitation anomalies (PRISM) ranked by percentile for May-September 2023. Source: WestWide Drought Tracker.

Detailed Summary

A list of five significant events reported this season is shown in Table 4. These events were selected for having both widespread impacts and various locations across the entire state, providing a snapshot of headlines throughout the season.

Table 4. Five impactful flood and rain events over the 2023 forecast season.

FLOOD EVENT	DATE(S)	INTENSITY	IMPACTS
Western Colorado Snowmelt Flooding	May	High river flows due to rapid snowmelt from warm temperatures and above average winter snowpack	Diurnal Minor to Moderate Flood Stage at Lost Canyon Creek (Dolores) and Elk River (Milner), while nearly all rivers ran higher than average. Snowmelt induced flooding on Grizzly Creek burn area at Hanging Lake on May 3
Urban Corridor and Eastern Plains	May 10-12	5.30 inches in 24 hours in Castle Rock, numerous other 24-hr totals of 4+inches in Denver Metro	Significant urban street flooding including 4+ feet of water on roads near Colorado Springs. Numerous other road closures across Urban Corridor. DIA set new 3-day rainfall record
Record Breaking June Precipitation	June	Wettest June on record for large portions of the Urban Corridor and Eastern Plains	Several significant flood events and daily rainfall records broken. Elimination of drought conditions state-wide. 123 total flood reports. Federal disaster declaration for eastern Colorado for severe storms, flooding, and tornadoes June 8-23
Cameron Peak Debris Flows	May 11, June 8, June 11, July 20, July 31, August 2, September 14	High intensity, short-duration rainfall over the vulnerable burn area and saturated soils	A total of 7 separate debris flows on or associated with the Cameron Peak burn area. On July 20, 6 contractors required rescue due to high running water over Forest Road 129
Remnants of Tropical Storm Harold	August 24-28	24-hr totals of 2+ inches on the Grizzly Creek and East Troublesome burn areas. Isolated 24-hr totals of 4+inches on East Plains	3 debris flows on 3 separate days, 2 of which occurred on the Grizzly Creek burn area, closing parts of I-70 both times. 26 total flood reports from this period, most of which included flooded and washed-out roadways

May

May began with well-above average snowpack following a busy winter season. West of the Continental Divide, river basins experienced between 120-193% median SWE to start the month (Figure 11). The high snowpack caused many creeks and rivers on the Western Slope to run above normal, including Lost Canyon Creek and Elk River, which both diurnally cycled in and out of flood stage for much of the month. A pair of non-precipitation related debris flows occurred as a result of snowmelt and saturated soils in Routt County and the Grizzly Creek burn on May 1st and 2nd.

No rainfall related floods were reported during the first several days of May but reports quickly picked up in the second week of the month thanks to a slow-moving upper low which brought ample moisture and mid-level energy for widespread rainfall over eastern Colorado. May 9th started off the active streak of heavy rainfall with numerous intense thunderstorms along the Urban Corridor and Eastern Plains. Rain continued May 10-12th, which saw increasingly intense storms that brought flooding to the Front Range and adjacent plains (mainly to the Urban Corridor). On the 10th, U.S. Highway 50 in Penrose and U.S. Highway 160 in Walsenburg both experienced flooding, and in Security, local law enforcement reported 4-5 feet of water on roadways. On May 11th the Denver Metro Area saw a 24-hour total of 5.30 inches from a CoCoRaHs observer in Castle Rock along with several more reports of 4+ inches in the surrounding Palmer Ridge area. The Castle Rock storm center had only a 0.14% AEP at the 24-hour duration based on estimates from CO-NM REPS. Also on the 11th, Denver International Airport set a new 3-day rainfall record with a total of 4.47 inches. Due to the multiday rainfall event, several creeks and streams rose to flood stage, including Cherry Creek which peaked at Moderate flood stage on the 12th.

Following the active string of days, the state fell back into its more diurnally driven thunderstorm pattern until mid-May. A passing cold front caused showers and thunderstorms on the 17th and 18th brining heavy rainfall to the eastern half of the state. A trained spotter in Longmont reported 2 inches of rain in just 45 minutes on the 18th. Numerous flood reports were recorded within the Urban Corridor including 1 foot of standing water at a loading dock near Longmont. As the cold front moved east, scattered showers and thunderstorms lingered around bringing mostly light rainfall amounts. Western Colorado also saw thunderstorms on the 20th. The Elk River continued to diurnally cycle in and out of flood stage due to snowmelt throughout this time.

Afternoon thunderstorms, mainly east of the Continental Divide, persisted through the end of the month bringing on and off heavy rainfall events. There were two events at the end of the month, May 24th and 26th, which caused water rescues in Pueblo and the Denver Metro, respectively. After the 26th, no flood reports were recorded for the rest of the month.

June

June was even busier than May, with average to above average precipitation experienced across the state. This was due to a blocking pattern that featured a high-pressure center located northeast of Colorado. This helped stall out systems moving in from the west coast, which brought continuous moisture and lift to the state. A string of days during the first week of June saw widespread showers and thunderstorms, mainly east of the Continental Divide, with daily rainfall amounts generally up to 2 inches. Several flood reports from roadways to farmland were associated with these storms, most of which were on the Eastern Plains and Urban Corridor. Rainfall activity would only increase after the first week.

The Cameron Peak burn area received near-daily Flash Flood Warnings in early June. On June 8th, several debris flows were reported within the burn area, which caused sections of CO 14 to close. The Urban Corridor was also battered with repeated heavy rainfall during the early to middle part of the month. On June 11th, areas near Fort Collins saw 24-hour rainfall totals up to 4.26 inches, which has just a 0.57% AEP (CO-NM REPS). On June 12th, more intense storms brought record breaking rainfall to Colorado Springs. Up to 4.02 inches of rainfall was recorded in 24 hours near the city, and the two-day total reached 5.49 inches. For reference, a two-day total of 5.49 inches in Colorado Springs has just a 0.75% AEP. As expected, numerous flood reports were recorded during this stretch of rainfall, including multiple water rescues near Colorado Springs on the 10th and submerged cars near Boulder on the 12th.

The next active period of heavy rainfall arrived on the 21st to eastern Colorado as a passing trough draped a cold front across the plains, bringing lift alongside a passing shortwave and ample moisture needed to create some intense thunderstorms. On the 21st, a MesoWest rain gauge near Sterling recorded a 24-hour rainfall total of 5.26 inches, most of that falling within just a 3-hour span. Northern Colorado Springs received hail up to 2.50 inches in diameter and rainfall totals up to 2.29 inches, which caused streets on the north side of Colorado Springs to be submerged under several feet of water and stranded vehicles. Things did not get better as the sun went down on the 21st as concertgoers at Red Rocks Amphitheater were pummeled with heavy rainfall and hail up to 2 inches, leaving many injured. A water rescue occurred within the Denver Metro the same night and parts of I-70 in Denver closed due to flooding. A rain gauge near Aurora recorded 2.68 inches in a 2-hour period that night, which is just below the 1% AEP value of 2.75. Many areas of eastern Colorado received over 2 inches of rainfall when the 21st of June had concluded.

The Urban Corridor was once again slammed with heavy rainfall and severe weather on the 22nd. A supercell brought heavy rain, golf ball sized hail, and a rare urban tornado to the southern Denver Metro region. A rain gauge near Lakewood received 1.90 inches in one hour, which has just a 1.4% AEP, and resulted in widespread urban flooding. 24-hour rainfall totals in the metro reached up to 2.80 inches on the 22nd. The multiple days of rain also caused flooding along the Arkansas and South Platte Rivers. The South Platte River overtopped its banks, resulting in a closure of CO 144 near Fort Morgan. The Arkansas River at Avondale reached Major flood stage for a moment on June 22nd, causing CO 209 to close due.

As the month of June came to a close, a shortwave moved overhead and an accompanied cold front brought widespread storms again to the Northeast Plains and Urban Corridor. On the 29th, ample flooding occurred in

Denver after a storm brought up to 2 inches of rain in less than 2 hours. I-25 was flooded in several spots, which caused traffic jams and left vehicles stranded during rush hour. On 38th Street near Park Avenue, several feet of water on the road caused vehicles to become completely submerged. Finally, on the last day of June, scattered storms brought heavy rainfall and flooding north of Colorado Springs and to parts of the eastern plains. CR 13 in Weld County was under at least a foot of water and minor street flooding occurred north of Colorado Springs. Ultimately, a federal disaster declaration was issued by FEMA for the severe storms, flooding, and tornadoes that occurred in Colorado from June 8-23, specifically, counties on the Northeast and Southeast Plains,

July

Storms on Independence Day kicked off the first week of July, cancelling fireworks displays and causing flooding that stranded cars across the Denver Metro Area. On the 5th, the flood threat shifted to the Southeast Plains where major flood reports came in from La Junta and Las Animas. In La Junta, multiple cars were stranded in several feet of water near U.S. Highways 50 and 350 after a line of storms quickly dropped up to 2 inches of rain. Not too far away in Las Animas, roads were impassable due to high water, and flooding reached the doors of homes in the area. On the 6th, U.S. Highway 287 in Lamar experienced significant street flooding after a supercell storm moved through the area and producing 1.35 inches of rainfall, though 1.20 of that was in just an hour. The action continued on the 8th as widespread severe storms brought swaths of large hail and heavy rainfall to the eastern plains, U.S. Highway 36 in Bennett was under approximately 3 feet of water and several inches of water covered a road in Eaton during this time.

Things finally calmed down after the 8th, as the state fell into a 10-day streak of no flood reports, the longest stretch of the season so far. Monsoonal moisture brought the floodless streak to an end on the 19th as storms brought significant rainfall to parts of the Southeast Plains, the heaviest of which fell along U.S. Highway 350 between La Junta and Trinidad, causing a very large stretch of the highway to close due to flooding and the resulting road damage. CoCoRaHS observers in the area recorded over 2 inches of rainfall in 24-hours. On the 20th, there were a multitude of intense storms east of the Continental Divide. The Cameron Peak burn area had two separate debris flows, one of which stranded 6 contractors that had to be rescued due to high water running over Forest Road 129. Along the Urban Corridor, storms brought intense rainfall which caused headaches in both Colorado Springs and Denver. In Colorado Springs, several vehicles were stranded along Powers Blvd and a mPING report of buildings filled with water was recorded in the area. In the Denver Metro Area, roads were flooded after a storm near Littleton dropped half an inch of rain in only 5 minutes, according to a CoCoRaHS observer. Rainfall was even more intense on the Eastern Plains. In Burlington, over 3 inches of rain were reported causing heavily flooded roads and water up to doors of homes and business in the area. The Purgatoire River also reached flood stage on the 20th and 21st after the intense rainfall on the Raton Ridge and Southeast Plains. After the 20th, storms and heavy rainfall become more isolated thanks to a decrease in available moisture. Conditions were relatively calm during this period, with just a few minor flood reports as scattered storms brought localized heavy rainfall. The relative lull in heavy rainfall did not last long though as more monsoon moisture brought widespread flooding at end the month.

The month of July ended with a bang. First, on the 29th, slow moving storms caused road flooding in Cañon City and on County Rd 520 near the Spring Creek burn area. Slow moving, intense storms brought several inches of rainfall to areas along the Urban Corridor on the 31st, including Manitou Springs, Castle Rock, and Fort Collins. In Fort Collins, 3.64 inches fell in 2 hours and Sedalia recorded 4.01 inches in 6 hours. Several roads in Fort Collins experienced considerable flooding including the intersection of College and Mulberry where several feet of water left cars floating. Near Colorado Springs, a water rescue occurred by the intersection of 8th and Cimarron. Significant road flooding was also reported in Wellington, Castle Pines, and Longmont. Near Deckers, CO 126 was forced to close due to multiple mudslides that occurred on and near the road. There was even a debris flow on the Hayman Fire burn area, a fire which occurred in 2002 so the scar is over 20 years old. Plum Creek near Sedalia quickly rose into minor flood stage after the rain. As the day ended, a total of 14 flood/flash flood warnings and advisories were issued between the NWS offices and 16 total flood reports were recorded.

August

August picked right up where July left off with continued monsoonal moisture and days of significant flooding. The first three days of the month were very active, especially for the Front Range, Urban Corridor, and Eastern Plains. On the 1st, roads in downtown Wiggins were under several feet of water, and roads were flooded in southern Jefferson County. Continuing west, in Meeker a CoCoRaHS reporter recorded a 2-day precipitation total of 7 inches after intense rainfall from July 31st and August 1st. That 2-day amount has only a 0.001% AEP. The Cameron Peak burn area again saw two separate debris flows on the 2nd after daily rainfall totals were as high as 1.89 inches on or near the scar, covering County Rd 44H. On the 3rd, a debris flow was reported on CO 139 near Rangely, and an NWS employee near Pueblo reported rainfall amounts of 2.16 inches in one hour. Though there was no lack of strong storms, flooding was kept to a minimum after the 3rd until the 14th, a rare flood-free stretch in the middle of monsoon season. Rainfall picked up again from the 14th to the 17th thanks to another round of monsoonal moisture. This time, the threat stayed mostly west of the Continental Divide. This period was highlighted by a debris flow on the Grizzly Creek burn area that spilled onto I-70, closing traffic in both directions. Other notable flood reports on the 14th include water up to the top of pickup truck wheels in a parking lot, and running flood water down North Avenue, both in Grand Junction.

The remnants of Tropical Cyclone Harold closed out August with another active stretch of heavy rainfall events. Moisture from the storm brought a string of flood days from the 24th to the 28th, some of which were quite significant. The period began with the Grizzly Creek burn area again under pressure from heavy rainfall, with up to 1.43 inches of rain falling at nearby Glenwood Canyon on the 24th. A debris flow on the burn area once again closed I-70 in both directions for several hours. On the same day, the East Troublesome burn area also received up to 2.26 inches of rainfall. On the 25th, another debris flow occurred near Silverthorne and multiple roads were washed out near Brush after 4.50 inches of rain fell in a 24-hour period. On the 26th, the Grizzly Creek burn area was once again under pressure, this time with over 2 inches of rainfall. Multiple debris flows on the burn area spilled onto the I-70 east bound lanes, closing them yet again. On the 27th, Red Mountain Rd northeast of Fort Collins became impassable after sections of the road were washed out, and on the 28th, around 6 inches of water covered an intersection near Pueblo. As the remaining moisture exited the state after the 28th, it left 26 different flood reports in its wake over the 5-day span. The state remained mostly dry for the last 3 days of the month.

September

September was a welcomed quiet end of the season, with many days completely dry statewide. The 10th and 14th were the only days in the entire month that saw any reports of flooding. On the 10th, flooding was reported in Rye and La Junta on the Southeast Plains, while the high elevations saw their first snowfall of the season. Flooding on the 14th was more significant, with numerous strong storms from the Front Range to the Eastern Plains. The day was highlighted by a debris flow that occurred on the East Troublesome burn area, closing CO 125 in both directions, and on the nearby Cameron Peak burn area, County Road 44H was also closed due to flooding. Additionally, Colorado Springs and the Denver Metro Area both experienced several reports of road flooding on the 14th. Outside of those two days, the state remained largely dry and by the end of the month, sizable portions of Southwest Colorado returned to moderate drought, with scattered areas of severe drought conditions (Figure 10).

Seasonal Stats

There was a total of 73 Flood Days over the 2023 forecast season, which is above the 2012-2022 average of 67 Flood Days. Figure 13 shows the daily number of rain gauge reports over one inch for each day of the season, separated by east and west gauge locations, as defined by the 5,250-foot elevation contour (see Figure 16). Also overlaid is the estimated areal extent of precipitation that exceeded one inch, measured by Stage IV gridded precipitation. There were 60 (28) days in total where at least one station measured at least one (two) inch over eastern Colorado and 72 (33) days over western Colorado. Days with large areal extent and several gauges both east and west over 1 inch can be interpreted as large-scale rainfall events, such as May 10th as well as June 21st. More localized rainfall events tend to cover smaller areas with fewer gauges reporting rainfall, such as July 19th and August 3rd. The addition of areal coverage allows more rural Flood Day events to be captured, where rain gauges for verification can be far and few between. One limitation for Flood Day identification is that rainfall intensity may have not occurred within an hour, so widespread events could be representative of a stratiform rainfall event which tend to not cause flooding issues. Figure 12 also shows the lackluster NAM this season with days of dry stretches during the month of July into mid-August. Thankfully May and June rainfall, along with a plentiful snowpack from the preceding winter season helped to temper the wildfire season.

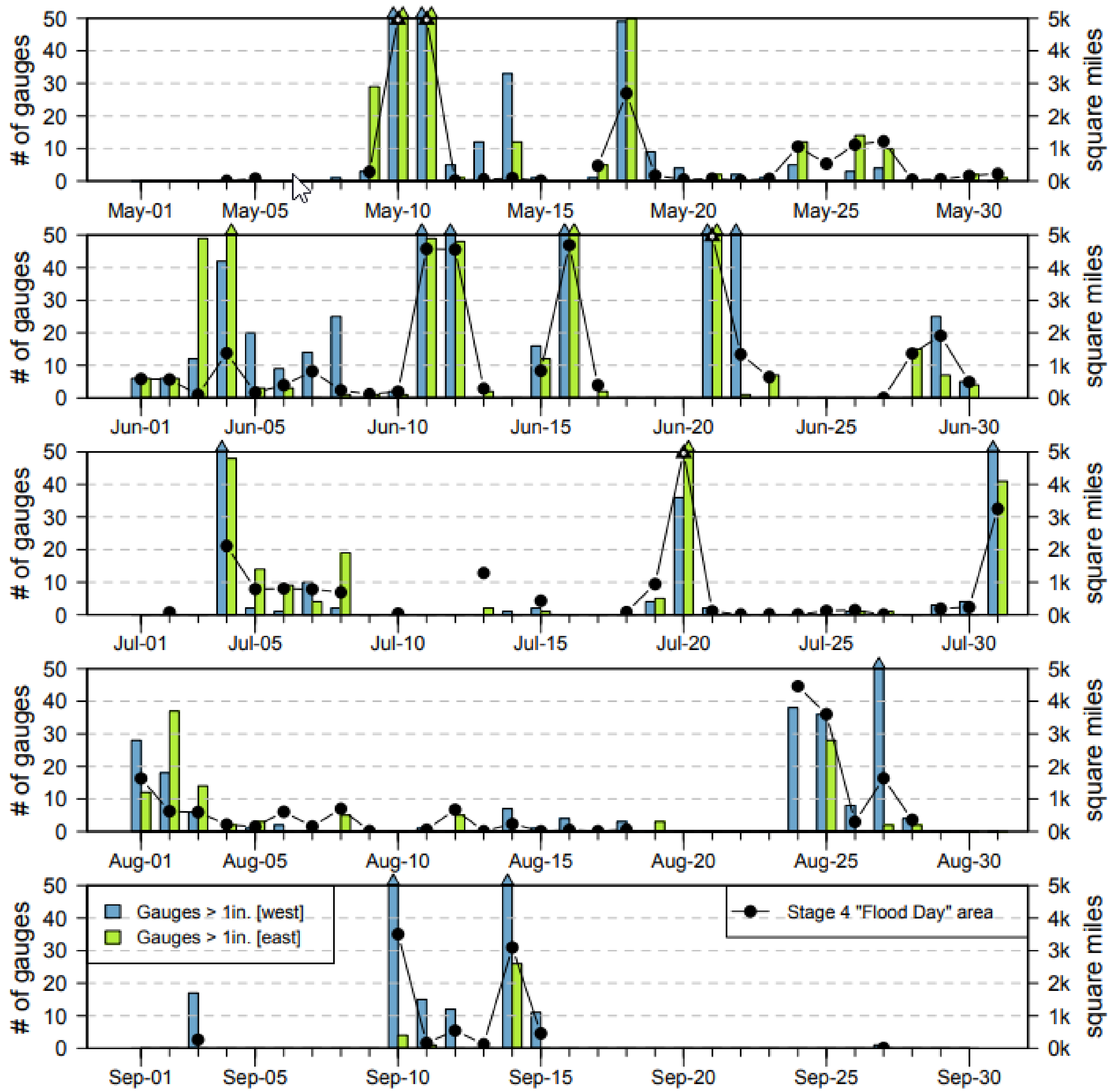

Figure 13: Daily summaries of number of gauges exceeding 1 inch of precipitation over "western" (blue) and "eastern" (green) areas. See Figure 16 for demarcation of these areas. A blue or green triangle indicates more than 50 gauges measuring 1 inch. See Appendix A for more detailed daily gauge statistics. Also shown is the estimated areal coverage of precipitation, in square miles, exceeding 1 inch based on NOAA Stage IV gridded precipitation product (line with black dots). Upward point triangles indicate an area in excess of 5,000 square miles. The total area of Colorado is 104,000 square miles.

There was a total of 273 individual flood reports this season. Flood reports came from various sources including NWS Local Storm Reports, CoCoRaHS observation remarks and significant weather reports that indicate flooding, social media reports of flooding with an identifiable location, and CDOT road conditions. Not surprisingly, June was the most active month for flood reports, with a total of 123 individual flood reports (Figure 14). Flood reports spanned across all 14 forecast zones, but the majority were reported along the Urban Corridor from Fort Collins to Colorado Springs. This makes sense due to the location of the majority of this season's precipitation focused on Northeast Colorado, the higher population to observe flood events, and widespread impervious surfaces that result in runoff.

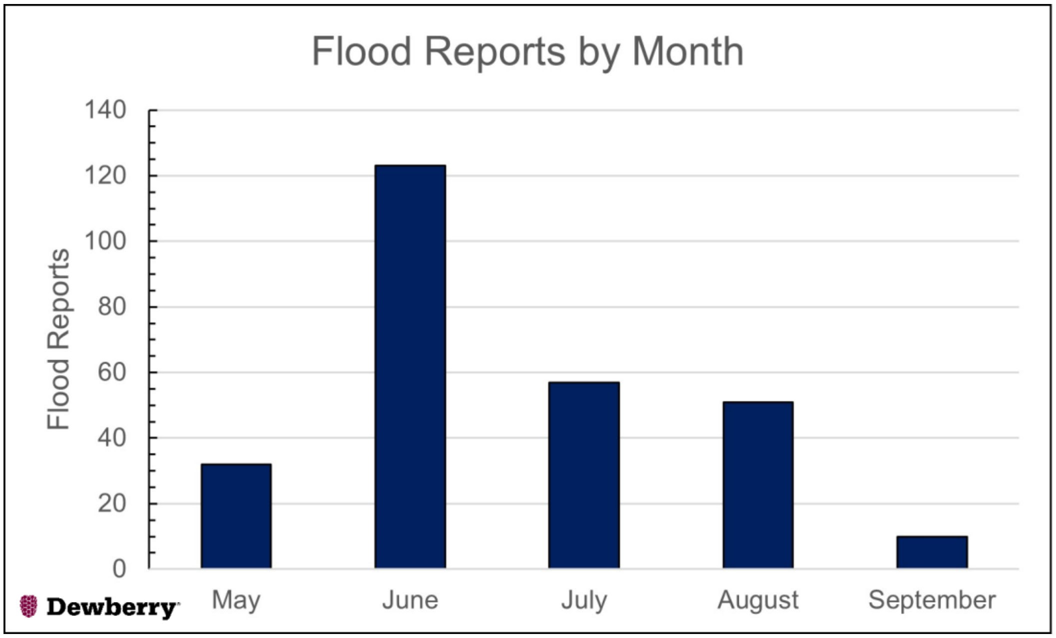

Figure 14: Number of flood reports per month of the 2023 season. May – 32, June – 123, July – 57, August – 51, September – 10. As expected, June saw the majority of flood reports this season. With the ongoing flood database, this figure will be updated to compare the flood reports by month between successive seasons.

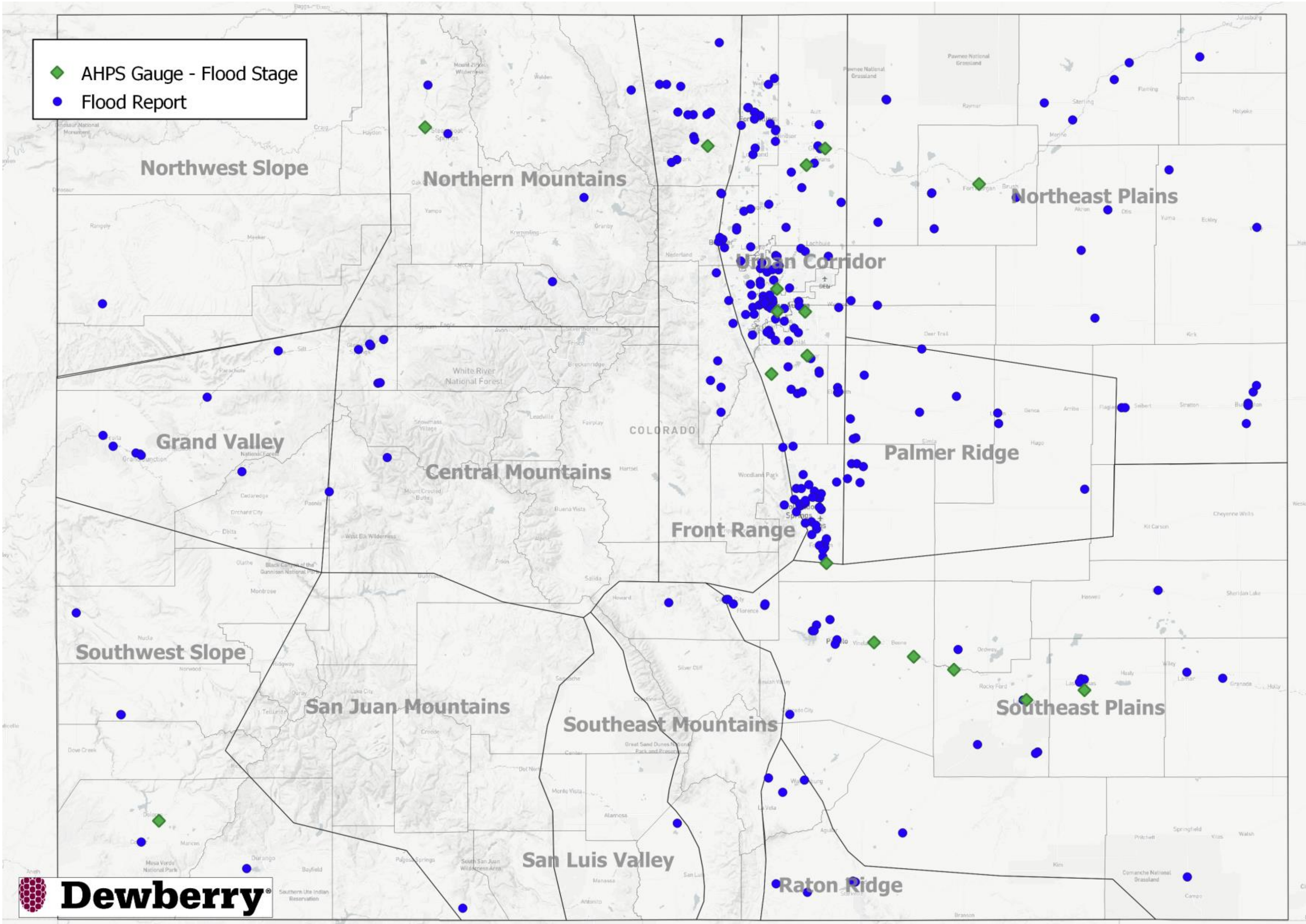

Figure 15: Map of all flood reports within the state from May 1 – September 30, 2023.

3) VERIFICATION METRICS

Data Sources

Daily FTB forecasts were verified on several factors, most notably the ability to: (i) identify days when flood threats were realized, (ii) specify the approximate location of the potential flooding without grossly overestimating the flood threat area, and (iii) minimize False Alarm forecasts where flooding was forecast but not observed. The inclusion of the Multi-Radar Multi-Sensor (MRMS) QPE product from the National Severe Storms Laboratory (NSSL), and rigorous treatment of daily QPE product bias based on scatter plots between rain gauges and their QPE values has also helped create a more thorough analysis. The Team continually places substantial effort on verification to increase forecast utility and, in turn, help improve future forecasts. The data sources and methodology used to verify the 2023 forecasts can be found in Appendix C.

FTB Verification Methodology

To determine if a flood threat was realized on a given day, a "Flood Day" identification system was developed to describe whether flooding and/or rainfall intensity capable of causing flooding was observed. A Flood Day is defined as a binary-type variable: it is either "Yes" when flooding and/or qualifying rainfall intensity is observed, or "No" otherwise. Note that, in practice, the latter condition is essential as flooding often goes undocumented or occurs in poorly gauged areas. Adding a measure based on rainfall intensity ensures a more comprehensive and consistent treatment of the issue. Given the large variance in the rainfall-runoff relationship across Colorado (see Appendix D), it would be difficult to describe a Flood Day with just a single intensity threshold. Thus, to provide some ability to cover relatively flatter eastern areas (higher threshold for flooding) compared with steeper central and western areas (lower threshold), a Flood Day is hereby defined when at least <u>one of following three</u> criteria is met in the issued flood threat area (e.g., Figure 17):

1. Gridded or observation based 1-hour and 2-hour rainfall exceeds (see Figure 16):
2. 1.00 in. west of the 5,250-foot elevation contour over the eastern plains
3. 1.50 in. east of the 5,250-foot elevation contour over the eastern plains
4. A qualifying NWS Local Storm Report (LSR) report is received. For more information, see Appendix C, data source "LSR" under "Storm Report". Note, only NWS LSRs were used for verification this season, not the flood report database collected and reported in the SPM.
5. If a Flood Day was based solely on the QPE data, additional conditions were checked. First, the areal coverage of qualifying rainfall must have exceeded ~50 square miles for each storm center. This helps to eliminate days with localized, marginal rainfall that is unlikely to cause flooding. Second, QPE bias plots were subjectively interpreted to ensure values were reasonable. See Appendix F for more information.

In verification reports from 2016 to 2021, the issuance of an NWS Flash Flood Warning would produce a Flood Day classification. However, due to varying topographic influences and uneven distribution of rainfall across the state (Appendix D), Flash Flood Warning issuance across Colorado NWS offices is not always consistent. Thus, NWS Flash Flood Warnings alone no longer cause a Flood Day classification. They could however contribute to a Flood Day if other factors are supportive. Note that this does NOT include Warnings issued over fire burn areas which have much lower rainfall intensity thresholds.

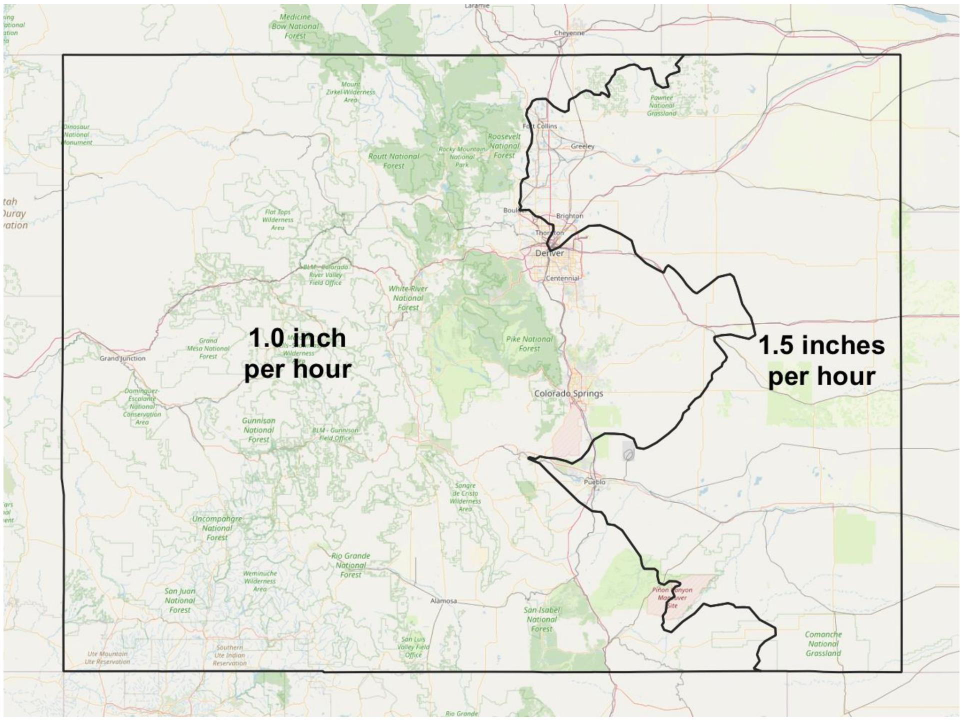

Figure 16: Colorado map with thick black line showing the 5,250-foot elevation contour line east of the Continental Divide, which acted as the demarcation in rainfall-runoff sensitivity. To the east, 1.50 inches in 1-hour is used to denote a "Flood Day"; to the west, 1 inch in 1-hour is used.

Despite the desire to create a purely objective Flood Day index, there are numerous reasons where the protocol above may yield an erroneous Flood Day classification. Thus, after an initial objective Flood Day calculation using the protocol above, a manual quality control procedure was completed to account for the overriding conditions shown in Table 5. As discussed previously, a significant addition to the manual procedure was the incorporation of a QPE bias assessment (BIAS in Table 5), which incorporates numerous factors and makes the previous years' HAIL and AREA conditions obsolete. Additionally, unlike in past years where the factors below generally resulted in a *removal* of an objectively defined Flood Day, the BIAS procedure is not one-way: it can either assign a Flood Day in a situation where QPE *underestimated* rain gauge data OR remove a Flood Day assignment if QPE *overestimated* rain gauges. This also explains why the number of instances where BIAS was applied was much higher than the HAIL and AREA methods in previous years. Simply stated, there are many days when the highest rain rates occur between rain gauges, and BIAS deciphers which of those instances are suggestive of a Flood Day. Lastly, since 1-hour and 2-hour gridded QPE and sub-hourly rainfall gauges are reliably available and the Program has new 24-hour thresholds for flooding set this season (2.75 inches west and 5 inches east), the Low Intensity (LI) flag used in past reports for long duration events has become obsolete and been removed as an overriding condition.

Table 5: Conditions warranting a change in the objective Flood Day classification

Condition	Label	Outcome	# Occurrences
Snowfall results in a qualifying 24-hour precipitation total, but minimal runoff does not support flooding.	Snow (SNOW)	Flood Day = 0	0
There is no rainfall over an area, but antecedent conditions and/or snowmelt cause riverine flooding.	Riverine (RIV)	Flood Day = 0	3
A Flood Day was only triggered by QPE guidance, which was determined to overestimate rainfall intensity (see Appendix F).	BIAS	Flood Day = 0	17

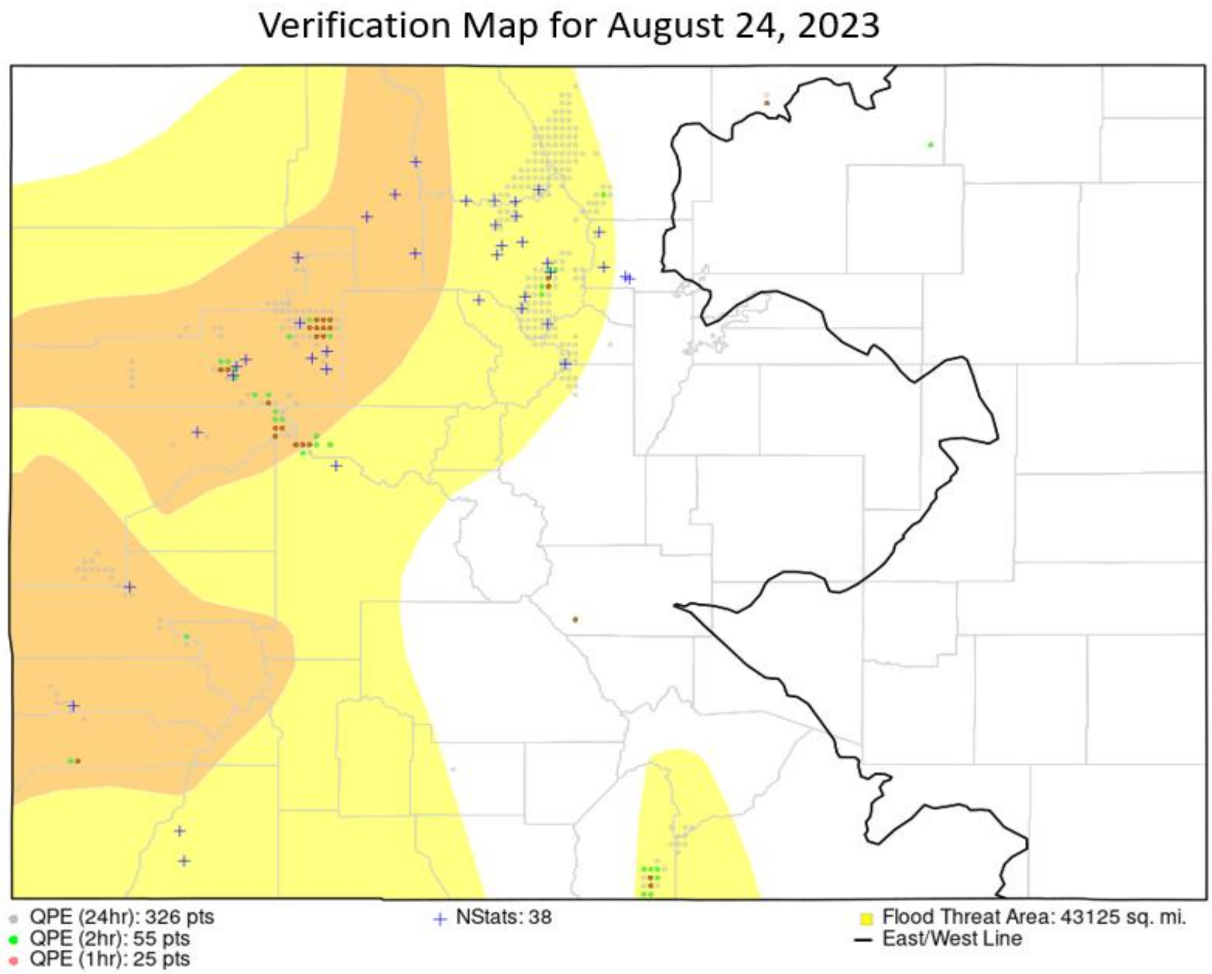

Figure 17: Example of daily verification map from August 24, 2023, showing qualifying 1-hour (red), 2-hour (green), and 24-hour (gray) MRMS grid points, qualifying rain gauges (blue crosses) and Moderate/Low threat areas (orange and yellow color fill, respectively).

FTB Results

Appendix A contains the Verification Worksheet that was used to assess forecast performance. To be consistent with previous seasons, the analysis herein is based on the initial flood threat map only and does NOT include any afternoon updates (PM Update) to the flood threat. Although, PM Update will be discussed in more detail below. As there is no single number that can comprehensively measure forecast accuracy, Table 7 shows the seven metrics that are used in this report, all based on the contingency table approach shown in Table 6. There are two possible outcomes when a Flood Day forecast is issued: (i) a Flood Day is observed [case (a) in Table 6], a "Hit", or (ii) a Flood Day is not observed [case (c) in Table 6], a "False Alarm". There are two additional scenarios that complete the set of all outcomes. First, if a "Flood Day" is not forecast, but is observed, this results in a "Miss" [case (b) in Table 6]. Second, if a non-Flood Day is forecast and a non-Flood Day is observed, this also results in a "Hit", although more specifically a "Dry Hit", which is often referred to as a correct negative [case (d) in Table 6]. Conventionally, real-time forecast operations generally strive to preferentially minimize the Miss Ratio, which, given the uncertainties with heavy rainfall forecasting, necessarily results in a higher False Alarm Ratio. CWCB has also supported this methodology. As shown in Table 7, target percentages for each metric have been established based on values accepted as reasonable within the forecasting community.

Table 6: Contingency table showing the four possible outcomes of forecasting and observing a Flood Day.

		Flood Day Forecasted	
		Yes	No
Flood Day Observed	Yes	(a) Hit	(b) Miss
	No	(c) False Alarm	(d) Hit (Dry)

Table 7: Description of metrics used for validating forecast accuracy.

Metric	Abbreviation	Calculations (see Table 6)	Summary	Goal
Accuracy or "Hit" Ratio	Hit %	$\frac{a+d}{a+b+c+d}$	Measures probability that all Flood Days and non-Flood Days are accurately forecast. Perfect forecast value is 100%.	>75%
Threat Score	TS	$\frac{a}{a+b+c}$	Measures probability that Flood Days (Hit) and non-Flood Days are accurately forecast. Perfect forecast value is 100%.	>60%
False Alarm Ratio	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 0%.	<20%
Probability of Detection	POD	$\frac{a}{a+b}$	Measures probability of accurately forecasting Flood Days. Perfect forecast value is 100%.	>75%
Miss Ratio	Miss %	$\frac{b}{a+b}$	Measure probability that a non-Flood Day is forecast but a Flood Day is observed. Perfect forecast value: 0%. Note the sum of the Miss % and POD equals 1.	<15%
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.	N/A

Table 8 shows the individual monthly and season-aggregated forecast verification. **Forecast verification performance exceeded all targets established in Table 7 for the season**. The overall **Hit Ratio (Hit %) of 90%** indicates that forecast performance remains high and well above the >75% targeted goal. More importantly, the **Probability of Detection (POD) was 86%.** This metric specifically singles out Hits vs. Dry Hits, which indicate accurate flood threat forecasts. The **False Alarm Ratio (FAR) is only 9%,** which is important because a lower FAR helps increase confidence in the forecasts that are issued by the Program. However, at the expense of the low FAR, the Miss Ratio (Miss %) increased. Nevertheless, the **14% Miss % is still low and meets Program goals**. As always, moving forward, the Program forecasters will try to find an optimal balance between the Miss % and FAR. It is important to stress that the Program errs on the side of caution in issuing threats, which often and necessarily results in a higher FAR, but lower Miss %. This is in stark contrast to the performance of the NWS analogous Flash Flood Watch product, which have a very low FAR, but at the expense of a significant Miss %.

Looking into the month-to-month performance, it was a very busy May and June with 34 Flood Days occurring. Table 8This is well above normal when compared to the 2014-2022 Program average of 25 Flood Days over the same period. One of the False Alarms issued in May (May 15th) was close to being categorized as a marginal Flood Day, which would have boosted the Teams' metrics. During the NAM (July and August), July was well below average with only 15 Flood Days occurring. July also had the highest Miss % (27%) with a total of 4 Misses. Forecasts improved heading into August, and the month was slightly more active with 20 Flood Days recorded. This is just around average. Of the 20 Flood Days, 10 of these occurred west of the Continental Divide, which is slightly below what is expected. The worsening drought over western Colorado during this same period indicates that these Flood Day storm cores were highly localized vs. widespread rainfall events. The season ended on its typical quiet note, with only 4 Flood Days during September. Although FAR and Miss % are below target goals, these numbers are inflated due to the low number of observed Flood Days. The lone Miss occurred on September 13th over the Raton Ridge where gridded QPE indicated a Flood Day over an area of approximately 175 square miles.

Table 8: Summary of forecast performance, by month and in total. Red font indicates performance did not meet program targets.

Forecast / Observed	May	Jun	Jul	Aug	Sep	Total
(a) Flood / Flood	13	17	11	19	3	63
(b) No Flood / Flood	2	2	4	1	1	10
(c) Flood / No Flood	3	1	0	1	1	6
(d) No Flood / No Flood	13	10	16	10	25	74
Total Days	31	30	31	31	30	153
Hit %	84%	90%	87%	94%	93%	90%
POD	87%	89%	73%	95%	75%	86%
FAR	19%	6%	0%	5%	25%	9%
Miss %	13%	11%	27%	5%	25%	14%

Taking a more in-depth look at Misses, 3 of the 10 Misses (see Appendix A) occurred on days where a Flood Threat was issued but Forecast Zones within the threat area did not reach Flood Day criteria. An example of this is shown in Figure 18 from July 21st. The Low threat was drawn along the Southeast Mountains, but the qualifying rates for a Flood Day occurred further north in the Front Range and southern Urban Corridor. In this case, the total flood area determined by QPE was about 60 square miles, so thankfully no flood reports were identified (Table 9). Of the remaining two events, both with a flood area of about 230 square miles, only July 29th had a flood report associated with it. Torrential downpours near Cañon City caused road flooding, and an outdoor event had tables and chairs washed down the street. While a marginal Miss can be somewhat understandable even with forecast advancements, how to deal with larger areal Misses will be addressed in the off-season. One way to avoid these in the future would be to error on the side of caution and draw larger threat areas that encompass all the heavy rainfall ingredients. Additionally, a PM Update could be issued if the morning forecast is not on track, or the favorable environment for heavy rainfall drastically changes.

Table 9: Days where a flood threat was drawn but did not overlap the Forecast Zone(s) where flooding occurred.

Date	Threat Level	Flood Area (sq mi)	Pluvial Flood Reports
July 21	Low	60	
July 29	Low	275	Flooded road curb to curb near Cañon City. Washed chairs and tables from outdoor event down the street.
July 30	Low	286	

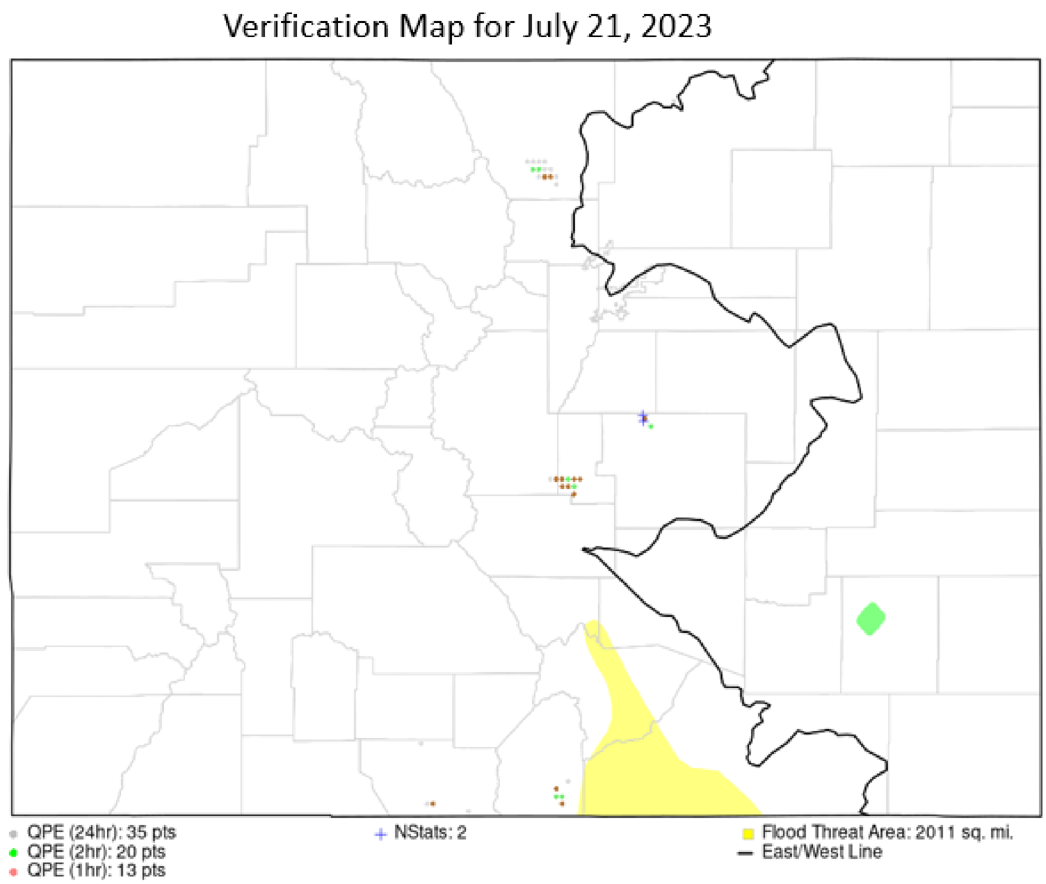

Figure 18: Daily verification map for July 21, 2023, showing qualifying 1-hour (red), 2-hour (green), and 24-hour (gray) MRMS grid points, qualifying rain gauges (blue crosses) and Low threat area (yellow color fill). There is also a riverine flood warning along the Purgatoire River near Las Animas (green color fill).

Table 10 (below) shows yearly performance summaries for the Program from 2012 to present. Despite a weaker than normal NAM, due to the active May and June rainfall, **the number of Flood Days was 73 this season**. **This is the highest number of Flood Days since the 2017 season, which had 76 Flood Days, and is 6 days above the 2012 to 2022 average**. **As far as hitting all the metrics laid out in Table 7, this is only the third time in Program history that this has been achieved since the overhaul of the verification procedure in 2014.** Although the POD was slightly down from the last season (6%), it is still well above the target goals. The FAR of 9% is the lowest in program history with the next closest FAR being 13% (2019 and 2020). There was a 6% increase in the Miss %, but 14% still meets Program goals. Finally, this is the first time since 2019 that the Bias has been below 1. This indicates slight under-forecasting of Flood Days. The Team aimed at reducing the FAR this season, but not at the expense of the Miss %, which was accomplished. Off-season improvements to forecast guidance will continue, which should allow the Team to have another successful season in 2024.

Table 10: Summary of yearly forecast performance since 2012. Note that the verification procedure was significantly enhanced in 2014, which makes it difficult to compare pre-2014 statistics to 2014-present.

Year	Hit %	TS	FAR	POD	Miss %	Threats Issued	Flood Days	Bias
2012	86%	N/A	18%	84%	16%	65	64	1.02
2013	84%	N/A	13%	85%	15%	83	85	0.98
2014*	76%	N/A	18%	73%	27%	75	84	0.89
2015	77%	N/A	25%	78%	22%	85	88	0.97
2016	84%	N/A	21%	88%	12%	93	91	1.02
2017	86%	N/A	15%	86%	14%	76	74	1.03
2018	87%	N/A	21%	82%	18%	52	50	1.04
2019	86%	65%	13%	72%	28%	48	54	0.83
2020	89%	67%	13%	74%	26%	41	34	1.21
2021	88%	73%	20%	90%	10%	65	58	1.12
2022	87%	71%	25%	92%	8%	64	52	1.25
2023	**90%**	**80%**	**9%**	**86%**	**14%**	**72**	**73**	**0.95**

Table 11 shows the forecast performance as a function of threat level. Note that the threat level in the table represents the highest threat issued for a given day. A robust forecast system should show higher skill as the threat level increases due to more confidence that heavy rainfall and/or flooding will be realized. This proves to be the case again in 2023 with an **82% Hit % for Low threats, while Moderate and High threats had 100% accuracy.** This is a slight improvement when compared to last season where there was one observed non-Flood Day for a Moderate threat (False Alarm). During the 2023 season, there were no days when a High Impact threat was issued. Work will continue in the off-season to discuss when and where these should be issued, especially if flooding is expected to significantly impact urban areas. It should be noted that the methodology in Table 11 does not penalize the three cases where Low threats were issued but verified for a different area and qualified as a Miss.

Table 11: Accuracy as a function of threat level, which corresponds to the (potential) impact. Note: threat levels categorization was reduced to the highest non-burn area threat level.

Threat Level	Observed Flood Day	Observed Non-Flood Day	Total Days
Low	27 (82%)	6 (18%)	33
Moderate	32 (100%)	0	32
High	7 (100%)	0	7
High Impact	0	0	0
Total	66 (92%)	6 (8%)	72

PM Updates

Occasionally, there are forecast uncertainties that make the morning flood threat assessment challenging. For example, cloud cover may be present causing uncertainty in afternoon instability, which would directly impact the chance for stronger thunderstorm development and resulting heavy rainfall. Or a forecast can change from what is predicted. For example, if dew points trend several degrees higher than the original forecast, rainfall rates are likely going to be higher than initially forecast. There may also be some uncertainty in the impact from rainfall. Often confidence for a flood event increases over the course of the day as ingredients come together. So, what is initially forecast as a Low flood threat may become a Moderate flood threat by the early afternoon. All these scenarios are reasons why a PM Update may be issued by the Team. A PM Update will include an update to the flood threat map, more accurate maximum rainfall intensities, and the specific locations that are most likely to see flood impacts. When possible, the Team tries to mention the possibility of a PM Update and where forecast uncertainty lies in the morning discussion. This will allow the end-user to tune back in by early afternoon (before rainfall begins) for any updates to the forecast. In addition to a short discussion explaining the PM Update issuance at the top of the day's FTB discussion, new social media posts are also disseminated to the Program's accounts.

Over the course of the 2023 season, there were eight PM updates issued (:). Of these updates, five featured upgrades of the morning threat level due to higher confidence in the chance of flooding later in the day. For example, the two Moderate threats in June were upgraded to High threats once there was better confidence in the placement of heavy rainfall. Both days "Hit" in the High threat area and widespread, impactful flooding occurred. Interestingly, the PM Updates issued on May 9 and May 17 ended up rectifying a morning forecast that was counted as a Miss in the verification. Therefore, overall metrics for the season would have improved to an 89% POD and 11% Miss % if PM Update metrics were counted in the verification. Both examples illustrate the value of these updates and demonstrate the importance of monitoring storm ingredients throughout the day for the best available flood forecast. Though it is ideal to provide FTB forecasts with maximum lead time, the changes made with the PM Updates are often still able to provide at least 1 to 2 hours of lead time.

Table 12: Dates where a PM Update was issued. Asterisks indicate an improvement from the morning forecast.

Dates	AM Threat	PM Threat	AM Outcome	PM Outcome
May 9*	None	Low	Miss	Hit
May 10	Moderate	Moderate	Hit	Hit
May 17*	None	Low	Miss	Hit
June 21	Moderate	High	Hit	Hit
June 29	Moderate	High	Hit	Hit
July 19	Low	Moderate	Hit	Hit
July 31	Moderate	Moderate	Hit	Hit
August 1	Moderate	Moderate	Hit	Hit

4) USER ENGAGEMENT

An online presence through the Program's website and social media accounts continues to be of importance for increasing the Program's audience and reputation. Even a perfect forecast can have little to no value if it is not properly disseminated, which is why the Program continues to participate in forecast communication through a diverse set of mediums. Like prior seasons, the Team provided end-users with four outlets to receive forecast updates and other flood threat information. Most significant is the Program website (Table 13), which has been the main form of communication since the Program began and underwent a complete redesign prior to this season. Beginning in 2017, the Team began providing an email alert option that sent the Flood Threat Bulletin's headline to end-user's inbox each morning with a link to the full post. The Team also continues to utilize the X social media platform to provide forecast updates, interesting hydrometeorological observations, and other informational messages. In 2018, a Facebook page was created to reach a separate demographic from X. All four forms of communication continue to be utilized with encouraging results on the social media front. Nonetheless, in the future, direct outreach to Office of Emergency Mangers, Police, Fire, or government entities that do not follow one or more of the Programs' accounts would be beneficial to expand the Program's utility.

Table 13: Website and social media accounts used by the Flood Threat Bulletin.

WEBSITE	ACCOUNT	ENGAGEMENT
Website	www.coloradofloodthreat.com	278 Subscribers (+113)
X (formerly Twitter)	@COFloodUpdates	1720 Followers (+129)
Facebook	@COFloodUpdates	638 Followers (+53)

Due to the always changing popularity of the various social media outlets and platform layout updates, it is recommended that the Program always monitor the effectiveness of its online presence and the popularity of the content that is shared by the Program. It is also important to note that, to some extent, all the communication methods described herein compete with one another (i.e., if an end-user uses X to view Program content, they may not use another method). Thus, providing end-users with options, but without excessive bombardment, is a logical strategy. Table 14 summarizes the most important social media and website usage metrics over the 2016- present period.

Table 14: The Program's website and social media usage metrics from 2016 to 2023

SOCIAL MEDIA METRIC	2016	2017	2018	2019	2020	2021	2022	2023
Email Subscribers (end of season)	--	19	35	128	131	142	165	**278**
Median Daily Website Viewership on **No-Threat Days**	24	18	22.5	51	27	46	42.5	**38.5**
Median Daily Website Viewership on **Low Threat Days**	32	22	44	66.5	44	48	70	**53**
Median Daily Website Viewership on **Moderate Threat Days**	41.5	34	58	98	56	86	98.5	**69.5**
Median Daily Website Viewership on **High/High Impact Threat Days**	90.5	42	117	106	212	191.5	185	**73**
X Followers	901	1,036	1,183	1,331	1,404	1,528	1,591	**1,720**
Avg. Daily X Impressions	1,874	1,973	2,059	1,597	1,590	3,299	1,782	**2,171**
Facebook Followers	--	--	155	272	323	421	585	**638**
Avg. Daily Facebook Reaches	--	--	--	--	440	456	953	**386**

Email Subscription and Website

The number of email subscriber increased by 113 this season, finishing the season with a count of 278. This is the greatest increase in subscriber count in Program history, beating the 2018-2019 increase of 93 new subscribers. The newly designed website utilizes the latest Google Analytics (GA4) to track website usage. Figure 19 shows daily website usage during 2023 (black) overlaid with the previous four seasons. As expected, median website viewership increases on days with increased flood threat. The 2023 median viewership on No Threat days was just 38.5, but 69.5 on Moderate and 73 on High/High Impact days. Usage peaked at 337 on May 11th when a Low flood threat was issued following two previous days of heavy rainfall. Usage remained high throughout June, a month with numerous Moderate and High flood threats. There was a total of 10 Moderate and 3 High flood threats issued from June 1st to 30th. During this period, the average number of daily users was 107, which is higher than 2023 season average of 67. Website usage for the remainder of the season decreased after July 1, averaging 43 daily uses. This decrease can likely be attributed to the decrease in daily flood threats issued and heavy rainfall events that occurred

Overall median website usage was down this season from 2022 but falls in line with Program averages. The exception to this is on High/High Impact Threat Days, which had a median of only 73 viewers, compared to the 2016-2022 average of 134. It is difficult to pinpoint exact reasons that website viewership may be down, particularly on High threat days, but improved bot filtering in GA4 this season may indicate artificially high viewership in previous season.

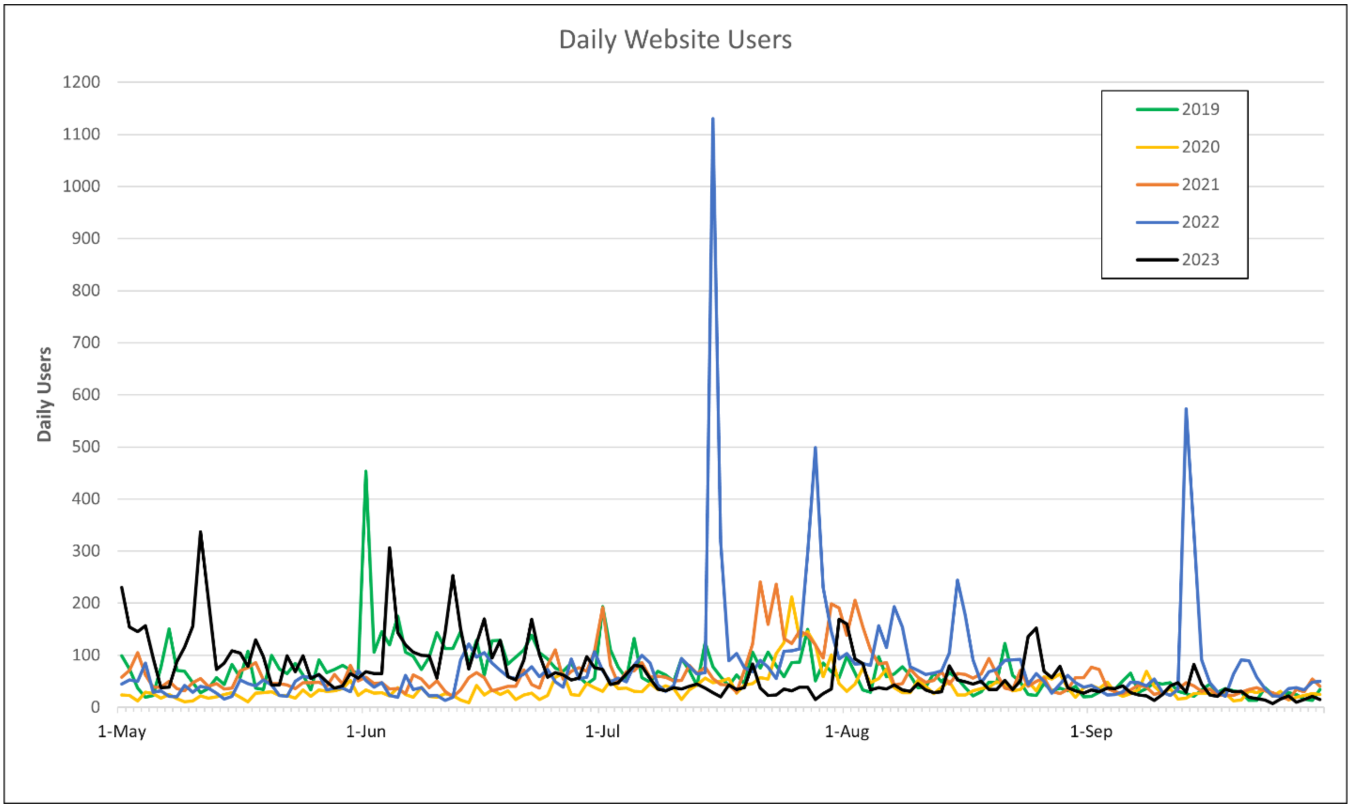

Figure 19: Daily Website users during 2019 (green), 2020 (yellow), 2021 (orange), 2022 (blue), and 2023 (black).

Social Media

During the historic floods of September 2013, the Program noted an opportunity to expand the outreach of the Flood Threat Bulletin to better inform the public of the current and forecasted flood situation. The method that was selected was the X social media platform, with the goal being to provide updates on any impending flood related threat across Colorado in a concise, headline-style matter. The X account was an immediate success during the September floods, and it was assimilated into daily operations starting in 2014 to provide (i) meteorological information in the form of links to our forecast products (FTB and FTO), (ii) "nowcasts", of interesting flood-related weather conditions or observations, (iii) life threatening National Weather Service Flash Flood Warnings, and (iv) heavy rain/flooding reports from the public and National Weather Service offices. Additionally, due to the wealth of hydrometeorological data that is collected in support of the daily FTB and biweekly FTO posts, the Program's social media strategy attempts to maximize the way this data is leveraged by creating unique posts. For example, Figure 20 is a pair of Tweets sent on August 25th indicating the potential for extremely heavy rainfall for significant portions of the state. These Tweets combined saw over 8,400 Impressions and 4 Retweets; the season average number of impressions is 2100 and retweets is 5. The #cowx hashtag on X was also the main source of social media reports for the SPM, though by the end of the season it proved to be less and less useful. This is suspected to be due to a general decrease in X users stemming from high-profile volatility within the company, and changes to the timeline algorithm prioritizing users that pay a subscription fee.

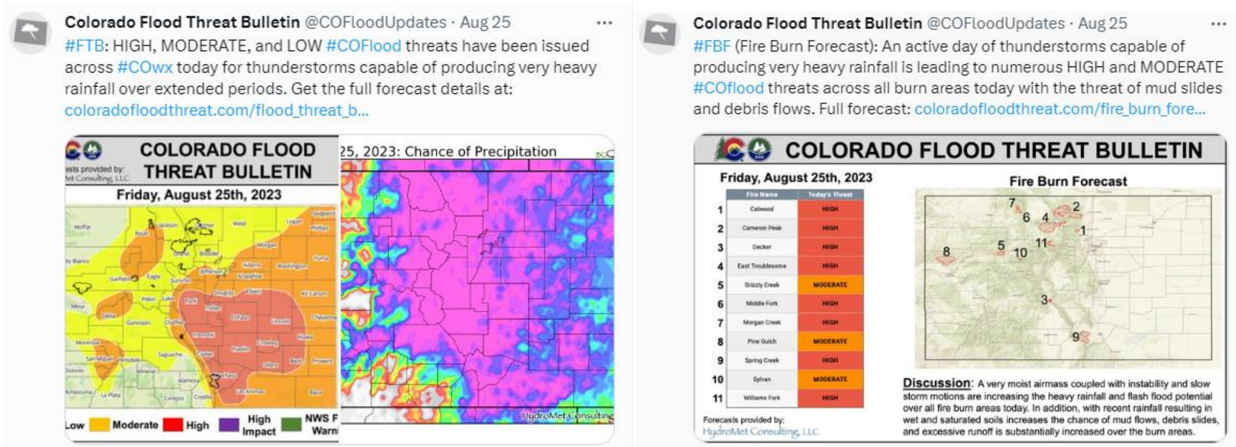

Figure 20: A pair of Tweets sent on August 25, 2023. These Tweets saw a combined 8400 Impressions

The Program's X account, @COFloodUpdates, continues to increase viewership since its inception with the total number of followers up to 1,720 by the end of 2023 season. This is a moderate increase in followers (+ 129) from the end of the 2022 season. A good portion of the Program's success can be attributed to the number of Retweets from well-followed and respected accounts such as the Colorado Emergency Management (69K+ followers) and the Colorado Climate Center (4K followers), and FEMA Region 8 (44K+ followers). This season there were 633 Retweets, which is down from 765 last season. As always, Retweets by popular media accounts can add new X followers, and at the same time expose the Program to a more diverse group of end-users such as when Reed Timmer became a Follower this season. Over the 2023 season, the Program created 301 unique Tweets, 15 fewer than 2022.

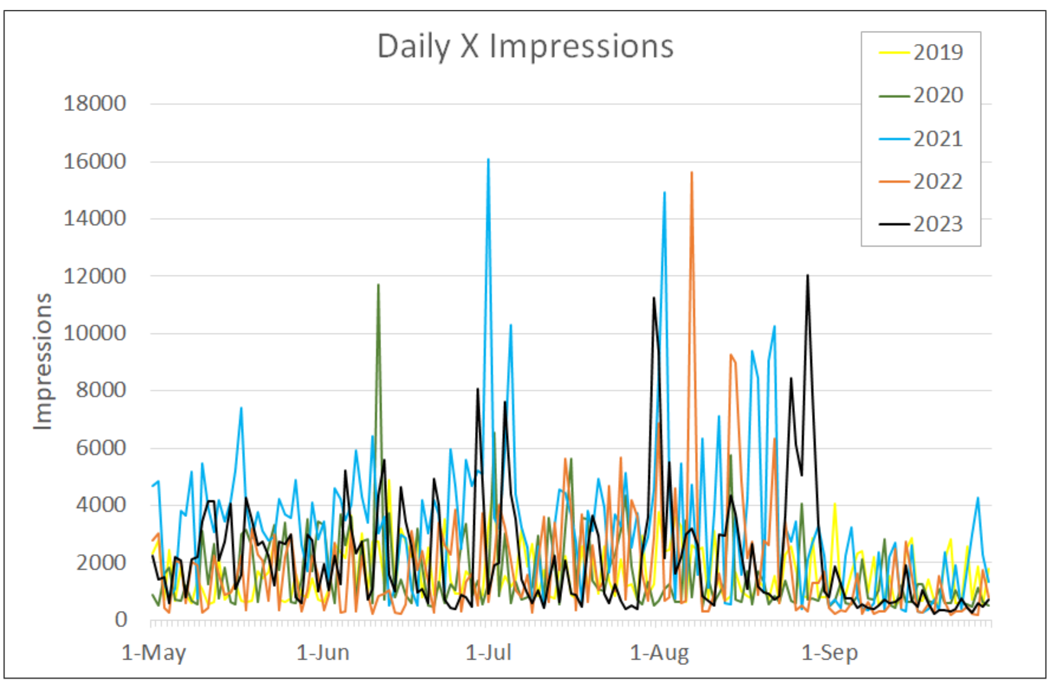

Figure 21: Daily X Impressions during 2019 (yellow), 2020 (green), 2021 (blue), 2022 (orange), and 2023 (black).

The most notable Followers of the Program's X account over the years are as: Colorado Emergency Management, FEMA Region 8, Colorado Flood DSS, READY Colorado, 9News Denver, CoCoRaHS, ESRI, AAA Colorado, Red Cross Denver, Colorado State Patrol Troop 1E, Denver Sheriff, Colorado.gov, NWS – Grand Junction, NWS – Pueblo, NWS – Goodland, NWS – Boulder, Colorado Climate Center, CU Boulder, Durango Herald, Forest Service ARP, KDVR FOX31 Denver, FOX31/CW Pinpoint Weather, CBS Denver, KKTV 11 News, CASFM, Pikes Peak Red

Cross, Northern Colorado Red Cross, Colorado National Guard, CASFM, Denver Water, The Disaster Channel, Weather West, Colorado Wildfire Info, GMUG National Forests, and Colorado Springs Gazette. Although not mentioned by name, various police precincts, city/county government offices, TV and newspaper reporters and meteorologists from across the state, radio stations, academia meteorologists, individual citizens of Colorado, private meteorologists, fire and rescue units also follow the Program's X account. We will continue to engage local media as new accounts continue to be created each season.

Since the X account has been successful at circulating the FTB forecast products, a Facebook account for the Program was created at the beginning of the 2018 season. The main push behind the idea was that the Facebook page would likely reach a different demographic of potential end-users. The **@COFloodUpdates** handle was reused for the Facebook page to keep uniformity across the social media accounts. All posts on Facebook were also updated simultaneously with the X account, so information exchange would be consistent. One drawback to Facebook is that posts do not show up on the News Feed chronically, so end-users must visit the page directly for up-to-date flood information. The Facebook platform can be best utilized for upcoming events laid out in the FTO and special in-season analyses, since these are not as time sensitive as ongoing forecasts.

Facebook, like X, has its own set of analytics called Insights, which can be used to evaluate the success of an additional social media account. By the end of its sixth season, the Facebook account gained several new Followers putting the total at 638. While this number continues to be quite a bit lower than the X account, the number of Followers increased approximately 9% from the end of the 2022 season, which shows the media platform still has utility despite the changes to the platform over this season. The most similar analytic to X Impressions is post "Reaches". Reaches are defined as the number of people who had any posts from our page enter their screen, and they can also assess the effectiveness of each post. The use of specific hashtags also plays a large role in expanding viewership on all social media platforms and helps grab attention on specific holidays when outdoor recreation can be increased. A hashtag is a method of organizing messages into categories that the hashtag is supposed to succinctly summarize. For example, the #COFlood hashtag is one that the Program consistently uses and has become almost completely dedicated to our products. Hashtags are searchable through X and Facebook and using these relevant and popular hashtags such as #COwx or #COFlood allows people looking for specific information to be directed to our products. The following is a list of common tags that were used in 2023: #FTB, #FTO, #SPM, #COwx, #COFlood, #COFire, and #CODrought.

Email Alerts

A subscription for receiving the daily FTB headline to an end-user's email began on April 28th, 2017. As of October 1st, there are 278 active subscribers, which is a substantial increase from the 165 subscribers at the end of last season. Continuing to increase the number of subscribers should continue to be a key objective for the Program, which could be achieved by another preseason campaign. It is also recommended to consider other methods on how to better advertise the email subscription option, such as a prior idea of reaching out to local Emergency Managers that do not follow the Program. Finally, a reminder email should be sent out to subscribers in mid-April alerting them of the return of the FTB May 1st, 2024, and inform end-users of any additional upgrades to the products.

Outreach

Following the successful user training webinar in 2022, a series of recorded videos of the webinar were uploaded to YouTube and a link was included on the Program website for the 2023 season on the "About" page. Topics of the training webinar included a brief history of the program, detailed discussions of each product (FTB, FBF, FTO, SPM, and Streamflow Tracker) and how they are produced by forecasters, followed by a question-and-answer session. YouTube analytics has recorded 47 total views of all webinar videos over the last calendar year, most of which occurred in late Spring 2023, prior to the season beginning. The low number of views on the videos suggests more effort can be made in publicizing the user training to the public prior to and throughout the flood season.

The dedicated outreach budget for 2023 was used to attend CWCB's Water Availability Task Force April Meeting, held on April 20, 2023. The team provided a demonstration of the updated Program website. Additionally, budget was used to submit an abstract and attend the Colorado Association of Stormwater and Floodplain Managers annual conference in Keystone, CO in September 2023. The presentation titled "Colorado Flood Threat Bulletin: Where We've Been, Where We Are, and Where We are Going" was well received by conference attendees during the Hazard Management I session on Monday, September 18.

5) CONCLUSIONS

1. There was a pronounced difference between rainfall totals over the eastern and western halves of Colorado this season. Eastern Colorado received much more precipitation, which helped alleviate early season drought conditions. May and June rainfall over eastern Colorado was well above average to record breaking, and many daily rainfall records were broken during this period (Figure 12). During July, the monsoon was slow to begin and could be characterized as inconsistent and weak, especially over western Colorado. July ended up being the record driest for many areas over southwest Colorado. During August (the typical height of the monsoon over western Colorado), the southern San Juan Mountains ranked in the 10th percentile for precipitation. Despite a strong snowpack and drought-free conditions in May, drought conditions returned to western Colorado by mid-July.

2. Riverine flooding due to snowmelt and runoff from rainfall was a common occurrence during May and June. Routt, Moffat, and Mesa Counties had ongoing riverine flooding from snowmelt for 21 days during May, but thankfully major flooding issues were adverted. During June, ongoing rainfall events caused several rivers and creeks over eastern Colorado to flood due to the record-breaking rainfall which included portions of the Arkansas River, South Platte River, Fountain Creek, and Box Elder Creek.

3. Even with the slow monsoon season, there were 72 flood threats issued, so an above average season. Of these threats, 33 were Low threats, 32 Moderate and 7 High threats. Areas over the Palmer Ridge saw up to 40 days with flood threats issued, while the normally active San Juan Mountains only saw up to 15 days (see Figure 25, Appendix E). This is the lowest number of flood threats issued for western Colorado since at least 2016.

4. The FBF continued to be a successful addition to the Program with high viewership on disseminated forecasts. The same 11 burn areas from 2022 were forecast for again this season, but with higher rainfall intensity thresholds (Table 3). There were 13 flood events over the burn areas this season. Seven of these occurred on Cameron Peak, and there was a water rescue from the event on July 20th where an estimated 1.3 inches of rain fell in 3 hours (15% AEP). Grizzly Creek had four flood events this season, three directly related to rainfall and one due to snowmelt. The remaining two reports were on East Troublesome and Spring Creek.

5. Forecast verification metrics were some of the best in Program history (Table 10). This is the third time since 2014 that all the Programs goals were met. This season also saw the lowest all-time False Alarm Rate at 9%, which should help increase confidence in the forecasts that are issued. The Miss Ratio was at 14% (1% below the goal) and the Probability of Detection was 86%. Metrics would have slightly improved if PM Updates were included in the analysis. These seasonal stats should boost confidence for Program end-users.

6. This season saw the largest increase in email subscribers with 278 by the end of the season, up from 165 in 2022. Website viewership was down this season compared to last year but fell in line with Program averages while continuing to see increased viewership on days with a threat issued. Social media accounts on X and Facebook also had increases in viewership, proving value in disseminating Program information acrossthe various platforms.

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APPENDIX A – FORECAST VERIFICATION WORKSHEET

Table 15 shows the daily verification worksheet documenting the intensity and coverage of heavy precipitation, along with whether a Flood Threat was issued. An asterisk (*) next to the date indicates that an afternoon update was issued. To be consistent with previous seasons, the analysis herein is based on the initial flood threat map only and does NOT include any afternoon updates to the flood threat. Two asterisks (**) indicate that a threat was issued, but that it did not encompass the heavy rainfall event, so it was counted as a "Miss" (this is a new upgrade beginning in 2022). Dates where an NWS Flood or Flash Flood Watch was issued due to rainfall, not snowmelt or riverine flooding, are shaded in green. These have been filtered to exclude burn area only Flash Flood Watches. Lastly, new 24-hour flood thresholds were created for the Program this season (2.75 inches west & 5 inches east). These values are bolded when exceeded in the worksheet for Max 24hr-E and Max 24hr-W for ST4 and MRMS data.

The columns in the table are described below.

<u>NSSL MRMS Quantitative Precipitation Estimate:</u> Contains the sub-categories below.

Max 1hr-E (inches): Maximum 1-hour precipitation east of the 5,250 ft. elevation contour.

Max 2hr-E (inches): Maximum 2-hour precipitation east of the 5,250 ft. elevation contour.

Max 1hr-W (inches): Maximum 1-hour precipitation west of the 5,250 ft. elevation contour.

Max 2hr-W (inches): Maximum 2-hour precipitation west of the 5,250 ft. elevation contour.

Max2 4hr-E (inches): Maximum 24-hour precipitation east of the 5,250 ft. elevation contour.

Max 24hr-W (inches): Maximum 24-hour precipitation west of the 5,250 ft. elevation contour.

<u>NOAA Stage IV (ST4) Quantitative Precipitation Estimate:</u> Contains the sub-categories below.

Max 24hr-E (inches): Maximum 24-hour precipitation east of the 5,250 ft. elevation contour.

Max 24hr-W (inches): Maximum 24-hour precipitation west of the 5,250 ft. elevation contour.

<u>QPE</u>: Contains the highest total number of 24-hour points exceeding Flood Day threshold between the MRMS and Stage IV data. Note that 1 point is equivalent to about 5.5 square miles of areal coverage.

<u>Rain Gauges</u>: Contains the sub-categories below. See Appendix C for more information about gauge networks considered in this analysis. All values shown are 24-hour totals.

NStats (number): Total number of rainfall gauges exceeding Flood Day thresholds statewide.

Max-E (inches): Maximum observed rainfall from all gauges, east of the 1600m contour.

Max-W (inches): Maximum observed rainfall from all gauges, west of the 1600m contour.

<u>Flood Reports</u>: Whether or not a flooding or qualifying heavy rainfall report was received that day.

<u>Flood Day</u>: Denotes whether or not the day qualified as a Flood Day.

<u>Threat</u>: Highest category of the Flood Threat.

<u>Total Threat Area</u>: Areal coverage (square miles) the issued Flood Threat covered that day.

<u>Flags</u>: An overriding factor to the objective Flood Day classification due to the following.

SNOW: Snowfall results in a qualifying Flood Day 24-hour precipitation total but did not result in flooding.

RIV: Riverine flooding from antecedent rainfall/snowfall, but no concurrent Flood Day threshold precipitation was observed.

BIAS: Indicates significant discrepancy, both overestimates and underestimates, between gridded QPE and rain gauge estimates that required a manual adjustment of the Flood Day assignment (see Appendix F)

<u>Flood Day Classifications</u>: Indicates the leading source that led to the assignment of a Flood Day.

LSR: NWS Local Storm Report(s) indicating flooding.

GAUGE: Quality Controlled rainfall gauge(s) reporting a qualifying rainfall rate.

GRIDDED: Gridded QPE (MRMS or ST4) reporting a qualifying rainfall rate over a ~50 square mile area.

<u>Outcome</u>: Classification of Flood Threat into the following three categories. Note that a blank implies a correct forecast though no Flood Day occurred (dry case).

False Alarm*:* A Flood Day was forecasted, but a non-Flood Day was observed,

Miss: A Flood Day was observed but not forecasted or the flood threat was not issued over the region that received heavy rainfall,

Hit: A Flood Day was observed and forecasted correctly.

Table 15: Daily FTB Verification Worksheet

	NSSL MRMS Quantitative Precipitation Estimate						NOAA ST4 Quantitative Precipitation Estimate		QPE	Rain Gauges			Flood Reports							
Date	Max1hr E	Max2hr E	Max1hr W	Max2hr W	Max24hr E	Max24hr W	Max24hr E	Max24hr W	24hr Flood Area (Max)	NStats	Max-E	Max-W	Reports	NWS Warning or Advisory	Flood Day	Threat	Total Threat Area	Flags	FD Classification	Outcome
Units	inches	inches	inches	inches	inches	inches	inches	inches	points	number	inches	inches	number				Miles			
1-May	0	0	0.16	0.27	0	0.33	0.01	0.26	0		0.36	0								
2-May	0.18	0.3	0.53	0.58	0.44	0.88	0.31	1.1	0	0	0.46	0.33								
3-May	1.04	1.1	0.6	0.61	1.09	0.65	1.46	0.32	0	0	0.32	0.46								
4-May	1.61	2.78	0.93	0.93	3.89	1.11	2.72	0.95	3	0	0.56	0.75								
5-May	1.15	1.78	0.4	0.4	1.85	0.42	2	0.3	14	0	0.67	0.6								
6-May	0.4	0.4	0.48	0.48	0.5	0.57	0.31	0.25	0	0	0.13	0.3								
7-May	1.14	1.2	0.3	0.31	1.54	0.54	1.01	0.56	0	0	0.36	0.42								
8-May	1.37	1.37	0.43	0.51	1.78	0.59	1.47	0.51	6	1	0.7	1.12								
9-May*	1.89	2.26	1.11	1.38	2.59	1.39	2.22	1.02	90	15	2.01	1.38		YES	Yes				GAUGE	Miss
10-May*	1.45	2.26	1.78	2.13	3.48	**3.26**	2.9	**3.05**	1311	455	3.5	4.23	2	YES	Yes	Mod	18		LSR	Hit
11-May	1.73	2.24	1.98	2.65	3.95	**4.98**	4	**5.03**	4012	969	4.58	5.91	1	YES	Yes	Low	17		LSR	Hit
12-May	0.54	0.86	1.47	1.87	1.17	2.57	1.17	1.27	11	6	1.79	1.42		YES				BIAS		
13-May	0.31	0.52	0.7	0.85	0.8	1.88	0.75	1.16	11	12	0.64	1.93								
14-May	1.31	2.61	0.46	0.8	2.8	1.26	1.36	1.38	17	36	2.67	1.65								
15-May	0.38	0.56	0.88	0.93	0.63	1.51	0.49	1.19	6	1	0.4	1.08				Low	7			FA
16-May	1.05	1.07	0.52	0.52	1.46	0.76	1.24	0.52	0	0	0.68	0.91								
17-May*	2.56	3.02	1.72	1.75	3.32	2.17	3.02	2.48	100	5	3.15	1.02			Yes				GAUGE	Miss
18-May	2.76	4.16	2.78	4.25	**5.24**	**5.09**	**6.16**	**4.45**	505	62	2.73	2	3	YES	Yes	Mod	52		LSR	Hit
19-May	0.17	0.22	0.84	1.47	0.36	1.97	0.4	2.32	34	9	0.49	1.94			Yes	Low	15	BIAS	GAUGE	Hit
20-May	2	2.27	1.99	2.11	2.67	2.28	1.6	1.55	45	4	0.94	1.27			Yes	Low	4		GRIDDED	Hit
21-May	2.27	3.07	1.15	1.18	3.37	1.44	3.26	0.97	21	0	1.37	0.94		YES	Yes	Low	9		GRIDDED	Hit
22-May	0.43	0.44	1.47	1.77	0.79	1.92	0.66	1.46	11	2	0.24	1.13						BIAS		
23-May	1.66	1.73	2.15	2.31	2.38	2.41	1.42	1.52	51	1	0.15	1.25			Yes	Low	14		GAUGE	Hit

	NSSL MRMS Quantitative Precipitation Estimate						NOAA ST4 Quantitative Precipitation Estimate		QPE	Rain Gauges			Flood Reports							
Date	Max1hr E	Max2hr E	Max1hr W	Max2hr W	Max24hr E	Max24hr W	Max24hr E	Max24hr W	24hr Flood Area (Max)	NStats	Max-E	Max-W	Reports	NWS Warning or Advisory	Flood Day	Threat	Total Threat Area	Flags	FD Classification	Outcome
24-May	2.88	3.06	2.54	3.28	3.18	**3.52**	2.73	**4.74**	357	7	2.76	1.93	1	YES	Yes	Mod	52		LSR	Hit
25-May	2.6	3.61	2.03	2.74	4.31	**3.41**	2.99	2.63	164	0	0.77	0.86		YES	Yes	Mod	17		GRIDDED	Hit
26-May	2.35	2.73	1.77	2.46	3.44	**3.06**	2.6	**2.96**	246	3	1.29	1.22	1	YES	Yes	Mod	39		GAUGE	Hit
27-May	2.86	4.79	1.07	1.8	**6.15**	2.02	**5.58**	1.75	222	6	1.99	1.56		YES	Yes	Low	21		GAUGE	Hit
28-May	1.74	2.69	0.69	0.93	2.79	1.23	2.03	0.91	10	0	0.8	0.57				Low	4	BIAS		FA
29-May	1.4	1.92	0.65	0.88	2.59	1.13	2.25	0.76	20	0	0.77	0.4				Low	13			FA
30-May	2.87	3.74	0.76	0.77	4.7	0.83	3.66	0.6	62	1	2	0.91		YES	Yes	Low	13		GRIDDED	Hit
31-May	2.72	2.85	0.74	0.75	3.03	1.39	3.51	1.21	47	1	2.24	0.68		YES	Yes	Low	12		GRIDDED	Hit
1-Jun	1.8	2.04	2.26	2.87	2.41	**3.39**	1.48	2.5	106	7	2.21	1.38		YES	Yes	Mod	16		GRIDDED	Hit
2-Jun	2.23	2.71	1.04	1.44	3.16	1.76	2.62	1.75	131	7	1.93	1.9		YES	Yes	Low	9		GRIDDED	Hit
3-Jun	0.97	1.01	1	1.47	2.32	1.88	1.9	1.19	34	26	1.97	2.1	1					RIV		
4-Jun	1.16	1.38	1.15	1.49	2.22	2.18	1.98	1.55	313	47	2.17	3.25		YES	Yes	Low	14		GRIDDED	Hit
5-Jun	1.15	1.56	1.65	1.89	2.31	2.18	1.24	1.79	53	21	2.03	1.65	1	YES	Yes	Mod	16		GAUGE	Hit
6-Jun	1.75	2.57	2.69	3.29	3.36	**3.56**	2.87	2.69	149	9	1.42	2.22	2	YES	Yes	Mod	18		LSR	Hit
7-Jun	1.56	1.78	1.98	2.37	3	**3.37**	2.54	**3.08**	208	14	0.68	1.72		YES	Yes	Mod	40		GAUGE	Hit
8-Jun	2.02	2.25	2.59	2.85	3.01	**2.91**	1.99	2.27	61	26	1.6	2.39		YES	Yes	Low	15		GAUGE	Hit
9-Jun	1.59	1.82	1.72	1.8	2.32	1.91	1.91	1.38	56	0	1.16	0.9		YES		Low	20	BIAS		FA
10-Jun	2.12	2.19	2.59	2.92	2.43	**3.07**	2.14	1.62	62	2	1.26	2.17		YES				BIAS		
11-Jun	3.87	5.05	3.6	5.49	**5.68**	**7.91**	4.86	**6.42**	842	137	4.26	3.62	17	YES	Yes	Mod	19		LSR	Hit
12-Jun	2.23	3.11	2.02	3.43	3.88	**5.52**	3.22	**5.13**	1004	93	2.62	3.82	6	YES	Yes	High	55		LSR	Hit
13-Jun	2.06	2.5	1.47	1.59	3.19	2.12	2.68	1.56	96	1	1.59	0.96		YES	Yes	Mod	17		GRIDDED	Hit
14-Jun	0.54	0.79	1.31	1.31	0.86	1.31	0.87	0.93	4	0	0.48	0.78					2			
15-Jun	2.67	4.92	1.63	1.83	**5.39**	2.32	2.48	2.01	232	18	2.5	1.81		YES	Yes	Mod	53		GAUGE	Hit
16-Jun	2.96	4.44	1.61	1.61	**6.16**	**3**	3.71	2.72	919	75	2.94	2.81	3	YES	Yes	High	35		LSR	Hit
17-Jun	2.17	2.68	1.71	2.44	3.13	2.67	2.17	2.02	144	0	1.37	0.85	1	YES	Yes	Mod	39		LSR	Hit
18-Jun	0	0	0.07	0.08	0.01	0.08	0	0.07	0	0	0.25	0.3	1					RIV		

	NSSL MRMS Quantitative Precipitation Estimate						NOAA ST4 Quantitative Precipitation Estimate		QPE	Rain Gauges			Flood Reports							
Date	Max1hr E	Max2hr E	Max1hr W	Max2hr W	Max24hr E	Max24hr W	Max24hr E	Max24hr W	24hr Flood Area (Max)	NStats	Max-E	Max-W	Reports	NWS Warning or Advisory	Flood Day	Threat	Total Threat Area	Flags	FD Classification	Outcome
19-Jun	1.59	2.11	0	0	2.36	0	0	0.12	4	0	0.13	0.4	1					RIV		
20-Jun	1.37	1.78	0.02	0.03	1.89	0.05	1.11	0.04	3	0	0.04	0.2								
21-Jun*	3.05	4.62	3.97	5.2	**7.63**	**6.17**	**6.45**	**5.21**	1614	222	5.26	3.4	34	YES	Yes	Mod	42		LSR	Hit
22-Jun	1.55	1.74	2.7	3.12	1.93	**4.63**	1.49	**2.95**	274	56	1.05	2.8	5	YES	Yes	High	44		LSR	Hit
23-Jun	2.85	3.88	1.7	1.72	3.94	1.73	3.09	1.64	215	2	2.51	0.27		YES	Yes				GAUGE	Miss
24-Jun	0	0	0	0	0	0.01	0	0.01	0	0	0.22	0.43								
25-Jun	0	0	0	0	0	0.02	0	0	0	0	0.3	0.35								
26-Jun	1.76	2.46	1.31	1.83	2.47	1.84	1.2	0.39	8	0	0.42	0.63						BIAS		
27-Jun	1.71	1.85	0.3	0.3	2.13	0.3	1.59	0.25	4	0	0.69	0.2								
28-Jun	1.89	2.36	0.31	0.32	2.69	0.32	2.94	0.23	248	10	3.1	0.36		YES	Yes				GAUGE	Miss
29-Jun*	2.59	3.47	2.91	3.83	4.79	**4.88**	3.31	**3.28**	442	26	1.74	2.3	14	YES	Yes	Mod	35		LSR	Hit
30-Jun	2.4	2.76	1.88	2.1	3.03	2.59	2.5	1.95	287	7	1.65	1.65		YES	Yes	High	45		GAUGE	Hit
1-Jul	0.37	0.38	0.89	0.92	0.4	1.07	0.22	0.56	1	0	0.32	0.85								
2-Jul	2.26	2.79	1.85	2.13	2.96	2.2	2.51	1.2	43	0	0.85	0.51			Yes	Low	11		GRIDDED	Hit
3-Jul	0.71	0.71	0.73	0.73	0.96	0.8	0.74	0.4	0	0	0.42	0.4								
4-Jul	2.41	3.1	1.93	1.95	3.2	**3.14**	1.85	2.47	384	67	1.82	2.87		YES	Yes	Mod	28		GAUGE	Hit
5-Jul	2.13	3.33	1.88	3.15	4.86	**3.7**	3.7	**3.08**	360	9	2.12	2.58	4	YES	Yes	Low	11		LSR	Hit
6-Jul	2.33	3.1	1.16	1.74	3.47	1.79	2.3	1.22	287	4	1.89	1.69	3	YES	Yes	Mod	21		LSR	Hit
7-Jul	2.64	3.1	2.08	3	3.7	**3.22**	2.64	2.26	378	11	2.15	2		YES	Yes	Mod	24		GRIDDED	Hit
8-Jul	2.36	2.58	1.57	1.63	3.2	2.05	2.98	1.83	322	9	3.1	1.09	1	YES	Yes	Mod	38		LSR	Hit
9-Jul	0.47	0.57	0.54	0.78	0.65	0.93	0.17	0.42	0	0	0.46	0.47								
10-Jul	1.94	2.07	0.82	0.89	2.21	0.99	1.79	0.59	12	0	0.65	0.32						BIAS		
11-Jul	0.08	0.08	0.3	0.32	0.09	0.36	0	0.84	0	0	0.44	0.43								
12-Jul	0.44	0.46	0.39	0.52	0.52	0.6	0.36	0.28	0	0	0.16	0.42								
13-Jul	3.33	3.68	2.04	2.23	**5.02**	**4.4**	3.18	**2.99**	374	0	1.45	0.79		YES	Yes	Mod	10		GRIDDED	Hit
14-Jul	0.59	0.93	0.7	1.17	1.36	1.45	1.25	0.92	5	1	0.31	2.48								

	NSSL MRMS Quantitative Precipitation Estimate						NOAA ST4 Quantitative Precipitation Estimate		QPE	Rain Gauges			Flood Reports							
Date	Max1hr E	Max2hr E	Max1hr W	Max2hr W	Max24hr E	Max24hr W	Max24hr E	Max24hr W	24hr Flood Area (Max)	NStats	Max-E	Max-W	Reports	NWS Warning or Advisory	Flood Day	Threat	Total Threat Area	Flags	FD Classification	Outcome
15-Jul	2.85	3.02	2.41	2.87	4.07	**3.43**	3.28	**3.03**	182	2	1.09	1.74			Yes	Low	7		GRIDDED	Hit
16-Jul	0.01	0.01	0.02	0.02	0.03	0.02	0	0.03	0	0	0.41	0.43								
17-Jul	0.41	0.41	0.35	0.38	0.41	0.41	0.13	0.26	0	0	0.07	0.73								
18-Jul	2.07	3	1.19	1.19	3.01	1.19	2.33	0.98	37	0	0.48	0.5						BIAS		
19-Jul*	2.81	2.92	1.75	2.16	3.07	2.67	2.89	1.57	273	7	2.58	1.14	1	YES	Yes	Low	14		LSR	Hit
20-Jul	2.46	3.34	1.96	2.46	**5.94**	2.66	4.88	2.47	1930	75	3.07	2.6	8	YES	Yes	High	50		LSR	Hit
21-Jul**	0.96	0.97	2.03	2.2	0.98	2.5	0.91	1.91	35	2	0.5	1.35			Yes	Low	2		GRIDDED	Miss
22-Jul	0.95	1.05	1.22	1.27	1.18	1.29	0.95	1.12	3	0	0.89	0.33								
23-Jul	0.8	1.06	1.18	1.33	1.12	1.54	0.69	1.42	4	0	0.15	0.4								
24-Jul	1.3	1.32	1	1.46	1.41	1.69	1.02	1.53	4	0	0.53	0.67								
25-Jul	1.54	2.22	1.59	1.59	2.26	1.66	1.89	1.99	39	0	0.85	0.73						BIAS		
26-Jul	1.53	1.83	1.3	1.69	1.83	2.53	1.44	1.84	92	1	1.03	1.44			Yes				GRIDDED	Miss
27-Jul	1.77	1.93	1.42	1.88	1.96	2.13	1.48	1.31	42	0	1.25	0.71						BIAS		
28-Jul	2.26	2.31	1.94	1.94	2.71	1.99	2.15	1.23	50	0	0.85	0.87						BIAS		
29-Jul**	1.67	2.13	2.05	2.39	2.56	2.57	2.06	2.17	111	3	0.2	1.11	1	YES	Yes	Low	18		LSR	Miss
30-Jul**	1.44	2.15	1.98	2.47	2.16	2.68	1.68	2.11	127	4	0.38	1.7			Yes	Low	10		GAUGE	Miss
31-Jul*	2.39	2.94	3.29	4.49	4.56	**5.63**	2.26	**4.03**	780	154	3.86	4.4	5	YES	Yes	Mod	51		LSR	Hit
1-Aug*	2.68	3.85	2.92	3.42	4.46	**3.96**	3.06	2.1	585	31	1.69	1.93	4	YES	Yes	Mod	62		LSR	Hit
2-Aug	2.98	5.02	1.69	2	**5.31**	2.61	2.26	1.82	270	21	1.62	2.36	4	YES	Yes	Mod	41		LSR	Hit
3-Aug	2.46	2.94	1.97	2	2.98	2.41	1.94	1.61	264	9	2.76	2.2		YES	Yes	Mod	28		GAUGE	Hit
4-Aug	2.08	3.35	0.82	0.99	4.95	1.41	3.74	1.32	62	0	1.26	0.77		YES	Yes	Low	13		GRIDDED	Hit
5-Aug	1.87	2.05	1.73	1.81	2.06	2.17	1.51	1.5	189	1	1.2	1.04			Yes	Low	21		GRIDDED	Hit
6-Aug	1.02	1.08	1.31	1.34	1.52	2.28	1.13	1.85	135	2	0.88	2.15		YES		Low	5	BIAS		FA
7-Aug	1.65	2.26	1.81	1.84	2.92	2.29	2.15	1.88	48	0	0.5	0.5			Yes	Low	14		GRIDDED	Hit
8-Aug	2.47	3	1.83	2.55	4.85	**4.15**	2.51	2.37	327	2	1.57	0.57		YES	Yes	Mod	10		GRIDDED	Hit
9-Aug	0.85	0.85	0.98	1.26	0.85	1.44	0.53	1.79	3	0	0.5	0.66								

	NSSL MRMS Quantitative Precipitation Estimate						NOAA ST4 Quantitative Precipitation Estimate		QPE	Rain Gauges			Flood Reports							
Date	Max1hr E	Max2hr E	Max1hr W	Max2hr W	Max24hr E	Max24hr W	Max24hr E	Max24hr W	24hr Flood Area (Max)	NStats	Max-E	Max-W	Reports	NWS Warning or Advisory	Flood Day	Threat	Total Threat Area	Flags	FD Classification	Outcome
10-Aug	0.59	0.59	0.6	0.6	0.59	0.68	0.53	0.69	0	0	0.2	0.43								
11-Aug	0.84	1.04	2.53	2.92	1.1	**3.5**	0.46	1.82	28	1	0.1	1.2			Yes				GRIDDED	Miss
12-Aug	2.35	3.13	1.89	2.27	3.57	2.57	3.17	1.81	222	3	1.82	0.96		YES	Yes	Mod	15		GAUGE	Hit
13-Aug	0.05	0.07	1.17	1.43	0.07	2.08	0.05	1.17	17	0	0.27	1			Yes	Low	7		GRIDDED	Hit
14-Aug	0	0	2.93	3.32	0	**3.85**	0	**2.77**	42	7	0.07	1.8	1	YES	Yes	High	19		GAUGE	Hit
15-Aug	0	0	1.64	1.85	0	1.85	0	1.54	11	1	0.07	1.29			Yes	Mod	10		GAUGE	Hit
16-Aug	0.37	0.41	1.86	2.27	0.41	2.7	0.31	1.79	35	4	0.11	2.1	1	YES	Yes	Low	8		LSR	Hit
17-Aug	0.02	0.02	1.57	2.11	0.05	**3.16**	0.04	1.24	28	0	0.12	0.95	2	YES	Yes	Low	16		LSR	Hit
18-Aug	0.41	0.41	0.89	1.34	0.42	1.44	0.37	1.44	11	3	0.21	1.39		YES	Yes	Mod	21		GAUGE	Hit
19-Aug	1.22	1.52	1.03	1.03	2.42	1.89	1.24	0.96	26	1	1.51	0.99						BIAS		
20-Aug	0.02	0.02	0.01	0.01	0.02	0.01	0	0	0	0	0.11	0.31								
21-Aug	0.33	0.33	0.63	0.65	0.33	1.09	0.31	0.42	0	0	0.15	0.3								
22-Aug	0.11	0.11	0.8	0.94	0.14	1.15	0.09	0.58	1	0	0.27	0.7								
23-Aug	0.59	0.61	1.22	1.22	0.89	1.22	0.36	0.98	1	0	0.17	0.7								
24-Aug	1.18	1.55	2.82	3.4	1.56	**4.06**	1.03	**3.1**	811	38	0.72	2.45	4	YES	Yes	Mod	43		LSR	Hit
25-Aug	2.7	3.95	2.37	3.22	**5.27**	**4.18**	3.7	**3.12**	794	37	2.08	2.26	1	YES	Yes	High	86		LSR	Hit
26-Aug	0.09	0.1	2.08	2.33	0.11	2.57	0.12	**2.82**	120	8	0.25	2.55		YES	Yes	Mod	17		GAUGE	Hit
27-Aug	1.65	1.86	2.94	3.54	2.41	**3.8**	2.21	**3.1**	391	52	1.06	2.87	1	YES	Yes	Low	19		LSR	Hit
28-Aug	1.94	2.39	2.3	2.66	2.8	**2.93**	1.88	2.21	250	5	1.56	3.95	1	YES	Yes	Mod	38		LSR	Hit
29-Aug	0	0.01	0.04	0.04	0.01	0.06	0	0.14	0	0	0.08	0.4								
30-Aug	0.42	0.42	1.28	1.59	0.49	1.69	0.3	0.76	6	0	0.07	0.46								
31-Aug	0.01	0.01	0.95	1.06	0.01	1.06	0	0.37	1	0	0.07	0.4								
1-Sep	0.09	0.09	0.48	0.49	0.09	0.5	0.04	0.41	0	0	0.08	1								
2-Sep	0.09	0.09	0.69	0.8	0.09	0.87	0.06	0.55	0	0	0.06	0.4				Low	1			FA
3-Sep	0.63	0.67	1.05	1.3	0.69	2.12	0.61	1.97	48	17	0.36	2.83		YES	Yes	Low	19		GAUGE	Hit
4-Sep	0.43	0.78	0.78	0.82	1.06	0.83	0.76	0.62	0	0	0.16	0.4		YES						

	NSSL MRMS Quantitative Precipitation Estimate						NOAA ST4 Quantitative Precipitation Estimate		QPE	Rain Gauges			Flood Reports							
Date	Max1hr E	Max2hr E	Max1hr W	Max2hr W	Max24hr E	Max24hr W	Max24hr E	Max24hr W	24hr Flood Area (Max)	NStats	Max-E	Max-W	Reports	NWS Warning or Advisory	Flood Day	Threat	Total Threat Area	Flags	FD Classification	Outcome
5-Sep	0	0	0	0	0	0	0	0	0	0	0.05	0.3								
6-Sep	0	0	0.01	0.01	0	0.01	0	0	0	0	0.09	0.3								
7-Sep	0	0	0.01	0.01	0	0.01	0	0	0	0	0.04	0.31								
8-Sep	0.15	0.15	0.09	0.11	0.15	0.12	0.07	0.04	0	0	0.06	0.16								
9-Sep	1.27	1.54	0.2	0.2	1.87	0.2	1.1	0.23	2	0	0.05	0.25								
10-Sep	1.44	1.5	3	3.56	2.18	**3.85**	2.13	2.02	762	67	1.54	1.93			Yes	Mod	22		GAUGE	Hit
11-Sep	0.5	0.52	0.59	0.7	1	1.52	1	1.6	30	15	1.09	2.16								
12-Sep	0.76	0.98	1.43	1.54	1.26	1.67	0.77	2.15	99	12	0.45	2.25		YES				BIAS		
13-Sep	1.06	1.09	1.75	2.04	1.61	2.35	1.11	2.17	48	0	0.2	0.93		YES	Yes				GRIDDED	Miss
14-Sep	2.65	4.04	2.23	3.1	**5.09**	**3.98**	3.41	**3.05**	564	106	2.85	2.93	2	YES	Yes	Low	17		LSR	Hit
15-Sep	0.57	0.73	1.29	1.82	0.91	2.18	0.85	1.56	83	11	0.65	1.94						BIAS		
16-Sep	0	0	0.08	0.09	0	0.09	0	0.24	0	0	0.11	0.4								
17-Sep	0.04	0.04	0.04	0.04	0.04	0.05	0	0.03	0	0	0.03	0.1								
18-Sep	0.03	0.03	0.52	0.55	0.03	0.62	0.02	0.73	0	0	0.08	0.66								
19-Sep	0.62	0.7	1.05	1.33	0.7	1.39	0.35	0.98	7	0	0.22	0.59		YES				BIAS		
20-Sep	0.17	0.18	0.33	0.42	0.2	0.49	0.19	0.37	0	0	0.06	0.65								
21-Sep	1.13	1.13	1.14	1.16	1.73	1.22	0.9	0.79	2	0	0.29	0.64								
22-Sep	0.72	0.72	0.63	0.63	0.74	0.63	0.66	0.48	0	0	0.38	0.64								
23-Sep	0	0	0.05	0.05	0.01	0.06	0	0.23	0	0	0.03	0.39								
24-Sep	0	0	0.09	0.09	0	0.09	0	0.06	0	0	0.03	0.5								
25-Sep	0	0	0.04	0.06	0	0.05	0	0.01	0	0	0.04	0.35								
26-Sep	0.01	0.01	0.05	0.05	0.22	0.16	0.18	0.07	0	0	0.07	0.31								
27-Sep	0	0	0.01	0.01	0.01	0.01	0	1.19	2	1	0.04	1.22								
28-Sep	0.01	0.02	0.06	0.06	0.02	0.07	0.01	0.05	0	0	0.02	0.17								
29-Sep	0	0	0.01	0.02	0	0.03	0	0.01	0	0	0.02	0.5								
30-Sep	0.59	0.79	0.57	0.92	1.24	1.08	0.89	1	1	0	0.71	0.39								

APPENDIX B – BURN AREA VERIFICATION WORKSHEET

Table 16 is a daily verification worksheet documenting heavy precipitation and associated debris flow/flash flooding reports over burn areas featured in the FBF. Shading within a cell indicates that a flood threat was issued with the color corresponding to the Program's four-tier threat system. The color yellow corresponds to a "Low" threat, orange to a "Moderate" threat, red to a "High" threat and purple to a "High Impact" threat. A blank cell indicates that no specific burn area threat was issued for that day. The text provided in Table 16 are described below.

Burn Area: The names of the 11 burn areas that were forecast this season. More information can be found in Table 3.

FLOOD: Indicates that a debris flow report was recorded from a LSR (see Appendix C), social media reports (X and Facebook) or personal contacts.

QPE: Marks days that the QPE threshold was exceeded. These thresholds are set at the beginning of the season using historical data from the previous season. If the burn area is new, the threshold is set to 0.25 inches per hour. Thresholds used for this worksheet are:

1. Cameron Peak and East Troublesome: **0.50 inches per hour**
2. Grizzly Creek, Morgan Creek, Sylvan, Pine Gulch, and Williams Fork: **0.75 inches per hour**
3. Calwood, Decker, Middle Fork, and Spring Creek: **1.00 inch per hour**

Table 16: Daily Burn Area Verification Worksheet

	0.5 in/hr		0.75 in/hr					1.0 in/hr			
Date	**Cameron Peak**	**East Troublesome**	**Grizzly Creek**	**Morgan Creek**	**Sylvan**	**Pine Gulch**	**Williams Fork**	**Calwood**	**Decker**	**Middle Fork**	**Spring Creek**
1-May											
2-May											
3-May											
4-May											
5-May											
6-May											
7-May											
8-May											
9-May											
10-May											
11-May	**FLOOD**										
12-May											
13-May											
14-May											
15-May											
16-May											
17-May											
18-May	**QPE**										
19-May											
20-May	**QPE**										
21-May											
22-May		**QPE**				**QPE**					
23-May											
24-May	**QPE**										
25-May	**QPE**										

Date	0.5 in/hr		0.75 in/hr					1.0 in/hr			
	Cameron Peak	East Troublesome	Grizzly Creek	Morgan Creek	Sylvan	Pine Gulch	Williams Fork	Calwood	Decker	Middle Fork	Spring Creek
26-May											
27-May	QPE										
28-May											
29-May											
30-May											
31-May											
1-Jun	QPE										
2-Jun											
3-Jun	QPE										
4-Jun	QPE										
5-Jun	QPE										
6-Jun	QPE	QPE									QPE
7-Jun	QPE	QPE						QPE			
8-Jun	FLOOD										
9-Jun	QPE										
10-Jun		QPE									
11-Jun	FLOOD										
12-Jun	QPE										
13-Jun											
14-Jun											
15-Jun	QPE		QPE								
16-Jun											
17-Jun											
18-Jun											
19-Jun											
20-Jun											
21-Jun											

Date	0.5 in/hr		0.75 in/hr					1.0 in/hr			
	Cameron Peak	East Troublesome	Grizzly Creek	Morgan Creek	Sylvan	Pine Gulch	Williams Fork	Calwood	Decker	Middle Fork	Spring Creek
22-Jun								**QPE**			
23-Jun											
24-Jun											
25-Jun											
26-Jun											
27-Jun											
28-Jun											
29-Jun	**QPE**										
30-Jun	**QPE**	**QPE**									
1-Jul	**QPE**										
2-Jul											
3-Jul											
4-Jul	**QPE**										
5-Jul	**QPE**										
6-Jul											
7-Jul	**QPE**										
8-Jul	**QPE**										
9-Jul											
10-Jul											
11-Jul											
12-Jul											
13-Jul											
14-Jul											
15-Jul	**QPE**										
16-Jul											
17-Jul											
18-Jul											

Date	0.5 in/hr		0.75 in/hr					1.0 in/hr			
	Cameron Peak	East Troublesome	Grizzly Creek	Morgan Creek	Sylvan	Pine Gulch	Williams Fork	Calwood	Decker	Middle Fork	Spring Creek
19-Jul											
20-Jul	FLOOD	QPE									
21-Jul											
22-Jul											
23-Jul											
24-Jul											
25-Jul											
26-Jul		QPE									
27-Jul											
28-Jul	QPE										
29-Jul	QPE										FLOOD
30-Jul	QPE	QPE									
31-Jul	FLOOD	QPE				QPE	QPE				
1-Aug	QPE	QPE	QPE					QPE			
2-Aug	FLOOD	QPE									
3-Aug	QPE										
4-Aug											
5-Aug	QPE										
6-Aug	QPE										
7-Aug											
8-Aug											
9-Aug											
10-Aug											
11-Aug											
12-Aug											
13-Aug											
14-Aug											

Date	0.5 in/hr		0.75 in/hr					1.0 in/hr			
	Cameron Peak	East Troublesome	Grizzly Creek	Morgan Creek	Sylvan	Pine Gulch	Williams Fork	Calwood	Decker	Middle Fork	Spring Creek
15-Aug											
16-Aug			FLOOD								
17-Aug											QPE
18-Aug		QPE	QPE								
19-Aug	QPE										
20-Aug											
21-Aug											
22-Aug											
23-Aug	QPE										
24-Aug	QPE	QPE	FLOOD			QPE	QPE				
25-Aug	QPE						QPE				QPE
26-Aug		QPE	FLOOD			QPE					QPE
27-Aug	QPE	QPE			QPE	QPE					QPE
28-Aug	QPE										
29-Aug											
30-Aug											
31-Aug											
1-Sep											
2-Sep											
3-Sep	QPE		QPE								
4-Sep											
5-Sep											
6-Sep											
7-Sep											
8-Sep											
9-Sep											
10-Sep	QPE										

Date	0.5 in/hr		0.75 in/hr					1.0 in/hr			
	Cameron Peak	East Troublesome	Grizzly Creek	Morgan Creek	Sylvan	Pine Gulch	Williams Fork	Calwood	Decker	Middle Fork	Spring Creek
11-Sep											
12-Sep											**QPE**
13-Sep						**QPE**					**QPE**
14-Sep	**FLOOD**	**FLOOD**									
15-Sep											
16-Sep											
17-Sep											
18-Sep											
19-Sep		**QPE**									
20-Sep											
21-Sep											
22-Sep											
23-Sep											
24-Sep											
25-Sep											
26-Sep											
27-Sep											
28-Sep											
29-Sep											
30-Sep											

APPENDIX C – DATA SOURCES

Below are the data sources used for verification in this final report. Questionable observations within each data source were noted and discarded based on comparison with other data.

Data Source	Additional Information	Access
	Rain Gauges	
CoCoRaHS	Community Collaborative Rain, Hail and Snow Network. Daily precipitation accumulations from up to 1,300 observers across Colorado. This data is generally reported in the morning and encompasses the previous 24 hours of precipitation accumulation. Only reports received from 6AM to 9AM are used to ensure that measurements are consistent with the forecast period.	https://www.cocorahs.org
NRCS	Natural Resources Conservation Service. SNOTEL hourly precipitation data was used and also aggregated into daily accumulations at approximately 65 high-elevation sites across Colorado.	https://www.nrcs.usda.gov/wps/portal/wcc/home
MesoWest	University of Utah's hourly precipitation data, which has many contributing networks. The major networks include: Colorado Agricultural Meteorological Network (CoAgMet), Climate Reference Network (CRN), Hydrometeorological Automated Data System (HADS), interagency Remote Automatic Weather Stations (RAWS) and Soil Climate Analysis Network (SCAN). Secondary networks (i.e. lower quality) also include the Citizen Weather Observer Program (CWOP). Hourly precipitation data was used along with aggregated 24-hour totals.	https://mesowest.utah.edu
USGS	United States Geological Survey. Sub-hourly precipitation data was aggregated into a rolling 1-hour totals and daily accumulations. This data source is particularly helpful over the high terrain fire burn areas and the more populated areas of Teller and El Paso Counties.	https://co.water.usgs.gov/infodata/COPrecip/index.html
Personal Weather Stations (PWS)	In addition to using CWOP station data via MesoWest (see above), other personal weather station network data was accessed via the Ambient Weather network, Weather Underground and Aeris Weather. At this time, PWS data is only used subjectively to inform on heavy rainfall that occurs in poorly gauged areas. However, subject matter expert judgment could have affected the BIAS flag in Appendix A.	http://www.ambientweather.net https://www.weatherunderground.com https://www.pwsweather.com
	Gridded Quantitative Precipitation Estimate (QPE)	
MRMS	NSSL Multi-Radar Multi-Sensor. This is a near real-time hourly gridded product based on an initial best-guess of radar, satellite and weather model rainfall estimates that is corrected with gauge data. The resolution of the product is roughly 1km; however, due to Colorado's large spatial extent (~100,000 square miles, or roughly 300,000 MRMS grid points), the native grid was re-sampled to roughly 4 km (2.6 mile) resolution to be directly comparable to Stage IV QPE (see below). MRMS 24-hour, maximum 1-hour, and maximum 2-hour QPE were used for verification.	https://mrms.nssl.noaa.gov
Stage IV	NOAA Stage IV. This is an hourly product based on a radar-estimated, gauge-adjusted technique using all NWS NEXRAD radars and many quality-controlled rain gauges. The horizontal resolution is about 4 km (2.6 mile). Due to the availability of more consistent MRMS data at the 1-hour and 2-hour interval, only 24-hour Stage IV QPE was used.	https://data.eol.ucar.edu/dataset/21.093

Data Source	Additional Information	Access
Storm Reports		
LSR	Local Storm Report. Obtained from the four NWS offices that are responsible for Colorado: Boulder, Pueblo, Grand Junction, and Goodland (KS) using the IEM. Reports were only included if they contained the following phrases: “Heavy Rain”, “Flash Flood”, “Flood” or “Debris Slide”. Reports involving the term “Heavy Rain” were retained only when the magnitude of rainfall exceeds 0.50 in. Like CoCoRaHS data, reports of 24-hour accumulation were only retained if the report ending time was between 6AM and 9AM. If a ”Heavy Rain” report did not specify a magnitude, it was dismissed unless the observer’s note contained a specific reference to flooding.	https://mesonet.agron.iastate.edu/lsr/
Flood Reports	Flood reports obtained from the Program’s web-based report submission system, subject to quality control by the Team.	No Public Access
NWS Warning and Advisory Products		
NWS	National Weather Service warning and advisory Geographic Information Systems (GIS) data. Obtained from the IEM, this data source includes metadata such as the location and when the product was issued. Flash Flood Warning, Riverine Flood Warning and Areal Flood Advisory products were included for verification.	https://mesonet.agron.iastate.edu/request/gis/watchwarn.phtml

APPENDIX D - COLORADO CLIMATE

Colorado's geographic position and over 10,000 feet of topographic contrast can be conducive to both short-term flash flooding from single thunderstorms and prolonged heavy rainfall and flooding as most recently occurred over the Front Range during September of 2013. Moreover, the placement of the Continental Divide separates the state into contrasting climates. To the east, the relatively close proximity of Gulf of Mexico moisture supports higher rainfall intensity, especially over shorter durations compared to areas west of the Continental Divide. However, the hillier terrain to the west implies that less rainfall is required to generate problematic runoff. For example, over the eastern Plains, hourly rainfall rates of 1.5 inches or more are typically required to cause excessive runoff. For western areas, hourly rainfall rates of less than 1 inch could cause issues. Furthermore, hillier terrain can play host to mud and debris flows, in addition to the usual flash flooding concerns that are experienced statewide. The following section summarizes key aspects of Colorado's physiographic features that play an essential role in daily flood forecasting.

a) Importance of Continental Divide

The most important control of heavy rainfall potential in Colorado (even more important than elevation, by itself) is arguably the position relative to the Continental Divide. Figure 22 (Atlas 14, 2017) shows the stark differences in rainfall recurrence statistics at Denver (east of the Continental Divide) compared to Silt (west of the Continental Divide). While both locations have a similar elevation of about 5,300 feet, the 30-minute 10-year rainfall at Denver (1.09 inches) is 81% higher than the analogous value for Silt (0.60 inches). Similarly, the 30-minute 100-year rainfall at Denver (1.91 inches) is 80% higher than the analogous value at Silt (1.06 inches). In short, despite other possibly counteracting factors, this contrast consistently results in more flood threats east of the Continental Divide compared to its Western counterpart (also see Appendix E).

Denver, CO

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.217 (0.174-0.270)	0.267 (0.214-0.334)	0.358 (0.286-0.448)	0.439 (0.349-0.552)	0.562 (0.435-0.737)	0.665 (0.500-0.877)	0.774 (0.561-1.04)	0.892 (0.619-1.22)	1.06 (0.704-1.48)	1.19 (0.770-1.68)
10-min	0.317 (0.255-0.396)	0.392 (0.314-0.489)	0.524 (0.418-0.656)	0.644 (0.511-0.808)	0.823 (0.637-1.08)	0.973 (0.732-1.28)	1.13 (0.821-1.52)	1.31 (0.906-1.79)	1.55 (1.03-2.17)	1.75 (1.13-2.46)
15-min	0.387 (0.310-0.483)	0.478 (0.383-0.597)	0.639 (0.510-0.800)	0.785 (0.623-0.986)	1.00 (0.776-1.32)	1.19 (0.892-1.57)	1.38 (1.00-1.86)	1.59 (1.11-2.19)	1.89 (1.26-2.65)	2.13 (1.37-3.00)
30-min	0.545 (0.437-0.680)	0.670 (0.537-0.837)	0.892 (0.713-1.12)	1.09 (0.868-1.37)	1.39 (1.08-1.82)	1.64 (1.23-2.17)	1.91 (1.38-2.56)	2.19 (1.52-3.01)	2.60 (1.73-3.64)	2.93 (1.89-4.11)
60-min	0.683 (0.548-0.853)	0.834 (0.669-1.04)	1.10 (0.881-1.38)	1.35 (1.07-1.69)	1.71 (1.33-2.25)	2.02 (1.52-2.67)	2.35 (1.70-3.16)	2.71 (1.88-3.72)	3.21 (2.14-4.50)	3.62 (2.33-5.09)
2-hr	0.822 (0.666-1.02)	0.998 (0.807-1.23)	1.31 (1.06-1.63)	1.60 (1.28-1.99)	2.04 (1.59-2.65)	2.40 (1.83-3.14)	2.80 (2.05-3.72)	3.22 (2.26-4.38)	3.83 (2.57-5.31)	4.32 (2.81-6.02)

Silt, CO (near Glenwood Springs)

Duration	Average recurrence interval (years)									
	1	2	5	10	25	50	100	200	500	1000
5-min	0.116 (0.091-0.147)	0.148 (0.116-0.188)	0.205 (0.159-0.261)	0.255 (0.198-0.327)	0.329 (0.248-0.447)	0.391 (0.287-0.537)	0.456 (0.323-0.645)	0.525 (0.356-0.768)	0.623 (0.406-0.941)	0.701 (0.443-1.07)
10-min	0.170 (0.133-0.215)	0.217 (0.170-0.276)	0.299 (0.233-0.382)	0.373 (0.289-0.479)	0.482 (0.364-0.654)	0.572 (0.420-0.787)	0.667 (0.473-0.945)	0.769 (0.522-1.13)	0.912 (0.594-1.38)	1.03 (0.649-1.57)
15-min	0.207 (0.162-0.263)	0.264 (0.207-0.336)	0.365 (0.285-0.466)	0.455 (0.353-0.584)	0.588 (0.443-0.798)	0.698 (0.512-0.960)	0.814 (0.576-1.15)	0.938 (0.637-1.37)	1.11 (0.725-1.68)	1.25 (0.792-1.91)
30-min	0.264 (0.207-0.336)	0.346 (0.270-0.440)	0.484 (0.377-0.617)	0.604 (0.468-0.775)	0.776 (0.583-1.05)	0.915 (0.670-1.25)	1.06 (0.748-1.49)	1.21 (0.819-1.76)	1.42 (0.923-2.14)	1.58 (1.00-2.42)
60-min	0.343 (0.269-0.436)	0.431 (0.337-0.548)	0.580 (0.452-0.741)	0.710 (0.550-0.911)	0.897 (0.674-1.21)	1.05 (0.768-1.44)	1.21 (0.852-1.70)	1.37 (0.928-2.00)	1.60 (1.04-2.41)	1.78 (1.12-2.72)
2-hr	0.422 (0.334-0.532)	0.516 (0.407-0.651)	0.677 (0.532-0.856)	0.817 (0.638-1.04)	1.02 (0.772-1.36)	1.18 (0.874-1.60)	1.35 (0.965-1.88)	1.53 (1.05-2.20)	1.78 (1.17-2.64)	1.97 (1.26-2.97)

Figure 22: Subset of NOAA Atlas 14 rainfall recurrence statistics for (top) Denver and (bottom) Silt. Note that the elevation of both locations is about 5,300 feet above sea level.

b) Seasonality

Seasonality is likely the second most important factor in controlling heavy rainfall potential in Colorado. As shown in Figure 23, early in the operational season (May), the highest potential for heavy rainfall is almost exclusively east of the Continental Divide, and in particular the northeast quadrant of the state (PRISM, 2017). During early June (not shown), snow is a significant factor in the Front Range and Gore Mountains. Meanwhile, by August (Figure 23 bottom), average rainfall decreases sharply north of the Palmer Ridge and increases significantly over the southeast quadrant of the state as well as in the San Juan Mountains (due to moisture transport into the region by the North American Monsoon). The flood threat largely evolves in a similar fashion.

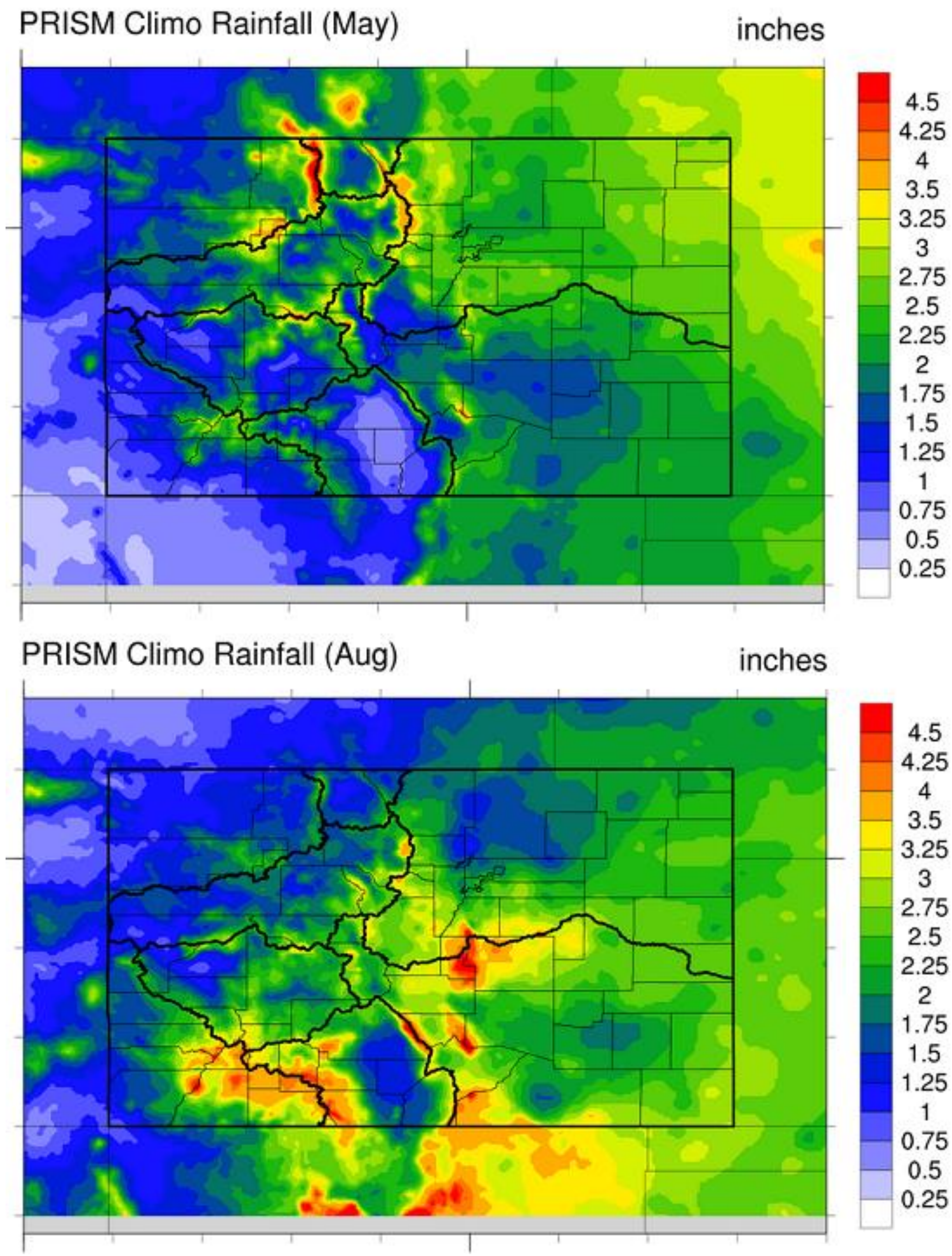

Figure 23: Monthly average precipitation for (top) May and (bottom) August. Source: Oregon State University PRISM group.

c) Surface characteristics

While a significant focus of the Flood Threat Bulletin is heavy rainfall potential, an equally important factor is surface characteristics such as slope, ground cover type, soil type, antecedent rainfall, etc. Collectively, these factors can cause significant sensitivity when translating between rainfall and runoff. Figure 24 shows the 1-hour Flash Flood Guidance (FFG) for central and eastern Colorado from their respective River Forecast Centers. These products are updated daily by the National Weather Service River Forecast Centers. Note that, in general, FFG is significantly higher over the eastern Plains compared to the higher terrain. For example, along the Kansas border, the 1-hour FFG could be just under 6 inches, while over the northern Front Range, it is between 1 and 2 inches. An even starker example of the importance of surface characteristics is over a fresh fire burn area, where the burnt, and now resultant hydrophobic soil mass, can cause significant flooding concerns for even 0.25 inches of rainfall per hour. This can be seen over Huerfano and Fremont County where the Spring Creek and Decker burn areas reside, respectively (pink in the top figure). Surface characteristics play an integral role in translating the heavy rainfall threat to a flooding potential.

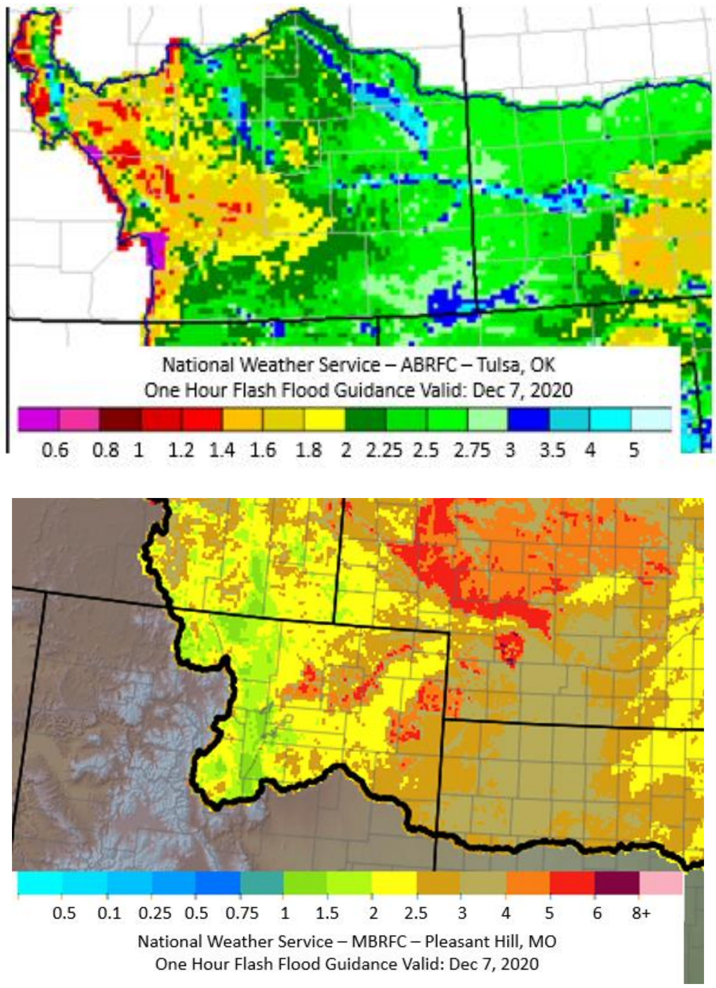

Figure 24: 1-hour Flash Flood Guidance for central and eastern Colorado, valid December 7th, 2020. Source: National Weather Service River Forecast Centers.

APPENDIX E – FLOOD THREATS ISSUED

Figure 25 shows the total number of days when a given location was under a flood threat during the 2016 to 2023 operational seasons. Note that this does not distinguish the type of flood threat (e.g., Low versus Moderate). For reference, there are normally 153 days during the forecast season with 154 days during 2018. The maps also include riverine NWS Flood Warnings which were present a total of 21 days of the 2023 season. As a result, portions of Elkhead Creek and the Elk River in Routt County can be seen in 2023 image. There is also a secondary maximum in Mesa County along the Dolores River, which had a Flood Warning for 11 days this season.

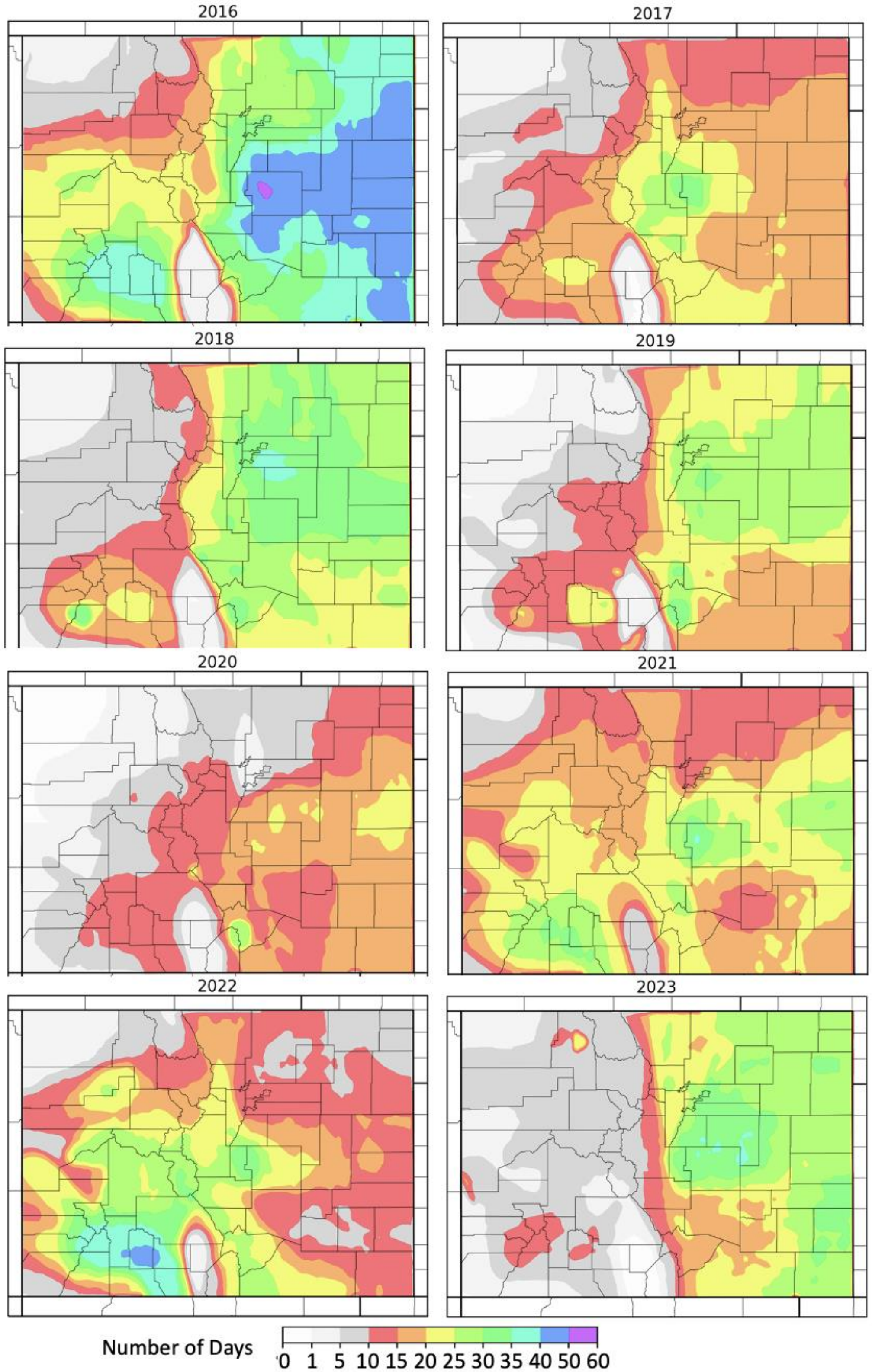

Figure 25: Number of days with a flood threat issued from 2016 to 2023. Note that until 2021, burn areas were considered within the FTB. After 2020, they were covered by the FBF.

APPENDIX F – QPE BIAS ASSESSMENT

An assessment of QPE product bias over the 2023 forecast season showed a systematic tendency for both the MRMS and Stage IV to slightly *overestimate* precipitation when compared directly to gauges, in situations where over 0.25 inches of precipitation were estimated OR observed. This is similar to findings from last season. For example, as shown in Figure 26, over the course of the season, the MRMS product overestimated precipitation about 25% more often as it underestimated it.

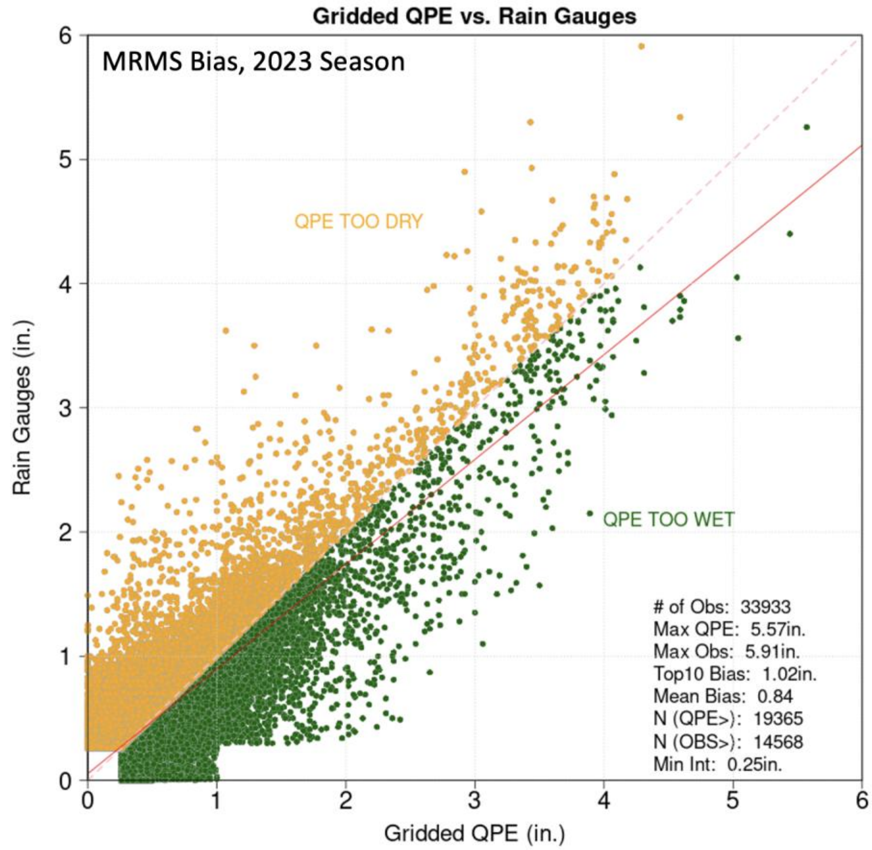

Figure 26: 2023 Seasonal (May-September) MRMS QPE vs Rain Gauge plot that shows overestimation of the gridded QPE product.

However, despite the overall bias shown above, there were significant variations on an event-by-event basis. These likely arose from numerous factors known to affect QPE, including but not limited to variations in the atmospheric moisture profile, sub-cloud layer depth, dynamic Z-R relationships within a storm, distance from radar sites, the presence or absence of hail, as well as cloud temperature. To gain some perspective on how the overall MRMS bias can vary, two events are provided below (Figure 27). On June 14th (top) moderate steering flow and a dry boundary layer were present for widely scattered rainfall that developed over western Colorado and the mountains. Of the 336 stations with measurable rainfall over 0.10 inches, QPE overestimated rainfall at 178 stations, while underestimating the remaining 47%. The mean bias was 0.19 inches, but the top 10 bias increased to 0.36 inches. On June 16th (bottom), widespread rainfall developed over east-central Colorado where numerous observations over 1 inch were recorded. Opposite of June 14th, the mean bias (0.81 inches) was much lower than top 10 bias (-0.08 inches), and the number of observations increased to 1,245. The increase in observations helped to reduce the bias in the stronger rainfall core estimations and shows the tendency of MRMS to overestimate the storm cores when an event is not sampled well by gauges. Therefore, MRMS and Stage IV biases were subjectively assessed for each event, to determine Flood Day classification.

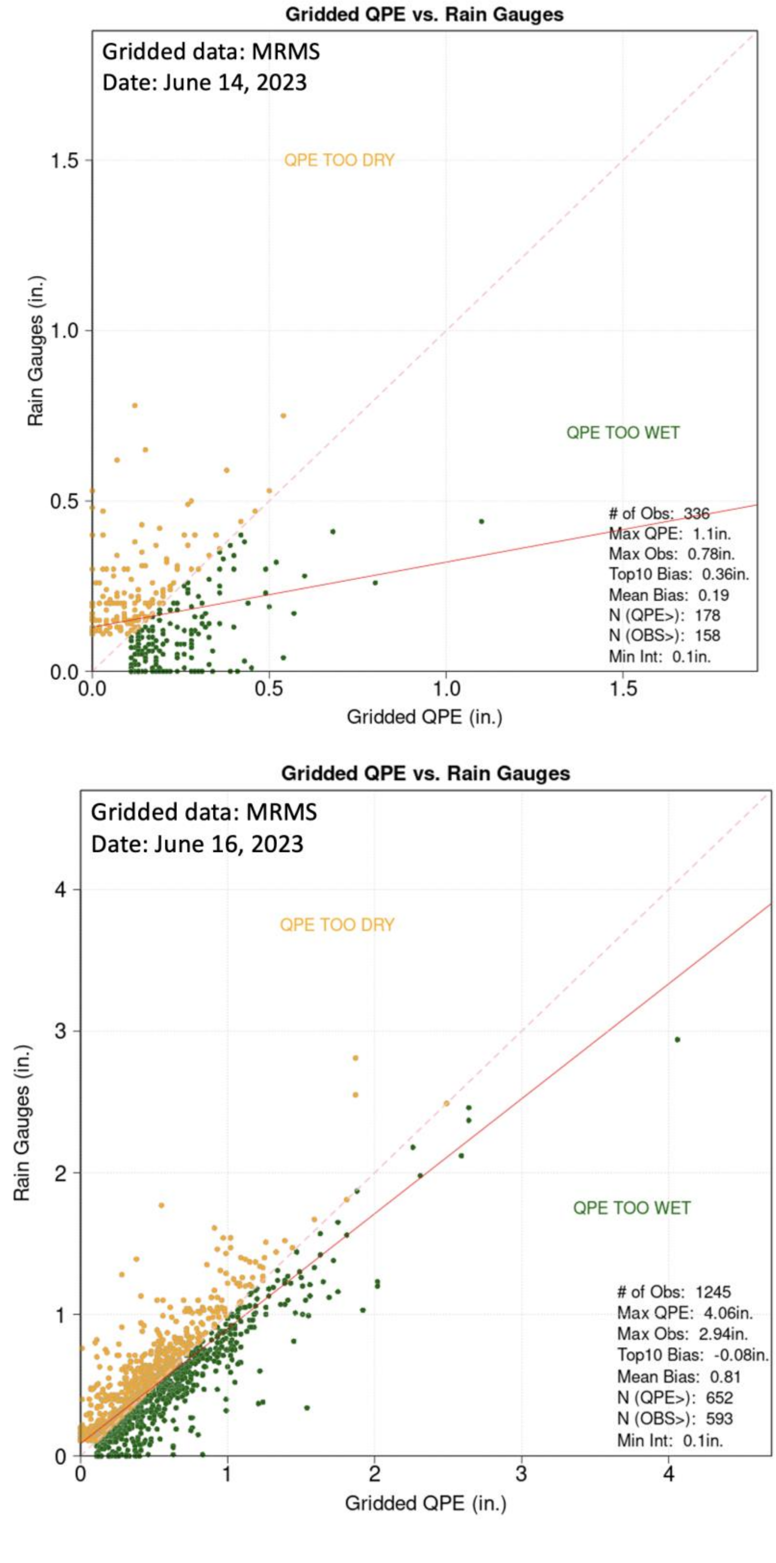

Figure 27: An example of MRMS gridded QPE versus rain gauge scatter plots from June 14th (top) and June 16th (bottom). The images show that the QPE bias is not constant and must be assessed on a daily level to help assign the Flood Day classification.

Finally, Figure 28 looks at the MRMS mean daily bias across each county for the 2023 forecast season from June to September. May was excluded due to snowfall events skewing 24-hour totals. The blue shades, mostly east of the Continental Divide, indicate an overestimation of precipitation for select counties. There is a 0.25 to 0.50 inch bias for Conejos County, indicating a large overestimation by MRMS. This may be somewhat related to the lack of sample size with only 9 observations available this season that exceeded 0.25 inches. The light red shades indicate a slight underestimation of rainfall by MRMS with dark red, as seen over southwest Colorado, indicating as much as a 0.25 to 0.50 inch underestimation of daily precipitation for days where rainfall exceeded 0.25 inches. The same analysis, but for Stage IV in Figure 29 indicates a similar spatial pattern though the mean bias trends lower than MRMS, except over Delta County where the bias is larger. The ingestion of CoCoRaHS data into this QPE, especially over areas with large population centers, helps Stage IV outperform MRMS in this analysis.

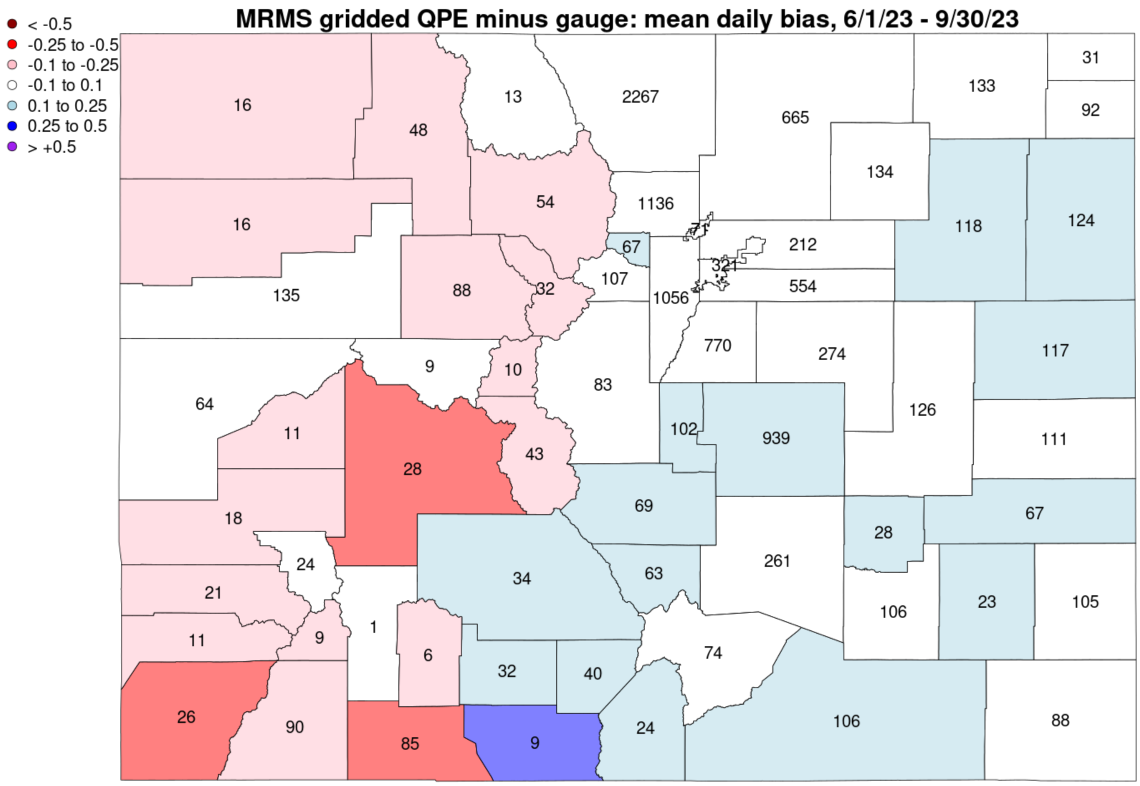

Figure 28: MRMS mean daily bias within each county from June to September of 2023. Blue (red) shading represents an overestimation (underestimation) of precipitation and the numbers in each county represent the number of observations OR estimates over 0.25 inches going into the calculation.

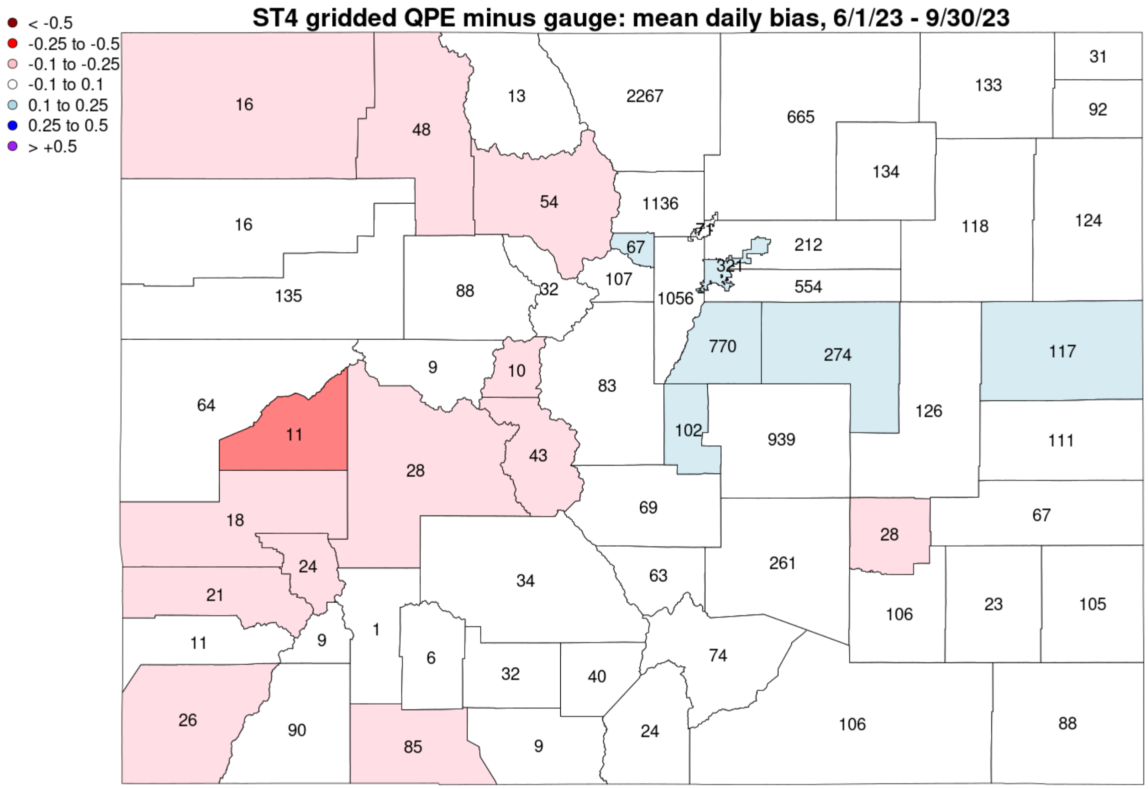

Figure 29: Stage IV mean daily bias within each county from June to September of 2023. Blue (red) shading represents an overestimation (underestimation) of precipitation and the numbers in each county represent the number of observations OR estimates over 0.25 inches.

As a takeaway, the general underestimation of precipitation by both datasets across western Colorado has been noted in past seasons, and it is likely directly related to lack of radar coverage due to beam blockage from the complex topography over the area. Additionally, the number of observations within a given county can vary quite drastically. Counties that have only a few observation points should be interpreted with caution. The low number of observations over western Colorado speaks to the spotty nature of the precipitation this season and lack of multi-day synoptic events. Generally speaking, the areas without a bias (-0.10 to 0.10 inches) tend to occur in areas of higher population where more gauges are available for QPE calibration, especially over the Front Range and Urban Corridor where CoCoRaHS was founded.