Colorado Flood Threat Bulletin – 2019 Final Report

NOVEMBER 15, 2019

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2019 Colorado Flood Threat Bulletin

Final Report

1) INTRODUCTION

In 2017, the Colorado Water Conservation Board (CWCB) made a 5-year award of the Colorado Flood Threat Bulletin program (hereafter, Program) to Dewberry. Dewberry has been the provider of this service for the CWCB since 2012. We are continually committed to improving all aspects of the Program each operational season, although the core features remain the same due to their acceptance by community users. The Program runs during the warm season from May 1 through September 30 and requires (i) the daily issuance of a Flood Threat Bulletin (FTB) describing and visualizing the flood threat in Colorado, (ii) the twice weekly (Monday/Thursday) issuance of a 15-day Flood Threat Outlook (FTO), highlighting periods of rapid snowmelt and locally heavy rainfall, or conversely, the development of drought conditions due to lack of precipitation, and (iii) a daily State Precipitation Map (SPM) product that recaps the past 72-hours of hydrometeorological conditions across the state. For the 2019 operational season, all forecasts were developed or overseen by Dewberry meteorologists Dana McGlone (FTB, FTO, SPM), Brad Workman (FTB, SPM) and Carson Jones (FTB, SPM). Archived forecasts are available through the Program's website www.coloradofloodthreat.com. Dana McGlone served as the primary contact and project meteorologist for Dewberry, Danny Elsner served as the Project Manager and Ken Cecil served as Principle-in-Charge.

The objective of this Final Report is to: (i) perform a rigorous validation of forecast performance, (ii) summarize the weather conditions over the 2019 operational season, (iii) document additional services provided for the WY2019 snowpack, and (iv) measure Program viewership.

Daily Flood Threat Bulletin (FTB)

The FTB is designed for daily issuance during the contract period by 11:00 AM. When possible, FTB forecasts were issued as early as possible to provide more lead time to community users. This was especially important on days where there was an elevated flood threat. The FTB outlines 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. Additional information includes a characterization of the threat of attendant severe weather (tornadoes, high winds, hail, etc.), the probability and intensity of thunderstorm rainfall rates and expected totals. Table 1 summarizes the five-tier category system that is used to characterize the flood threat: None, Low, Moderate, High and High Impact. Continued from 2017, an upgrade to the FTB was the inclusion of daily updates, as warranted, during situations with a particularly threatening and/or rapidly evolving flood threat. This also included posting updates to the social media accounts as this remains an efficient way to disseminate flood threat information to the user community. There were two such days in 2019 that this update was implemented.

Table 1: Description of the five 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 flooding 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.

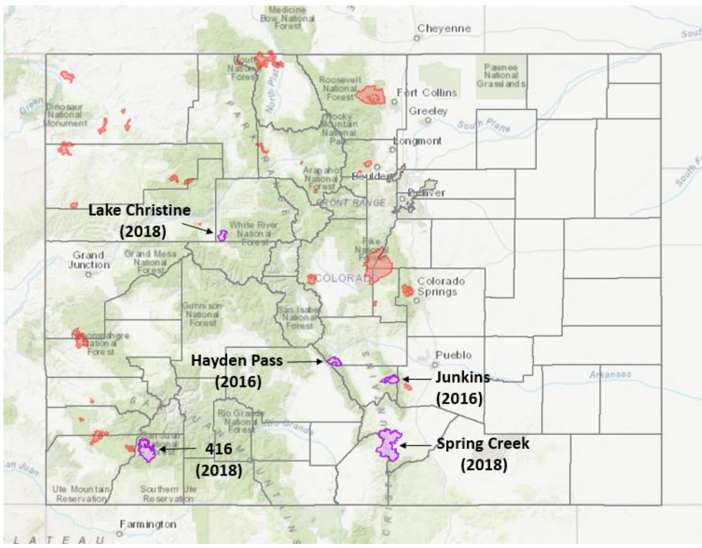


Figure 1: Wildfire burn areas that were featured on the daily FTB maps during 2019. The labeled burn areas (purple) were identified as the most hazardous and received daily dedicated flood threats by Dewberry.

Of particular concern for flash flooding are recent wildfire burn areas over steep terrain; especially those near population centers and highly-traveled roads. So, also included on the daily FTB threat map are all recent burn areas across the state. For a burn area to be included, the fire had to occur over steep terrain, have occurred in the last 5 years and burned at least 700 acres. For the larger, complex and more historic wildfires (such as the Hayman Fire in 2002), Dewberry worked with the Colorado State Forest Service (special thank you to Weston Tool and Ryan Lockwood) to determine if the burn areas had recovered enough to be removed from the map. 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 in close proximity to high population and/or major roads. This season there were five wildfire burn areas monitored by Dewberry (Figure 1): 416 (2018), Lake Christine (2018), Spring Creek (2018), Junkins (2016) and Hayden Pass (2016). New to this season is an updated validation for burn area issued threats. This is a necessary step as there were 18 days over the last two seasons where the only threat issued, in the FTB, was over a burn area. More information and guidelines on this process can be found in the Verification Metrics section of this report (page 9).

The threat of daily flooding is conveyed to the user community 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 2). The

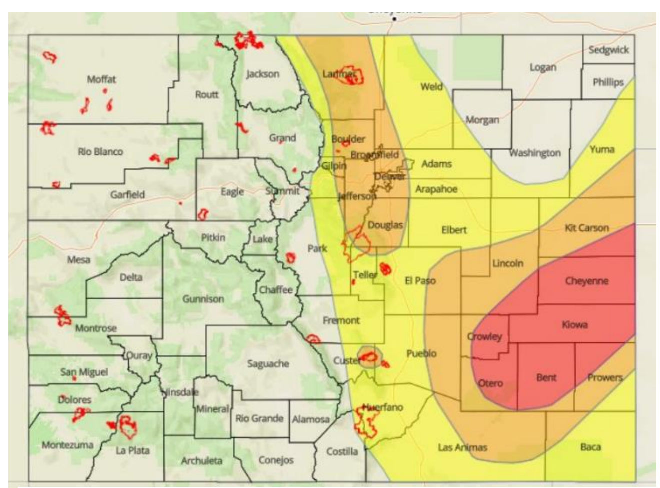


Figure 2: Example of the FTB map from July 20th, 2019. The Low, Moderate and High threats are highlighted in yellow, orange and red, respectively. A Moderate threat was also issued for the Junkins burn area.

evolution of this presentation to a more communicative graphical form enhanced the spatial and temporal threat areas visualization. All forecasts continue to be archived in a blog-style manner available on the product's website.

Flood Threat Outlook (FTO)

The FTO is a bi-weekly product issued on Mondays and Thursdays by 3PM to address the 15-day threat of flooding across the state. This product addresses both the extended threat of flooding (snowmelt and precipitation driven) and a precipitation outlook by river basin. The FTO continues to be structured in an event-based manner, where rainfall is partitioned by its forcing features and presented in a timeline. New to this season, due to the high snowpack from WY2019, was a specific snowpack/riverine forecast from May to early July. A snowmelt flooding threat was added to the timeline during this period, and all NWS Flood Warnings were added to the daily FTB threat maps. Riverine flooding events from snowmelt, though outside the scope of the Program, will be addressed prior to the start of the 2020 season, and upgrades to our current products will be implemented for improved end-user communication.

An example of a threat "timeline" is shown below in Figure 3 from June 13th. Another focus of the FTO this season was the improving drought conditions due above average snowpack and an anomalously wet May. Reservoir levels were also tracked throughout the season in the FTOs, alongside monthly departures from normal of temperature and precipitation. Upgrades to the FTO layouts and maps are anticipated for the 2020 season to account for the latest weather technology.

FTO 06-13-2019: Uptick in Storm Activity and Moisture over the Weekend with Minor Flooding Forecast over the San Juan Mountains, Southeast Mountains & San Luis Valley

June 13, 2019 by Dana McGlone ·

Issue Date: Thursday, June 13th, 2019
Issue Time: 1:30PM MDT
Valid Dates: 6/14 – 6/28

Colorado Flood Threat Outlook

Next 15 Days	Fri 14-Jun	Sat 15-Jun	Sun 16-Jun	Mon 17-Jun	Tue 18-Jun	Wed 19-Jun	Thu 20-Jun	Fri 21-Jun	Sat 22-Jun	Sun 23-Jun	Mon 24-Jun	Tue 25-Jun	Wed 26-Jun	Thu 27-Jun	Fri 28-Jun
Precipitation			Event #1												
Snowmelt															

No Apparent Threat | Elevated Threat | High Threat
FLOOD THREAT LEGEND
Twitter: @COFloodUpdates

Figure 3: Example of an FTO headline from 2019 illustrating the threat "timeline" with the snowmelt forecast.

State Precipitation Map (SPM)

Updated 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 Estimate (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 MetStat, Inc. Data was visualized through the use of a custom built, Dewberry-hosted webmap using Mapbox API. 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 gage 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 greatly 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. As for the 2019 season, an update was made to the gauge quality control (QC) algorithm to better handle remote station and high elevation QPE.

Current ongoing research is focused on disaggregating the bias corrected gridded data back down into hourly grids to find the best available max QPE grids. The addition of the new Alamosa radar will also likely improve known “radar holes”. These updates will hopefully be available to the public and operational by May 1, 2020. An example of the daily SPM layout is shown in Figure 4. In addition to the map-based visualization, Dewberry forecasters provided text-based summaries of recent hydrometeorological conditions (including extreme rainfall values, flooding, debris slides, hail, wind, tornadoes and wildfire activity). The discussions were often supplemented with highlights using CoCoRaHS gages, COOP sites, Urban Drainage and Flood Control District’s ALERT rain gages, SNOTEL data and NWS Local Storm Reports.

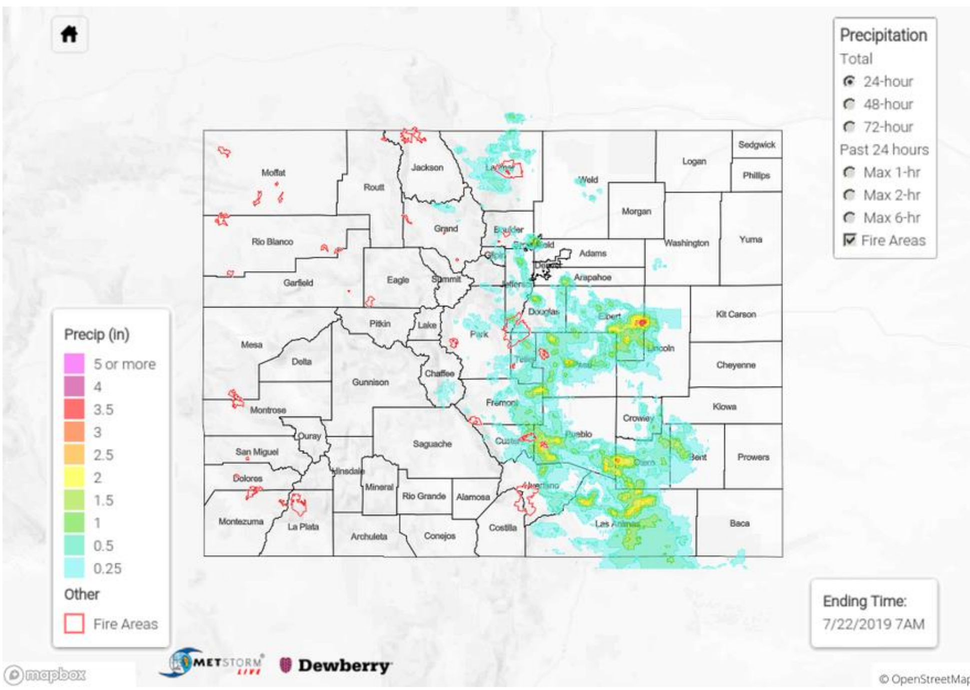


Figure 4: Example of SPM from July 22, 2019.

Performance metrics

Table 2 shows the final year-to-date number of all products provided, and the percent provided on time. Out of 350 total products delivered, 345 were delivered on-time or ahead of time. The three late products were 3 SPMs, 1 FTB and 1 FTO, all of which were posted within an hour of their deadline. Note that Table 2 also shows September performance since there was no monthly Progress Report for September.

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. To avoid duplicated effort, a progress report was not prepared for September because all necessary information is contained within this Final Report.

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

		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	150	3	98%
	FTB	30	30	0	100%		FTB	153	152	1	99%
	FTO	9	9	0	100%		FTO	44	43	1	98%
	TOTAL	69	69	0	100%		TOTAL	350	345	5	99%

2) VERIFICATION METRICS

a) Data Sources and Methodology

The daily FTB flood threat forecasts were verified on their ability to both (i) identify days when flood threats were realized and (ii) specify the approximate location of the potential flooding without grossly overestimating the flood threat area. Dewberry continued to place substantial effort on verification to increase robustness and, in turn, improve future forecasts. With the updates included from the 2017 validation process and updates to the burn area validation this season, this year's verification is likely the most inclusive of the Program's history. Note that improvements beginning in 2017 included: creation of comprehensive daily validation maps (see Figure 6), the use of more quality controlled rain gages and more effort spent on manual day-by-day quality control to ensure that a threat is properly classified. The data sources and methodology used to verify 2019 forecasts are described below.

Observational Data Sources

a) Daily precipitation accumulation reports from about 850 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 9AM 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.
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) NOAA Stage IV gridded precipitation data (hereafter Stage IV), which is a publicly available hourly product based on a radar-estimated, gage-adjusted technique using all National Weather Service NEXRAD radars and many quality controlled rain gages. The horizontal resolution is about 4 km (2.6 miles). In addition to using the 24-hour total precipitation, maximum 1- and 2-hour amounts were calculated to better understand the nature of the precipitation (convective vs stratiform). Often times the 2-hour amounts exceeded 24-hour amounts (QC differences), so 2-hour QPE was utilized with caution.
e) Local storm reports (LSRs) obtained from the four NWS offices that are responsible for Colorado: Boulder, Pueblo, Grand Junction and Goodland (KS). 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. Similar to 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.
f) NWS warning and advisory shapefiles (obtained from Iowa State University), including metadata such as when the product was issued. Only Flash Flood Warning, Riverine Flood Warning and Areal Flood Advisory products were included in the analysis.

Verification Methodology (FTB)

To determine if a flood threat was accurate, a "Flood Day" classification 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 variable: it is either 1 when flooding and qualifying rainfall intensity is observed, or zero otherwise. Note that, in practice, flooding often goes undocumented, and that adding a measure based on rainfall intensity ensures a more comprehensive treatment of the issue. Given the large variance in the rainfall-runoff relationship across Colorado (see Appendix C), more than one rainfall threshold is required. Thus, a Flood Day is hereby defined when one of following two criteria is met in the threat area (Figure 6):

1) Gridded or observation based 1-, 2- and/or 24-hour rainfall exceeds (see Figure 5):
    a. 1.00 in. west of the 1,600 meter (5,250 foot) contour over the eastern plains
    b. 1.50 in. east of the 1,600 meter (5,250 foot) contour over the eastern plains

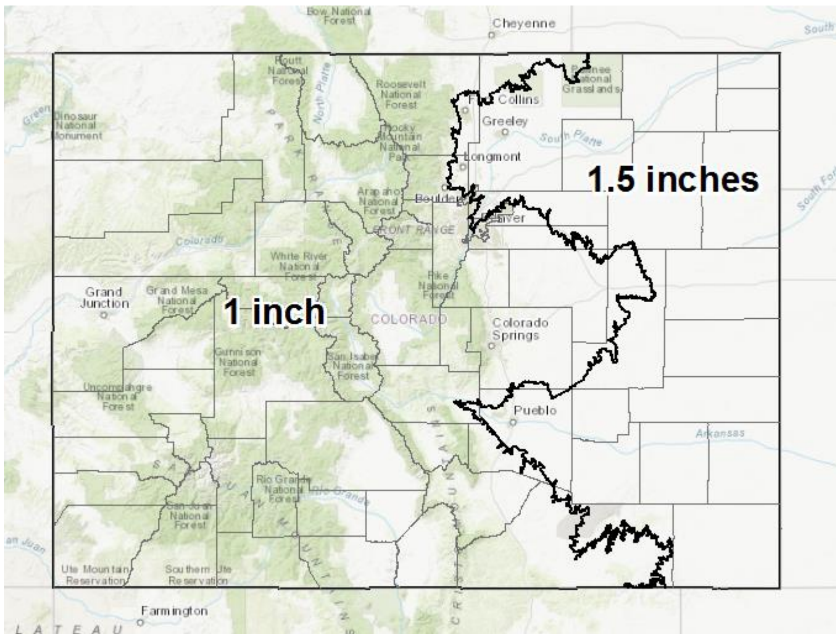


Figure 5: Colorado county map with thick black line showing the 1,600 meter (5,250 foot) elevation contour line east of the Continental Divide, which acted as the demarcation in rainfall-runoff sensitivity. To the east, a rainfall threshold of 1.50 inches per day was used to denote a "Flood Day"; to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

2) A qualifying NWS Local Storm Report (LSR) report described is received. For more information, see item (5) under Observational Data Sources, above.
3) An NWS flash Flood **Warning** is issued that day. An NWS **advisory**, alone, does not qualify as a Flood Day.
4) If a Flood Day is based solely on the Stage IV product, the areal coverage of qualifying rainfall must exceed 50 square-miles for *each* storm center. This helps to eliminate days with localized, marginal rainfall that is unlikely to cause flooding.

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 objective calculation of Flood Day using the protocol above, a manual quality control procedure was completed to account for the overriding conditions shown in Table 3. Note that multiple conditions could be met on any given day, reiterating the importance of having a manual quality control. In total, there were 35 days where overriding conditions were used, and seven of those days had multiple overriding conditions. Note that in years past, an overriding condition was "BURN", which described days where threat(s) were only issued for burn areas. Due to the separate burn validation analysis, from here on forward this overriding condition is no longer needed.

Table 3: 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	4
Long-duration low intensity precipitation causes qualifying 24-hour precipitation total but runoff does not support flooding.	Low Intensity (LI)	Flood Day = 0	6
There is no rainfall but antecedent conditions and/or snowmelt cause riverine flooding.	Riverine (RIV)	Flood Day = 0	15
Hail likely causes an overestimate in Stage IV resulting in qualifying precipitation totals.	Hail (H)	Flood Day = 0	2
The area of qualifying Stage IV precipitation exceeds 50 sq. mi. but is spread out over multiple (independent) areas, limiting flooding potential.	Multiple areas (AREA)	Flood Day = 0	16

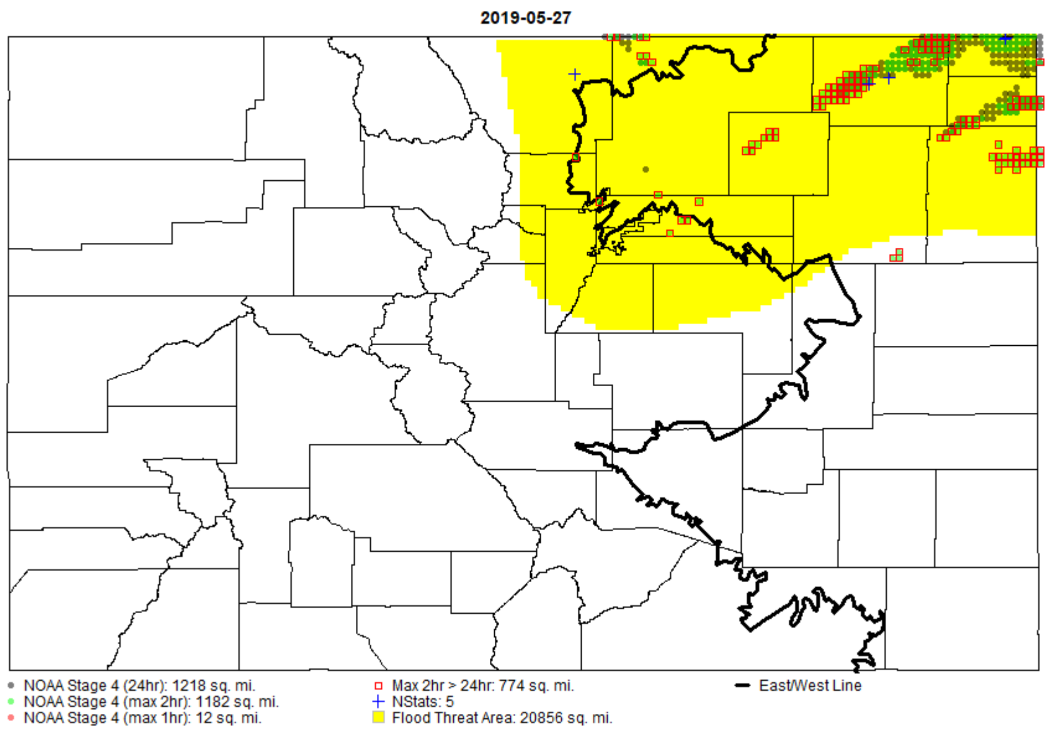


Figure 6: Example of daily validation map from May 27th, 2019 showing qualifying NOAA Stage IV pixels (gray dots), rain gages (blue crosses) and threat area (yellow color fill). For reference, qualifying Stage IV maximum 1-hour (red dot) and 2-hour (green dot) estimates are also shown, but note these were not solely used in defining a “Flood Day”. Red squares denote areas where maximum 2-hour Stage IV estimates exceeded the 24-hour estimate, an indication of the potential existence of hail and/or very high radar reflectivity. Note that the threat area does not distinguish between different threat levels.

Verification Methodology (Burn)

In 2017, Dewberry began to forecast threats over burn areas known to have flooding issues that put people and property at risk. High-risk burn areas are identified at the beginning of each season and are typically relatively large in scale (corresponds to a higher runoff threat) and are in close proximity to high population and/or major roads. The general rule of thumb for burn areas between 0 and 1 year old is that they need only rain rates of 0.25 inches per hour to trigger mud flows, debris slides and local stream flash flooding. After 1 year, the rain rates that burn areas are able to withstand increase at a rate of about 0.2 inches per hour per additional year. In most cases, this allows a burn area to fully recovery after about 5 years to the 1 inch per hour threshold.

High snowpack and a prolonged melting season during WY2019 helped decrease the wildfire threat this season. However, the (second most active) 2018 wildfire season produced a handful of high-profile burn areas, which needed to be monitored closely for flash flooding this season. There were five high-risk wildfire burn areas identified during the preseason analysis and specifically monitored by Dewberry (Figure 1): 416 (2018), Lake Christine (2018), Spring Creek (2018), Hayden Pass (2016) and Junkins (2016). Additional well-known wildfires were mentioned on higher threat days, such as Waldo Canyon, as they still tend to flood more frequently than surrounding areas when heavy rainfall occurs. During a preseason analysis using the prior season's data, 1-hour rain rate thresholds known to cause flooding issues were established for each of the aforementioned burn areas. While these rain rates may not always cause flooding issues, due to constant recovery of the burn area or rainfall not occurring directly over the center of a burn area, this is still the best process to determine thresholds prior to the season starting. This also allows for a more well-rounded validation process at the end of the season. Of course how burn areas responded to specific rain rates are internally monitored throughout the season, and threshold levels can be adjusted as needed. With that said, there were no adjustments made for the 2019 season.

There is no industry standard protocol on how to validate such a forecast, so some liberties were taken in regards to validation criteria. Stage IV data was used for QPE, and max QPE values were obtained both directly over the burn area and within a 10-mile radius of the burn area. The buffered QPE allows for errors in the imperfect, but improving, nature of heavy rainfall forecasts for validation. The burn area QPE (no buffer) will allow for a post-season analysis of rain rate thresholds that triggered flash flooding, mud flows and/or debris slides. A secondary benefit may be insight to the recovery of the burn area from the previous season(s).

To determine if a burn area flood threat was accurate, a similar "Flood Day" classification system was developed to describe whether burn area flooding occurred. **A Burn Area Flood Day is defined as a binary variable: it is either 1 when flooding is observed, or zero otherwise**. Since flooding often goes undocumented in these remote areas, max QPE with a 10-buffer (QPE-buffer) seemed like a reasonable and straightforward metric of rainfall to quantify rainfall intensity. It is important to note that the accuracy of burn area flood threats will likely be lower, possibly significantly lower than regular flood threats. Even with a 10-mile buffer, there are difficulties forecasting for such a small burn area. For example, the Junkins burn area is only about 30 sq. mi., which is smaller than the ~250 sq. mi. scale at which current forecasts begin to show skill. It is hopeful that off-season work with the NWS will help streamline and improve the burn area forecasting procedures and address discrepancies between burn scar forecast areas. For now, a Burn Area Flood Day is hereby defined when <u>one of following two</u> criteria is met for any listed burn area:

1) A qualifying NWS Local Storm Report (LSR) report described is received. For more information, see item (5) under Observational Data Sources, above.
2) Stage IV 1- and/or 2-hour QPE exceeds the assigned threshold for a burn area (see Table 4). 24-hour Stage IV data is used to QC the 2-hour QPE as 2-hour QPE has less QC, comparatively.

3) An NWS flash Flood **Warning** is issued that day that has a storm report within the **warning**, which was not present in the LSR database. An NWS **advisory or warning**, alone, does not qualify as a Flood Day.

Table 4: Burn areas forecast by the FTB for the 2019 season with their rain rate thresholds that are known to cause flash flooding issues.

Burn Area (Year)	Threshold (in/hour)
416 (2018)	0.50
Lake Christine (2018)	0.30
Spring Creek (2018)	0.40
Hayden Pass (2016)	0.75
Junkins (2016)	0.75

b) 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. In future years, the updated forecast maps may also be included in the validation.

As there is no single number that can comprehensively measure forecast accuracy, Table 3 shows the five metrics that are used in this report, all based on the contingency table approach shown in Table 6. In brief, there are two possible outcomes when a Flood Day forecast is issued: (i) a Flood Day is observed (case a in Table 5), a "Hit", (ii) a Flood Day is not observed (case c in Table 3), 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 5). Second, if a non-Flood Day is forecasted and a non-Flood Day is observed, this also results in a "Hit", although a dry one (case d in Table 5). Historically, the CWCB has always advocated for minimizing the Miss rate, which, given the uncertainties with heavy rainfall forecasting, necessarily results in a higher False Alarm rate. As shown in Table 6, target numbers for each metric have been established based on values accepted as reasonable within the forecasting community. These metrics only applies for the general flood forecasting, not burn area flood forecasting.

Table 5: 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 6: Description of metrics used for validating forecast accuracy.

Metric	Abbreviation	Calculation (see Table 5)	Summary	Goal
Accuracy or "Hit" rate	Hit %	$\frac{a+d}{a+b+c+d}$	Measures probability that Flood Days and non-Flood Days are accurately forecasted. Perfect forecast value is 100%.	>75%
Probability of Detection	POD	$\frac{a}{a+b}$	Measures probability of accurately forecasting Flood Days. Perfect forecast value is 100%.	>75%
False Alarm Rate	FAR	$\frac{c}{c+d}$	Measures probability that a Flood Day is forecasted but a non-Flood Day is observed. Perfect forecast value is 0%.	<20%
Miss Rate	Miss %	$\frac{b}{a+b}$	Measure probability that a non-Flood Day is forecasted 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 forecasted compared to those observed. Perfect forecast value is 1.0.	N/A

Table 7 shows the individual monthly and yearly aggregated forecast verification during the 2019 season. Over the course of the season, forecast performance achieved or exceeded two of the four targets established in Table 6 with one metric only 3% below the target. With an overall Hit Rate of 86%, forecast performance continued to be well above the >75% target and close to the highest recorded Hit Rate in Program history (87% - 2018). The Probability of Detection was at 72%, which is 3% from the goal (>75%). The False Alarm Rate dropped to a staggering 6%, which is well below the goal of <20%. With a drop in False Alarm rate, it's not surprising the Miss Rate increased as is the trade off with decreasing the False Alarm Rate. The Miss rate was 28%, which is 10% higher than last year and 13% above the goal of <15%. However, out of the 15 misses over the course of the season, nine had qualifying Flood Day area of less than 250 sq. mi. (24-hour QPE), which implies relatively localized areas of heavy rainfall. Only four of the misses were over areas with larger population centers. The process in which a Miss classification is defined shows the rigor with which the validation process is done. Further post-season analysis will be completed by Dewberry to reduce the Miss Rate as minimizing this is likely more of a priority to CWCB than decreasing the False Alarm Rate.

Looking at the month-to-month performance in Table 7, heavy rainfall occurrence was highest August, which is higher than expected with the monsoon season typically peaking for the majority of the state in July. Upon further analysis, there were five late Flood Days in August (between the 20th and 31st), which helped drive this Flood Day number upwards. If these days were removed, climatology would be distributed in a manner more consistent with climatology. Ironically, statewide, August precipitation was below average (27th driest on record) with only the Northeast Plains and pockets of the Southeast Plains receiving above normal precipitation. It is also interesting that portions of Delta and Montrose Counties had their driest August on record during a time when the monsoon typically peaks over the region. This just goes to show the sometimes complicated relationship of weather vs. climate.

There was some variability in the monthly performance, as can be expected due to smaller sample sizes. For example, during May, there were only 3 Flood Days, so the one missed flood forecast lead to a 33% Miss Rate. In the meantime, during August, 3 of the 17 Flood Days were not forecasted resulting in a much lower Miss Rate of 18%. There was an improvement in the July forecast when compared to last season. Last season, July had the highest False Alarm Rate of the forecast season, but this season, the False Alarm Rate dropped to 6%. It was one of two metrics that performed up to industry standard in every month (note: industry standard for False Alarm Rate <20%). The other metric that attained a high score was the Hit Rate, which performed well above industry standards (>75%) for all months. Work will continue to be done in the off-season to reduce Miss Rates as this is one of the most important metrics to the Program.

Table 7: 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	2	8	12	14	3	39
(b) No Flood / Flood	1	3	3	3	5	15
(c) Flood / No Flood	1	2	1	1	1	6
(d) No Flood / No Flood	27	17	15	13	21	93
Total Days	31	30	31	31	30	153
Hit %	94%	83%	87%	87%	80%	86%
POD	67%	73%	80%	82%	38%	72%
FAR	4%	11%	6%	7%	5%	6%
Miss %	33%	27%	20%	18%	63%	28%

Table 8 shows the yearly performance summaries from 2012 through the present. Overall, 2019 continues to show the success of the Program when all measures are taken collectively; however, the Miss Rate was 13% above the goal (<15%; Table 6). As is the trade off in between False Alarm Rate and Miss Rate, the Miss Rate was at an all-time Program low and 14% below the target goal. Minimizing both the False Alarm Rate and Miss Rate can be tenuous, and research to reduce the Miss Rate without subjecting the False Alarm Rate to sizable increases remains ongoing. The Hit Rate remained on pace with the Program's history at 86% and well above the target goal (>75%). Paired with the low False Alarm Rate, together this can be interrupted as high confidence in a forecast on the days threats were issued. Interestingly, only about 33% of the days with a threat issued had a threat level above low.

While validation and flood classification has undergone changes season to season, since the start of the Program, on average a forecast season experiences flooding on 74 of the 153 forecast days (48%). Similar to the 2018 season, only 35% of the forecast days (54 days) experienced flooding criteria, which is the second lowest in Program history and may slightly impact validation statistics with a lower sample size. The Bias for 2019 is actually under 1 this season, which differs from the last 3 seasons. This metric indicates under-forecasting of the flood threat, so more focus will be placed on limiting Misses in 2020.

Table 8: Summary of yearly forecast performance since 2012. Note that the validation procedure was significantly enhanced in 2014, which makes it difficult to compare pre-2014 statistics to 2014-present.

	Hit %	POD	FAR	Miss %	Threats Issued	Flood Days	Bias
2012	86%	84%	18%	16%	65	64	1.02
2013	84%	85%	13%	15%	83	85	0.98
2014*	76%	73%	18%	27%	75	84	0.89
2015	77%	78%	25%	22%	85	88	0.97
2016	84%	88%	21%	12%	93	91	1.02
2017	86%	86%	15%	14%	76	74	1.03
2018	87%	82%	11%	18%	52	50	1.04
2019	**86%**	**72%**	**6%**	**28%**	48	54	**0.83**

Table 9 shows the forecast performance as a function of threat level. Note, the threat level in the table represents the highest threat issued over a non-burn area. 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 9 shows this to be the case with an astonishing 88% verification when Low threats were issued. This is much higher than last season where Low threat forecasts verified 68% of the time (consistent with 2015, 2016 and 2017). **Moderate and High threats verified 93% and 100% of the time they were issued, respectively**. While flood threats should first represent the forecasters' confidence in flooding, most seasons have a slightly higher ratio of High to Moderate threats. The discrepancy between the number of Moderate and High threat when compared to Low threats implies that perhaps more elevated flood threats should have been issued. Previously discussed metrics also suggest that more overall threats should have been issued this season. It would be beneficial to revisit the Flood Threat definitions during the off-season in preparation with new forecasters for the 2019 operational season.

Table 9: Accuracy as a function of threat level. Note: threat levels were reduced to the highest non-burn area threat level.

	Observed Flood Day	Observed Non-Flood Day	Total Days
Low	28 (88%)	4 (12%)	32
Moderate	14 (93%)	1 (7%)	15
High	1 (100%)	0	1
High impact	0	0	0
Total	43 (90%)	5 (10%)	48

Table 10 shows the yearly aggregated forecast verification for burn area threats during the 2019 season. Currently, there are no established targets for burn areas, so the goals for forecast validation are used as a loose guideline. Note that using the given forecast performance metrics, one should expect much lower skill due to the small area of the burn areas. Surprisingly, metrics were on par with the forecast goals. Over the 153 days, 42 days classified as a Hit over at least one of the burn areas (Appendix B). Reminder that flooding did not have to occur for a Flood Day to be recorded. There was also a noticeable active streak from July 21st to August 11th where 20 of the 22 days were classified as a Hit, which is not surprising as there is a climatological peak in heavy rainfall activity during this period. The Hit Rate was 86% with the Probability of Detection measured at 78%. The False Alarm Rate was below 10% and the Miss Rates was 33%, which is satisfactory given the small forecast area. Accurate preseason threat thresholds are key for the analysis, so more preseason research will be completed next season to improve the current analysis.

If broken down by threat level (not shown), the largest improvements for the 2020 season would continue to be at the Low threat level, although metrics improved greatly from last season. There were 17 Low threats issued with five False Alarms. At the Moderate threat level, there were 21 threats issued with only three False Alarms. This shows improved skill, as expected, when the forecaster has increasing confidence. There was only one High threat issued, so next season there may need to be an improvement to the system in order to create more evenly distributed threats across the levels.

The Spring Creek burn area had the most Flood Days recorded (33 days), which is not surprising given its location, size and age (lower rain rate threshold). Of those 33 day, 55% of the Flood Days were triggered by the QPE-buffer. The Junkins burn area had the second most Flood Days (11 days), which given its location relative to Spring Creek is not too surprising, and QPE-buffer triggered 73% of the Flood Days. The high percentage of Flood Days triggered by the QPE-buffer unfortunately does not give much insight to the rain rate thresholds chosen at the beginning of the season. It more so just accounts for the low probability that a storm will track directly over the burn area. Further breaking down the trigger of a Flood Day, when the established rain rates fell directly over the burn area (QPE without a buffer), flooding was reported close to 100% of the time. Luckily, the Lake Christine burn area only experienced this once this season (along with the Junkins burn area). Hayden Pass and the 416 burn areas were able to avoided flash flooding all together. The metrics shown here and from last season continue to show value, which gives confidence in the utility of relying on the Flood Threat Bulletin for early warning (burn area) flooding detection.

Table 10: Summary of burn area forecast performance in total. A more robust validation system will be created for 2019.

Forecast / Observed	Total
(a) Flood / Flood	28
(b) No Flood / Flood	14
(c) Flood / No Flood	8
(d) No Flood / No Flood	103
Total Days	153
Hit %	86%
POD	78%
FAR	7%
Miss %	33%
Bias	0.86

3) CHARACTERIZATION OF FORECAST PERIOD WEATHER

Detailed Summary

The 2019 operational season was quite the rollercoaster in terms of precipitation. At the end of WY2018, Exceptional Drought (D4) covered 16% of the state with Moderate (D1) to Exceptional Drought (D4) covering nearly three-quarters of the state (Figure 7, top). However, by the end of May, drought-free conditions were present over the entire state (Figure 7, bottom). This was the first time in nearly 20 years of monitoring that drought-free conditions have been acheived. There were a couple of meteorological phenomena that allowed for the drought-free conditions.

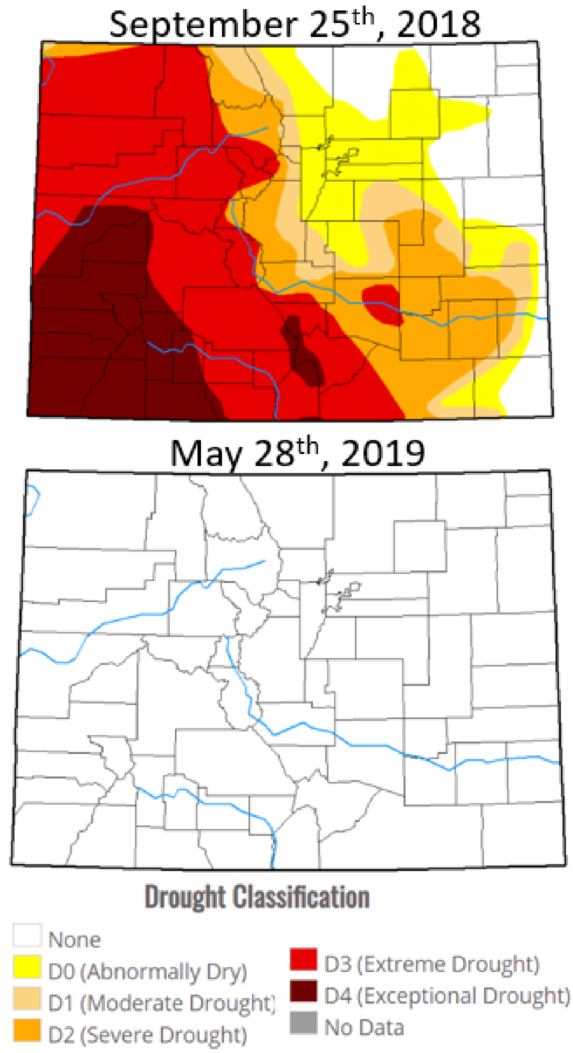


Figure 7: Precipitation (top) and temperature (bottom) anomalies for May-September 2018 using PRISM data. Source: Desert Research Institute.

First, there was impressive snowpack during the 2018-2019 winter. Particularly, the beginning of March had a couple large snow storms, which helped push Colorado's yearly accumulated SWE above normal (Figure 9). For the WY2019 statewide SWE topped out at 21.3 inches with a climatoloically normal peak in timing (early April), and it was about 4.5 inches above the median statewide value (1981-2010). While not the highest on record, SWE statewide did reach the 90th percentile from mid-March to early April.

In addition to the high snowpack, the spring was quite wet and cold. May had above average precipitaion statewide and was ranked 111 out of 125 (in terms of wetness) with portions of the southwest corner receiving 2 to 3 times above normal precipitation. The extension of cold temperatures into late May and June allowed most of the precipitaiton to fall as snow in the high country, so rain-on-snow events were far and few between. Figure 8 shows the date of the last freeze in 2019 (left) compared to the date of the median freeze (right). The image indicates that the last freeze was delayed anywhere between 10 to 20 days for 2019. These colder temperatures helped produce a late season snowstorm for the metro area on May 20th. While the official total at DIA was 3.4 inches, the metro area received up to 11 inches over the Palmer Divide. There were only three other instances where Denver received at least 3 inches after the start of Spring.

Furthermore, May 2019 was the 5th coldest on record for the state. The extension of the cold temperatures into Spring helped prolong the melting of the snowpack, and 2019 was the third latest in terms of meltout (2011 and 1995 were the latest, respectively). In turn, the sluggish melting of the snowpack allowed the dehydrated soils to absorb more water and combat the drought. A quick increase in temperature would have intensified the melting,

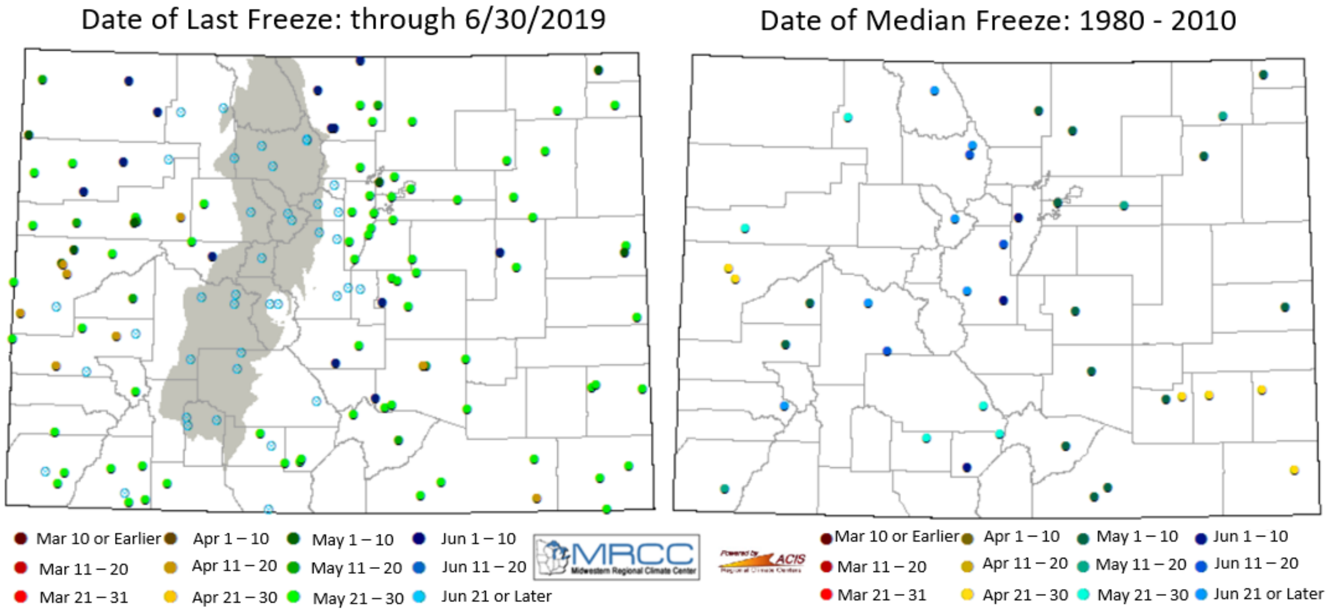


Figure 8: Date of the last freeze in 2019 (left) and date of the median freeze from 1980-2010 (right). Source: MRCC.

which in turn would have likely saturated soils and produced excess runoff. Overall, the high snowpack and a cold, wet start to spring combined to help Colorado recover from a historic drought over a very short period of time. Another perk of the excessive snowpack was that reserviors were able to recover from the previous, low snowpack season (see Figure 9, WY2018), and the reserviors low levels (ability to hold water) helped alleviate the swollen rivers. There were a handful of dam releases that caused minor flooding issues in June, but for the most part, major flooding issues were able to be averted.

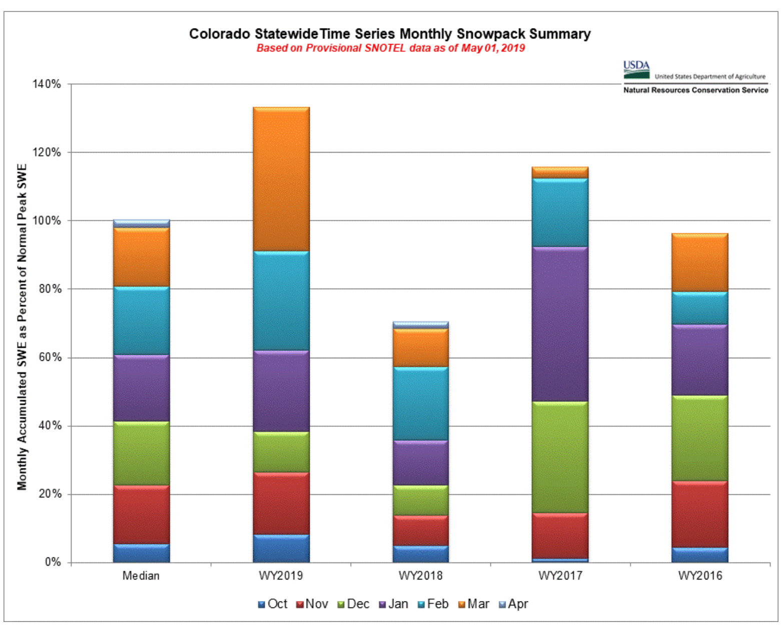


Figure 9: Colorado statewide accumulated SWE as a percentage of normal. WY2019 exceeded 100% of normal in early March. Source: NRCS.

On a related note, the Program monitored riverine flooding quite intensely during the spring due to the high snowpack, and the Program even added special rivierine forecast sub-sections to the FTO and FTB. The FTO riverine outlooks specifically looked for "heat waves" that could trigger additional, rapid runoff to the high streamflows and rain on snow events. For the FTB, all NWS Flood Warnings (riverine) were added to the daily threat maps, and a riverine discussion section was added through the meltout. As always, the FTB also took into account heavy rainfall events over or near elevated flows for the daily flood threat maps. Although this was an unusual start to the season, upgrades for the 2020 season will help create additional products to address early season riverine flooding impacts across the state.

The month of June was fairly normal in terms of precipitation and slightly cooler than average for temperature. The Northwest Slope and southeast corner of the state received above average precipitation, and the southwest corner received slightly below normal precipitation. This below average precipitation for the San Juan Mountains was helpful as rivers and streams were elevated most of the month from the melting snowpack. The middle of June had an an active streak in terms of heavy rainfall and severe weather. On June 17th, just over 4 inches of rain fell in north, central Kit Carson County as a nearly stationary and back-building storm dropped heavy rainfall over a 2-hour period. This ended up registering as a 1 in 400 year event. Rainfall totals were similar over Kiowa County, which caused portions of Colorado 96 to be washed out just east of Eads.

As is typical, the heavy rainfall threat increased at the end of July with the onset of the North American Monsoon (NAM). It is a well-known fact that the end of July is climatologically the wettest and warmest time of the year for the majority of the state. On July 20th, a new high temperature record was set at John Marin Dam near Lamar. The temperature reading beat the previous record by 1°F measuring at 115°F. As for precipitation, by observing the number of Flood Days only, it seemed like only a slightly below normal monsoon season (activity). However, looking into July and August precipition patterns, both months were very dry over western Colorado and the mountains. This was good news for the 416 and Lake Christine burn areas as both are fairly fresh and flash flooding and debris slides can be triggered easily. However, as quickly as the drought recovered, it started to return. The drought officially returned (D0 – Abnormally Dry) on July 23rd over the southwest corner of the state. Climatologically normal precipitaiton fell over the adjacent, eastern plains with pockets of above normal rainfall for the northest corner and pockets along the Urban Corridor. For June through August, precipitation in total across the state, ranked 33rd for the driest on record (below average).

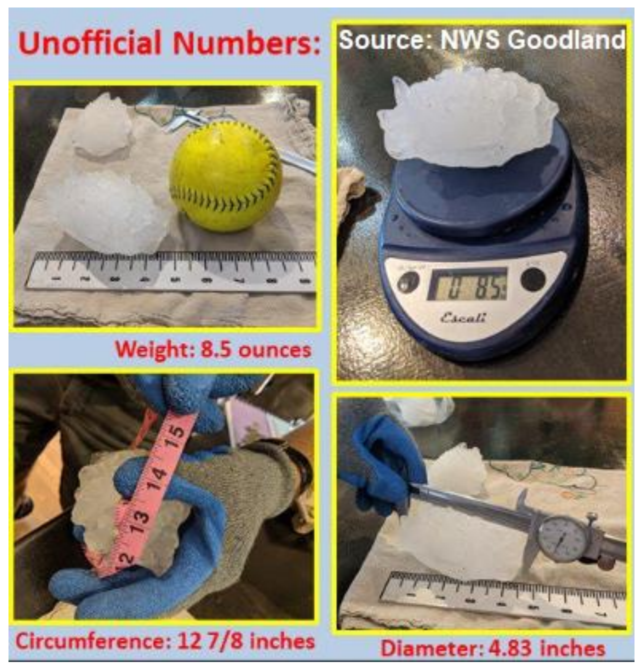


Figure 10: A new CO hailstone record was set on August 13th, 2019 in the town of Bethune, CO. The hailstone was measured at 8.5 ounces and was 4.83 inches in diameter. Source: NWS Goodland.

In tandem with the heavy rainfall, there were several large hail events throughout the season that caused a lot of damage to the crops over the eastern plains. May had 6 days where hail size was greater than 1.5 inches, June 12 days, July 7 days and August 5 days. One storm in particular stood out that occurred on August 13th. Close to the Colorado and Kansas border near the town of Bethune, CO, a new state hailstone record was set (Figure 10). A high CAPE and shear enviroment helped set the tone for severe thunderstorms during the late afternoon hours. Initial photos on social media of the hailstone show that it was even larger, but sublimination (ice to water vapor) occurred in the freezer. Official measurements for the hailstone were the following: weight - 8.5 ounches, circumference – 12.875 inches, and diameter – 4.83 inches.

The monsoon began to shutdown by mid-August, and by the end of August, D1 drought conditions (Moderate Drought) were reported over Montezuma and La Plata Counties. Portions of Delta and Montrose County had their driest August on record, and most of the Utah bordering counties were much below normal (bottom 10%). Only the Flat Tops region had above average rainfall for the month. On top of abnormally low rainfall, many areas in western Colorado (as well as Colorado Springs) had their warmest August on record. So it's not too surprising the drought returned.

A brief active heavy rainfall pattern returned to start September; however, the rainfall that occurred was over the Front Range and adjacent eastern plains. Starting on September 3rd, Flood Days occurred six of the next seven days with two Moderate threats issued. On Septemeber 6th (Moderate threat issued), very heavy rainfall fell over the Denver Metro area. On the synoptic scale that day, a cold front had pushed south and returned high moisture to the area. Precipitable Water (PW) was measured at 1.06 inches in the morning sounding at Denver. For reference, this placed PW in the 95th percentile for that time of year and broke a daily maximum record, so this could be considered a late season event. On top of high atmospheric moisture, storm motion was forecast to be under 10 mph with back-building storms possible due the continuous westerly component of the wind field (upslope flow). Sure enough, heavy rainfall occurred near Floyd Hill and the southern Denver Metro during the afternoon hours. An ALERT gage near Big Dry Creek at Heritage Region Park measured 2.64 inches in just over an hour, which caused a vechicle to be stranded at the C-470 and Yosemite intersection. As strong as Sepetember started, the heavy rainfall threat fizzled out with only two Flood Days realized after September 12th. September was also abnormally warm with several counties along the Front Range and over the high country having their warmest temperatures on record. Overall lack of rainfall and hot temperatures caused the enitre southwest quadrant of the state to move back into D1 drought (Moderate Drought) heading into October.

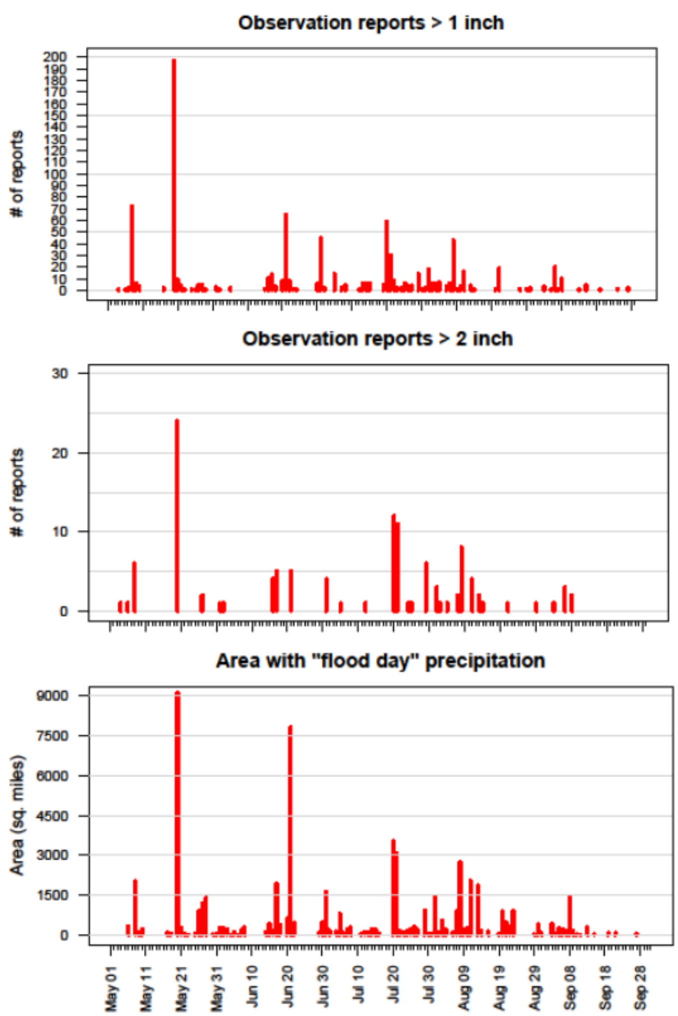


Figure 11: The number of daily observation reports exceeding (a) 1 and (b) 2 inches, and (c) the coverage of Flood Day precipitation, in sq. miles, from the gridded precipitation product. For reference in (c), the total area of Colorado is about 104,000 sq. miles

Seasonal Stats

Over the 153-day operational season, heavy rainfall activity was below average when compared to previous seasons, and slightly more active than 2018. Table 8 shows that 54 Flood Days were observed this season, which is about 30% below the 2012-2018 average of 77 days. Looking at Appendix D, a visual was created that shows the number of flood threats issued for a given locale. The Spring Creek, Junkins and 416 burn areas notably stand out on the image, which is a direct reflection of their ability to cause flooding issues due to their freshness. Not surprisingly, a secondary maximum was found over the Palmer Ridge, which is consistent with the climatology of summertime precipitation in Colorado. However, the number of threats issued over the Palmer Ridge (and state) continued to drop significantly from 2016 through 2018. This may have to do with more precisely drawn threat areas, but it may also reflect the higher Miss Rate. Western Colorado had the least active year, which likely had to do with the weak monsoon over the southwest corner. This area is usually quite climatologically active during late July into August, but as discussed above, it was quieter this season with the drought returning by the end of July. During the offseason in preparation for next season, the Progam will overlay Local Storm Reports over the last few years on the images to idenify active flood areas that may have been overlooked when drawing the threat maps.

Figure 11 shows the daily number of rain gage reports over 1 and 2 inches of rainfall, along with the area exceeding Flood Day thresholds as measured by the Stage IV gridded product. There were 77 days where at least 1 station measured a qualifying precipitation amount (see "NStats" column in Appendix A). There were 55 days where at least two stations measured qualifying amounts, and 16 days where at least 10 stations measured qualifying precipitation. There were only one day (May 20th) where over 100 gages measured qualifying precipitation. It should be noted that this event was associated with snow and low intensity rainfall. The large area of the storm and proximity of high population centers likely caused the ~200 gages metric.

In terms of Flood Day area (panel c), there were 14 days where over 1,000 sq. mi. recorded rainfall greater than 1.50 inches (1 inch) east (west) of the 1,600 meter contour, which is slightly lower than last season. There were four days where Flood Day area exceeded 3,000 sq. mi., indicative of widespread heavy precipitation: May 20th, June 21st, July 20th and July 21st. The first two dates had either snow or low intensity rainfall, so not much (if any) flooding was reported. However, on July 20th, the lone (non-burn) High threat day of the season was issued. Several rounds of storms fired over the high country and pushed into the adjacent eastern plains causing several intersections to flood from Denver to Pueblo with as much as 6 inches of standing water. There was a water rescue at west Colfax and 121st street after a vehical stalled in the high water. Over the eastern plains, Kiowa, Kit Carson and Crowley Counties received just over 3 inches of rain, which also caused flooding issues. The validation figure with the overlaid threats can be seen below (Figure 12).

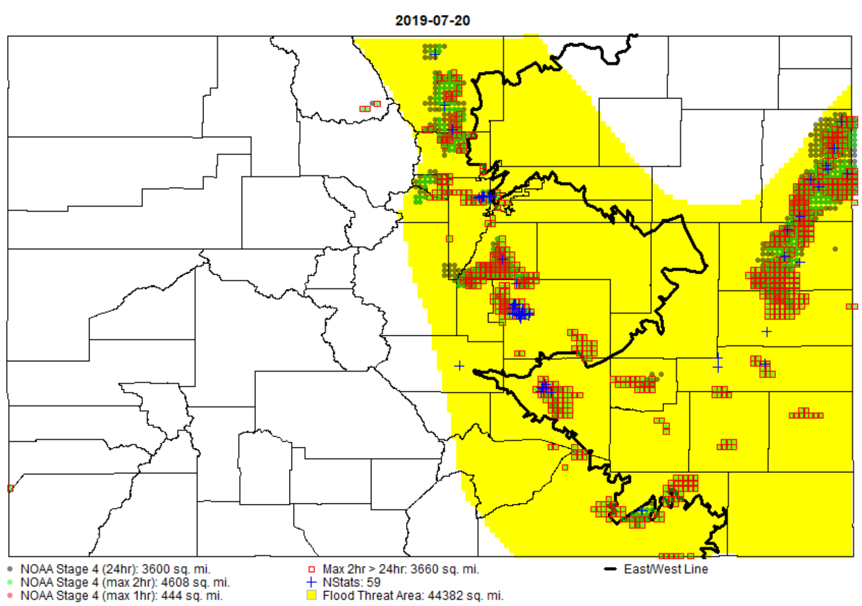


Figure 12: Rainfall observations over 1 inch for Stage IV and CoCoRaHS data on July 20th, 2019. The total threat area is in yellow with no distinction between threat levels for this image. The Junkins burn area had a Moderate threat issued for that day as well and verified with a report of 1.55 inches of rain near the burn area.

4) USER ENGAGEMENT

Social media and online presence continues to be improved upon each season as it is a critical piece of the Flood Threat Bulletin's success. Even a perfect forecast can have little to no value if it is not properly disseminated, so Dewberry continues to have many outlets for forecast communication. During 2019, Dewberry provided users with four options of how to receive forecast updates and other information. First and foremost is the program website (www.coloradofloodthreat.com), which has been the main communication form since the program began. Second, we continue to embrace the Twitter social media platform to provide forecast updates and other informational messages. Third, we continued the Facebook page to reach a separate demographic from Twitter (note: Facebook used similar or identical posts to Twitter). Finally, starting in 2017, Dewberry began providing an email alert option where users could receive a daily notification of the Flood Threat Bulletin headline in their email inbox. All four forms of communication continue to evolve with encouraging outcomes, which are described in more detail below.

Website

Figure 13 shows daily website usage during 2019 (blue) overlaid with the previous three seasons. As has been seen in the past, average daily site visits continue to be highest on days flood threats are issued (~84 users per day). There is a large 1-day peak June 1st (453 users), but it seems to be some sort of glitch with the website being pinged multiple times (error). Similarly there seems to be a noticeable peak in the data from early to mid-June, which might be related, so caution may be needed interpreting the data. During 2019, website average daily usage continued to grow with 66 users per day. This is a 300% increase since 2017! This is likely partially due to increase internet usage as a means of communication. Interestingly, website usage was up from the previous two seasons, even though the number of flood threats issued decreased (45 in 2019; 60 in 2018; 74 in 2017; 91 in 2016). There may be a few reasons to account for the increase in site usage. One, there was an early season campaign by Kevin Houck about the Program, which likely drove viewership to the site throughout the season. Two, for the most part, after viewership increased at the end of May, most users continued to return to the website through the end of monsoon season. This indicates that the Program is continuing to gain traction as a successful early detection flood tool, and it provides useful information to the end-users. Figure 13 indicates a slight drop off in viewership towards the end of July, so new techniques will be implemented in 2020 to make sure the website continues to discuss relevant and diverse flood content.

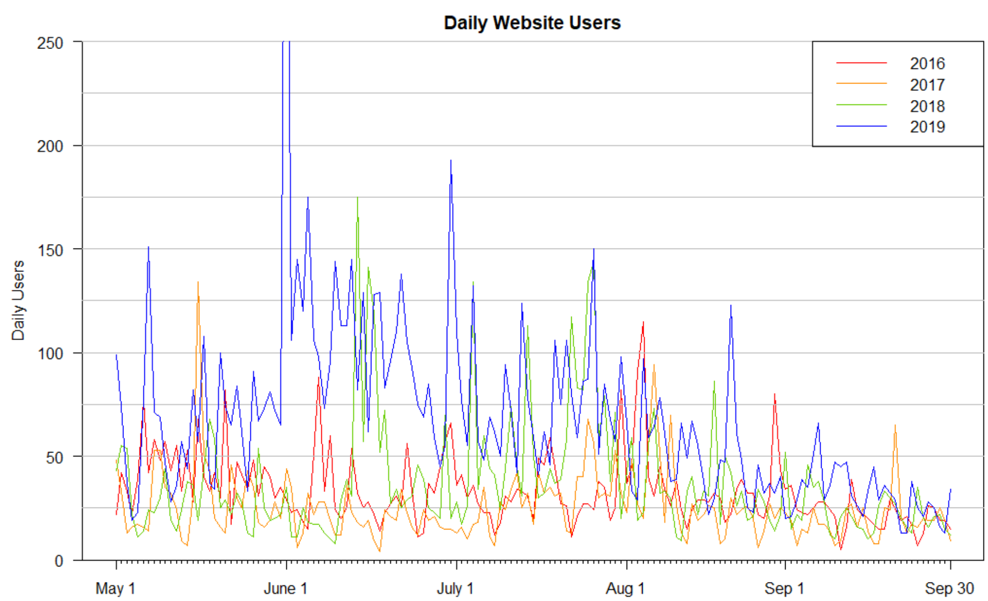


Figure 13: Daily website users during 2016 (red), 2017 (orange), 2018 (green) and 2019 (blue).

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 matter. The Twitter account was a great success during the September floods, and 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, (iii) the most current 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 daily FTB operations, the Program's social media strategy attempts to maximize the way this data is leveraged in unique posts. For example, Figure 14 shows a Tweet that highlights the late nature of the snowmelt and compares the melting of the snowpack to previous seasons. Messages such as these have shown their value by being well received by social media users through ample retweets and impressions.

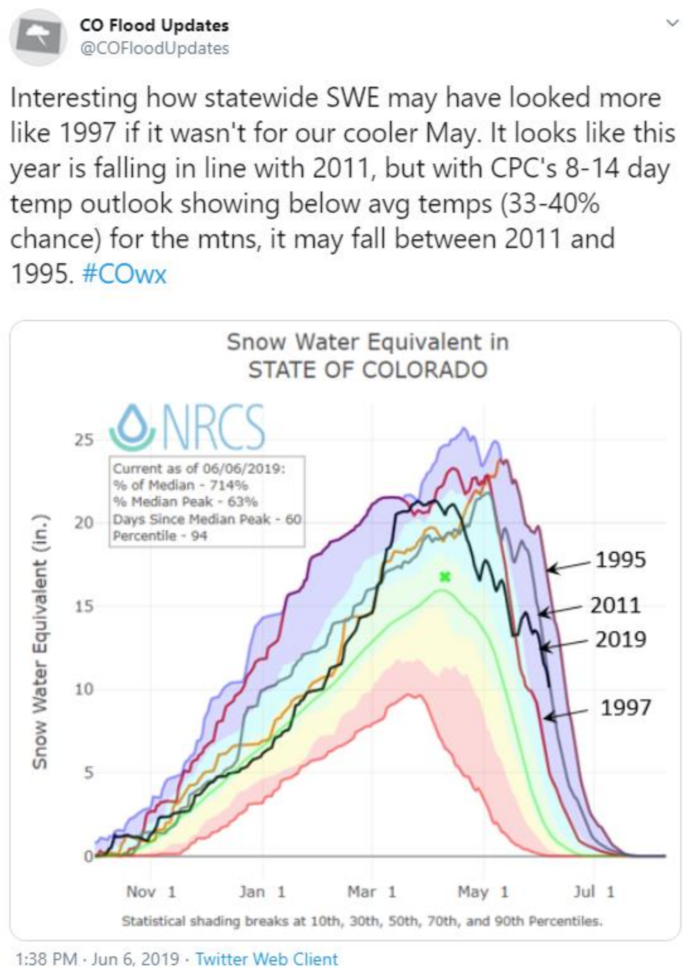


Figure 14: Example of a tweet with a unique image from the 2019 season. This tweet was related to the statewide SWE and late meltout of the snowpack in relation to other seasons.

The FTB's Twitter account, **@COFloodUpdates**, continued to gain usage since its inception with the total number of followers up to 1,331 by the end of the 2019 season (an increase of ~150 compared to the end of the 2018 season). This can be partially attributed to the number of retweets a few of our tweets received, especially from accounts like Colorado Emergency Management, which has over 53.9K Twitter followers. **@COFloodUpdates** continues to be featured in the 9NEWS Local Market science section and mentioned by their associated twitter account (@LocalMarket9; 17.6K followers). The continued increase of viewership of our tweets expand our outreach to those who may not have known about the **@COFloodUpdates** account and the FTB website otherwise.

Arguably, the most useful data variable 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 15 shows the daily impressions received during 2019 (blue line) as well as those for the 2016 through 2018 seasons. There is a slight decrease in the number of overall daily impressions. During the 2019 season, the Program disseminated 217 Tweets (about 90 less than 2017 and 15 less than 2018) and received a total of about 245K impressions (down from 313K in 2018). Of the 217 Tweets, only 78 of them received over 1,000 impressions. Off season work needs to be completed to assess which posts are most successful as well as the commonality of the "unsuccessful" Tweets. There will also be a conscious effort to increase the number of Tweets sent out during the 2020 season. This includes unique images such as that created in Figure 14.

Currently, the most notable followers of our Twitter account are the following: Colorado Emergency Management, 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 FTB Twitter account.

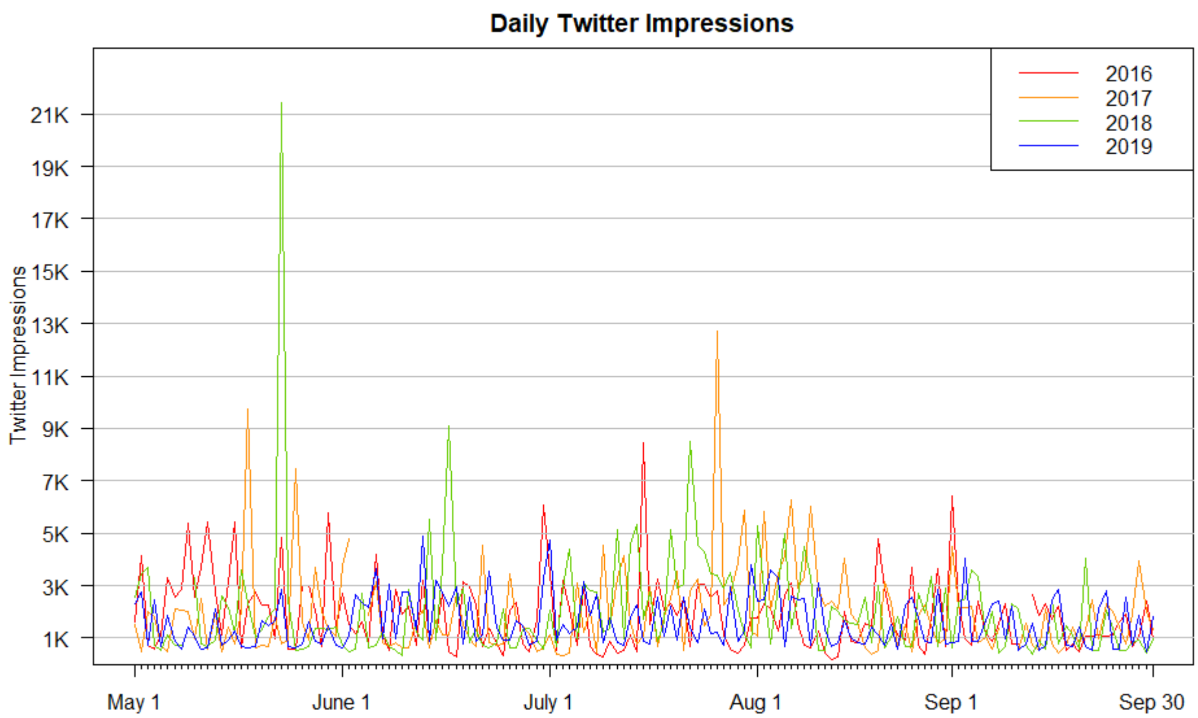


Figure 15: Daily Twitter impressions during 2019 (blue), 2018 (green), 2017 (orange), and 2016 (red).

Since the Twitter account was so successful at disseminating the FTB products, it was decided that Dewberry would open a Facebook account and create a Colorado Flood Threat Bulletin page at the beginning of the 2018 season. The main push behind the idea was that the Facebook page would reach a different demographic of potential 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, companies and organizations. 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.

Facebook, similar to 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 the second season, the Facebook account gained an additional 108 likes (250 total) and 117 followers (272 total), which are the equivalent of Twitter followers. While this number continues to be quite a bit lower than the Twitter account, it increased well over 50%, which shows the second media platform has value. The Facebook page will continue to be used in 2020 as it does not take much effort to write posts since the posts are close to, if not identical, to the Tweets. Secondly, after a quick cross-reference of account names, many of the individuals who liked the Facebook page do not have Twitter accounts. This means the Facebook page is achieving its goal of reaching a different demographic. Also, the majority of the "likes" on the page are from individuals, rather than companies and organizations, since Facebook accounts are, by and large, for personal use. Lastly, the Facebook timeline (main page) operates in a different manner than the Twitter feed (main page) as posts on the timeline aren't always in chronological order. While not ideal to early alert flood product, this can allow a post of a FTB product to be highlighted in different way as it will not quickly get buried behind other posts.

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 indicate the effectiveness of each post. This is most important on days when threats are issued, and, in fact, the highest average of reaches occurred during the core of the monsoon season from mid-June to mid-August. During this period, the average number of reaches per day was 657, which is down from 931. On average for the 2019 season, we had 626 reaches per day (down from 871) with a range from 120 to 5,842. The largest of the reaches was achieved on May 7th when the first flood threat of the season was issued. The post highlighted heavy rainfall and small hail for the Urban Corridor that could cause drainage issues over a populated area. This post had 76 reactions, comments and shares along with 846 post clicks. Of those post clicks, 217 looked at the photos and 35 clicked the link to the website for more detailed flood information. This statistic shows how important images are to supplement the flood threat message. In order to improve our Facebook statistics for next season, equal emphasis will be placed on the message's text and supplemental image(s).

The use of specific hashtags also play a large role in expanding viewership on all social media platforms. 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 we commonly use, and has become almost completely dedicated to our products. Hashtags are searchable through Twitter and Facebook, and using relevant popular hashtags such as #COwx or #COFlood allows people looking for specific information to be directed to our tweets. The following is a list of common tags that were used, as well as unique tags that were used to target specific events where flooding could be a relevant concern.

- Common hashtags: #FTB, #FTO, #STP, #COwx, #COFlood, #COFire
- Unique hashtags: #Monsoon, #CODrought, #LaborDay, #MemorialDay

It's always important to keep in mind social media trends are very fluid, so the Program will continue to monitor and reassess (i) whether Twitter and Facebook are the most effective platforms they can be for the FTB service, and (ii) the best way to keep posts dynamic and relevant for end-users. It can also valuable to note the similarities and difference between the social media platforms for optimal usage by the end-users. For example, Facebook users tend to engage more in conversation, while Twitter users are more interested in quick updates and concise details. This will be an important topic to dive more into in the off-season as it may not make sense that posts on the two social media platforms are always identical. The fact that the link to the FTB website was placed on every post, and it was only clicked a fraction of the time (compared to photo views) throughout the season, also points to the same conclusion.

Email Alerts

A subscription for receiving daily email notifications of the Flood Threat Bulletin was begun on April 28, 2017. As of November 30, thanks to the preseason campaign by Kevin Houck, there were 127 active subscribers. This is an additional 100 users from last season. Furthermore, there were no instances where a subscriber asked to be removed from the service. During the off-season it will be important to assess the content and quality of the information provided in the email. So far choosing to receive the Bulletin through email alerts has not decreased website traffic as one might just check the threat level. Boosting the number of subscribers is a key objective of the Program's as the goal is to provide as many communication options as reasonable. We must continue to learn and adapt to user preferences for flood information dissemination. Dewberry is always considering methods on how to better advertise the email subscription option as well as content included in the email. Similar to last season, a reminder email will be sent out to subscribers in mid-April alerting them of the return of the FTB May 1st, 2020.

5) CONCLUSIONS

- Statewide, 2019 was only slightly more active than 2018 (the quietest year on record) with only 54 Flood Days and 45 (non-burn) threats issued. This is about 30% below the 2012-2018 average of 77 days. New to 2019 was an updated burn area threat validation. There were 42 Burn Area Flood Days and 36 burn-specific threats issued. The winter of 2018-2019 helped Colorado recover from a large drought in a short period of time. Just as quickly as the drought recovered, it returned. It resurfaced first over the southwest corner of the state, and increased into August (27th driest August on record statewide). Portions of Delta and Montrose Counties had their driest August on record in a time that is normally active in terms of rainfall (NAM). High temperatures statewide in August in September also helped dry out the soil.

- The longest stretch of active weather occurred during the height of the monsoon season from July 20th to August 16th where a Flood Day occurred on 21 days of the 28 day period. It was during the start of this period one of the most notable flood events of 2019 occurred. On July 20th, the lone (non-burn) High threat day of the season was issued. Several rounds of storms fired over the high country and pushed into the adjacent eastern plains causing several intersections to flood from Denver to Pueblo with as much as 6 inches of standing water. There was a water rescue at west Colfax and 121st street after a vehical stalled in the high water. Over the eastern plains, Kiowa, Kit Carson and Crowley Counties received just over 3 inches of rain, which also caused flooding issues.

- Overall, forecast accuracy during 2019 continues to show the success of the Program when all measures are taken collectively. Over the course of the season, forecast performance achieved or exceeded two of the four targets established in Table 6 with one metric only 3% below the target. With an overall Hit Rate of 86%, forecast performance continued to be well above the >75% target and close to the highest recorded Hit Rate in Program history (87% - 2018). The Probability of Detection was at 72%, which is 3% from the goal (>75%). The False Alarm Rate dropped to a staggering 6%, which is well below the goal of <20%. With a drop in False Alarm rate, it's not surprising the Miss Rate increased as is the trade off with decreasing the False Alarm Rate. The Miss rate was 28%, which is 10% higher than last year and 13% above the goal of <15%. Further post-season analysis will be completed by Dewberry to reduce the Miss Rate as minimizing this is likely more of a priority to CWCB than decreasing the False Alarm Rate. As far as threats issued, Moderate and High threats verified 93% and 100% of the time they were issued, respectively.

- Surprisingly, burn scar forecast accuracy metrics were on par with the forecast goals. Over the 153 days, 42 days classified as a Hit over at least one of the burn areas. There was also a noticeable active streak from July 21st to August 11th where 20 of the 22 days were classified as a Hit, which is not surprising as there is a climatological peak in heavy rainfall activity during this period. The Hit Rate was 86% with the Probability of Detection measured at 78%. The False Alarm Rate was below 10% and the Miss Rates was 33%, which is satisfactory given the small forecast area. Accurate preseason threat thresholds are key for the validation. Upon further analysis, when the established rain rates fell directly over the burn area (QPE without a buffer), flooding was reported close to 100% of the time. This indicates the rain rate thresholds established at the beginning of the season were appropriate, and this method can be applied again for the 2020 season.

- Website viewership continued to grow with average daily usage at 66 users per day. Average daily site visits continue to be highest on days flood threats are issued (~84 users per day). The preseason campaign by Kevin Houck added 100 subscribers to our email list (total of 127 active subscribers). The Program's Twitter account (@COFloodUpdates) continued to expand with 1,331 followers. The Facebook account also increased from ~100 likes to 250 likes from its first to second season. More work will be completed in the off season to make sure social media stays relevant as it is an integral piece of the Program's communication strategy.

6) REFERENCES

USGS Geospatial Multi-Agency Coordination (GeoMAC) Wildland Fire Support, https://rmgsc.cr.usgs.gov/outgoing/GeoMAC

APPENDIX A – FORECAST VERIFICATION WORKSHEET

Table 11 is a daily verification worksheet documenting the intensity and coverage of heavy precipitation, along with whether a Flood Threat was issued. The columns of Table 11 are described below.

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

- **Max1hr-E (inches)**: Maximum 1-hour precipitation east of the 5,250 feet elevation contour.
- **Max2hr-E (inches)**: Maximum 2-hour precipitation east of the 5,250 feet elevation contour.
- **Max1hr-W (inches)**: Maximum 1-hour precipitation west of the 5,250 feet elevation contour.
- **Max2hr-W (inches)**: Maximum 2-hour precipitation west of the 5,250 feet elevation contour.
- **Max24hr-E (inches)**: Maximum 24-hour precipitation east of the 5,250 feet elevation contour.
- **Max24hr-W (inches)**: Maximum 24-hour precipitation west of the 5,250 feet elevation contour.
- **Flood Area (square miles)**: Total area of precipitation exceeding Flood Day thresholds.

Rain Gages: Contains the sub-categories below.

- **Max East (inches)**: Number of rainfall gages exceeding Flood Day thresholds east of the 5,250 foot contour.
- **Max West (inches)**: Number of rainfall gages exceeding Flood Day thresholds west of the 5,250 foot contour.
- **NStats (number)**: Total number of rainfall gages exceeding Flood Day thresholds statewide.

NWS Issues: Contains the sub-categories below.

- **FA_FF**: Total number of Flash Flood Warnings and Areal Flood Advisories issued that day.
- **FL_HY**: Total number of Flood Warnings and/or other hydrological warnings issued that day.

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.

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

- *SNOW*: Frozen precipitation that exceeded “flood-day” standards and did not result in flooding.
- *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.
- *H*: An overestimate of rainfall totals in the NOAA Stage IV precipitation estimates due to excessive hail scattering of the radar beam. On this type of day, typically only the Stage IV product triggered a Flood Day.
- *AREA*: Flood Day area threshold exceeded, but was spatially scattered and was unlikely to cause flooding.

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 11: Daily FTB Verification Worksheet

	NOAA Stage IV Quantitative Precipitation Estimate							Rain Gages			NWS Issues						
Date	Max1hr-E	Max2hr-E	Max1hr-W	Max2hr-W	Max24hr-E	Max24hr-W	Flood Area	Max East	Max West	NStats	FA_FF	FL_HY	Reports	Flood Day	Threat	Flags	Outcome
Units	inches	inches	inches	inches	inches	inches	square miles	inches	inches	number	number	number					
1-May	0.76	1.49	0.49	0.77	0.78	0.65	0	0.08	0.9	0	1	0	HIT			RIV	
2-May	0.50	0.96	0.28	0.53	0.67	0.34	0	0.59	0.8	0	0	0					
3-May	0.43	0.85	0.08	0.14	0.49	0.08	0	0.01	0.36	0	0	0					
4-May	1.27	2.38	0.46	0.92	1.30	0.51	0	3	0.1	1	0	0					
5-May	0.21	0.38	0.17	0.34	0.46	0.13	0	0.04	0.11	0	0	0					
6-May	1.06	2.08	1.28	2.41	1.74	1.76	313	3.5	0.1	1	0	0		YES			Miss
7-May	0.64	1.26	0.60	1.16	1.26	0.76	0	1.33	1.5	2	0	0			Low		False Alarm
8-May	0.59	1.15	0.67	1.26	1.41	2.60	2023	0.92	2.96	72	0	0	HIT			LI/SNOW	
9-May	0.12	0.24	0.30	0.55	0.54	1.31	71	0.36	1.9	6	0	0	HIT			LI	
10-May	0.05	0.11	0.67	1.29	0.14	1.45	218	0.03	1.25	3	0	0				AREA/LI	
11-May	0.18	0.35	0.15	0.27	0.34	0.32	0	0.04	0.5	0	0	0					
12-May	0.04	0.08	0.06	0.12	0.04	0.19	0	0	0.4	0	0	0					
13-May	0.17	0.33	0.15	0.27	0.17	0.15	0	0.01	0.4	0	0	0					
14-May	0.38	0.70	0.26	0.40	0.53	0.30	0	0.01	0.2	0	0	0					
15-May	0.35	0.66	0.10	0.17	0.40	0.17	0	0	0.93	0	0	0					
16-May	0.20	0.36	0.11	0.21	0.28	0.31	0	0.07	0.3	0	1	0					
17-May	0.64	1.26	0.28	0.54	0.94	1.25	94	0.35	1.85	2	0	0	HIT			AREA/RIV	
18-May	0.85	1.50	1.35	2.38	1.42	1.70	65	1.22	0.6	0	0	0				AREA	
19-May	0.28	0.55	0.17	0.34	0.54	0.56	0	0.1	0.5	0	0	0					
20-May	1.26	2.44	1.18	2.08	2.99	3.28	9089	2.55	3	197	0	0	HIT			SNOW	
21-May	0.49	0.89	0.76	1.49	1.48	1.40	260	1.36	1.54	9	0	0	HIT			SNOW	
22-May	0.10	0.18	0.34	0.69	0.29	1.19	18	0.01	1.2	4	0	0					
23-May	0.47	0.86	0.40	0.77	0.78	1.01	6	0.27	1.1	1	0	0					
24-May	0.03	0.06	0.30	0.56	0.05	0.46	0	0.01	0.8	0	0	0					
25-May	0.99	1.95	0.81	1.52	1.45	1.26	65	0.95	1.1	1	0	0				AREA	

	NOAA Stage IV Quantitative Precipitation Estimate							Rain Gages			NWS Issues						
Date	Max1hr-E	Max2hr-E	Max1hr-W	Max2hr-W	Max24hr-E	Max24hr-W	Flood Area	Max East	Max West	NStats	FA_FF	FL_HY	Reports	Flood Day	Threat	Flags	Outcome
Units	inches	inches	inches	inches	inches	inches	square miles	inches	inches	number	number	number					
26-May	1.61	3.16	1.18	2.32	2.31	1.66	897	1.29	1.17	1	2	0	HIT	YES	Low		Hit
27-May	1.59	2.98	0.71	1.40	2.58	1.46	1197	2.71	1.01	5	2	0	HIT	YES	Low		Hit
28-May	1.10	2.04	0.65	1.06	1.80	1.61	1392	1.07	1.3	5	0	0				LI/SNOW	
29-May	0.09	0.17	0.27	0.53	0.12	0.94	0	0.04	1	1	0	0					
30-May	1.10	2.13	0.82	1.50	1.31	1.40	18	0.05	0.4	0	0	0					
31-May	0.62	1.18	2.58	4.03	0.68	2.59	24	0.11	0.4	0	0	0					
1-Jun	1.17	2.29	1.12	2.23	1.66	1.47	277	1.42	2.78	3	2	1	HIT	YES	Low		Hit
2-Jun	2.69	5.33	0.74	1.35	3.46	0.88	248	3.55	0.71	1	0	0		YES	Low		Hit
3-Jun	1.50	2.92	1.58	2.55	1.62	1.95	218	0.29	0.75	0	1	1	HIT	YES			Miss
4-Jun	0.86	1.66	0.70	1.29	1.56	0.75	6	0.49	0.4	0	0	1					
5-Jun	1.10	2.14	1.08	2.11	1.59	1.27	100	1.47	1.24	2	9	0	HIT		Low	AREA	False Alarm
6-Jun	0.33	0.61	1.03	1.64	0.33	1.17	6	0.09	0.4	0	1	0				RIV	
7-Jun	0.97	1.90	1.17	2.30	1.11	1.86	177	0.34	0.66	0	3	1	HIT	YES			Miss
8-Jun	1.33	2.64	0.78	1.55	1.53	1.77	283	0.09	0.3	0	3	3		YES	Low		False Alarm
9-Jun	0.01	0.04	0.02	0.04	0.02	0.05	0	0	0.2	0	1	0				RIV	
10-Jun	0.00	0.04	0.22	0.41	0.00	0.28	0	0.01	0.1	0	1	3				RIV	
11-Jun	0.09	0.18	0.09	0.18	0.16	0.16	0	0.02	0.2	0	2	0				RIV	
12-Jun	0.22	0.44	0.89	1.61	0.34	0.89	0	0.01	0.4	0	2	2				RIV	
13-Jun	0.69	1.36	0.83	1.63	0.97	0.97	0	0.13	0.2	0	1	6				RIV	
14-Jun	1.65	3.19	0.96	1.82	2.83	1.32	112	0.23	0.3	0	4	0				AREA/RIV	
15-Jun	2.06	3.77	1.16	2.30	2.75	1.64	419	1.2	1.15	1	6	1	HIT	YES	Low		Hit
16-Jun	1.40	2.80	2.06	3.75	1.91	2.77	136	1.47	3.93	11	7	1	HIT	YES	Low		Hit
17-Jun	1.84	3.66	1.34	2.61	3.96	2.52	1935	4.77	1.48	14	24	0	HIT	YES	Mod		Hit
18-Jun	1.44	2.84	1.27	2.46	1.52	1.92	372	1.16	1.35	3	0	0		YES	Mod		Hit
19-Jun	0.39	0.76	0.38	0.74	0.57	0.66	0	0.02	0.5	0	0	0					
20-Jun	1.20	2.29	1.19	2.32	1.70	1.44	608	1.18	1.67	8	1	0				H/LI/RIV	

	NOAA Stage IV Quantitative Precipitation Estimate							Rain Gages			NWS Issues						
Date	Max1hr-E	Max2hr-E	Max1hr-W	Max2hr-W	Max24hr-E	Max24hr-W	Flood Area	Max East	Max West	NStats	FA_FF	FL_HY	Reports	Flood Day	Threat	Flags	Outcome
Units	inches	inches	inches	inches	inches	inches	square miles	inches	inches	number	number	number					
21-Jun	0.84	1.65	0.95	1.85	1.16	2.47	7804	1.45	3	65	3	3	HIT	YES	Low		Hit
22-Jun	2.23	4.38	0.91	1.81	2.57	1.37	454	1.85	1.42	8	3	0	HIT	YES	Low		Hit
23-Jun	0.77	1.29	0.40	0.79	1.08	0.76	0	1.09	1	1	0	1				RIV	
24-Jun	0.17	0.26	0.15	0.27	0.19	0.72	0	0.01	1.4	1	0	0					
25-Jun	0.69	1.33	0.57	1.02	0.78	0.57	0	0	0.5	0	0	0					
26-Jun	0.89	1.55	0.09	0.16	1.33	0.09	0	0	0.5	0	0	0					
27-Jun	0.65	1.19	0.47	0.93	0.66	0.49	0	0.05	0.5	0	0	1					
28-Jun	0.35	0.65	1.87	3.58	0.46	0.62	0	0.01	0.3	0	0	0					
29-Jun	0.77	1.35	0.87	1.50	1.13	1.43	88	0.03	0.47	0	1	0				AREA	
30-Jun	1.56	3.04	1.18	2.31	3.14	1.96	454	1.02	1.83	6	5	3		YES	Low		Miss
1-Jul	1.43	2.77	1.10	2.02	2.90	2.42	1610	2.3	1.87	45	16	2	HIT	YES	Mod		Hit
2-Jul	1.26	2.17	1.36	2.60	1.47	1.39	177	0.41	1.52	2	4	4	HIT	YES	Low		Hit
3-Jul	0.38	0.72	0.43	0.84	0.38	0.77	0	0.01	0.3	0	0	0					
4-Jul	1.59	2.76	0.88	1.70	1.98	1.31	124	1.13	0.3	0	1	1				H/RIV	
5-Jul	1.55	3.00	1.46	2.87	2.55	2.13	796	1.61	2.21	14	7	0	HIT	YES	Mod		Hit
6-Jul	1.85	3.36	1.11	2.02	1.98	1.25	77	0.32	0.6	0	1	0			Low	AREA	False Alarm
7-Jul	1.25	2.45	1.44	2.82	2.39	1.11	195	1.2	1.12	2	2	0				RIV	
8-Jul	1.25	2.45	0.81	1.36	3.52	1.70	295	1.79	0.5	4	5	0	HIT	YES	Low		Hit
9-Jul	0.64	1.25	0.00	0.04	0.65	0.00	0	0.01	0.33	0	0	0					
10-Jul	0.00	0.04	0.17	0.31	0.00	0.34	0	0	0.2	0	0	0					
11-Jul	0.97	1.79	0.99	1.80	1.09	1.20	29	0.17	0.1	0	0	0					
12-Jul	1.30	2.55	0.36	0.61	2.23	0.45	94	0.27	3.2	1	2	0				AREA	
13-Jul	0.98	1.93	0.87	1.55	1.49	1.45	88	1.2	1.45	6	11	0	HIT			AREA	
14-Jul	1.46	2.79	0.83	1.57	3.03	1.36	218	0.66	1.54	6	13	0	HIT	YES	Low		Miss
15-Jul	1.14	2.22	0.99	1.91	2.24	1.24	201	1.5	1.4	6	4	0		YES	Low		Hit
16-Jul	0.99	1.92	1.37	2.47	1.22	1.46	53	0.33	0.4	0	0	0				AREA	
17-Jul	0.81	1.57	0.67	1.07	0.90	0.83	0	0.03	0.17	0	0	0					

	NOAA Stage IV Quantitative Precipitation Estimate							Rain Gages			NWS Issues						
Date	Max1hr-E	Max2hr-E	Max1hr-W	Max2hr-W	Max24hr-E	Max24hr-W	Flood Area	Max East	Max West	NStats	FA_FF	FL_HY	Reports	Flood Day	Threat	Flags	Outcome
Units	inches	inches	inches	inches	inches	inches	square miles	inches	inches	number	number	number					
18-Jul	0.00	0.04	0.00	0.04	0.00	0.08	0	0	0.9	0	0	0					
19-Jul	0.20	0.35	0.03	0.05	0.30	0.07	0	1.52	1.4	5	0	0				RIV	
20-Jul	1.73	3.41	1.67	3.13	3.26	3.38	3533	3.18	2	59	11	1	HIT	YES	High		Hit
21-Jul	2.09	3.92	2.15	4.27	2.73	3.34	3067	2.39	3.44	30	13	1	HIT	YES	Mod		Hit
22-Jul	0.80	1.25	1.10	2.17	0.95	1.96	153	0.01	1.56	8	9	0	HIT	YES	Mod		Hit
23-Jul	0.54	1.03	1.54	3.00	0.66	2.10	88	0	1.34	2	3	0		YES			Miss
24-Jul	0.97	1.94	0.92	1.79	1.31	1.48	130	0.46	2	2	5	0	HIT	YES	Low		Hit
25-Jul	2.00	3.57	1.40	2.62	2.41	1.47	212	1.83	2.13	6	4	0	HIT	YES	Mod		Hit
26-Jul	0.86	1.50	1.23	2.17	1.09	1.83	330	0.35	1.8	4	9	0	HIT	YES	Low		Hit
27-Jul	1.28	2.21	1.26	2.34	1.77	1.68	177	0.62	1.78	4	4	0		YES	Mod		Hit
28-Jul	0.28	0.49	0.27	0.50	0.36	0.32	0	0	0.7	0	0	0					
29-Jul	2.80	5.60	1.41	2.45	3.44	1.78	914	3.28	1.9	14	3	0	HIT	YES			Miss
30-Jul	0.76	1.38	1.04	2.06	0.98	1.44	53	0.01	1.21	1	2	0	HIT			AREA	
31-Jul	1.21	2.37	0.62	1.08	1.68	1.29	53	1.09	1.2	2	1	0				AREA	
1-Aug	1.40	2.73	1.63	3.20	2.23	2.49	1457	3.24	2.45	18	5	0	HIT	YES	Mod		Hit
2-Aug	0.95	1.68	1.08	2.03	1.01	1.31	94	1.16	2.36	6	9	0	HIT	YES	Low		Hit
3-Aug	0.73	0.95	1.65	3.18	0.88	1.74	543	0.05	1.5	6	7	0	HIT	YES	Low		Hit
4-Aug	1.23	2.26	0.70	1.05	2.20	1.04	218	2.26	1.23	7	6	0	HIT	YES	Low		Miss
5-Aug	0.56	1.10	0.81	1.46	0.68	0.93	0	1.22	0.6	0	2	0	HIT		Low		False Alarm
6-Aug	1.48	2.80	0.86	1.72	2.13	1.05	83	0.39	1.16	3	5	0	HIT				
7-Aug	1.71	3.35	1.12	2.13	3.20	1.92	879	2.24	1.23	6	4	0		YES	Low		Hit
8-Aug	1.69	3.23	2.40	4.26	2.16	3.61	2749	2.1	3.3	43	11	0	HIT	YES	Mod		Hit
9-Aug	1.26	2.35	1.54	3.00	1.47	2.65	201	0.12	1.35	1	7	0	HIT	YES	Low		Hit
10-Aug	1.36	2.58	0.93	1.74	1.92	1.50	248	1.44	1.65	3	2	0	HIT	YES	Low		Hit
11-Aug	1.40	2.74	1.12	1.97	2.50	1.69	2041	4	1.7	16	3	0	HIT	YES	Mod		Hit
12-Aug	0.37	0.62	0.86	1.54	0.37	0.91	0	0	0.7	0	0	0					
13-Aug	1.86	3.64	1.30	2.43	3.03	1.47	1852	2.27	0.5	4	4	0		YES	Low		Hit

	NOAA Stage IV Quantitative Precipitation Estimate							Rain Gages			NWS Issues						
Date	Max1hr-E	Max2hr-E	Max1hr-W	Max2hr-W	Max24hr-E	Max24hr-W	Flood Area	Max East	Max West	NStats	FA_FF	FL_HY	Reports	Flood Day	Threat	Flags	Outcome
Units	inches	inches	inches	inches	inches	inches	square miles	inches	inches	number	number	number					
14-Aug	1.59	3.07	1.74	3.09	2.05	2.22	147	2.11	0.2	1	1	0		YES			Miss
15-Aug	0.91	1.79	0.24	0.41	0.92	0.27	0	0.03	0.19	0	0	0					
16-Aug	1.38	2.72	1.39	2.60	1.95	1.64	124	1.03	0.7	0	0	0		YES	Low		Hit
17-Aug	1.09	2.02	0.91	1.80	1.30	0.98	0	0.28	0.2	0	0	0					
18-Aug	0.00	0.04	0.00	0.04	0.00	0.09	0	0	0.2	0	0	0					
19-Aug	1.35	2.70	0.05	0.10	2.21	0.06	53	0.03	0.3	0	1	0				AREA	
20-Aug	2.07	3.99	2.00	3.92	2.58	3.13	879	1.79	0.2	1	1	0		YES	Low		Hit
21-Aug	1.54	2.58	1.48	2.91	1.78	1.77	472	2.18	1.71	19	11	0		YES	Mod		Hit
22-Aug	1.67	3.34	1.74	3.44	2.04	2.22	295	1.01	0.4	0	1	0		YES			Miss
23-Aug	2.14	4.23	1.81	3.50	3.37	3.12	902	1.45	0.2	0	3	0		YES	Low		Hit
24-Aug	0.71	1.32	0.04	0.07	0.81	0.05	0	0.02	0.2	0	1	0				RIV	
25-Aug	0.02	0.04	0.05	0.10	0.03	0.11	0	0	0.2	0	0	0					
26-Aug	0.01	0.04	0.74	1.40	0.02	0.75	0	0	0.22	0	0	0					
27-Aug	0.32	0.58	0.38	0.62	0.32	0.48	0	0.12	1.1	1	0	0					
28-Aug	0.81	1.38	0.11	0.21	1.31	0.19	0	0.08	0.5	0	0	0					
29-Aug	1.02	1.64	1.18	2.12	1.11	1.34	12	0	2.3	1	0	0					
30-Aug	1.53	2.85	1.46	2.85	2.47	2.33	395	1.91	0.9	2	2	0		YES	Low		Hit
31-Aug	1.16	2.00	1.00	1.85	1.62	1.42	83	0	0.7	0	1	0				AREA	
1-Sep	0.52	1.05	0.45	0.73	0.58	0.65	0	0.06	0.2	0	1	0					
2-Sep	0.27	0.52	0.48	0.83	0.47	0.59	0	0.04	0.1	0	0	0					
3-Sep	0.48	0.95	1.08	2.05	0.61	2.23	413	0.21	2.38	3	1	0		YES			Miss
4-Sep	0.60	1.11	1.34	2.16	0.67	2.10	41	0.11	0.4	0	0	0					
5-Sep	1.80	3.33	1.52	2.77	2.10	2.15	254	0.08	1.1	1	0	0		YES			Miss
6-Sep	0.40	0.77	1.09	2.14	0.57	1.76	212	0.02	2.73	20	9	0		YES	Mod		Hit
7-Sep	1.35	2.49	1.22	2.25	2.11	1.34	147	1.23	1.46	1	1	0		YES	Low		Hit
8-Sep	1.75	3.40	0.76	1.48	2.69	1.24	1422	2.59	1.41	10	2	0		YES	Mod		Hit
9-Sep	1.61	3.01	0.18	0.34	4.04	0.21	147	0.27	0.6	0	1	0		YES			Miss

	NOAA Stage IV Quantitative Precipitation Estimate							Rain Gages			NWS Issues						
Date	Max1hr-E	Max2hr-E	Max1hr-W	Max2hr-W	Max24hr-E	Max24hr-W	Flood Area	Max East	Max West	NStats	FA_FF	FL_HY	Reports	Flood Day	Threat	Flags	Outcome
Units	inches	inches	inches	inches	inches	inches	square miles	inches	inches	number	number	number					
10-Sep	1.35	2.65	0.38	0.73	1.58	0.55	18	0.05	0.67	0	0	0					
11-Sep	0.94	1.85	0.47	0.84	1.31	1.08	6	0.74	0.59	0	0	0					
12-Sep	0.05	0.08	0.02	0.04	0.05	0.19	0	0.1	0.4	0	0	0					
13-Sep	1.64	2.90	1.86	3.53	2.27	2.79	289	0.05	1	1	1	0		YES			Miss
14-Sep	0.00	0.04	0.05	0.10	0.00	0.07	0	0	0.4	0	0	0					
15-Sep	0.00	0.04	0.32	0.59	0.00	1.23	35	0	1.44	5	0	0			Mod		False Alarm
16-Sep	0.25	0.47	0.42	0.80	0.45	0.75	0	0	0.4	0	0	0					
17-Sep	0.07	0.14	0.16	0.31	0.10	0.29	0	0	0.5	0	0	0					
18-Sep	0.32	0.50	0.15	0.23	0.35	0.23	0	0.01	0.4	0	0	0					
19-Sep	1.57	2.86	0.12	0.23	1.90	0.20	77	1.85	0.3	1	0	0				AREA	
20-Sep	0.18	0.29	0.41	0.79	0.21	0.71	0	0	0.6	0	0	0					
21-Sep	1.19	2.32	0.53	0.96	1.71	0.69	77	0.21	0.4	0	0	0		YES			Miss
22-Sep	0.01	0.04	0.01	0.04	0.01	0.08	0	0.01	0.3	0	0	0					
23-Sep	0.03	0.05	0.15	0.31	0.03	0.25	0	0	0.2	0	0	0					
24-Sep	0.05	0.09	0.01	0.04	0.05	0.00	0	0	1	1	0	0					
25-Sep	0.00	0.04	0.01	0.04	0.00	0.02	0	0	0.1	0	0	0					
26-Sep	0.00	0.04	0.09	0.16	0.00	0.03	0	0	0.3	0	0	0					
27-Sep	0.23	0.45	0.33	0.52	0.80	1.71	59	0.31	1.46	2	0	0				LI	
28-Sep	0.13	0.23	0.08	0.14	0.13	0.10		0.01	0.2	0	0	0					
29-Sep	0.00	0.04	0.29	0.58	0.00	0.46	0	0.01	0.28	0	0	0					
30-Sep	0.29	0.48	0.09	0.16	0.43	0.15	0	0.02	0.9	0	0	0					

APPENDIX B – BURN AREA VERIFICATION WORKSHEET

Table 12: Daily Burn Area Verification Worksheet a daily verification worksheet documenting heavy precipitation and flash flooding over burn areas, along with whether a Burn Area Flood Threat was issued. Not all worksheets are included, but are available upon request. The columns of Table 11 are described below.

Burn Area: The names of the five burn areas that were forecast this season. "YES" denotes that the day qualified as a Flood Day.

Threat Issued: A number indicates that that a Flood Threat was issued. The number "1" corresponds to a "Low" threat, "2" to a Moderate threat, "3" to a High threat, and "4" to a Very High threat.

Threat: Highest category of the Burn Area Flood Threat.

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

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 12: Daily Burn Area Verification Worksheet

	Burn Area					Threat Issued					Threat		
Date	416	Hayden Pass	Junkins	Lake Christine	Spring Creek	416	Hayden Pass	Junkins	Lake Christine	Spring Creek		Flood Day	Outcome
1-May													
2-May													
3-May													
4-May													
5-May													
6-May													
7-May													
8-May													
9-May													
10-May													
11-May													
12-May													
13-May													
14-May													
15-May													
16-May													
17-May													
18-May													
19-May													
20-May													
21-May													
22-May													
23-May													
24-May													
25-May													
26-May													

	Burn Area					Threat Issued					Threat		
Date	416	Hayden Pass	Junkins	Lake Christine	Spring Creek	416	Hayden Pass	Junkins	Lake Christine	Spring Creek		Flood Day	Outcome
27-May													
28-May													
29-May													
30-May					YES							YES	Miss
31-May													
1-Jun					YES							YES	Miss
2-Jun													
3-Jun													
4-Jun													
5-Jun					YES		1	1		2	Mod	YES	Hit
6-Jun					YES							YES	Miss
7-Jun													
8-Jun													
9-Jun													
10-Jun													
11-Jun													
12-Jun													
13-Jun													
14-Jun													
15-Jun			YES		YES		1	1		1	Low	YES	Hit
16-Jun					YES							YES	Miss
17-Jun			YES		YES		1	2		1	Mod	YES	Hit
18-Jun													
19-Jun													
20-Jun													
21-Jun				YES								YES	Miss
22-Jun				YES			1	1		1	Low	YES	Miss
23-Jun													

	Burn Area					Threat Issued					Threat		
Date	416	Hayden Pass	Junkins	Lake Christine	Spring Creek	416	Hayden Pass	Junkins	Lake Christine	Spring Creek		Flood Day	Outcome
24-Jun													
25-Jun													
26-Jun													
27-Jun													
28-Jun													
29-Jun					YES							YES	Miss
30-Jun					YES	1			1		Low	YES	Miss
1-Jul					YES		1	1		2	Mod	YES	Hit
2-Jul			YES		YES							YES	Miss
3-Jul													
4-Jul													
5-Jul					YES		1	1		1	Low	YES	Hit
6-Jul								1		2	Mod		False Alarm
7-Jul	YES					1	1			1	Low	YES	Hit
8-Jul													
9-Jul													
10-Jul													
11-Jul													
12-Jul													
13-Jul				YES	YES	2				1	Mod	YES	Hit
14-Jul						1	1	1	1	1	Low		False Alarm
15-Jul	YES				YES		1	1		1	Low	YES	Hit
16-Jul													
17-Jul													
18-Jul													
19-Jul													
20-Jul								2		1	Mod		False Alarm
21-Jul			YES		YES		1	2		3	High	YES	Hit

	Burn Area					Threat Issued					Threat		
Date	416	Hayden Pass	Junkins	Lake Christine	Spring Creek	416	Hayden Pass	Junkins	Lake Christine	Spring Creek		Flood Day	Outcome
22-Jul		YES	YES		YES		2	2		2	Mod	YES	Hit
23-Jul	YES	YES				2	2	1		2	Mod	YES	Hit
24-Jul	YES				YES	2			1		Mod	YES	Hit
25-Jul		YES	YES			1	1	2	1	2	Mod	YES	Hit
26-Jul			YES		YES	1	1	1	1	2	Mod	YES	Hit
27-Jul			YES	YES		2	2	2	2	2	Mod	YES	Hit
28-Jul													
29-Jul					YES							YES	Miss
30-Jul					YES							YES	Miss
31-Jul													
1-Aug	YES					2			2		Mod	YES	Hit
2-Aug			YES		YES		2	2		2	Mod	YES	Hit
3-Aug					YES	2	1	1		1	Mod	YES	Hit
4-Aug	YES			YES	YES	2	2	2	2	2	Mod	YES	Hit
5-Aug					YES			1		1	Low	YES	Hit
6-Aug	YES				YES							YES	Miss
7-Aug		YES				2				1	Mod	YES	Miss
8-Aug			YES					2		1	Mod	YES	Hit
9-Aug					YES			1		1	Low	YES	Hit
10-Aug					YES	2	1	1	1	1	Mod	YES	Hit
11-Aug					YES	1				1	Low	YES	Hit
12-Aug													
13-Aug													
14-Aug													
15-Aug													
16-Aug													
17-Aug													
18-Aug													

	Burn Area					Threat Issued					Threat		
Date	416	Hayden Pass	Junkins	Lake Christine	Spring Creek	416	Hayden Pass	Junkins	Lake Christine	Spring Creek		Flood Day	Outcome
19-Aug													
20-Aug													
21-Aug			YES		YES			1		1	Low	YES	Hit
22-Aug													
23-Aug													
24-Aug													
25-Aug													
26-Aug													
27-Aug													
28-Aug													
29-Aug													
30-Aug					YES			1		1	Low	YES	Hit
31-Aug					YES							YES	Miss
1-Sep													
2-Sep													
3-Sep					YES		1	1		1	Low	YES	Hit
4-Sep													
5-Sep													
6-Sep					YES		1	2		2	Mod	YES	Hit
7-Sep													
8-Sep						1	1	1		1	Low		False Alarm
9-Sep													
10-Sep						1					Low		False Alarm
11-Sep													
12-Sep													
13-Sep													
14-Sep													
15-Sep						2	2	2		2	Mod		False Alarm

	Burn Area					Threat Issued					Threat		
Date	416	Hayden Pass	Junkins	Lake Christine	Spring Creek	416	Hayden Pass	Junkins	Lake Christine	Spring Creek		Flood Day	Outcome
16-Sep						1					Low		False Alarm
17-Sep													
18-Sep													
19-Sep						1					Low		False Alarm
20-Sep													
21-Sep													
22-Sep													
23-Sep													
24-Sep													
25-Sep													
26-Sep													
27-Sep													
28-Sep													
29-Sep													
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 flows and debris slides, in addition to the usual flash flooding concerns that are experienced statewide. The following section summarizes key aspects of Colorado's 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 16 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 west (also see

Figure 19 in 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 16: 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 17, early in the operational season (May, June), the highest potential for heavy rainfall is almost exclusively east of the Continental Divide, and in particular the northeast quadrant of the state. Snow is significant factor in the Front Range and Gore Mountains through early June. Meanwhile, by August, 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.

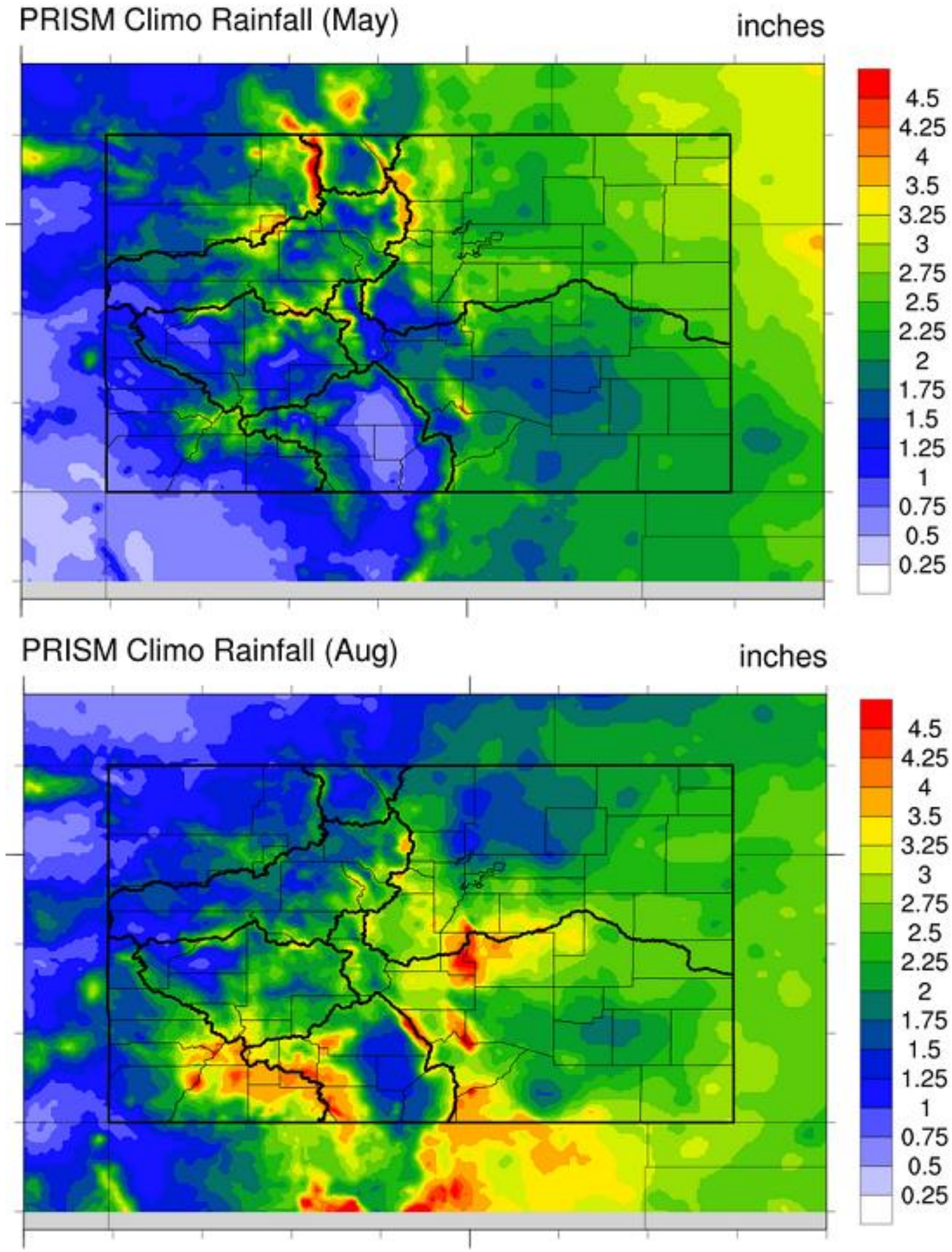


Figure 17: Monthly average precipitation for (top) May and (bottom) August. Source: Oregon State University PRISM group.

c) Surface characteristics

While a significant focus of the Flood Threat Bulletin is only 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 18 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 as high as 3 inches, while over the northern Front Range, it can be below 0.75 inches. An even starker example of the importance of surface characteristics is over a fresh fire burn area, where the burnt now hydrophobic soil mass can cause significant flooding concerns for even 0.25 inches of rainfall per hour. This can be seen over Huerfano County where the Spring Creek resides (pink in the top figure). Surface characteristics play an integral role in the translating the heavy rainfall threat to a flooding potential.

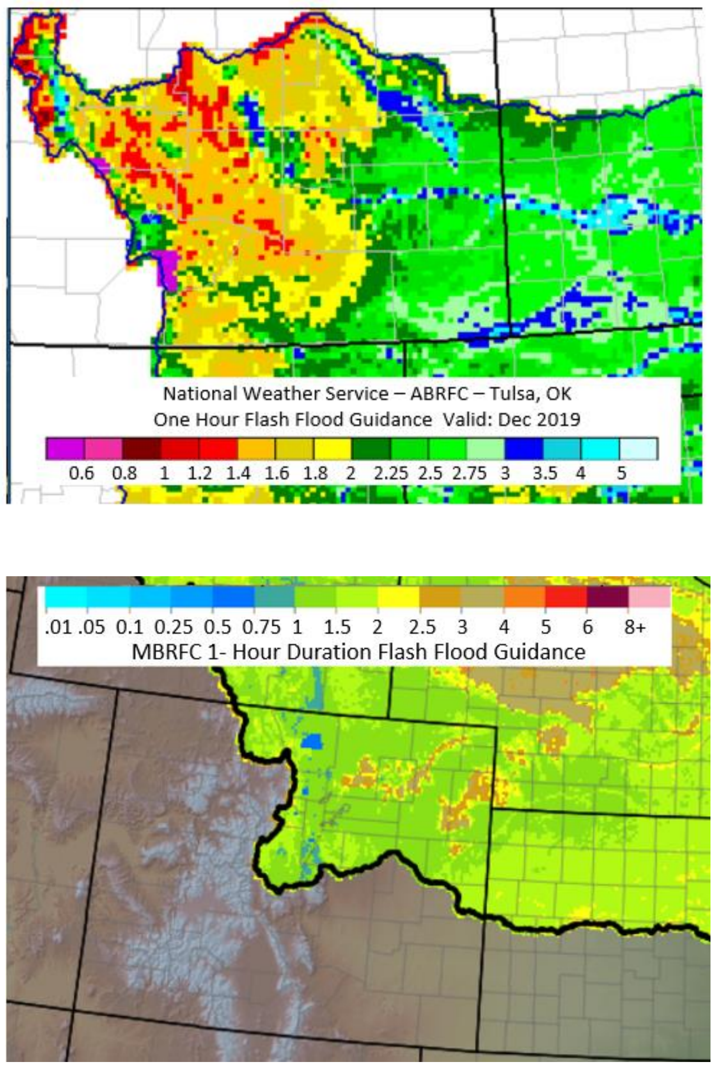
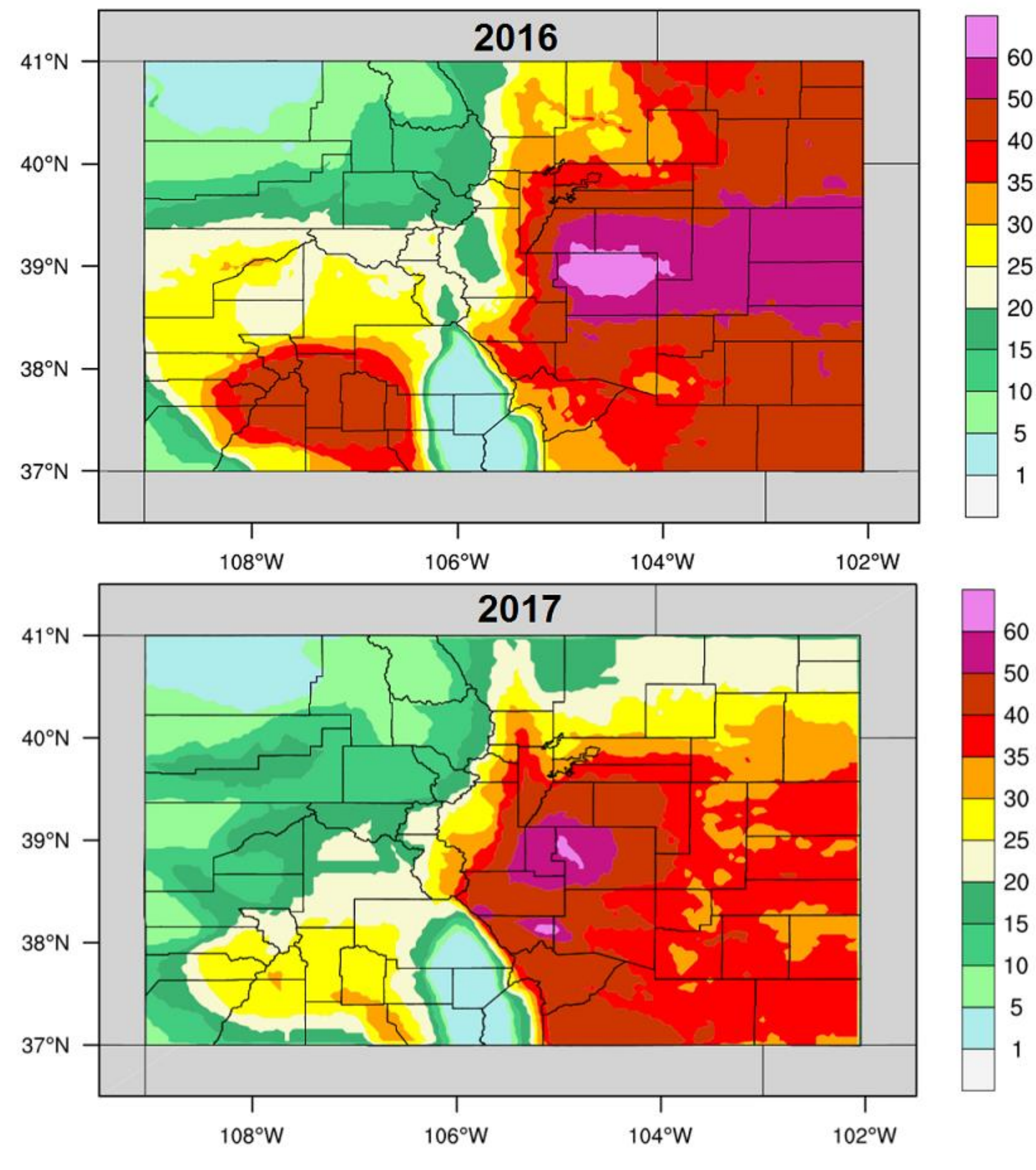


Figure 18: 1-hour Flash Flood Guidance for central and eastern Colorado, valid December 12th, 2019. Source: National Weather Service River Forecast Centers.

APPENDIX D – FLOOD THREATS ISSUED

Figure 19 shows the total number of days when a given location was under a flood threat during the 2016 to 2019 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.



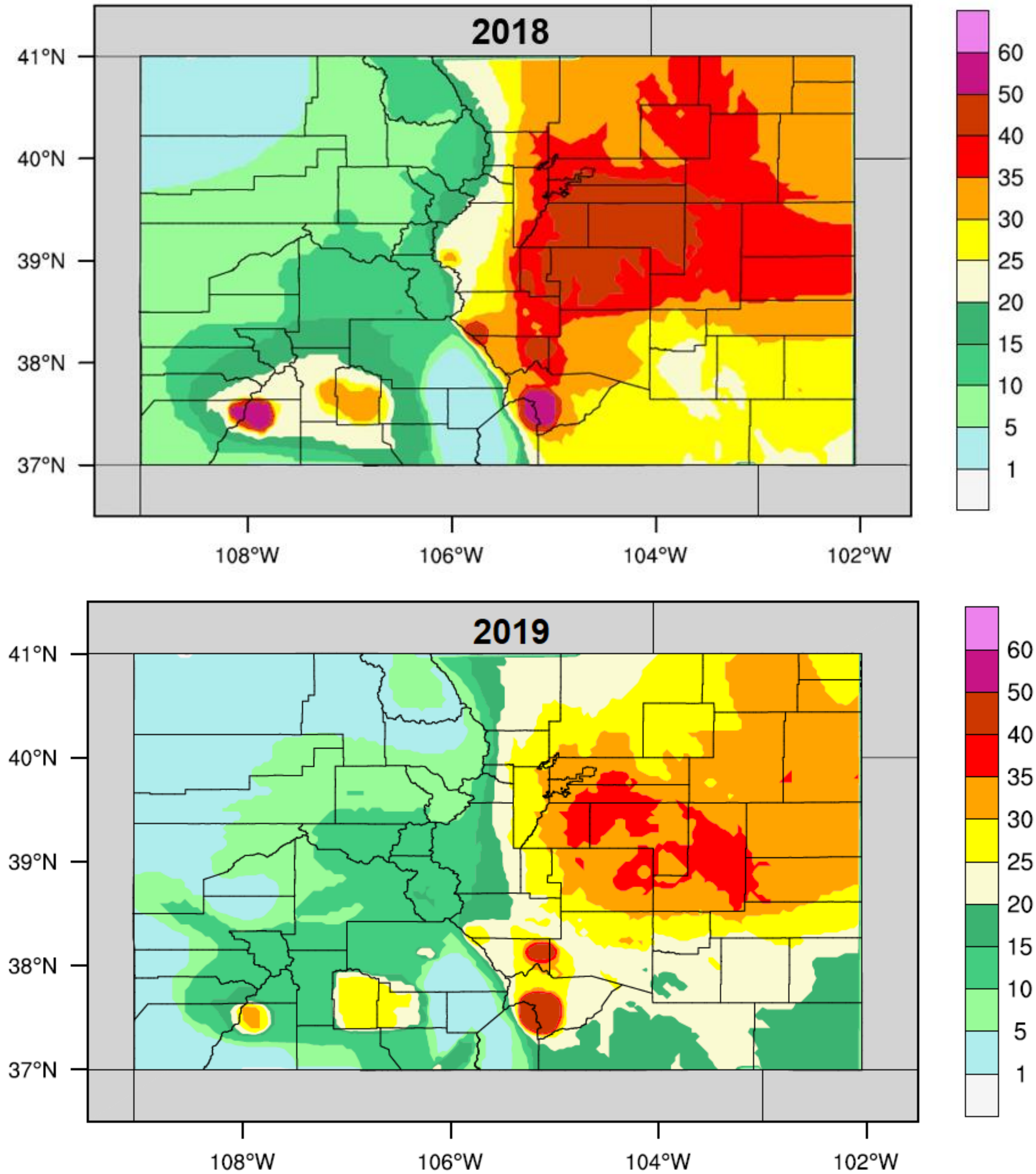


Figure 19: Number with days with a flood threat issued, burn area or otherwise, during 2016 to 2019 operational season (order is descending from top to bottom).