Colorado Flood Threat Bulletin – 2021 Final Report

NOVEMBER 15, 2021

PREPARED BY:

Dewberry

990 S Broadway, Suite 400
Denver, CO 80209

HydroMet Consulting

2164 Zang Street
Golden, CO 80401

PREPARED FOR:

COLORADO
Colorado Water Conservation Board
Department of Natural Resources

C/O Kevin Houck
1313 Sherman St., Room 721
Denver, CO 80203
Phone: 303-866-3441
Fax: 303-866-4474

Contents

Contributors

Mathew Mampara
Principle in Charge
mmampara@dewberry.com
703.849.0612

David Sutley, PE
Project Manager
dsutley@dewberry.com
303.951.0612

Alyssa Hendricks Dietrich
Project Meteorologist
ahdietrich@dewberry.com
703.206.0833

Dmitry Smirnov, PhD
Subconsultant
HydroMet Consulting, LLC
hydrometconsulting@gmail.com
919.619.2125

Dana McGlone
Subconsultant
HydroMet Consulting, LLC
hydrometconsulting@gmail.com
303.921.5999

This page is intentionally blank.

2021 Colorado Flood Threat Bulletin

Final Report

1) INTRODUCTION

The 2021 forecast season (May 1st to September 30th) was the final year of a 5-year award given to Dewberry to produce the Colorado Flood Threat Bulletin (hereafter, Program) on behalf of the Colorado Water Conservation Board (CWCB). Dewberry has provided this service for the CWCB since 2012 with the double objective of producing and disseminating reliable forecasts as well as incorporating the frontier of hydro-meteorological research into operations to benefit the CWCB and all end-users. The three legacy Program products include:

- (i) the daily Flood Threat Bulletin (FTB) that both describes and visualizes the flood threat across the state of Colorado; note that hereafter, any mention of "FTB" refers to this particular product, whereas all general references to the project are denoted by "Program";
- (ii) 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;
- (iii) the daily State Precipitation Map (SPM) that recaps the past 24- to 72-hours of hydrometeorological conditions and includes flood reports.

New to the 2021 forecast season is the daily Fire Burn Forecast (FBF) product. This standalone wildfire forecast system was created to supplement the existing FTB product by removing the fire burn areas from the daily FTB discussion. As will be seen in this report, the timing of the FBF introduction turned out quite timely, with numerous burn area flooding events experienced in 2021.

For the 2021 operational season, Dewberry continued to be the Program's Project Manager with subconsultant HydroMet Consulting, LLC (HMC) brought in mainly to provide forecasts (together, hereafter referred to as Team). Dewberry meteorologist Alyssa Dietrich produced the SPM and identified flood events to be logged in the FBF. The Programs' forecasts (FTB/FTO/FBF) were developed by HMC meteorologists Dmitry Smirnov and Dana McGlone, who also contributed to a handful of SPM posts. Archived forecasts remain available through the Program's website www.coloradofloodthreat.com. David Sutley served as the primary contact and 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 weather over the 2021 forecast season, evaluate Program viewership, and to document upgrades made to the Program prior to May 1, 2021 start date.

Daily Flood Threat Bulletin (FTB)

The FTB is designed for daily issuance during the forecast period by 11:00 AM. When possible, FTB forecasts are issued earlier to provide more lead time to end-users, which is especially important on days where there is an elevated flood threat. The FTB forecasts the daily threat level of flooding across the state, the nature of the threat, and the time period in which the threat of flooding would be the greatest in a zone-specific manner (there are fourteen Forecast Zones). Additional information provided by the FTB includes a characterization of the threat of severe weather (tornadoes, high winds, hail, etc.), the probability and intensity of thunderstorm rainfall rates, and expected totals. Table 1 summarizes the six-tier category system that is used to characterize the flood threat. The first five-tiers indicate the flood threat: None, Low, Moderate, High, and High Impact. The last tier, 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 is updated during the afternoon hours. There were four such forecast updates needed this season, and social media updates were also issued to notify end-users about the evolving flood threat.

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

THREAT	DESCRIPTION
NONE	No flood threat is expected.
LOW	Low probability (<50%) that isolated/widely scattered flooding will occur. If flooding occurs, low impact/severity is anticipated.
MODERATE	Moderate probability (50-80%) of flooding occurring.
HIGH	High probability (>80%) of flooding occurring.
HIGH IMPACT	High probability (>80%) of *high-impact* flooding due to a combination of factors including, but not limited to: high population density, antecedent rainfall and/or long-term duration.
NWS WARNING	Active NWS Flood Warnings (riverine).

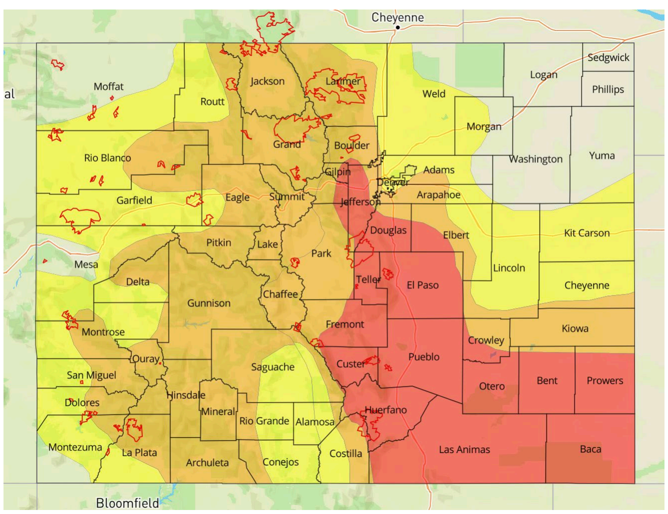


Figure 1: Example of the FTB map from July 31st, 2021. The Low, Moderate and High threats are highlighted in yellow, orange and red, respectively.

The threat of daily flooding is conveyed to the end-user through the use of graphics and text. The graphical component to the product includes a map of the state of Colorado with county boundaries and a color-coded threat to succinctly illustrate the range of flooding threats across Colorado (Figure 1). The evolution of this presentation to a more communicative graphical format enhances the threat area visualization and possible impacts. Additionally, a scroll over feature was added to the maps in 2019 that pops up maximum rain rates and potential hazards by threat level. All forecasts continue to be archived in a blog-style manner and are available on the product's website. New to the Program in 2020, riverine flooding events from snowmelt, could be reported through the "Report a Flood" tab at the top of the website. This "Report a Flood" tool was created to fill the gray area between what the Program forecasts (i.e., flooding caused by rainfall) and what the Program does not forecast (i.e. riverine flooding caused by other factors such as snowmelt, ice jams, dam releases, etc.).

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 and precipitation-driven flood threat, and it provides a precipitation forecast map for the entire state when meaningful precipitation is expected. The FTO continues to be structured in an event-based manner, where rainfall is partitioned by its forcing features and presented in a timeline.

An example of a threat "timeline" is shown below in Figure 2 from May 27th. This FTO illustrates the addition of the snowmelt riverine flood threat, which peaks at the beginning of the warm season. Reservoir levels, and other metrics important to categorize drought conditions, were also tracked throughout the season in the FTOs, alongside our typical monthly departures from average temperature and precipitation. Upgrades to the FTO map, similar to the FTB map, now allow for more interaction by end-users.

FTO 05-27-2021: Another Prolonged Period Of Unsettled Weather, Then First Taste Of Summer Heat

May 27, 2021 by Dima Smirnov · (Edit)

Issue Date: Thursday, May 27, 2021
Issue Time: 1:30PM MDT
Valid Dates: 5/28-6/11

Colorado Flood Threat Outlook

Next 15 Days	Fri 28-May	Sat 29-May	Sun 30-May	Mon 31-May	Tue 1-Jun	Wed 2-Jun	Thu 3-Jun	Fri 4-Jun	Sat 5-Jun	Sun 6-Jun	Mon 7-Jun	Tue 8-Jun	Wed 9-Jun	Thu 10-Jun	Fri 11-Jun
Precipitation			Event #1												
Snowmelt															

Twitter: @COFloodUpdates

No Apparent Threat | Elevated Threat | High Threat
FLOOD THREAT LEGEND

Figure 2: Example of an FTO headline from 2021 illustrating the threat "timeline" with the addition of a snowmelt outlook.

State Precipitation Map (SPM)

In July of 2017, Dewberry upgraded from the State Total Precipitation (STP) map to the State Precipitation Map (SPM). The SPM product expanded the Quantitative Precipitation Estimates (QPE) to include 48- and 72-hour accumulations, as well as maximum 1-, 3- and 6-hour precipitation over the past 24-hour period at 500-meter resolution. The new QPE, called MetStorm Live, was obtained from sub-consultant DTN, and data is visualized through a custom built, Dewberry-hosted webmap. Daily monitoring of the SPM performance in 2017 suggested that the product underestimated rainfall to the west of the Continental Divide during several monsoonal events. On June 11, 2018, a bias adjustment was added to the 24-, 48- and 72-hour rainfall accumulations. The enhancement combines daily CoCoRaHS precipitation data, a basemap, and a radar estimated rainfall grid to produce a bias adjustment to the original 24-hour MetStorm Live grid. The bias adjustment improved the underestimation of rainfall over the San Juan Mountains and southeast corner of the state due to topography and radar ranging issues. It also helps improve overestimations of rainfall associated with hail contamination, especially over the eastern plains. In early 2019, an update was made to the gauge quality control (QC) algorithm to better handle remote station locations and high elevation QPE. 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.

An example of the daily SPM is shown in Figure 3. In addition to the map-based visualization, meteorologists provided text-based summaries of recent hydrometeorological conditions including extreme rainfall values in a historical context, flooding, debris slides, hail, wind, tornadoes and wildfire activity. Discussions are also supplemented with gauge data from CoCoRaHS, COOP, Mile High Flood District's ALERT, SNOTEL and NWS Local Storm Reports. The relatively new "Report a Flood" tool on the website brought in four reports from three different days this season, and it is recommended that this feature is highlighted more frequently to help increase usage in the future.

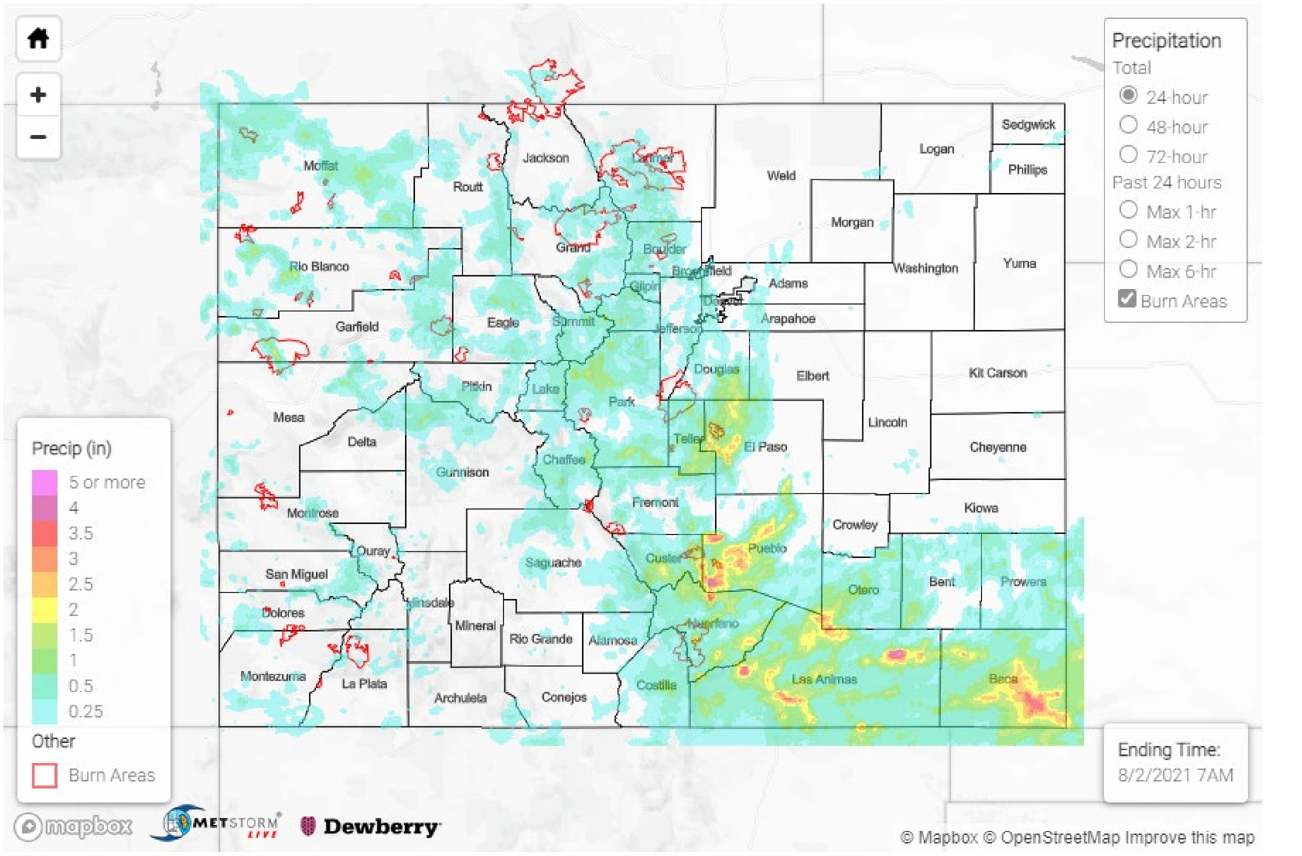


Figure 3: Example of SPM QPE from August 1st, 2021 showing the previous day's precipitation.

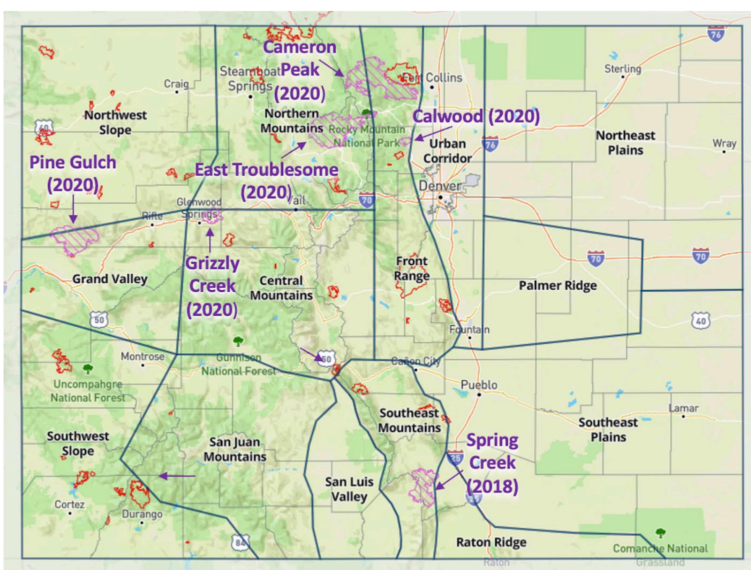


Figure 4: Wildfire burn areas that were featured on the daily FTB/FTO maps for 2021. The labeled burn areas (purple shade) were identified as the most hazardous and received daily dedicated flood threats in the FBF. Source: National Interagency Fire Center

Fire Burn Forecast (FBF)

There is concern for extremely dangerous runoff, mud flows, and debris slides over recent wildfire burn areas located over steep terrains, especially those near population centers and highly traveled roads. During the 2020 wildfire season, Colorado experienced three of its largest fires on record with a total of seven fires exceeding 10,000 acres in size. In the past, wildfire forecasting has been indirectly incorporated into the FTB (Dewberry, 2020). This has presented a challenge for operations given the stark difference between runoff sensitivity over burn areas compared to nearby unscarred areas. After the historical 2020 wildfire season, this challenge was significantly exacerbated, which was the motive behind creating the Fire Burn Forecast (FBF) product. 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. The main objective of the new 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.

This forecast season, there were six potentially dangerous burn areas identified and monitored by the Team in the FBF: Calwood (2020), Cameron Peak (2020), East Troublesome (2020), Grizzly Creek (2020), Pine Gulch (2020) and Spring Creek (2018). Other burn areas over steep terrain that had occurred in the last 5 years and burned at least 700 acres were also included on the daily FTB/FTO maps (Figure 2). Ideally, each 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 FTB: 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. A couple of the larger and more complex historic wildfires (such as the Hayman Fire in 2002) remain on the map until the Colorado State Forest Service informs the Program that burn areas have recovered enough to be removed from the map. In 2020, FTB and FTO maps were updated to allow end-users to click on a burn area to see its name, year of occurrence, and the number of acres burned.

An example of a daily FBF is shown in Figure 5. The daily forecast table shows three measures of antecedent rainfall for the prior 24 hours (blue columns) 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. These estimates are derived from gridded, gauge-adjusted radar rainfall products. A separate column shows a subjective evaluation of whether flooding was reported in the past 24 hours. For "Today's Threat", the FBF 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. The rainfall thresholds estimated to cause flooding issues for each burn area are set at the beginning of each season, and then are adjusted midway through the season as necessary. The Team has attempted a high-level verification for burn area threats once again this season. More information and methodology can be found in Appendix D of this report.

Fire Name ▲	Max 3hr ▲	Avg 24hr ▲	Burn Area Coverage ▲	Flooding Reported Yesterday? ▲	Today's Threat ▲
Calwood	0.0 in.	0.0 in.	0 %	NO	MODERATE
Cameron Peak	1.2 in.	0.1 in.	30 %	NO	HIGH IMPACT
East Troublesome	0.7 in.	0.1 in.	60 %	NO	HIGH
Grizzly Creek	1.4 in.	0.2 in.	>90 %	YES	MODERATE
Pine Gulch	1.1 in.	0.2 in.	>90 %	NO	LOW
Spring Creek	0.0 in.	0.0 in.	0 %	NO	LOW

The blue columns represent antecedent conditions from the past 24 hours.

Figure 5: An example of a daily FBF forecast post from July 30th, 2021.

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, 496 were delivered on-time or ahead of time. The seven late products were 2 SPMs, 1 FBF and 3 FTOs, all of which were posted within the hour of their 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 2 weeks after the end of the month.

Table 2: On-Time performance metrics for all issued products (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	151	2	99%
	FTB	30	30	0	100%		FTB	153	153	0	100%
	FTO	9	9	0	100%		FTO	44	41	3	93%
	FBF	30	30	0	100%		FBF	153	151	1	99%
	TOTAL	99	99	0	100%		TOTAL	503	496	7	99%

2) CHARACTERIZATION OF FORECAST PERIOD WEATHER

Overview

Overall, the 2021 operational season saw average to slightly above average activity, though heavy rain, flooding, and debris flows were reported several times each month from all areas of the state (Table 4). One reoccurring theme of the season was the sharp gradient in drought conditions between east and west of the Continental Divide, even with the active season (Figure 8). After Eastern Colorado experienced one the wettest springs on record, drought conditions were completely eliminated by early summer, while Western Colorado remained gripped in “exceptional drought”, only for drought to return in the east by the end of September. After a few very quiet seasons, this season also saw the return of a relatively active North American Monsoon (NAM), which brought day after day of heavy rain to Colorado, especially in July and early August (Figure 6). As expected after the devastating 2020 fire season, which included the three largest fires in state history, the burn areas were particularly vulnerable and faced several days of flood events throughout the season (Table 3). Interstate-70 though Glenwood Canyon was closed for weeks at time after massive debris flows in the steep canyon following the Grizzly Creek fire, making national headlines.

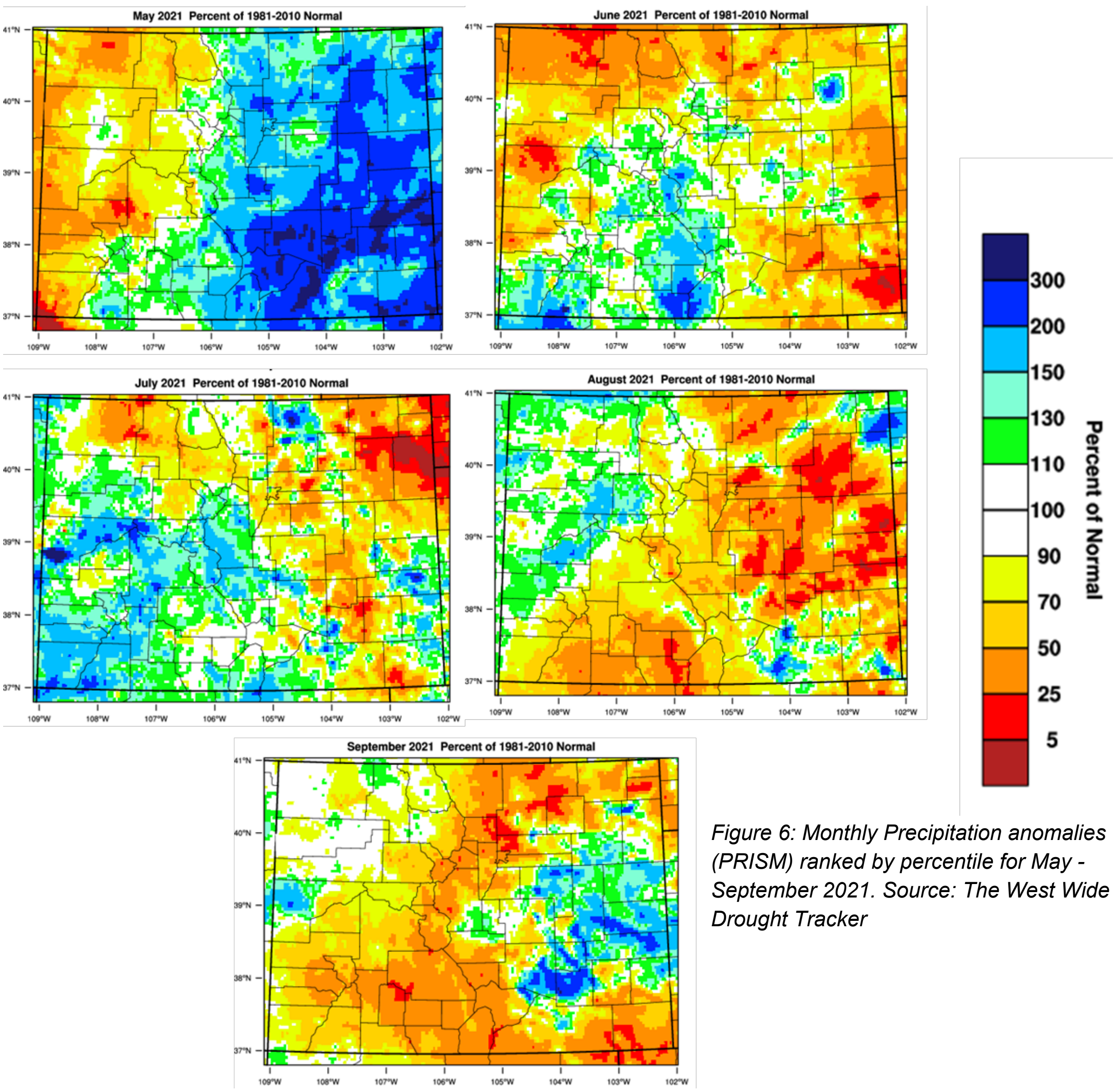


Figure 6: Monthly Precipitation anomalies (PRISM) ranked by percentile for May - September 2021. Source: The West Wide Drought Tracker

Table 3 : Number of days a flood was reported on each of the 2021 FBF burn areas. Due to the rural nature of many of the burn areas and closures following floods, it is possible that counts are underestimated.

			Number of Days With…			
Wildfire	**Date of Fire**	**Burn Acreage**	**Debris Flows**	**High QPE**	**Debris Flows + High QPE**	**Threats Issued**
Calwood	Oct 2020	10,106	1	11	12	42
Cameron Peak	Aug 2020	208,913	5	31	36	51
East Troublesome	Oct 2020	193,812	6	9	15	44
Grizzly Creek	Aug 2020	32,631	11	6	17	45
Pine Gulch	July 2020	139,007	4	11	15	30
Spring Creek	Jun 2018	108,045	4	10	14	32

Detailed Summary

Table 4. The Top 5 most impactful flood and rain events over the 2021 forecast season.

	Date(s)	Intensity	Impacts
1. Cameron Peak	July 20th	Estimated rainfall up to 2" with a large area greater than 1" in 30 minutes over the western portion of burn area	Loss of life with significant mud flows and debris slides reported throughout Cache la Poudre Canyon.
2. Grizzly Creek	Jun 26th - Jul 5th; Jul 20th - Aug 3rd	USGS gauge max 15-min rainfall 1.10" (7/29); Radar estimated storm totals up to 2.23" (7/29, 7/31)	I-70 was closed for several days throughout July and August due to the highway being washed out in several places along with numerous debris flows. Flood reports are estimated.
3. Holyoke, CO	August 19th	Holyoke CoAgMet gauge reported 8.11"; up to 9" of rain estimated by radar	Significant flash flooding (roads, ditches, creeks), tornado, 1" hail, 65mph+ wind gusts.
4. Wet Mountains	July 31st	Daily total of 5.03" observed in Pueblo; up to 7" of rain estimated by radar (Baca County)	Road flooding, field ponding, river flooding (Arkansas River near Avondale spiked to 4,500 cfs)
5. Western CO Late Monsoon Surge	August 18th - 19th	CoCoRaHS recorded 2.20" in Paonia; GJT breaks two daily rainfall records (1.26" 2-day total)	Debris flows, 50mph+ wind gusts, small hail & snow. Two-day rainfall event brings much needed rainfall to drought stricken western CO, especially the Grand Valley region.

May

Snow water equivalent on May 1st was well below normal across all major basins in Colorado, except for the South Platte basin (Figure 7). As the first few weeks of the 2021 forecast season got underway, a series of low-pressure frontal systems produced late spring, heavy mountain snow in the Northern, Central and Front Range Mountains, accompanied by rain at lower elevations along the Urban Corridor and Eastern Plains. Cameron Pass and Trail Ridge Road picked up 14 and 13 inches of new snow, respectively, between systems that came though between May 3rd and 11th. These late season snowfall events helped to improve drought conditions in Northern and Eastern Colorado, while the long-duration, low-intensity nature of precipitation minimized the flood threat. By May 12th, the SNOTEL snow water equivalent percent of normal in the South Platte basin increased to 112%, while the rest of the major basins in the state continued to fall below normal with snowmelt underway, especially in Southwest Colorado.

A series of active weather days resulted in flooding May 16th-18th in Southern and Eastern Colorado. A flash flood event took place in Downtown Stratton on May 16th, where water ran across roadways after 2.00 inches of rain fell accompanied by severe weather, including funnel clouds and large, damaging hail. Flooding also occurred in Trinidad on May 22nd after more than 3 inches of rain fell in less than 24-hours.

With the end of May came the main portion of the snowmelt season and the potential for riverine flooding, though the threat of riverine flooding was minimal this forecast season. The Purgatoire River near Las Animas in Southeast Colorado reached flood stage May 25th-26th, and the Cache La Poudre in Northern Colorado saw similarly high streamflows around then as well, despite little rainfall in the preceding days. Flooding also occurred along the Arkansas River in Southeast Colorado on May 30th, including water flowing across the highway thanks to snowmelt and the continued active weather pattern in Southern Colorado.

Most of the precipitation during the month of May occurred east of the Continental Divide, with portions of the Southeast Plains and Raton Ridge picking up 300% of normal (Figure 6, top left). Conversely, the Western Slopes and portions of the Grand Valley hovered between only 25-70% of normal precipitation for May, increasing the sharp contrast in drought conditions between the east and west.

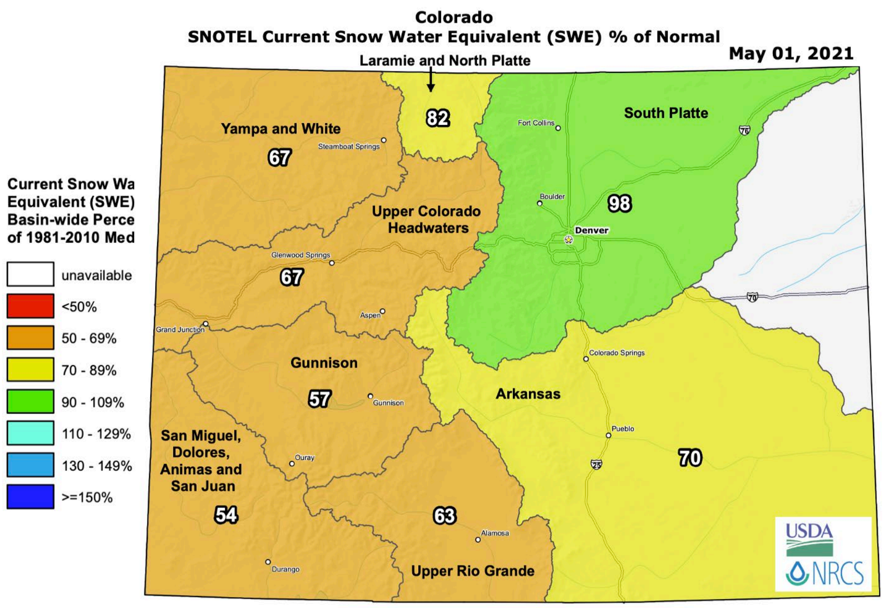


Figure 7: Basin-wide SNOTEL Snow Water Equivalent Percent of Normal on May 1st, 2021, showing near average totals for the South Platte Basin and concerningly low totals for the rest of the state of Colorado. Source: Natural Resources Conservation Service

June

By June 1st, the active atmospheric pattern had eliminated nearly all drought conditions east of the Continental Divide (Figure 8, left), and by June 8th, all drought conditions officially remained limited to the west. June also saw an increase in severe thunderstorm activity, again largely constrained to east of the Continental Divide along the Urban Corridor, Palmer Ridge, and Eastern Plains. After a series of heavy rainfall and thunderstorms tracked over the Cameron Peak burn area, soils became saturated and lead to a debris flow on June 1st.

Mid to late June saw the arrival of the NAM, which helped to moderate fire danger. However, the climatologically early arrival of the NAM also helped produce additional flooding and debris flows across the state. June 25th saw flooding both east and west, from Olathe to Grand Junction. On June 26th, the first public flood report of the season was received using the "Report a Flood" tool when several days of heavy, monsoonal rainfall resulted in urban stream flooding over the metro area, bringing Cherry Creek near Parker into "Action" stage (just below "Minor" flood). June 26th saw the first (of many) debris flows over the Grizzly Creek burn area, which temporarily closed I-70 (Table 4). Moderate rainfall (0.50-1.00 inches in 72-hours) highlighted the sensitivity of this particular burn area. Another debris flow occurred over the Grizzly Creek area on June 28th, this time covering an 80-foot wide and 5-foot deep area of the interstate. On the very last day of June, flooding was reported in rural Weld County after a nearly stationary convective system dropped up to 5 inches of rain in just 2 hours.

June finished with the Southwest Slope, San Juan Mountains, San Luis Valley and portions of the Central Mountains receiving normal to above normal rainfall (Figure 6, top right), especially on the New Mexico Border in the San Luis Valley, with up to 200% of normal rainfall. Elsewhere, precipitation was less than half of the average normal for the month of June, and isolated locations in the Grand Valley and Southeast Plains only received up to 25% of normal.

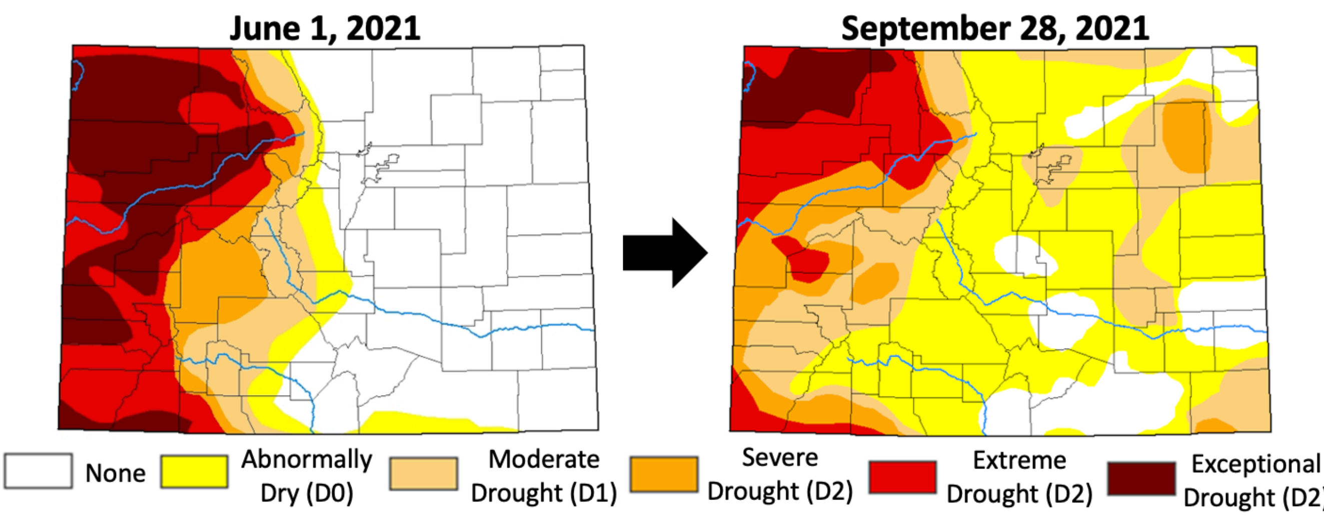


Figure 8: U.S. Drought Monitor update valid on June 1st, 2021 (left) and September 28th, 2021 (right) showing the drastic difference in conditions between east and west of the Continental Divide. The eastern half of the state reached drought free conditions after an unusually wet spring, while the western half of the state remains gripped in a multi-year drought much of the Western US is facing (left). By September 28, 2021 (right), there was a reemergence of drought conditions across Eastern Colorado and the slight improvement of conditions in Western Colorado. *Source: The U.S. Drought Monitor is jointly produced by the National Drought Mitigation Center at the University of Nebraska-Lincoln, the United States Department of Agriculture, and the National Oceanic and Atmospheric Administration. Map courtesy of NDMC.*

July

July picked up right where June left off in terms of monsoonal moisture and heavy rainfall across the state. Moisture was accompanied by intense convection, especially on the Eastern Plains, thanks to a strong trough dominating the weather pattern. An intense thunderstorm in Greeley on July 1st resulted in significant road flooding after 3-4 inches of rain fell in an hour. On the same day, Pueblo broke their daily rainfall record with 1.24 inches of rain, which also caused major street flooding and road closures. Both the Cache la Poudre and Arkansas Rivers rapidly rose in response to the sudden bursts of heavy rainfall from these thunderstorms. Similarly, on June 2nd, flash flooding was reported following thunderstorms on the Spring Creek burn area in Southern Colorado near La Veta and Walsenburg.

The beginning of July also brought more closures of I-70 due to debris flows in Glenwood Canyon (Table 4). Again, relatively little rain actually fell over the Grizzly Creek burn area, further highlighting the scar's extreme sensitivity to rainfall. Additional early July floods were reported over the Cameron Peak, East Troublesome, Pine Gulch, and

Hayden Pass burn areas, as well as near Estes Park, 11-Mile Canyon Reservoir, Poncha Springs and Poncha Pass, and Texas Creek in Fremont County. After the exit of a trough on July 7th, a high-pressure ridge settled over the state, clearing out moisture and creating hot and dry conditions. The ridge also trapped nearby wildfire smoke from the Muddy Creek and Sylvan fires burning in the state, and advected plenty more smoke in from massive fires burning along the West Coast, causing air quality issues.

By mid-month, monsoonal moisture returned as another low-pressure trough entered the state. This began a period of over 2 weeks from July 16th – August 4th where flood threats were issued daily. A deadly flood and debris flow occurred in the Poudre Canyon on July 20th (Table 4) after over an inch of rain fell on the burn area in 30 minutes. Video of the event shows a fast-moving, nearly black river from all the ash coming downstream. In the coming days, debris flows would also be reported on the East Troublesome, Spring Creek, Pine Gulch, and Hayden Pass burn areas after similar heavy rain, as well in Avon, Rifle, Victor, Grand Junction, Cameo, Placerville, Redstone, Telluride, and Buena Vista. After nearly five days of heavy rain saturating the soils across the high elevations and western slope, an impressive eight flood or debris flow reports were made in a single day on July 24th from Pitkin, San Miguel, Montrose, Mesa, Pueblo and Saguache counties. Another major debris flow was reported in Glenwood Canyon on July 29th, again closing I-70, after widespread rainfall in the Central Mountains. I-70 remained closed for nearly two weeks, so there were likely several "unrecorded" debris flows that also took place during the closure. In the mix, there were also several days of severe thunderstorms in the Eastern Plains and Palmer Ridge, where localized heavy rainfall resulted in street flooding in Colorado Springs, Burlington, and Broomfield. Heavy rain across the Wet Mountains on July 31st caused road and field flooding, as well as a spike in the Arkansas River at Avondale (Table 4).

In all, the very active July wrapped up with the Southwest Slope, San Juan Mountains, Grand Valley and portions of the Central Mountains receiving normal to above normal (up to 200% of) July rainfall (Figure 6, middle left). A small portion of Northern Colorado also saw above normal rainfall, which included portions of the Cameron Peak burn area. Even with the surge of monsoonal moisture into the state throughout July, drought conditions remained persistent in Western Colorado, highlighting the severity of the multi-year drought the west is experiencing. While there was some thunderstorm activity on the Eastern Plains during this time, average July rainfall was below normal. The tri-state area in Northeast Colorado only received between 5-25% of their normal July rainfall.

August

The NAM continued to dominate the weather pattern in August, beginning on August 1st with a well-defined trough that produced another round of heavy rainfall that resulted in a debris flow on the Pine Gulch burn area. This event was followed by another series of impressive flood days from August 2nd-3rd. During this period, heavy rain fell across the high elevations and caused seven separate flood events, including over the Pine Gulch, Spring Creek, Decker, Grizzly Creek, and East Troublesome burn areas, and in the towns of Crestone and Placerville. In Placerville, deep trenches were left behind on August 2nd after flood waters scoured gravel roads and over two feet of debris ran across paved roadways. The monsoon surge then spilled into the Eastern Plains, where on August 4th over 1.5 inches of rain fell in two hours in Lamar and caused water ponding on roads.

As August progressed, an overall drying pattern increased time between periods of heavy rainfall. However, this drying ridge pattern allowed smoke to infiltrate into Colorado from wildfires across the west. At several points during the month of August, Denver had the worst air quality reported in the entire world. August also saw record breaking heat for much of Colorado, and the reemergence of drought conditions east of the Continental Divide on the Northeast Plains as most of the monsoonal surges remained south and west. August continued to see severe weather days as well, with threats of high winds, large hail, and a tornado or two.

By August 18th-20th, another deep plume of monsoonal moisture associated with a low-pressure system made its way into Colorado from the west, prompting Flood Warnings over the vulnerable burn areas and causing a heavy rain induced debris flow north of Craig in the Northwest Slope. Grand Junction set a daily rainfall records for both days, with just over 1.26 inches of rain in total (Table 4). The rapid eastward progression of the trough and plume of moisture over the two-day period caused widespread rainfall and even snow at some of the highest elevations of the Central Mountains. Once the plume moved over the Eastern Plains, a supercell thunderstorm was able to form followed by several training thunderstorms over Holyoake and nearby towns in the Northeast Plains. A CoAgMET station in Holyoke recorded 3.26 inches of rain in a single hour on August 19th, and a total of 8.06 inches of rain in a 12-hour period (Table 4), which amounts to well over a 1000-year return period event (NOAA Atlas 14).

The remaining days of August were largely hot, dry, and smoky, with limited afternoon thunderstorm coverage across the Urban Corridor, Palmer Ridge, and Eastern Plains. Only portions of the Grand Valley and Northwest Slope received around or above normal precipitation during this period, along with an isolated areas of the Eastern Plains; the isolated area in Northeast Colorado is due to the extreme rainfall event in Holyoke (Figure 6, middle right). Much of the state received between 25-70% of normal, and by the end of August, drought conditions had returned to the Northeast Plains, Palmer Ridge, and Southeast Plains.

September

It did not take much time into the month of September for the late season return of monsoonal moisture, this time a surge was associated with the tropical remnants of Hurricane Laura. Over a three-day period from September 1st-3rd, widespread rainfall was reported across the state which began over the western slope. Another daily rainfall record was set in Grand Junction on September 1st, where 0.76 inches of rain fell. The eastward progression of the moisture caused heavy rain and a minor debris flow in Grand County, likely associated with recovering soils from the East Troublesome burn area; snow was also reported at the high elevations. By September 3rd, widespread rainfall was concentrated on the Urban Corridor, Eastern Plains, and Palmer Ridge, accompanied with high winds and severe hail – enough to blanket the Southern Denver suburbs like snow.

September mostly continued August's hot and dry trend, with record breaking heat across the state by mid-month. Daily high temperature records were broken across Southern Colorado at all three long-term climate stations: Colorado Springs, Pueblo, and Alamosa. The high temperatures were accompanied by dangerous air quality comprised of wildfire smoke and urban pollution. Eventually, fall-like conditions began to emerge after the passage of a cold-front, which brought another snow event to the high elevations from September 19th to 23rd, while scattered showers and thunderstorms persisted over the lower elevations.

The relentless monsoon season of 2021 did not go out easy though, as one last plume of moisture made its way into the state from the southwest beginning on September 26th, which brought showers to the Southwest Slope and San Juan Mountains. On September 28th, a debris flow was reported over the Pine Gulch burn area near DeBeque after long periods of intermittent rain with embedded convection. On September 29th, there were four different debris flows or minor flooding reported: the first was over the Grizzly Creek burn area, which temporarily closed I-70 again; second in Fruita, after heavy rain in the Little Salt Wash Creek; third across the Urban Corridor, where minor street flooding was reported; and finally the fourth in rural Montrose County, where heavy rainfall caused a rock slide on US141.

Despite the few pulses of late season moisture, September ended up dryer than normal for much of Colorado, especially in the Southwest and Central Colorado (Figure 6, bottom), with the exception of portions of the Eastern Plains. Nearly all the progress made in eliminating drought conditions east of the Continental Divide was lost, with "severe drought" reestablishing itself over the Northeast Plains. West of the Continental Divide saw some drought improvement, as the area of "exceptional drought" decreased slightly – roughly 2% in total area. Still, "moderate" to "extreme" drought covered nearly the entire region (Figure 8, right).

Seasonal Stats

There was a total of 58 Flood Days over the 2021 forecast season, which is below the 2012-2020 average of about 69. Over the course of the season, 65 flood threats were issued, including 23 Moderate and 4 High threats. Appendix D shows the number of flood threats issued for a given location over the last 5 years. Although not unlike previous seasons, burn areas were particularly threatened by heavy rainfall over the course of the season. All six of the major burn areas monitored by the Program experienced flooding, many with multiple events.

Figure 9 shows the daily number of rain gauge reports over one and two inches of rainfall, respectively, as well as the total area exceeding Flood Day thresholds measured by the Stage IV gridded product. There were 71 days in total where at least one station measured over 1 inch, 35% higher than the historic low observed last season. There were then 46 days in which at least two stations received a qualifying precipitation amount. For more widespread events, there were 20 days where at least 10 stations measured qualifying precipitation, which is 40% more when compared to 2020. The biggest increase over the last two forecast seasons was in the number of days in which 100 or more stations saw qualifying precipitation, which makes sense given the more active season. For the 2021 forecast season, there were a total of four days where over 150 stations received qualifying precipitation; and on the third day of the 2021 season, over 200 reports exceeding one inch were made. This is the highest daily total of qualifying stations for the operational season, and it is the first time over 200 stations reported one inch or more since 2017. This early season, widespread event was associated with snow in the high elevations and low intensity precipitation for the lower elevations, so there was no flooding reported.

As for Flood Day Area (Figure 9, bottom), there were 19 days where over 1,500 sq. mi. recorded rainfall greater than 1.50 inches (1 inch) east (west) of the 1,600-meter contour. This is another sharp increase from last year's six total days exceeding 1,500 sq. mi. This season there were three days when flood area exceeded 6,000 sq. mi., an indicator of the relatively active flood season.

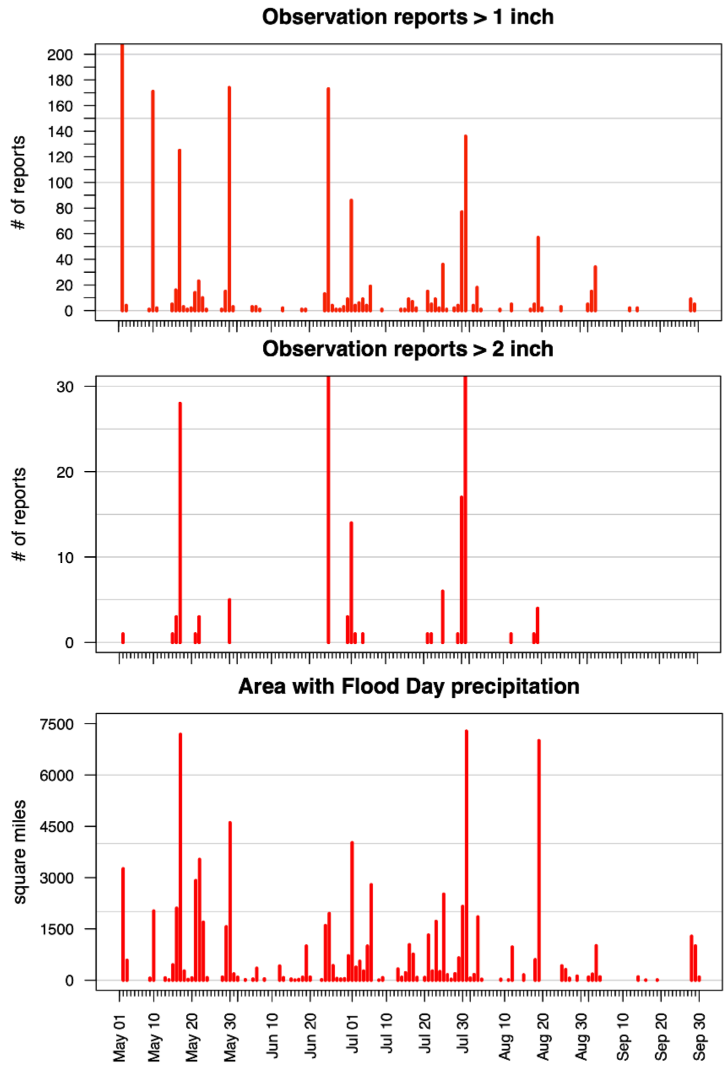


Figure 9: The number of daily observation reports exceeding (top) 1 and (middle) 2 inches, and (bottom) the coverage of Flood Day precipitation, in sq. miles, from the gridded precipitation product. For reference in (c), the total area of Colorado is about 104,000 sq. miles.

3) VERIFICATION METRICS

a) 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 forecasted but not observed. The Team has continually placed substantial effort on verification to increase forecast utility and, in turn, help improve future forecasts. **This year, two major verification enhancements were added. First, the inclusion of the Multi-Radar Multi-Sensor (MRMS) QPE product from the National Severe Storms Laboratory (NSSL)**. **Second, a rigorous treatment of daily QPE product bias based on scatter plots between rain gauges and their QPE values.** The data sources and methodology used to verify 2021 forecasts are described below.

Data Sources: Rain Gauges

a) Daily precipitation accumulation reports from up to 1,300 CoCoRaHS observers across Colorado. This data is generally reported in the morning and encompasses the previous 24-hours. We use only reports that are received from 6AM to 10AM to ensure that measurement is consistent with the forecast period. Questionable observations were noted and discarded based on comparison with other data.

b) Natural Resources Conservation Service (NRCS) SNOTEL hourly precipitation, which was aggregated into daily accumulation at approximately 65 high-elevation sites across Colorado. Questionable observations were noted and discarded based on comparison with other data.

c) The University of Utah's MesoWest hourly precipitation data, which has many contributing networks. The majority of the data came from: 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). Hourly data was aggregated into 24-hour totals, and questionable observations were noted and discarded based on comparison with other data.

d) United States Geological Survey (USGS) sub-hourly precipitation data, which is particularly helpful over the higher terrains, fire burns, and more populated areas of Teller and El Paso Counties. The sub-hourly data was aggregated into a rolling 1-hour totals. This methodology allows for the true 1-hour rainfall to be retained, which in year's prior had been truncated at the hour. This fixed a potential underestimation of the true 1-hour rainfall value.

Data Sources: Quantitative Precipitation Estimates (QPE)

e) NSSL MRMS gridded precipitation data, hereafter MRMS, is a publicly available, near real-time hourly product. MRMS is based on an initial best-guess of radar (NWS and others), satellite and weather model informed rainfall estimates, and corrected with high quality precipitation gauge data. It is produced on a roughly 1 km (0.6 mile) grid. 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 herein.

f) NOAA Stage IV gridded precipitation data, hereafter Stage IV, is a publicly available 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). In past years, maximum 1-hour, maximum 2-hour, and 24-hour QPE were all used. However, 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 this year.

Data Sources: Storm Reports

g) Local storm reports (LSRs) obtained from the four NWS offices that are responsible for Colorado: Boulder, Pueblo, Grand Junction, and Goodland (KS) from the Iowa Environmental Mesonet. 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 10AM. If a “Heavy Rain” report did not specify a magnitude, it was dismissed unless the observer’s note contained a specific reference to flooding.

h) Flood reports obtained from the Program’s web-based report submission system, subject to quality control by the Team.

Data Sources: NWS Warning and Advisory products

i) NWS warning and advisory GIS data (obtained from the Iowa Environmental Mesonet), including metadata such as when the product was issued. Flash Flood Warning, Riverine Flood Warning and Areal Flood Advisory products were included in the analysis.

b) 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 C), it would be difficult to describe a Flood Day with just a single intensity threshold. Thus, to provide some ability to cover relatively flat 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 four</u> criteria is met in the issued flood threat area (e.g. Figure 11):

1) Gridded or observation based 1-, 2- and/or 24-hour rainfall exceeds (see Figure 10):
    a. 1.00 in. west of the 1,600-meter (~5,250 foot) elevation contour over the eastern plains
    b. 1.50 in. east of the 1,600-meter (~5,250 foot) elevation contour over the eastern plains
2) A qualifying NWS Local Storm Report (LSR) report described is received. For more information, see item (g) under Observational Data Sources, above.
3) An NWS Flash Flood **Warning** is issued that day. Note that this does NOT include Warnings issued over fire burn areas, which have much lower intensity thresholds. An NWS Flood **Advisory**, alone, does not qualify as a Flood Day, but could contribute if other factors were supportive.
4) 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 E for more information.

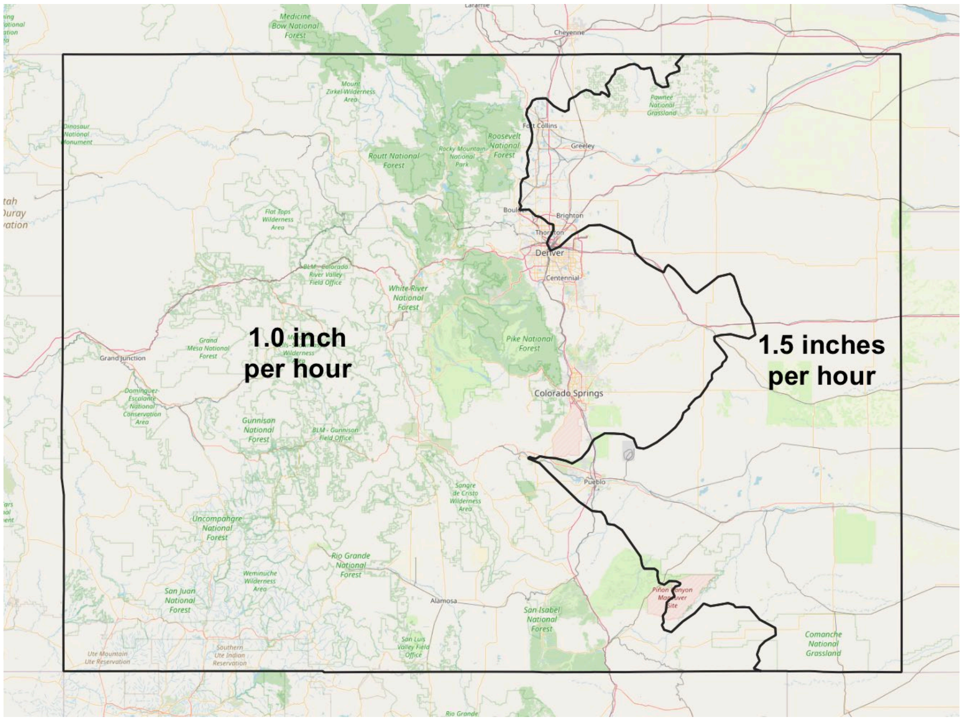


Figure 10: Colorado map with thick black line showing the 1,600 meter (~5,250 foot) elevation contour line east of the Continental Divide, which acted as the demarcation in rainfall-runoff sensitivity. To the east, a rainfall threshold of 1.50 inches per day was used to denote a "Flood Day"; to the west, it was 1.00 inch.

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, BIAS deciphers which of those instances are suggestive of a Flood Day.

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	2
Long-duration low intensity precipitation causes qualifying 24-hour precipitation total, but runoff does not support flooding.	Low Intensity (LI)	Flood Day = 0	5
There is no rainfall, 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 E).	BIAS	Flood Day = 0	33

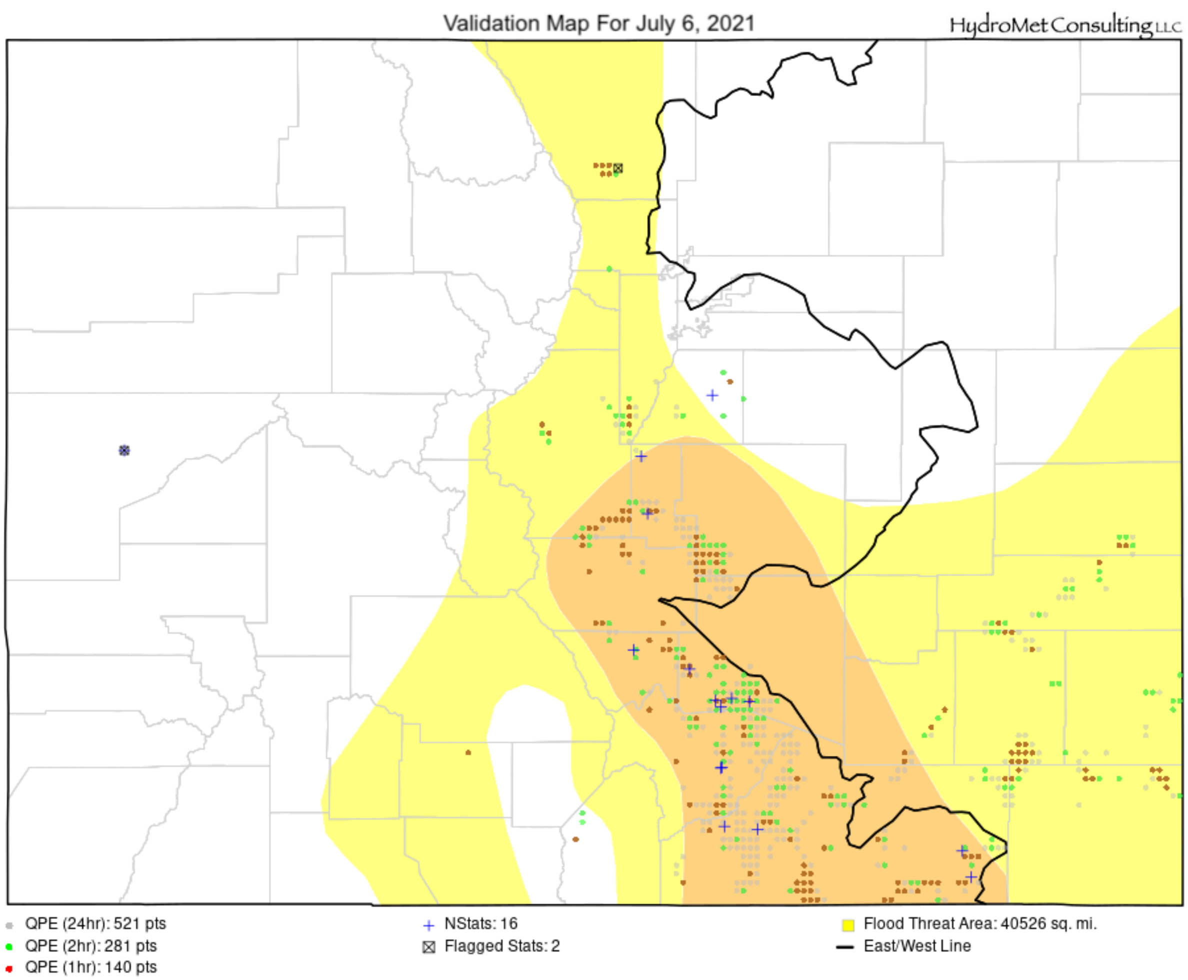


Figure 11: Example of daily verification map from July 6th, 2021 showing qualifying 1-hour, 2-hour and 24-hour MRMS grid points (gray), rain gauges (blue crosses) and threat area (yellow color fill).

c) 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 to the flood threat. 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 forecasted, but is observed, this results in a "Miss" [case (b) in Table 6]. Second, if a non-Flood Day is forecasted 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 rate, which, given the uncertainties with heavy rainfall forecasting, necessarily results in a higher False Alarm rate. 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	Calculation (see *Table 6*)	Summary	Goal
Accuracy or "Hit" rate	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 Rate	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 achieved or exceeded four of the five targets established in Table 7, while the remaining metric (False Alarm Ratio) was on par with the 20% goal. With an overall Hit Rate (Hit %) of 88%, forecast performance continued to be **well above** the >75% target. **Furthermore, the Probability of Detection (POD) was 90%, which is the best performance in this metric since at least 2012**. The False Alarm Rate (F) was slightly higher than previous years, but it was on par with the Program's 20% goal. **Meanwhile, the low Miss Rate (Miss %) of 10% was also not only well beyond the Program's goal but also represented the best performance since 2012, just like POD**. Just like in past years, the days that did see a Miss were very marginal events that had limited heavy rainfall area.

Looking at the month-to-month performance in Table 8, July stood out as the most active month by far, with 23 Flood Days observed. This was due to a prolonged period of active monsoonal flow (also see Section 2). Forecast performance was solid in July with a Hit rate of 90%, POD of 96% and a Miss rate of only 4%. July saw two High threat days (July 1st and July 31st), along with an unusually high number of Moderate threats issued (11). In fact, there were an equal number of Moderate threats as Low threats during July, whereas typically Low threats are issued twice as often. August also experienced several active periods with two more High threats issued (August 2nd and August 19th). Of particular note, August 19th experienced the state's highest daily rainfall over the season (and very likely 2021) at just under 9 inches along the Kansas border of the Northeast Plains (Holyoke). That day had an initial Moderate threat for the area, which was bumped up to a High threat by mid-afternoon (a High threat was ongoing for western Colorado).

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	8	8	22	10	4	**52**
(b) No Flood / Flood	1	3	1	0	1	**6**
(c) Flood / No Flood	1	2	2	5	3	**13**
(d) No Flood / No Flood	21	17	6	16	22	**82**
Total Days	31	30	31	31	30	**153**
Hit %	94%	83%	90%	84%	87%	**88%**
POD	89%	73%	96%	100%	80%	**90%**
FAR	11%	20%	8%	33%	43%	**20%**
Miss %	11%	27%	4%	0%	20%	**10%**

Table 9 shows the yearly performance summaries from 2012 through the present. The number of Flood Days rebounded during 2021 to 58 after three relatively quiet seasons from 2018-2020. Overall, forecast performance was arguably as good, or better, than any time during the Program's history. However, the False Alarm Rate (also seen in the bias) while on par with the Program's 20% goal, can continue to improve as the Team develops new Colorado-specific forecast guidance products to complement the manual aspect of forecasting. Lastly, it is important to reiterate the significance of the enhanced verification procedure using MRMS data as well as the QPE bias correction assessment. These should lead to better understanding of Colorado's heavy rainfall climatology, especially during instances of (i) smaller storm size and (ii) storms forming over poorly gauged regions, which will ultimately improve forecasting ability.

Table 9: 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.

	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**

Table 10 shows the forecast performance as a function of threat level. Note, 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 flooding will be realized. Similar to previous seasons, **Table 10 shows this to be the case with a 74% Hit rate for Low threats, an 87% Hit rate for Moderate threats and a continued 100% Hit rate for High threats.** Fortunately, there were no days when a High Impact threat was issued this season (although several were issued for burn areas).

Table 10: 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	28 (74%)	10 (26%)	38
Moderate	20 (87%)	3	23
High	4 (100%)	0	4
High Impact	0	0	0
Total	52 (80%)	13 (20%)	65

4) USER ENGAGEMENT

An online presence through the Program's website and social media accounts continues to be of growing 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 many online media outlets. Like prior seasons, the Team provided end-users with four outlets to receive forecast updates and other flood threat information (Table 11). Most significant is the Program website, which has been the main form of communication since the Program began. Beginning in 2017, Dewberry 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 embrace the Twitter social media platform to provide forecast updates, interesting hydrometeorological observations, and other informational messages. Finally, in 2018, a Facebook page was created to reach a separate demographic from Twitter. All four forms of communication continue to be utilized with encouraging results on the social media front. Nonetheless, direct outreach to Office of Emergency Mangers (OEM), 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 11: Website and social media accounts used by the Flood Threat Bulletin.

Platform	Account	Engagement
Website	www.coloradofloodthreat.com	186 Subscribers
Twitter	@COFloodUpdates	1,528 Followers
Facebook	@COFloodUpdates	421 Followers & 390 Likes

Website

Figure 12 shows daily website usage during 2021 (black) overlaid with the previous four seasons. Website usage was very high from late June to early August. This period aligns with two prolonged periods of monsoonal rainfall that occurred from June 23rd to July 6th and again from July 20th to August 4th. During this period, average daily site visits were above 150 for 8 days, which was the highest in Program history. Similar to past seasons, the average daily site visits were typically highest on days that flood threats are issued (84 vs 45 end-users per day on non-threat days). The flood threat daily end-user number (84 end-users per day) is up roughly 42% from last season (59 end-users per day), and days when an elevated threat was issued (Moderate or High) had 122 visitors. This indicates that the more threatening (potential) flooding messages are being better received by end-users, which is important for the Programs' goal of early detection and enhanced awareness. Viewership peaked on July 23rd when 236 end-users accessed the website during a day that a large Moderate threat was issued for the Front Range and portions of the western high terrains. This is encouraging that the post reached so many end-users as it was a Friday, which is typically when Colorado mountain activity ramps up for the weekend.

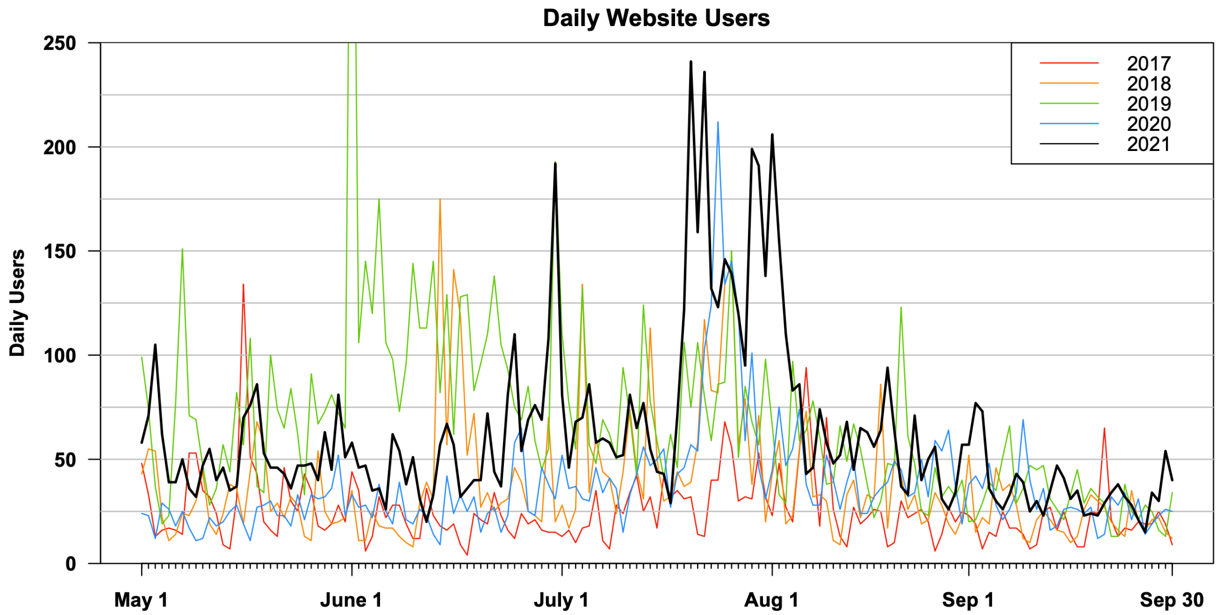


Figure 12: Daily website users during 2017 (red), 2018 (orange), 2019 (green), 2020 (blue) and 2021 (black).

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 Twitter social media platform, with the top-level goal being to provide updates on any impending flood-related threat across Colorado in a concise, headline-style matter. The Twitter account was an immediate success during the September floods, and it was expanded 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 bi-weekly FTO posts, the Program's social media strategy attempts to maximize the way this data is leveraged by creating unique posts. For example, Figure 13 is a capture of a Twitter message ("Tweet") created on July 4th that looked at radar estimated rainfall over the Grizzly Creek burn area that produced excessive runoff and debris flows. This Tweet produced over 5,000 Impressions; and during the month of July, six Tweets reached 4,000+ Impressions. Thus, Twitter represents a tested and effective social media strategy for the Program's product dissemination.

The Program's Twitter account, **@COFloodUpdates**, continues to gain viewership since its inception with the total number of followers up to 1,528 by the end of 2021 season. This is an increase in followers of about ~125 from the end of the 2020 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 (60K+ followers) and the Colorado Climate Center. This season, FEMA Region 8 (43K+ followers) began to follow the Program's account, which could be a useful relationship to build. As always, retweets by popular media accounts typically increase the number or Twitter followers, or at the least, exposure to a more diverse group of possible end-users of the Programs' products.

Impressions	5,065
Total engagements	75
Media engagements	36
Detail expands	14
Profile clicks	9
Likes	8
Retweets	4
Hashtag clicks	2
Replies	1
Link clicks	1

Figure 13: Example of a unique Tweet that provided insight to a flash flood event that occurred over the Grizzly Creek burn area on July 3rd. This Tweet engaged 75 end-users (36 from media) and had over 5K Impressions. This not only helped increase Program viewership, but also indicated public interest in a post-burn area flash flood assessment.

One of the more useful data variables from Twitter Analytics is “Impressions.” Impressions are defined as the number of times Twitter users saw a particular tweet and demonstrates the effectiveness of the use of specific hashtags and interactions (retweets) from other accounts that may have more followers. Figure 14 shows the daily Impressions received during 2021 (black line) as well as those for the 2017 through 2020 seasons. The average daily Impressions for 2021 was ~3.3K with the next closest year being 2018 where average daily Impressions were ~2K. This statistic indicates both the popularity of the social media platform as well as its favorable impact on the Program’s exposure. While it is likely that the Impressions were up due to a more active flood season (especially after several quiet years), it is undoubtable that the Program’s viewership is higher each year. Over the 2021 season, the Program created 280 unique Tweets (~50 more than 2020) and received a total of ~500K Impressions (double that of 2020). Of the 280 Tweets, 127 of them received over 1,000 Impressions, which is an increase of roughly 45% from last season. Due to the ever-changing nature of social media, off season work is recommended to maximize viewership of the Programs’ Tweets.

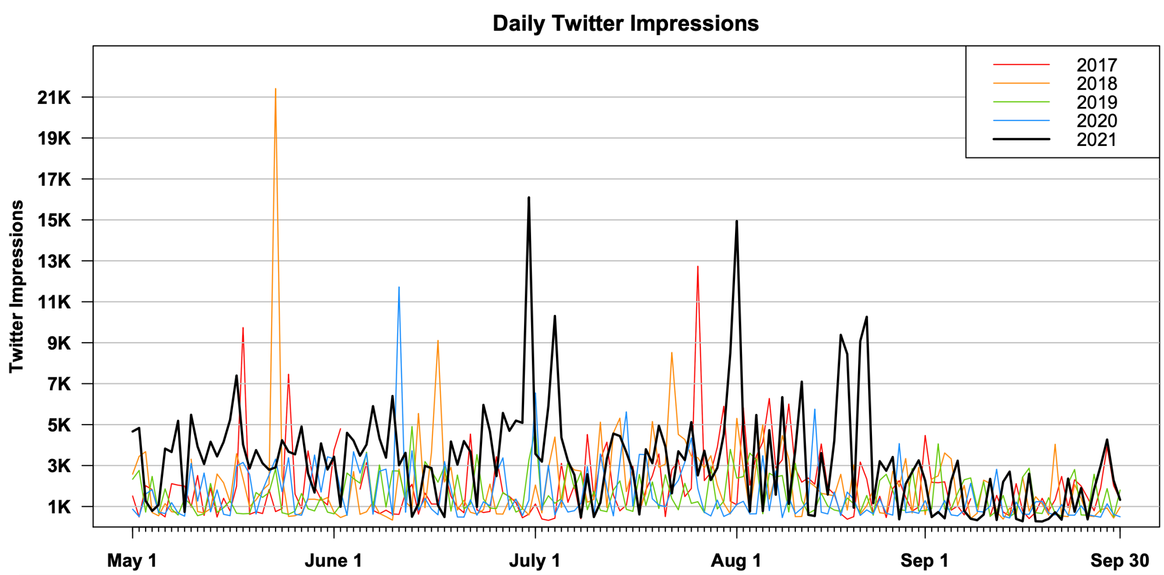


Figure 14: Daily Twitter Impressions during 2021 (black), 2020 (blue), 2019 (green), 2018 (orange), and 2017 (red).

Our most notable followers of our Twitter account remain steady: 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 Twitter account. We will continue to engage local media as new accounts continue to be created each season.

Since the Twitter account was so successful at circulating the FTB 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. On top of that, Facebook continues to be the most popular social media platform in America, while Twitter has more limited audience made up of millennials, corporations, and organizations. It remains to be seen what impact, if any, the privacy issues at Facebook will have on the public's opinion and Facebook's efficacy as a social media platform. 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 Twitter 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.

Facebook, like Twitter, has its own set of analytics called Insights, which can be used to evaluate the success of the additional social media account. By the end of its fourth season, the Facebook account gained several Likes and Followers putting the total at 390 Likes and 421 Followers. While this number continues to be quite a bit lower than the Twitter account, the number of Followers increased approximately 40% from the end of the 2020 season, which shows the media platform still has utility. The most similar analytic to Twitter Impressions are 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. This is most important on days when threats are issued, for example on August 3rd (Moderate threat) the Facebook post reached ~2.2K end-users. A post on August 17th, warning of a potential Elevated threat on Wednesday and Thursday over western Colorado had 7K Reaches and 32 comments, which is the most in Program history. Perhaps the Facebook platform can be best utilized for this application of upcoming events (FTO, specifically) that are not as time sensitive due to the lack of chronological order of the News Feed

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 Twitter 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 2021: #FTB, #FTO, #COwx, #COFlood, #COFire, #Monsoon2021 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 November 1st, there are 186 active subscribers, which is up an additional 17 end-users from the end of the 2020 season. During the off-season, it is recommended to assess the value of sending out a similar email for the FTO headline (threat timeline) or FBF forecasts (threat table), as it may be a well-received and complementary product to the FTB subscription. Likewise, content and quality of the information provided in the emails should be discussed.

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. The preseason campaign lead by the CWCB Project Manager prior to the start of the 2019 season helped significantly increase the number of active subscribers (+100). It is also recommended to consider other methods on how to better advertise the email subscription option, such as prior idea of reaching out to local OEMs 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, 2022 and inform end-users of any additional upgrades to the products.

Yearly Summary

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 of the communication methods described herein compete with one another (i.e. if an end-user uses Twitter 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 12 summarizes the most important social media and website usage metrics over the 2016-present period. As anticipated, it illustrates an increase in popularity across all methods of forecast communication. The most impressive metric is the average daily website viewership. At the end of the 2020 season, there was a concern about viewership dropping to only 37 end-users per day after an active 2019 season. Whether this season was a more active one in terms of rainfall, there was better teasing of posts through social media, or the FBF increased use of the website, it seems that average daily viewership has returned back to 2019 metrics (63 end-users). Another impressive metric is that average daily Twitter Impressions has almost doubled since last season (3,299) while the account has only gained 124 Followers. The high number of Impressions, especially when compared to Facebook Reaches, implies that Twitter continues to be the best method to reach end-users. Overall, the popularity of the Program continues to rise across all its platforms when compared to prior seasons.

Table 12: The Program's website and social media usage metrics from 2016 to 2021.

	2016	2017	2018	2019	2020	2021
Email Subscribers	--	11	25	127	169	186
Avg Daily Website Viewership	33	25	37	66	37	63
Twitter Followers	901	1,036	1,183	1,331	1,404	1,528
Avg Daily Twitter Impressions	1,874	1,973	2,059	1,597	1,590	3,299
Facebook Followers	--	--	155	272	323	421
Avg Daily Facebook Reaches	--	--	--	--	440	456

5) CONCLUSIONS

- Overall, the 2021 May-September forecast season brought very warm temperatures, with several parts of western and central Colorado experiencing near record warmth over the course of that span (see Section 2). From the perspective of precipitation, it was near average on a statewide basis though there were relatively small pockets across most of the state that experienced above normal rainfall. The 2021 North American Monsoon was quite active overall, but most of the very heavy rainfall stayed south and west of Colorado, and only slightly above normal activity was experienced in our state. Nonetheless, it was an extremely active season for fire burn flood events in Colorado, in large part due to the burned areas' high sensitivity to rainfall.

- The 2021 forecast season experienced 58 Flood Days, which is below the 2012-2020 average of 69 Flood Days, but also higher than the recent quieter years of 2018-2020 (see Table 9). There were 65 days with threats issued, 38 of which were Low threats, 23 Moderate and 4 with High threats.

- Forecast verification metrics continued to show encouraging performance with an overall Hit Rate of 88%. Notably, the Probability of Detecting a Flood Day (90%) and Miss Rate (10%) metrics were the best in the Program's history since at least 2012. The False Alarm Rate was 20%, which is on par with Program goals. July was by far the most active month with 24 flood threats issued (13 Moderate or High), and a total of 23 Flood Days observed. Forecast verification in July was very good with the Probability of Detecting a Flood Day at 96% and a Miss rate of only 4% (see Table 8).

- A notable enhancement of the forecast verification protocol was the inclusion of a second source of gridded precipitation estimates, the MRMS product from the National Severe Storms Laboratory (full discussion on page 17). An in-depth assessment of this product's strengths and weaknesses, along with a comparison to the existing Stage IV product, allowed for a better determination of when a Flood Day truly occurred. It is expected that more experience with this data will result in a better overall awareness of Colorado Flood Day climatology, especially for instances of marginal, small-scale storms that can cause flooding but are missed by precipitation gauge networks.

- The standalone Fire Burn Forecast product that launched during 2021 was quite timely, as the large fire burns of recent years experienced numerous days with excessive runoff (see Table 3 and Appendix B). There were at least 31 confirmed instances of flooding over the six major burn areas covered by the FBF, with dozens of additional possible events that were suggested by high estimated rainfall intensity. In terms of impact, the most severe event occurred over the Cameron Peak burn on July 20th, when heavy rainfall caused a devastating mud/debris flow that destroyed homes, property and unfortunately caused the loss of several lives. The other burn area with notable problems was Grizzly Creek, where a prolonged stretch of heavy rainfall during mid- and late-July caused the closure of I-70 due to significant structural damage (see Table 4).

- Website viewership on active weather days had a significant increase in average daily usage from 59 end-users per day (2020) to 84 end-users per day. Average daily site visits continue to be highest on days with elevated flood threats (Moderate or High) are issued (~122 end-users per day). The email list has a total of 186 active subscribers, which is up 17 subscribers from last season. The Program's Twitter account, arguably its most popular social media account, (@COFloodUpdates) continues to expand with 1,528 Followers, and the Facebook account increased from 323 to 421 Followers.

6) REFERENCES

Abatzoglou, J.T., D.J. McEvoy, and K.T. Redmond, in press, The West Wide Drought Tracker: Drought Monitoring at Fine Spatial Scales, Bulletin of the American Meteorological Society.

Dewberry. Colorado Flood Threat Bulletin - 2020 Final Report, https://www.dewberry-hydromet.com/CWCB/CWCB_FinalReport_2020.final.pdf, created November 2020.

Iowa State University. Iowa Environmental Mesonet, http://mesonet.agron.iastate.edu/lsr/#BOU,PUB,GJT,GLD/, accessed 29 October 2021.

National Drought Mitigation Center, University of Nebraska-Lincoln. U.S. Drought Monitor, https://droughtmonitor.unl.edu/, accessed November 2021.

National Interagency Fire Center. Wildland Fire Open Data, https://data-nifc.opendata.arcgis.com, created November 2020.

NOAA Atlas 14, Precipitation-Frequency Atlas of the United States. Precipitation Frequency Data Server, www.nws.noaa.gov/oh/hdsc/, created Nov 2017.

NOAA National Centers for Environmental Information. National Temperature and Precipitation Maps, https://www.ncdc.noaa.gov/temp-and-precip/us-maps, accessed November 2021.

NOAA Stage IV, Gridded Precipitation D. UCAR Data Server, https://data.eol.ucar.edu/dataset/113.003.

PRISM Climate Group, Oregon State University, http://prism.oregonstate.edu, created July 2017.

APPENDIX A – FORECAST VERIFICATION WORKSHEET

Table 13 is a 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 updated 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. The columns of Table 13 are described below.

NSSL MRMS Quantitative Precipitation Estimate: Contains the sub-categories below.

- **Max1hr-E (inches)**: Maximum 1-hour precipitation east of the 1,660m elevation contour.
- **Max2hr-E (inches)**: Maximum 2-hour precipitation east of the 1,660m elevation contour.
- **Max1hr-W (inches)**: Maximum 1-hour precipitation west of the 1,660m elevation contour.
- **Max2hr-W (inches)**: Maximum 2-hour precipitation west of the 1,660m elevation contour.
- **Max24hr-E (inches)**: Maximum 24-hour precipitation east of the 1,660m elevation contour.
- **Max24hr-W (inches)**: Maximum 24-hour precipitation west of the 1,660m elevation contour.
- **Flood Area (points)**: Total number points exceeding Flood Day thresholds.

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

- **Max24hr-E (inches)**: Maximum 24-hour precipitation east of the 1,660m elevation contour.
- **Max24hr-W (inches)**: Maximum 24-hour precipitation west of the 1,660m elevation contour.
- **Flood Area (points)**: Total number points exceeding Flood Day thresholds.

Rain Gauges: Contains the sub-categories below.

- **NStats (number)**: Total number of rainfall gauges exceeding Flood Day thresholds statewide.
- **Max (inches)**: Maximum observed rainfall from all gauges, statewide.

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

Flood Day: Denotes whether or not the day qualified as a Flood Day.

Threat: Highest category of the Flood Threat.

Total Threat Area: Number of miles the issued Flood Threat covered that day.

Flags: An overriding factor to the objective Flood Day classification due to the following.

- *LI*: Low-intensity precipitation that exceeded "flood-day" standards and did not result in flooding.
- *RIV*: Riverine flooding from antecedent rainfall/snowfall, but no concurrent Flood Day threshold precipitation was observed.
- *BIAS*: An overestimation of rainfall totals when compared to daily observations. This category was trigged by use of gridded QPE and observations scatter plots (see Appendix E).

Outcome: 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,
- *Hit*: A Flood Day was observed and forecasted correctly.

Table 13: Daily FTB Verification Worksheet

	NSSL MRMS Quantitative Precipitation Estimate									NOAA ST4 Quantitative Precipitation Estimate			Rain Gauges		Flood Reports					
Date	Max1 hr-E	Max2 hr-E	Max1 hr-W	Max2 hr-W	Max24 hr-E	Max24 hr-W	1hr Flood Area	2hr Flood Area	24hr Flood Area	Max24 hr-E	Max24 hr-W	24hr Flood Area	NStats	Max	Reports	Flood Day	Threat	Total Threat Area	Flags	Outcome
Units	inches	inches	inches	inches	inches	inches	points	points	points	inches	inches	points	number	inches				miles		
1-May	0.05	0.06	0.11	0.11	0.06	0.12	0	0	0	0	0.09	0	0							
2-May	1.52	1.52	1.37	1.39	1.67	1.77	4	4	227	2.32	1.94	565	200	2.05			Low	17	BIAS; SNOW	False Alarm
3-May	0.49	0.54	0.43	0.57	1.13	2.02	0	0	15	1.08	1.36	101	5	2.78					LI; SNOW	
4-May	0.37	0.41	0.44	0.44	0.41	0.45	0	0	0	0.31	0.68	0	1	0.5						
5-May	0.43	0.49	0.3	0.41	0.49	0.41	0	0	0	0.5	0.52	0	0							
6-May	0	0	0.01	0.01	0	0.01	0	0	0	0	0.01	0	0							
7-May	0.55	0.92	0.47	0.47	0.92	0.47	0	0	0	0.59	0.22	0	0							
8-May	1.21	1.29	0.79	0.83	1.58	1.09	0	0	2	1.39	0.86	0	0							
9-May	0.19	0.29	0.33	0.47	0.36	0.61	0	0	0	0.39	1.22	10	0							
10-May	0.78	1.09	1.25	1.3	2.1	2.44	6	7	163	1.77	1.83	351	39						LI	
11-May	0.22	0.29	0.56	0.96	0.38	0.98	0	0	0	0.78	0.82	0	0							
12-May	0.28	0.28	0.12	0.12	0.28	0.12	0	0	0	1.07	0.13	0	1							
13-May	0.1	0.1	0.04	0.05	0.1	0.06	0	0	0	2.33	0.09	12	0							
14-May	1.42	2.58	1.04	1.15	2.58	1.24	1	13	16	1.63	0.85	2	0						BIAS	
15-May	2.7	3.61	1.5	1.76	4.51	1.84	33	75	89	2.92	1.58	78	4			Yes	Low	20		Hit
16-May	2.83	4.75	2.18	2.47	6.83	2.48	167	308	481	4.11	2.15	365	8	2.9	4	Yes	Mod	28		Hit
17-May*	2.38	2.9	3.06	3.72	3.66	5.87	119	206	1350	3.4	4.34	1246	110	4	2	Yes	Mod	52		Hit
18-May	1.38	1.76	0.52	0.65	1.81	1.28	0	1	25	1.94	1.87	47	4	3.75	1	Yes	Mod	11	LI	Hit
19-May	1.69	1.98	1.36	1.48	1.98	1.63	4	12	17	1.62	1.23	4	0	1.7			NWS Warning	0	BIAS	
20-May	1.33	1.41	0.57	0.57	1.41	0.57	0	0	0	2.34	0.4	12	2						BIAS; LI	
21-May	1.27	1.68	1.23	1.23	1.68	1.91	7	9	316	1.3	3.29	505	14	1.18					BIAS	
22-May	1.66	1.95	1.68	2.5	2.57	3.04	69	227	551	2.45	3.87	612	21	1.41	1	Yes	Low	27		Hit
23-May	2.47	3.22	1.65	2.43	4.04	2.7	82	307	386	3.6	2.24	294	4	0.8		Yes	Low	10		Hit

	NSSL MRMS Quantitative Precipitation Estimate									NOAA ST4 Quantitative Precipitation Estimate			Rain Gauges		Flood Reports					
Date	Max1 hr-E	Max2 hr-E	Max1 hr-W	Max2 hr-W	Max24 hr-E	Max24 hr-W	1hr Flood Area	2hr Flood Area	24hr Flood Area	Max24 hr-E	Max24 hr-W	24hr Flood Area	NStats	Max	Reports	Flood Day	Threat	Total Threat Area	Flags	Outcome
24-May	2.09	2.81	0.72	0.74	3.76	0.74	8	27	32	3.84	0.28	13	0			Yes				Miss
25-May	0.94	1.2	0	0	1.2	0	0	0	0	0.53	0.01	0	0				NWS Warning	0		
26-May	1.64	2.26	0.36	0.47	2.28	0.47	2	12	12	1.41	0.35	0	0				NWS Warning	0	BIAS	
27-May	0	0	0.45	0.5	0	0.5	0	0	0	0	0.22	0	0							
28-May	1.61	1.62	2.14	2.33	1.62	2.34	16	19	20	0.59	1.97	16	0						BIAS	
29-May	2.65	3.41	2.39	3.09	4.99	3.52	139	291	442	3.81	2.44	271	9		2	Yes	Mod	26		Hit
30-May	1.9	1.96	2.28	2.9	2.43	4.12	92	177	606	3.99	3.51	798	107	2		Yes	Mod	39		Hit
31-May	0.4	0.57	1.56	1.8	0.74	2	7	15	39	0.6	1.78	32	4	0.9					BIAS	
1-Jun	1.9	2.16	1.36	1.4	2.74	1.47	23	38	48	2.18	0.86	15	0						BIAS	
2-Jun	0.14	0.14	0.58	0.58	0.14	0.87	0	0	0	0.05	0.49	0	0							
3-Jun	0.01	0.01	0.8	0.99	0.01	1.03	0	0	2	0	1.2	3	0						BIAS	
4-Jun	0	0	1.16	1.22	0	1.22	4	7	7	0	0.76	0	0						BIAS	
5-Jun	0.33	0.34	1.64	2.48	0.34	2.75	14	31	32	0.11	1.34	6	3			Yes				Miss
6-Jun	1.87	3.16	2.19	2.6	3.31	2.88	83	155	191	2.26	1.86	61	0			Yes	Low	3		Hit
7-Jun	1.49	1.65	1.1	1.35	1.65	1.38	2	7	7	1.36	0.98	0	0						BIAS	
8-Jun*	0.63	1.18	0.89	0.93	1.18	0.93	0	0	0	0.74	1.16	7	0							
9-Jun	0.01	0.01	0	0	0.01	0	0	0	0	0	0.03	0	1							
10-Jun	0.15	0.15	0	0	0.15	0	0	0	0	0.02	0.01	0	0							
11-Jun	0	0	0	0	0	0	0	0	0	0	0	0	0							
12-Jun	2.59	3.87	2.42	3.06	3.91	3.09	71	117	120	2.07	2.24	72	0			Yes				Miss
13-Jun	1.19	1.34	2.09	2.72	1.35	3.01	15	24	27	0.84	1.55	13	4			Yes	Low	11		Hit
14-Jun	0.51	0.51	0.83	0.97	0.51	0.97	0	0	0	0.39	1	0	0							
15-Jun	0.5	0.5	1.85	2.8	0.5	2.8	9	11	12	0.33	1.48	6	0						BIAS	
16-Jun	1.13	1.95	1.27	1.37	2.05	1.49	4	9	9	1.6	0.97	1	0				Low	4	BIAS	False Alarm
17-Jun	0.47	0.51	1.4	1.82	0.54	1.85	8	10	10	0.35	1.7	4	0						BIAS	
18-Jun	1.54	1.61	2	2.66	1.61	2.67	31	52	54	0.98	2.11	15	0			Yes	Low	34		Hit

	NSSL MRMS Quantitative Precipitation Estimate									NOAA ST4 Quantitative Precipitation Estimate			Rain Gauges		Flood Reports					
Date	Max1 hr-E	Max2 hr-E	Max1 hr-W	Max2 hr-W	Max24 hr-E	Max24 hr-W	1hr Flood Area	2hr Flood Area	24hr Flood Area	Max24 hr-E	Max24 hr-W	24hr Flood Area	NStats	Max	Reports	Flood Day	Threat	Total Threat Area	Flags	Outcome
19-Jun	2.07	2.86	1.77	1.83	2.89	2	57	85	113	2.46	1.85	173	1			Yes	Low	11		Hit
20-Jun	1.07	1.24	1.26	1.57	1.32	1.97	10	13	20	1.6	1.91	16	0	1.13					BIAS	
21-Jun	0.12	0.13	0.04	0.06	0.12	0.07	0	0	0	0.08	0.07	0	1							
22-Jun	0.41	0.41	0.44	0.48	0.41	0.47	0	0	0	0.05	0.17	0	0							
23-Jun	1.28	1.51	0.21	0.32	1.51	0.47	0	1	1	1.99	0.66	3	0						BIAS	
24-Jun	2.04	3.59	2.54	4.01	3.8	4.17	111	226	391	3.47	2.83	277	12	3.5		Yes	Low	41		Hit
25-Jun	1.91	2.56	2.17	2.35	2.74	2.81	100	181	404	2.5	2.59	338	231	0.79	1	Yes	Mod	63		Hit
26-Jun	0.88	1.17	1.06	1.77	1.73	1.84	2	6	102	1	1.59	74	5	1.4	1				BIAS	
27-Jun	1.6	1.63	1.15	1.44	1.63	1.85	4	10	15	1.68	1.2	9	4		2	Yes	Low	13		Hit
28-Jun	1.39	1.56	0.58	0.76	1.56	0.77	0	2	2	1.94	0.86	6	2				Low	16	BIAS	False Alarm
29-Jun	0.85	0.98	1.19	1.51	1.11	1.59	4	8	14	0.46	1.38	8	4			Yes				Miss
30-Jun	3.1	4.8	2.5	3.36	5.08	4.28	35	74	102	4.06	3.31	124	7		2	Yes	Mod	66		Hit
1-Jul	2.59	3.48	2.82	3.65	3.72	4.76	306	521	831	3.28	3.84	697	90	4.4	10	Yes	High	55		Hit
2-Jul	1.1	1.79	2.67	3.13	1.79	3.13	58	114	126	1.26	1.92	66	3		2	Yes	Low	17		Hit
3-Jul	2.32	3.17	1.85	2.72	3.23	2.72	80	120	129	2.62	2	96	5	2	2	Yes	Low	7		Hit
4-Jul	2.89	2.94	2.22	2.51	2.94	2.87	92	163	192	1.8	2.14	47	8		5	Yes	Low	14		Hit
5-Jul	1.63	1.75	2.18	2.48	1.75	2.69	82	140	225	1.82	2.39	173	5	2.25	4	Yes	Mod	37		Hit
6-Jul	2.76	2.9	2.52	3.5	3.37	4.64	140	281	521	2.76	3.21	484	16	1.5	5	Yes	Mod	41		Hit
7-Jul	0.29	0.29	0.61	0.61	0.29	0.95	0	0	0	0	0.36	0	0							
8-Jul	2.43	3.34	1.17	1.4	3.39	1.41	8	16	19	0.62	1.04	1	0						BIAS	
9-Jul	1.85	1.85	1.87	2.86	2.27	2.91	23	39	49	1.29	1.71	13	1						BIAS	
10-Jul	0.1	0.1	0.85	0.85	0.1	0.85	0	0	0	0.05	0.21	0	0							
11-Jul	0	0	0.81	1.06	0	1.06	0	1	1	0	0.66	0	1							
12-Jul	0.03	0.03	0.7	1.12	0.03	1.15	0	1	1	0.02	0.6	0	1							
13-Jul	2.89	3.77	2.37	2.46	5.48	2.66	96	166	202	3.69	1.73	57	1	1		Yes	Low	9		Hit
14-Jul	1.93	2.82	1.76	1.84	2.82	2.27	27	48	80	2.74	1.58	15	1	0.78	2	Yes	Mod	81		Hit

	NSSL MRMS Quantitative Precipitation Estimate									NOAA ST4 Quantitative Precipitation Estimate			Rain Gauges		Flood Reports					
Date	Max1 hr-E	Max2 hr-E	Max1 hr-W	Max2 hr-W	Max24 hr-E	Max24 hr-W	1hr Flood Area	2hr Flood Area	24hr Flood Area	Max24 hr-E	Max24 hr-W	24hr Flood Area	NStats	Max	Reports	Flood Day	Threat	Total Threat Area	Flags	Outcome
15-Jul	1.71	2.16	1.97	2.35	2.16	2.41	47	66	73	1.88	2.51	38	0			Yes				Miss
16-Jul	2.99	4.7	1.88	2.25	4.73	2.31	124	224	278	3.81	1.44	180	5	1.7	3	Yes	Low	22		Hit
17-Jul	2.52	2.72	3.22	3.58	2.89	3.74	126	215	248	2.4	2.28	132	6			Yes	Low	25		Hit
18-Jul	1.84	2.07	0.85	0.95	2.07	0.98	9	21	22	1.82	0.76	14	1	2.1			Low	6	BIAS	False Alarm
19-Jul	0.04	0.04	2.1	2.3	0.04	2.3	2	2	2	0	0.82	0	0				Mod	8	BIAS	False Alarm
20-Jul	0.04	0.04	1.54	1.96	0.04	1.97	11	31	34	0.02	1.62	14	0		3	Yes	Low	37		Hit
21-Jul	1.06	1.06	2.35	4.07	1.06	4.17	152	236	366	0.98	3.33	229	23	1.92	5	Yes	Mod	54		Hit
22-Jul	1.46	1.5	2.16	2.62	1.5	2.67	64	130	159	0.99	2.29	47	6	1.75	4	Yes	Mod	53		Hit
23-Jul	2.29	3.92	2.52	3.66	4.35	3.87	80	163	402	3.14	3.03	298	11	1.31	4	Yes	Mod	54		Hit
24-Jul	2.07	3.9	1.6	2.86	4.4	3.09	42	77	109	3.32	2.49	44	6	3	12	Yes	Mod	51		Hit
25-Jul	3.11	3.52	2.31	3.16	5.5	3.34	272	476	624	2.9	2.98	436	36	2	8	Yes	Mod	62		Hit
26-Jul	1.61	2.34	1.59	2.22	2.41	2.27	24	43	50	2.66	2.03	28	2	1.61		Yes	Mod	34		Hit
27-Jul	1.18	1.21	1.39	1.9	1.21	2.25	8	15	16	0.89	1.21	5	2	1.27		Yes	Low	25		Hit
28-Jul	0.39	0.58	2.36	2.46	0.58	2.52	44	83	102	0	1.53	33	2	1.17	2	Yes	Low	21		Hit
29-Jul	0.21	0.22	2.65	3.06	0.22	3.4	119	189	282	0.09	3.15	113	3		2	Yes	Low	49		Hit
30-Jul*	2.42	3.07	2.65	2.89	4.16	3.11	208	344	515	2.49	2.38	374	53	3.69	9	Yes	Mod	65		Hit
31-Jul	3.02	4.54	2.92	3.96	6.04	5.96	322	637	1382	7.06	4.69	1262	157	5.03	31	Yes	High	89		Hit
1-Aug	0.26	0.39	1.86	2.35	0.39	2.78	22	42	57	0.34	1.2	11	1	3.58	1	Yes	Mod	40		Hit
2-Aug	0	0	1.94	2.39	0	2.61	26	49	89	0	1.35	29	3	0.91	3	Yes	High	56		Hit
3-Aug	2.53	3.26	2.91	3.24	3.59	3.92	74	154	389	3.12	3.51	321	22	0.5	1	Yes	Mod	60		Hit
4-Aug	2.81	3.32	0.65	0.65	4.62	0.68	11	16	19	1.93	0.83	5	0	1.22	1		Low	31	BIAS	False Alarm
5-Aug	0.1	0.11	1.11	1.36	0.11	1.47	1	3	4	0.1	0.92	0	0							
6-Aug	1.09	1.22	1.13	1.33	1.55	1.33	2	7	16	1.39	0.99	0	0						BIAS	
7-Aug	0.86	0.91	1.21	1.24	0.91	1.24	4	6	6	0.92	0.72	0	0							
8-Aug	0.24	0.24	0.01	0.01	0.24	0.01	0	0	0	0	0.03	0	0							
9-Aug	1.27	1.97	0.08	0.08	2.61	0.08	0	2	16	1.94	0.07	5	1						BIAS	

	NSSL MRMS Quantitative Precipitation Estimate									NOAA ST4 Quantitative Precipitation Estimate			Rain Gauges		Flood Reports					
Date	Max1 hr-E	Max2 hr-E	Max1 hr-W	Max2 hr-W	Max24 hr-E	Max24 hr-W	1hr Flood Area	2hr Flood Area	24hr Flood Area	Max24 hr-E	Max24 hr-W	24hr Flood Area	NStats	Max	Reports	Flood Day	Threat	Total Threat Area	Flags	Outcome
10-Aug	1.32	1.32	0.69	0.69	1.32	0.69	0	0	0	0.9	0.43	0	0							
11-Aug	2.14	2.37	1.21	2.04	2.41	2.04	6	13	13	1.7	0.8	2	0						BIAS	
12-Aug	2.59	3.87	2.43	2.95	5.39	2.95	137	241	295	3.24	2.41	168	4	6.05	1	Yes	Low	15		Hit
13-Aug	0.09	0.09	1.31	1.32	0.09	1.32	9	16	16	0.01	0.96	0	0				Mod	67	BIAS	False Alarm
14-Aug	1.33	1.81	1.42	1.79	1.87	2	5	13	19	0.79	0.95	0	0				Low	5	BIAS	False Alarm
15-Aug	1.94	2.02	1.73	2.2	2.02	2.24	42	69	74	0.92	1.64	27	0			Yes	Low	13		Hit
16-Aug	0.02	0.02	1.02	1.23	0.02	1.23	1	5	6	0.01	0.79	0	0				Low	13		False Alarm
17-Aug	0.23	0.23	1.25	1.39	0.23	1.46	2	4	4	0.1	0.98	0	0							
18-Aug	1.09	1.09	0.96	1.09	1.09	3.13	0	2	39	0.69	1.41	104	5	0.92	1	Yes	Mod	37		Hit
19-Aug*	3.17	4.66	1.26	1.64	8.63	1.91	165	300	928	9.18	2.2	1214	60	8.11	7	Yes	High	62		Hit
20-Aug	0.35	0.49	0.43	0.44	0.51	0.44	0	0	0	0.3	0.25	0	0	1.39						
21-Aug	1.02	1.12	1.16	1.35	1.12	1.35	1	9	9	1.11	0.53	0	0						BIAS	
22-Aug	0.04	0.04	0.07	0.1	0.04	0.11	0	0	0	0.01	0.09	0	1							
23-Aug	0.55	0.59	0.15	0.15	0.59	0.17	0	0	0	0.41	0.17	0	0							
24-Aug	0.16	0.16	0.45	0.45	0.16	0.45	0	0	0	0	0.17	0	0							
25-Aug	1.98	2.96	1.03	1.09	3.73	1.09	11	50	81	3.79	0.71	73	1			Yes	Low	18		Hit
26-Aug	2.19	3.11	1.98	2.18	3.17	2.21	26	47	61	2.8	2.07	54	0						BIAS	
27-Aug	1.36	2.48	1.89	2.09	2.95	2.43	11	22	27	1.54	1.96	10	0			Yes	Low	7	BIAS	Hit
28-Aug	1.41	1.77	0.85	1.02	1.77	1.04	0	3	3	0.74	0.66	0	0				Low	12		False Alarm
29-Aug	0.01	0.02	1.77	2.69	0.03	2.79	24	41	47	0	1.6	21	0			Yes	Low	2		Hit
30-Aug	0.84	1.09	0.43	0.5	1.09	0.5	0	0	0	0.72	0.29	0	0							
31-Aug	2.15	2.15	0.11	0.13	2.15	0.14	2	2	2	0.43	0.14	0	0							
1-Sep	1.03	1.54	0.78	1.26	1.59	2.11	0	3	31	1.04	1.22	16	5	0.96			Mod	36	BIAS	False Alarm
2-Sep	1.47	1.48	0.8	1.05	1.52	1.47	0	2	36	0.89	1.39	31	15	1.09			Low	15	LI	False Alarm
3-Sep	2.47	2.81	1.8	1.94	3.18	2.7	59	132	332	2.42	1.67	175	18	1.34		Yes	Low	31		Hit

	NSSL MRMS Quantitative Precipitation Estimate									NOAA ST4 Quantitative Precipitation Estimate			Rain Gauges		Flood Reports					
Date	Max1 hr-E	Max2 hr-E	Max1 hr-W	Max2 hr-W	Max24 hr-E	Max24 hr-W	1hr Flood Area	2hr Flood Area	24hr Flood Area	Max24 hr-E	Max24 hr-W	24hr Flood Area	NStats	Max	Reports	Flood Day	Threat	Total Threat Area	Flags	Outcome
4-Sep	1.27	1.52	2.8	2.89	1.52	2.94	33	48	54	1.11	2.44	17	0			Yes	Low	12		Hit
5-Sep	0.7	0.72	0	0	0.72	0	0	0	0	0.56	0	0	0							
6-Sep	0.75	0.85	0.37	0.57	0.85	0.57	0	0	0	0.75	0.39	0	0							
7-Sep	0	0	0	0	0	0	0	0	0	0	0.02	0	0							
8-Sep	0	0	0.13	0.23	0	0.23	0	0	0	0	0.13	0	1							
9-Sep	0.07	0.07	0.08	0.11	0.07	0.11	0	0	0	0	0.07	0	0							
10-Sep	0.23	0.23	0.03	0.03	0.24	0.05	0	0	0	0.1	0.03	0	0							
11-Sep	0.96	1.19	1.51	1.51	1.19	1.51	4	4	4	0.86	0.48	0	0							
12-Sep	1.43	1.48	1	1.26	1.48	1.26	0	6	6	1.42	0.98	0	1							
13-Sep	1.83	2.96	0.49	0.49	3	0.66	2	4	4	0.64	0.76	0	1							
14-Sep	1.43	2.28	1.3	1.3	2.27	1.31	6	15	16	1.63	1.38	17	2			Yes	Low	27		Hit
15-Sep	0	0	0.06	0.06	0	0.06	0	0	0	0	0.02	0	1							
16-Sep	1.26	1.26	0.02	0.02	3.16	0.06	0	0	22	1.51	0.02	1	0						BIAS	
17-Sep	0.02	0.02	0.02	0.02	0.02	0.02	0	0	0	0	0	0	0							
18-Sep	0.03	0.03	0.33	0.53	0.03	0.85	0	0	0	0	0.67	0	0							
19-Sep	0.09	0.12	1.13	2.22	0.13	4.13	2	12	42	0.13	1.02	2	0						BIAS	
20-Sep	0.3	0.4	0.4	0.52	0.54	0.76	0	0	0	0.38	0.82	0	0							
21-Sep	0.04	0.04	0	0	0.04	0	0	0	0	0.06	0.02	0	0							
22-Sep	0	0	0	0	0	0	0	0	0	0	0	0	0							
23-Sep	0.04	0.04	0.04	0.06	0.04	0.11	0	0	0	0.02	0.09	0	1							
24-Sep	0	0	0.04	0.04	0	0.04	0	0	0	0	0	0	1							
25-Sep	0	0	0.03	0.03	0	0.03	0	0	0	0	0.01	0	0							
26-Sep	0.03	0.03	0.27	0.34	0.03	0.35	0	0	0	0	0.57	0	0							
27-Sep	0.09	0.09	0.57	0.61	0.09	0.69	0	0	0	0.08	0.82	0	0				Low	6		False Alarm
28-Sep	0.44	0.51	1.41	2.27	0.51	3.48	5	11	73	0.4	2.04	223	11	0.6	1	Yes				Miss
29-Sep	1.09	1.54	1.65	2.24	1.8	2.48	22	30	54	1.15	2.01	174	6	1.05	1	Yes	Low	1		Hit

	NSSL MRMS Quantitative Precipitation Estimate									NOAA ST4 Quantitative Precipitation Estimate			Rain Gauges		Flood Reports					
Date	Max1 hr-E	Max2 hr-E	Max1 hr-W	Max2 hr-W	Max24 hr-E	Max24 hr-W	1hr Flood Area	2hr Flood Area	24hr Flood Area	Max24 hr-E	Max24 hr-W	24hr Flood Area	NStats	Max	Reports	Flood Day	Threat	Total Threat Area	Flags	Outcome
30-Sep	0.19	0.2	0.41	0.53	0.21	1.96	0	0	41	0.2	1.34	16	2	0.77					LI	

APPENDIX B – BURN AREA VERIFICATION WORKSHEET

Table 14 is a daily verification worksheet documenting heavy precipitation and 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 14 are described below.

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

FLOOD: Indicates that a debris flow report was recorded (Iowa State University, 2021).

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:

Calwood, Cameron Peak, East Troublesome, Grizzly Creek and Pine Gulch: **0.25 inches per hour**
Spring Creek: **0.75 inches per hour**

Table 14: Daily Burn Area Verification Worksheet

Date	Calwood	Cameron Peak	East Troublesome	Grizzly Creek	Pine Gulch	Spring Creek
1-May						
2-May			QPE			
3-May						
4-May						
5-May						
6-May						
7-May						
8-May						
9-May						
10-May						
11-May						
12-May						
13-May						
14-May		QPE				
15-May		QPE				
16-May						QPE
17-May	QPE	QPE				QPE
18-May						
19-May		QPE				

Date	Calwood	Cameron Peak	East Troublesome	Grizzly Creek	Pine Gulch	Spring Creek
20-May						
21-May						
22-May	QPE	QPE				
23-May						
24-May						
25-May						
26-May						
27-May						
28-May						
29-May		QPE				
30-May		QPE				
31-May						
1-Jun		FLOOD				
2-Jun						
3-Jun						
4-Jun						
5-Jun		QPE				QPE
6-Jun		QPE				
7-Jun						
8-Jun						
9-Jun						
10-Jun						
11-Jun						
12-Jun						
13-Jun						
14-Jun						
15-Jun						
16-Jun						
17-Jun						
18-Jun						
19-Jun		QPE				
20-Jun						
21-Jun						
22-Jun						
23-Jun						
24-Jun	QPE			QPE		
25-Jun	QPE	QPE			QPE	

Date	Calwood	Cameron Peak	East Troublesome	Grizzly Creek	Pine Gulch	Spring Creek
26-Jun	QPE			FLOOD		
27-Jun	FLOOD			FLOOD		
28-Jun						
29-Jun					QPE	
30-Jun		QPE	QPE			
1-Jul	QPE	QPE	QPE			QPE
2-Jul		QPE				FLOOD
3-Jul		QPE		FLOOD		
4-Jul		FLOOD	QPE			
5-Jul		QPE	FLOOD	FLOOD	FLOOD	
6-Jul	QPE	QPE				QPE
7-Jul						
8-Jul						QPE
9-Jul						
10-Jul						
11-Jul						
12-Jul						
13-Jul		QPE				
14-Jul		QPE		FLOOD	QPE	QPE
15-Jul						
16-Jul						
17-Jul						
18-Jul						
19-Jul						
20-Jul		FLOOD		FLOOD	QPE	
21-Jul		QPE	FLOOD			QPE
22-Jul		QPE	FLOOD	FLOOD	QPE	
23-Jul						
24-Jul					QPE	
25-Jul	QPE	QPE	QPE		QPE	FLOOD
26-Jul						
27-Jul						
28-Jul					QPE	
29-Jul			QPE	FLOOD	QPE	
30-Jul	QPE	FLOOD	FLOOD	QPE	QPE	QPE
31-Jul	QPE	FLOOD	QPE	FLOOD	FLOOD	FLOOD

Date	Calwood	Cameron Peak	East Troublesome	Grizzly Creek	Pine Gulch	Spring Creek
1-Aug					FLOOD	
2-Aug		QPE	QPE	QPE	QPE	FLOOD
3-Aug	QPE	QPE	FLOOD	FLOOD		QPE
4-Aug						
5-Aug						
6-Aug		QPE				
7-Aug						
8-Aug						
9-Aug						
10-Aug						
11-Aug						
12-Aug						
13-Aug						
14-Aug		QPE				
15-Aug						
16-Aug						
17-Aug						
18-Aug		QPE		QPE		
19-Aug		QPE		QPE		
20-Aug						
21-Aug						
22-Aug						
23-Aug						
24-Aug						
25-Aug						
26-Aug						
27-Aug						
28-Aug						
29-Aug						
30-Aug						
31-Aug						
1-Sep						
2-Sep			FLOOD			
3-Sep		QPE		QPE		
4-Sep						
5-Sep						

Date	Calwood	Cameron Peak	East Troublesome	Grizzly Creek	Pine Gulch	Spring Creek
6-Sep						
7-Sep						
8-Sep						
9-Sep						
10-Sep						
11-Sep						
12-Sep						
13-Sep						
14-Sep						
15-Sep						
16-Sep						
17-Sep						
18-Sep						
19-Sep						
20-Sep						
21-Sep						
22-Sep						
23-Sep						
24-Sep						
25-Sep						
26-Sep						
27-Sep						
28-Sep		QPE	QPE		FLOOD	
29-Sep		QPE		FLOOD		
30-Sep						

APPENDIX C - 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 (hereafter, CD). Figure 15 (Atlas 14, 2017) shows the stark differences in rainfall recurrence statistics at Denver (east of the CD) compared to Silt (west of the CD). 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 CD compared to its Western counterpart (also see Appendix D).

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 15: 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 16, 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 significant factor in the Front Range and Gore Mountains. Meanwhile, by August (Figure 16 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.

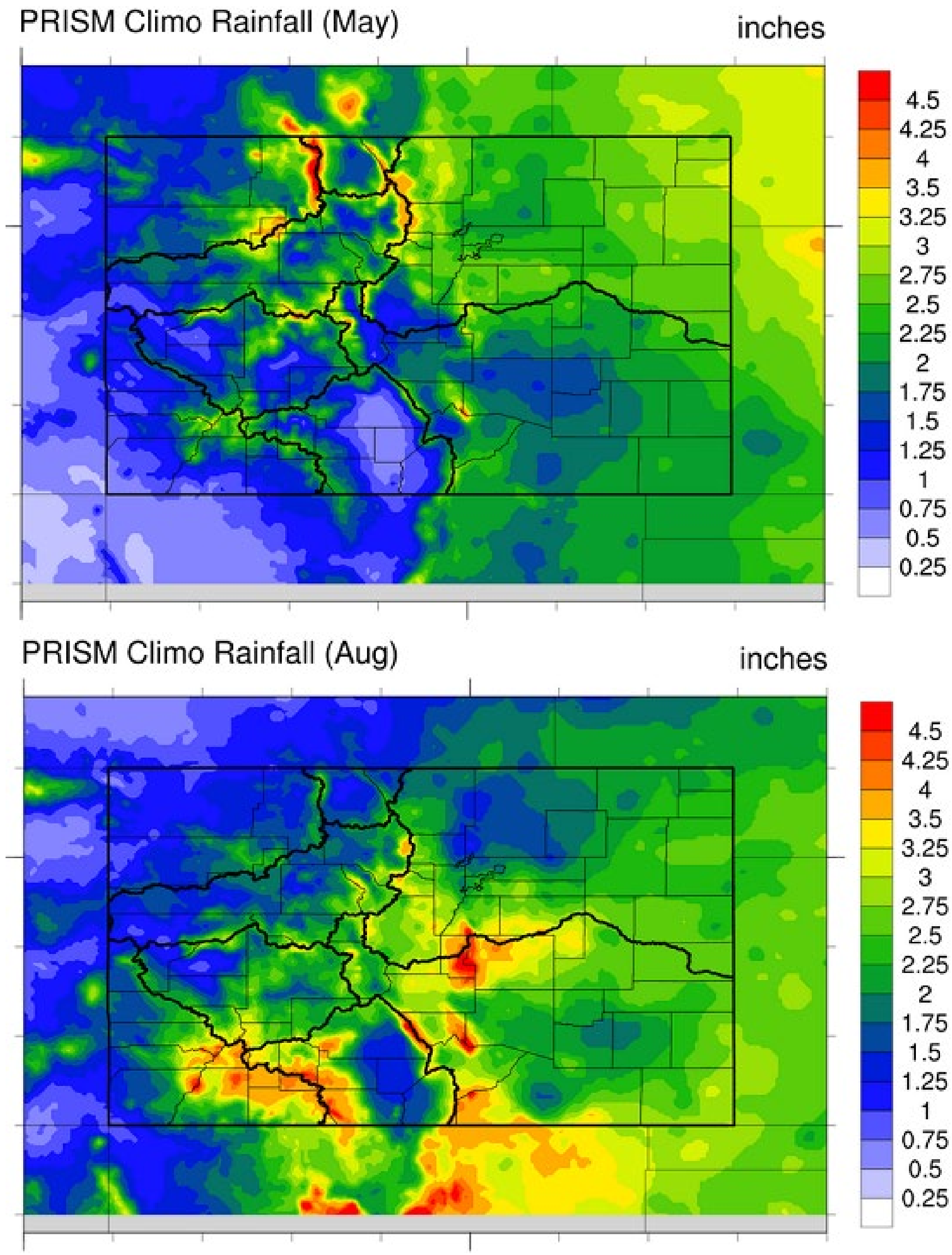
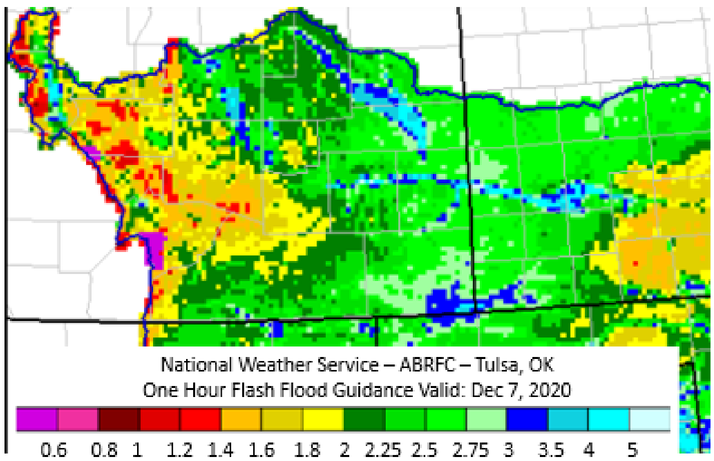


Figure 16: Monthly average precipitation for (top) May and (bottom) August. Source: Oregon State University PRISM group.

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 17 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 the translating the heavy rainfall threat to a flooding potential.



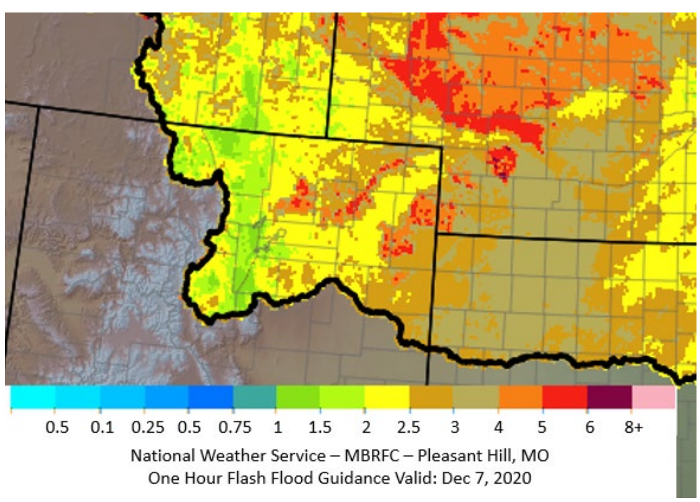


Figure 17: 1-hour Flash Flood Guidance for central and eastern Colorado, valid December 7th, 2020. Source: National Weather Service River Forecast Centers.

APPENDIX D – FLOOD THREATS ISSUED

This section shows the total number of days when a given location was under a flood threat during the 2016 to 2021 operational seasons in descending order. 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.

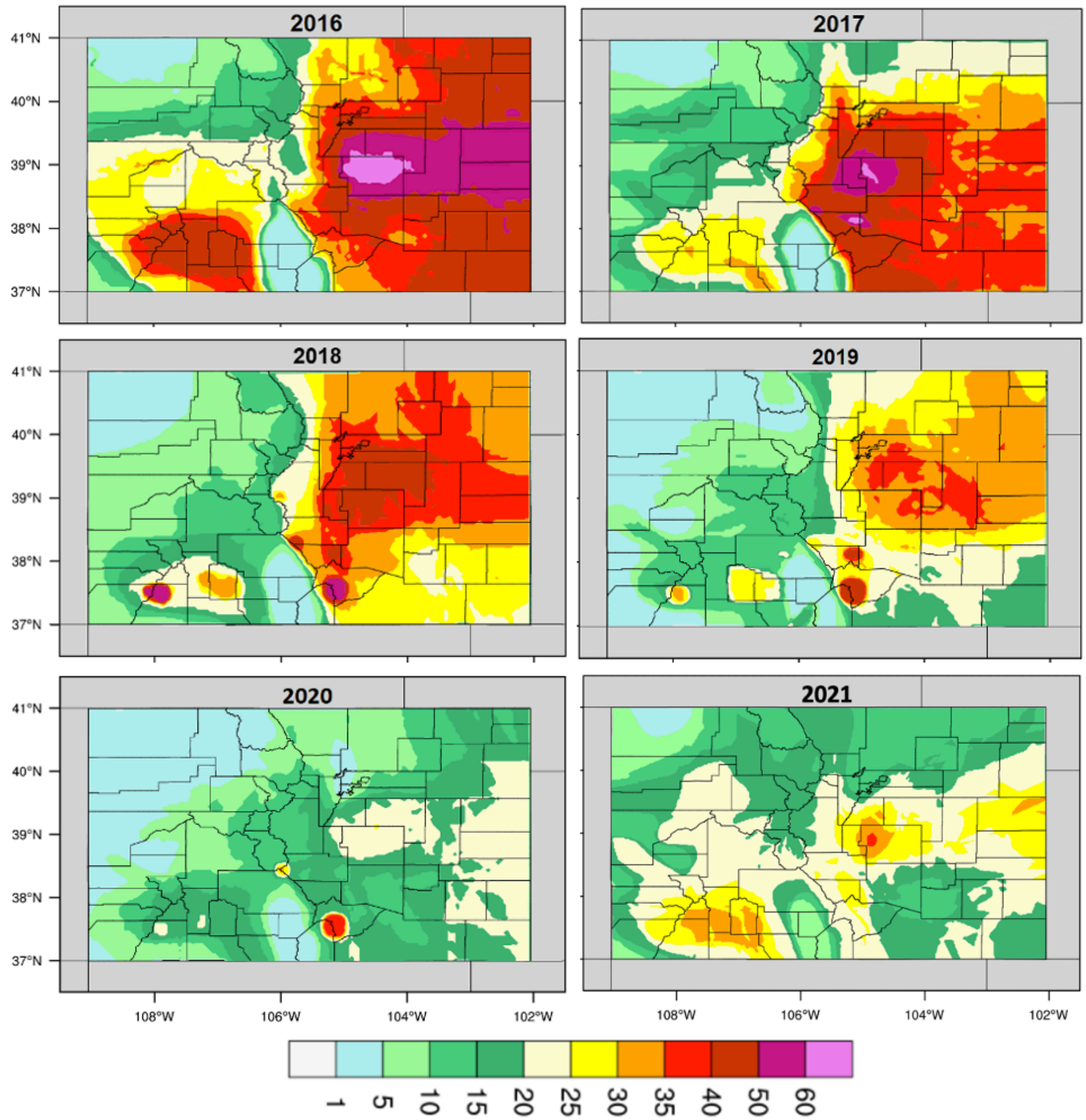


Figure 18: Number with days with a flood threat issued, burn area or otherwise, from 2016 to 2021.

APPENDIX E – QPE BIAS ASSESSMENT

An initial assessment of QPE product bias over the 2021 forecast season showed a systematic tendency for both the MRMS and Stage IV to *overestimate* precipitation when compared directly to gauges. For example, as shown in Figure 19, over the course of the season, the MRMS product overestimated precipitation almost twice as often as it underestimated it. The MRMS bias was higher than Stage IV, despite the overall better performance of MRMS compared to Stage IV (not shown).

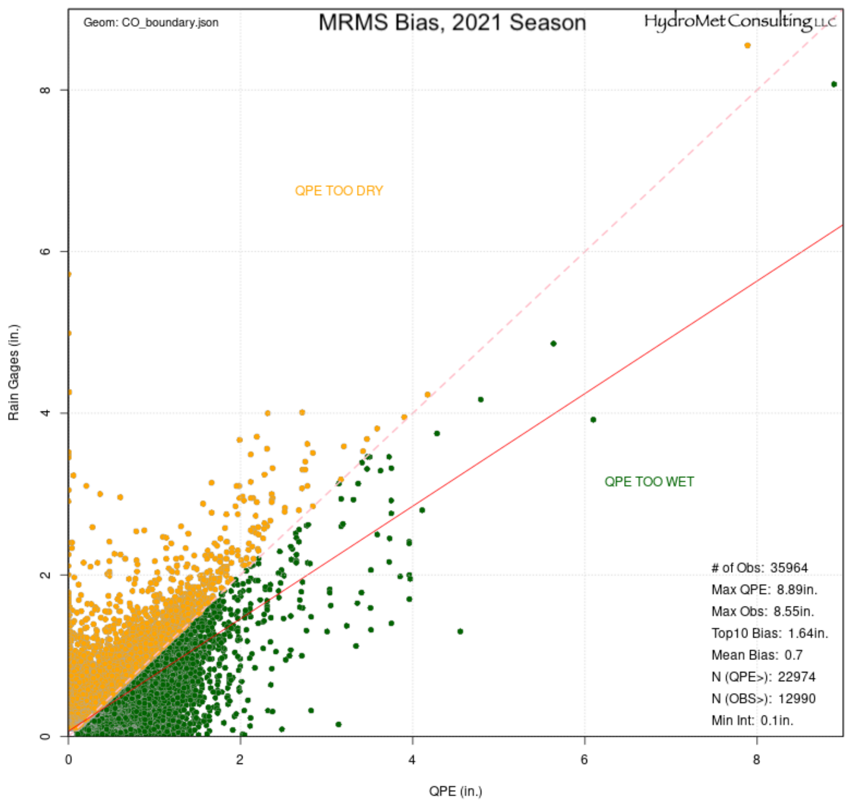


Figure 19: Scatter plot showing the bias of the MRMS QPE product, compared to gauges, over the entire 2021 forecast season across all reliable gauges within Colorado. Green points show when QPE overestimated rainfall, while orange points show when QPE underestimated rainfall. The dashed pink line shows a 1:1 (perfect) relationship, while the solid red line shows a linear regression.

However, despite the biases 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, slow versus fast moving storms, distance from radar sites, the presence or absence of hail, as well as cloud temperature. To gain some perspective on the implications of these, Figure 20 shows the MRMS bias (representative of the QPE bias, in general) from two events with different atmospheric setups. On July 31st (top), widespread heavy rainfall fell across Colorado and the MRMS performed well. Of 929 stations with meaningful rainfall, QPE overestimated rainfall at 535, while underestimating at 394. Meanwhile, on July 9th (bottom), isolated storms occurred in a relatively dry atmosphere, while also producing hail. These factors resulted in a gross overestimate of rainfall: of 126 stations with meaningful rainfall, MRMS overestimated 117 of these while underestimating only 9. The average overestimate was roughly by a factor of two. An important implication from the July 9th event is that on days where heavy rainfall largely skirts between reliable precipitation gauges, there is general potential to overestimate rainfall severity. To account for this, MRMS and Stage IV biases were subjectively assessed for each event, to determine if a Flood Day classification was warranted.

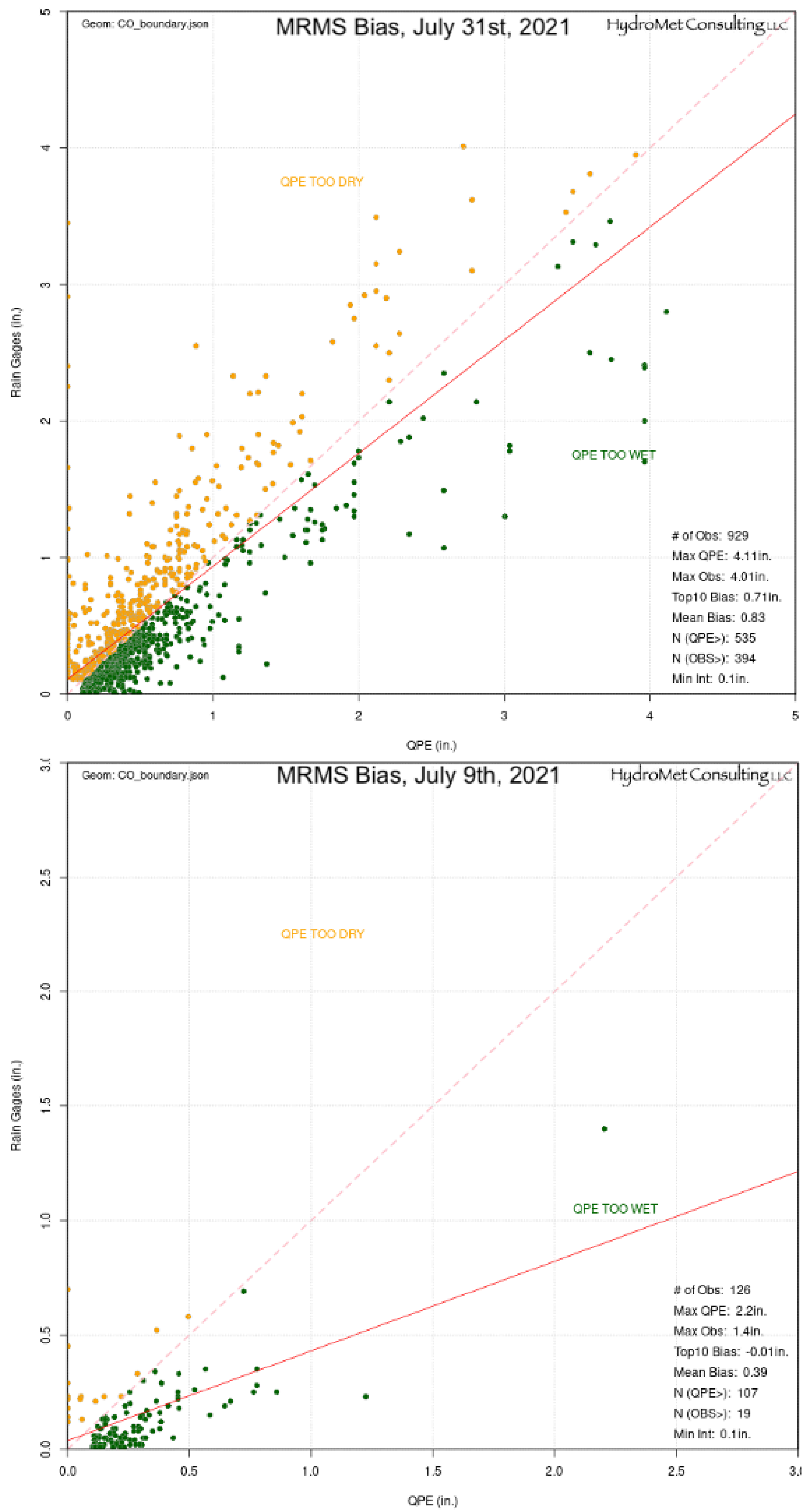


Figure 20: Same as Figure 19, except (top) for July 31st, highlighting generally good performance by QPE, and (bottom) July 9th, highlighting very poor performance by QPE with a significant over-estimate detected.