Colorado Flood Threat Bulletin – 2018 Final Report

NOVEMBER 15, 2018

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Contents

1) Introduction 3

2) Verification Metrics 9

3) Characterization of Forecast Period Weather 17

4) User Engagement 23

5) Conclusions 28

6) References 29

Appendix A – Forecast Verification Worksheet 30

Appendix B – Burn Area Verification Worksheet 37

Appendix C - Colorado Climate 42

Appendix D – Flood Threats Issued Map 45

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2018 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 2018 operational season, all forecasts were developed or overseen by Dewberry meteorologists Dana McGlone (FTB, FTO, SPM) and Brad Workman (FTB, FTO, SPM). Dewberry also sub-contracted with MetStat, Inc. to provide 20 days of FTB and SPM products, which were developed by meteorologists Brian Crow and Brad Wells. 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 Sam Crampton served as Principle-in-Charge.

This objective of this Final Report is to: (i) perform a rigorous validation of forecast performance, (ii) summarize weather conditions and the developing drought during the 2018 operational season, (iii) document all additional services provided, 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 by 9:30 AM to provide as much lead time as possible to end-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.

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.

Of particular concern for flash flooding are recent wildfire burn areas that occur nearly every year across the state. Low snowpack during the 2017-2018 winter, paired with drier than normal conditions throughout the spring and summer, lead to 2018 being one of the most active wildfire seasons (second only to 2002). While there were ~1,500 fires officially recorded in the Federal, State and Local agencies database of wildfires, only 20 of those fires met the criteria required to be included in the FTB threat maps. To be included in the daily FTB threat map, a wildfire 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 Forest Department (special thank you to 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.

There were a handful of wildfires specifically monitored over the 2018 season by Dewberry with additional wildfires monitored by the National Weather Service Weather Forecast Offices (NWS WFOs; Figure 1). Any wildfire specifically forecast for by Dewberry or NWS are labeled in the image. The majority of the wildfires on the map occurred during the 2017 and 2018 seasons, which means it only took rain rates between 0.25 and 0.5 inches per hour to trigger mud flows, debris slides and local stream flash flooding. New to this season, a validation for burn area threats has been attempted. This is a necessary step as there were 12 days 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 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 (snow-melt and precipitation driven) and a precipitation outlook by river basin. The FTO continued to be structured in an event-based manner, where rainfall was partitioned by its forcing feature and presented in a timeline.

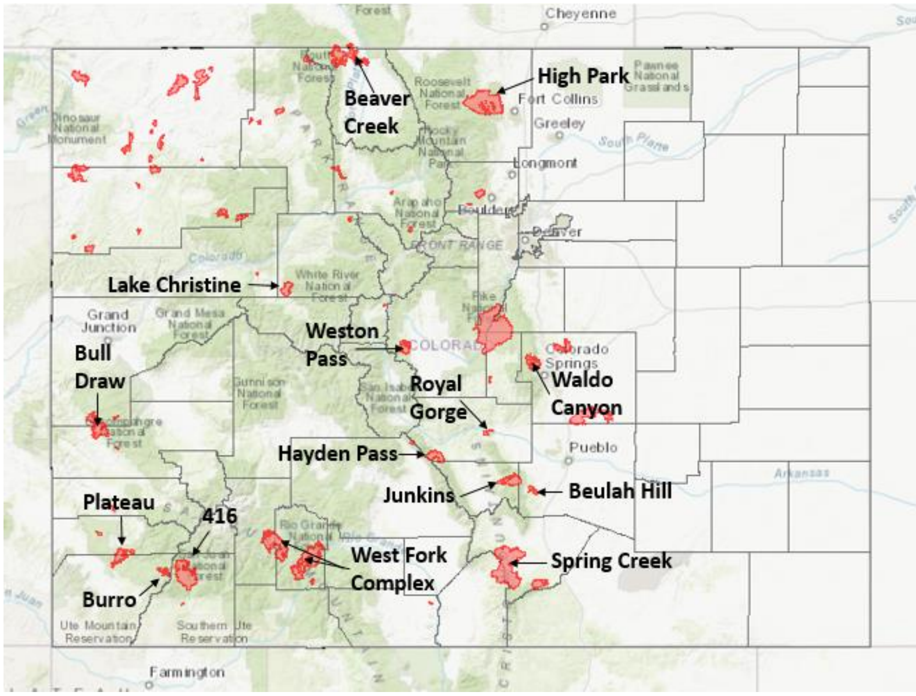


Figure 1: Wildfire burn areas that were featured on the daily FTB maps during 2018. The labeled burn areas (black) received at least one dedicated flood threat by either Dewberry or NWS during the season.

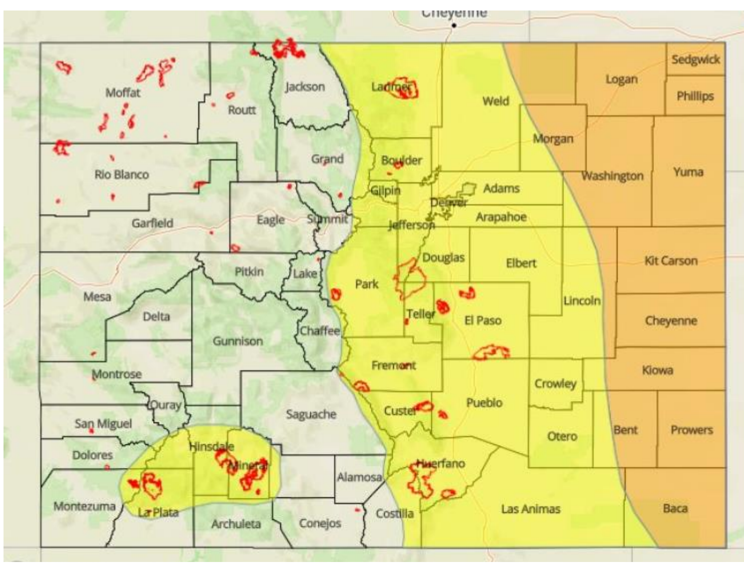
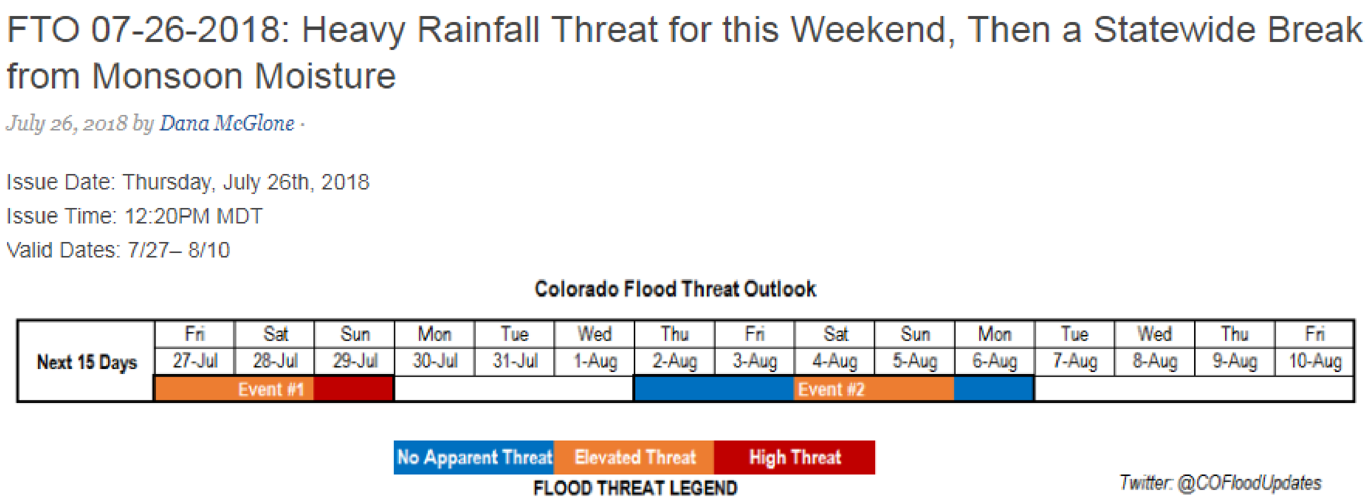


Figure 2: Example of the FTB map from July 29, 2018. The Low threat is highlighted in yellow (including the burn areas over the San Juan Mountains) and the Moderate threat is highlighted in orange.

An example of a threat "timeline" is shown in Figure 3 from July 26th. Another focus of the FTO this season was the developing and worsening drought over southwestern Colorado. Reservoir levels were tracked throughout the season in the FTOs, alongside monthly departures from normal of temperature and precipitation. Lastly, a special bulletin FTO was produced on June 14th, which was the first of its kind in the Program's history. Per CWCB's request, this FTO specifically tracked the remnants of Hurricane Bud that threatened western Colorado and the recent/ongoing 416 and Burro burn areas. The special edition FTO was well-received by users, thanks to its inclusion of specific storm information like storm motion, rain rates, and timing two days in advance of the event. This provided additional lead time useful for proper preparation by Emergency Managers and other entities involved in fighting the wildfires.



FTO 07-26-2018: Heavy Rainfall Threat for this Weekend, Then a Statewide Break from Monsoon Moisture

July 26, 2018 by Dana McGlone ·

Issue Date: Thursday, July 26th, 2018
Issue Time: 12:20PM MDT
Valid Dates: 7/27– 8/10

Colorado Flood Threat Outlook

Next 15 Days	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri	Sat	Sun	Mon	Tue	Wed	Thu	Fri
	27-Jul	28-Jul	29-Jul	30-Jul	31-Jul	1-Aug	2-Aug	3-Aug	4-Aug	5-Aug	6-Aug	7-Aug	8-Aug	9-Aug	10-Aug
		Event #1							Event #2						

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

Twitter: @COFloodUpdates

Figure 3: Example of an FTO headline from 2018 illustrating the threat “timeline”.

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. An example of the total rainfall with and without the bias correction can be found in Figure 4. The bias adjustment greatly improves 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.

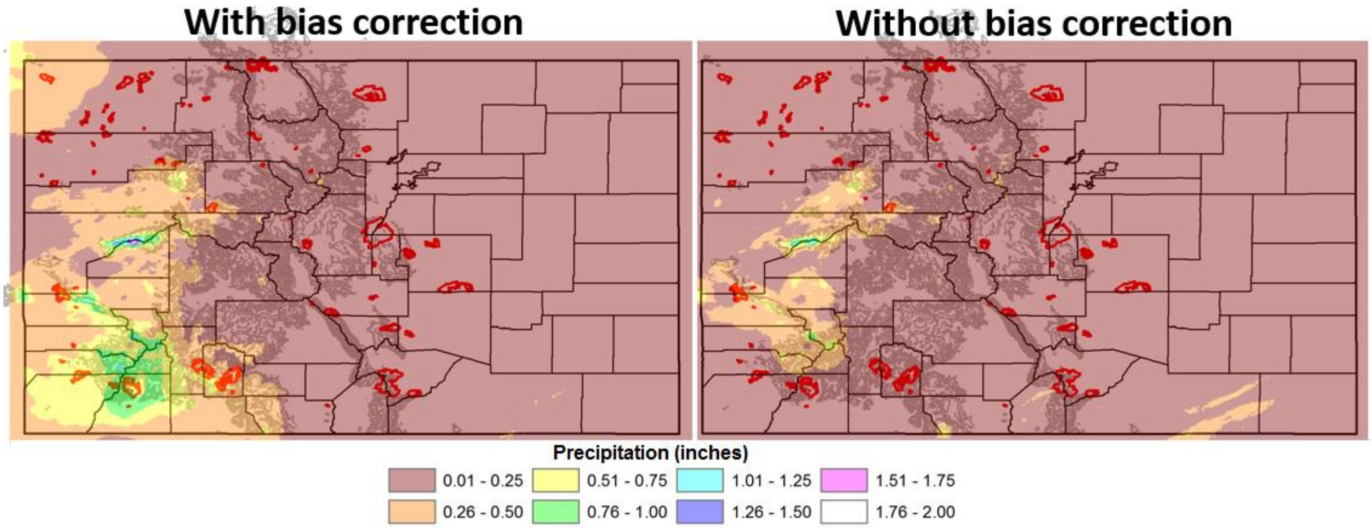


Figure 4: State Precipitation Map estimates of 24-hour rainfall ending October 2, 2018 at 7AM with and without the bias correction (left and right, respectively).

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. This update is expected to be operational by May 1, 2019. An example of the daily SPM layout is shown in Figure 5. 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.

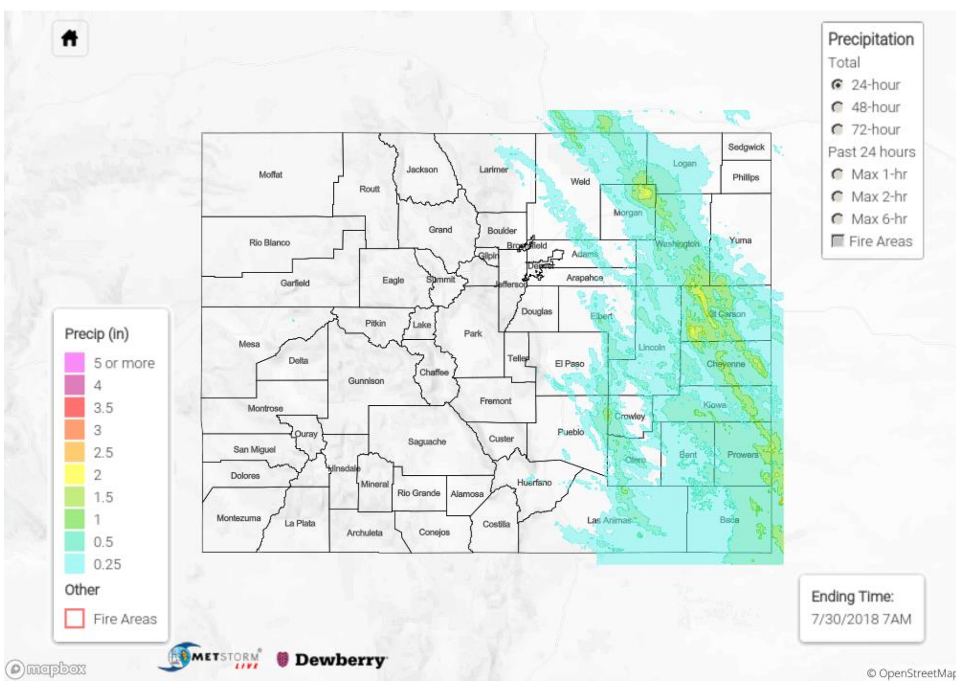


Figure 5: Example of SPM from July 30, 2018.

Performance metrics

Table 2 shows the final year-to-date number of all products provided, and the percent provided on time. Out of 349 total products delivered, 346 were delivered on-time or ahead of time. The three late products were 2 SPMs and 1 FTB, all of which were posted within 1.5 hours 11AM 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	29	1	97%	YTD	SPM	153	151	2	99%
	FTB	30	30	0	100%		FTB	153	152	1	99%
	FTO	8	8	0	100%		FTO	43	43	0	100%
	TOTAL	68	67	1	99%		TOTAL	349	346	3	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 to the 2017 validation process and the inclusion of burn areas in a separate validation for 2018, this year's verification is likely the most comprehensive of the Program's history. Note improvements beginning in 2017 included: creation of comprehensive daily validation maps (see Figure 7), 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 2018 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.
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 <u>one of following two</u> criteria is met in the threat area (Figure 7):

1) Gridded or observation based 24-hour rainfall exceeds (see Figure 6):
    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

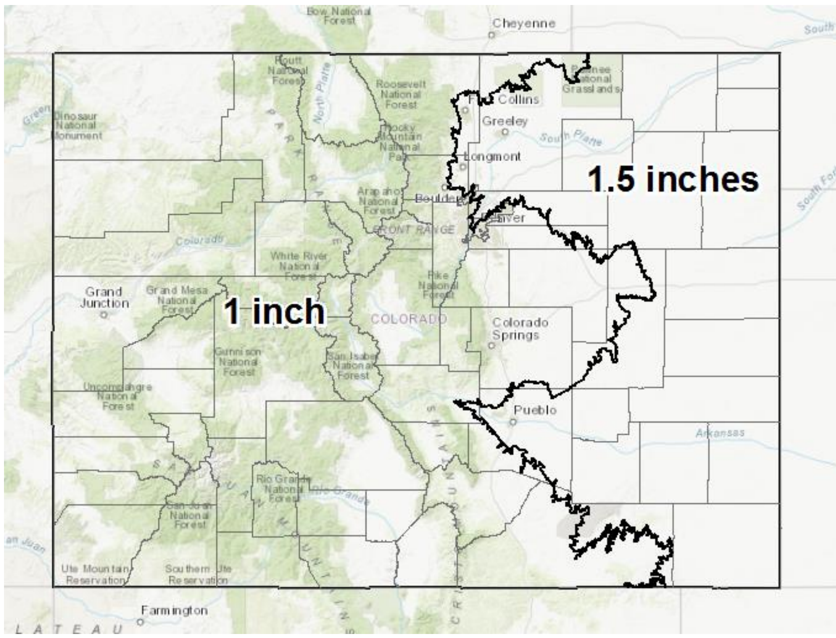


Figure 6: Colorado county map with thick black line showing the 1,600 meter (5,250 foot) elevation contour line east of the Continental Divide, which acted as the demarcation in rainfall-runoff sensitivity. To the east, a rainfall threshold of 1.50 inches per day was used to denote a "Flood Day"; to 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 17 days where overriding conditions were used.

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	1
Long-duration low intensity precipitation causes qualifying 24-hour precipitation total but runoff does not support flooding.	Low Intensity (LI)	Flood Day = 0	2
There is no rainfall but antecedent conditions and/or snow melt cause riverine flooding.	Riverine (RIV)	Flood Day = 1	0
Hail likely causes an overestimate in Stage IV resulting in qualifying precipitation totals.	Hail (H)	Flood Day = 0	0
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	3
Threat is only issued for a burn area.	Burn (BURN)	Flood Day = 0	12

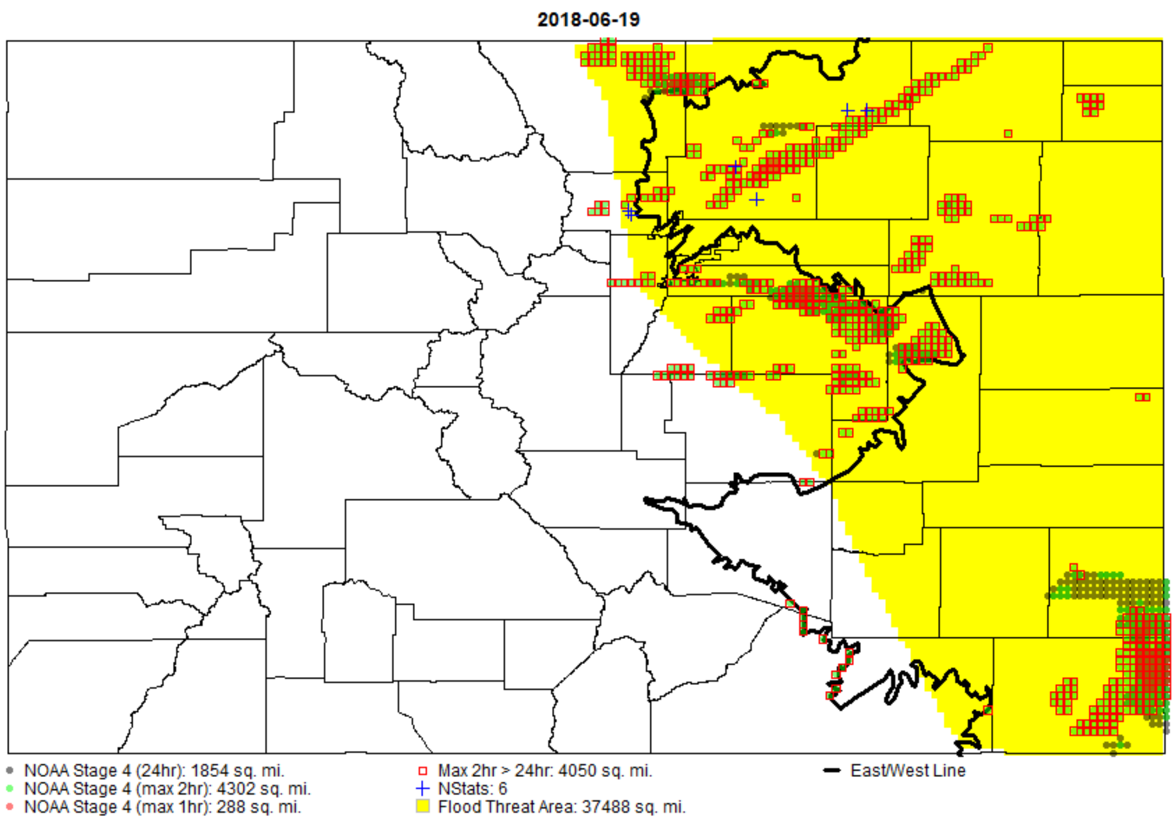


Figure 7: Example of daily validation map from June 19, 2018 showing qualifying NOAA Stage IV pixels (gray dots), rain gages (blue crosses) and threat area (yellow color fill). For reference, qualifying Stage IV maximum 1-hour (red dot) and 2-hour (green dot) estimates are also shown, but note these were not objectively 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. There were three burn areas that were monitored specifically during that season: Junkins, Beulah Hill and Hayden Pass. After internal review prior to the 2018 season, it seemed many older fires continued to have flash flooding problems as well. For the 2018 operation season, it was decided the FTB would undertake issuing threats for the most impactful burn areas: 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. As mentioned, 2018 was the second most active wildfire season in state history, which meant there were several additional burn areas added to the forecast throughout the season. 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. Of course, how burn areas respond to specific rain rates throughout the season are internally monitored and threat level forecasts are adjusted appropriately from the general rule of thumb.

Although forecasting flash flooding over burn areas is outside the scope of the Program, it is important to quantify the accuracy of the burn area forecasting to evaluate its value and usefulness in forthcoming operational seasons and to improve future procedures for burn area forecasting. In 2018, the first (and only) High Impact threat was issued for a burn area on June 16th. This event drove a record number of users to the website and gave the Program all-important visibility, with the potential to increase daily viewership. Thus, it is essential to assess the accuracy of the burn area flood threats. At present, there is no protocol on how to validate such a forecast, since specific flood threat rainfall thresholds for known high-impact burn areas were not established at the start of the season. More off-season research is anticipated prior to the start of the 2019 season focused around the effects of slope, soil type and burn scar age/area ratios on flash flooding. The end product is expected to be individual rainfall thresholds for the most impactful burn areas, which can be used to issue burn area flood threats for the 2019 season.

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**. While flooding often goes undocumented, this was the most reasonable and straightforward metric since a rainfall intensity guide was not created prior to the start of the season. It is important to note that the accuracy of burn area flood threats will likely be lower, possibly significantly, than other forecasts due to the difficulty in forecasting for such a small area. For example, the Junkins burn scar is only about 30 sq. mi., which is smaller than the ~250 sq. mi. scale at which current forecasts begin to show skill. 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) An NWS flash flood **warning** is issued that day. An NWS **advisory**, alone, does not qualify as a Flood Day.

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 six metrics that are used in this report, all based on the contingency table approach shown in Table 5. In brief, there are two possible outcomes when a Flood Day forecast is issued: (i) a Flood Day is observed (case a in Table 4), 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 4). 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 4). 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 5, 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 4: 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 5: Description of metrics used for validating forecast accuracy.

Metric	Abbreviation	Calculation (see Table 4)	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 6 shows the individual monthly and yearly aggregated forecast verification during the 2018 season. Over the course of the season, forecast performance achieved or exceeded three of the four targets established in Table 5. With an overall Hit Rate of 87%, forecast performance continued to be well above the 75% target and is the highest recorded Hit Rate in Program history. The Probability of Detection was also high at 82%, which is above the target of 75%. The False Alarm Rate was 11%, which also achieved the target of less than 20%. Finally, the Miss Rate was 18%, or just above the target of below 15%. As is the trade off with decreasing the False Alarm Rate, the

Miss Rate for 2018 increased by 4%. However, out of the 9 misses over the course of the season, six had qualifying Flood Day area of less than 250 sq. mi. implying relatively localized areas of heavy rainfall. The process in which a Miss classification is defined shows the rigor with which the validation process is done. Further conversations will continue to be held with CWCB as minimizing the Miss Rate may be more of a priority than decreasing the False Alarm Rate.

Looking at the month-to-month performance in Table 6, heavy rainfall occurrence was seasonally distributed in a manner consistent with climatology, with 26 of 50 days occurring during July and August. There was some variability in the monthly performance as can be expected due to smaller sample sizes. For example, during September, there were only 4 Flood Days, and the one missed flood forecast lead to a 25% Miss Rate. In the meantime, during July, 1 of the 16 Flood Days was not forecasted resulting in a much lower Miss Rate of 6%. Not surprisingly, July had the highest False Alarm Rate due to instances where the atmospheric ingredients were present for heavy rainfall, but storms did not harness the full potential of the atmosphere for various reasons.

Table 6: 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	7	8	15	8	3	41
(b) No Flood / Flood	4	1	1	2	1	9
(c) Flood / No Flood	2	3	5	0	1	11
(d) No Flood / No Flood	18	18	10	21	26	93
Total Days	31	30	31	31	31	154
Hit %	81%	87%	81%	94%	94%	87%
POD	64%	89%	94%	80%	75%	82%
FAR	10%	14%	33%	0%	4%	11%
Miss %	36%	11%	6%	20%	25%	18%

Table 7 shows the yearly performance summaries from 2012 through the present. Overall, 2018 maintains the Program's success when all measures are taken collectively; however, the Miss Rate was 3% above the goal (Table 5). 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 remain ongoing. Variability in performance was also likely affected due to the decrease in the number of Flood Days for the 2018 operational season. 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 76.5 of the 153 forecast days (50%). For the 2018 season, only 50 of the 154 forecast days (32%) experienced flooding criteria, which is the lowest in Program history and may slightly impact validation statistics (lower sample size). The Bias for 2018 also slightly increased, which implies a minor over-forecasting of flood frequency.

Table 7: 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**

Table 8 shows the forecast performance as a function of threat level. Note, the threat level was in some cases reduced to match the highest threat issued over a non-burn area for a more accurate representation of the flood threat for the day. A robust forecast system should show higher skill as the threat level increases due to more confidence that flooding will be realized. Similar to previous seasons, Table 8 shows this to be the case. While Low threat forecasts verified 68% of the time (consistent with 2015, 2016 and 2017), **Moderate and High threats verified 100% of the time they were issued**. 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 implies that perhaps more High flood threats should have been issued. It would be beneficial to revisit the Flood Threat definitions during the off-season in preparation for the 2019 operational season.

Table 8: Accuracy as a function of threat level. Note: threat levels were reduced to the highest non-burn area level as needed.

	Observed Flood Day	Observed Non-Flood Day	Total Days
Low	23 (68%)	11 (32%)	34
Moderate	17 (100%)	0	17
High	1 (100%)	0	1
High impact	0	0	0
Total	41 (79%)	11 (21%)	52

Table 9 shows the yearly aggregated forecast verification for burn area threats during the 2018 season. While there are no established targets, forecast performance exceeded initial expectations. It is likely a more robust verification will produce more valuable metrics in the future. Of the 154 forecast days, burn area flash flooding occurred on 18 days with 11 of those days occurring in July (Appendix B). The Hit Rate was 79% with the Probability of Detection at 78%. Both the False Alarm and Miss Rates were under 25%, which is satisfactory given the small forecast area. If broken down by threat level (not shown), the largest improvements for the 2019 season would need to be at the Low threat level. There were 18 Low threats issued with a 100% False Alarm Rate using current criteria. However, if a NWS Flood Advisory allowed for a "Burn Area Flood Day", the False Alarm Rate would decrease to 56%. This shows the large variability and subjectivity of the False Alarm rate with the current validation criteria. As the threat level increased to Moderate and High, the False Alarm Rate decreased to 53% and 38%, respectively.

As mentioned, the only High Impact threat issued this season was for the 416 and Burro burn areas on June 16th as remnants of Hurricane Bud moved over the southwest corner of the state and ushered in high Precipitable Water values. With this being a fresh burn area and guidance indicating 24-hour rainfall amounts exceeding 1 inch with rain rates in the 0.50-0.75 inch per hour range, it was not surprising when a debris slide was reported on Highway 550 just north of Durango. CoCoRaHS observers across La Plata County reported 0.70 inches near the burn area for the 24-hour period with localized values exceeding 1 inch further south. 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 (Table 11).

Table 9: Summary of burn area forecast performance in total. A more robust validation system will be created for 2019.

Forecast / Observed	Total
(a) Flood / Flood	14
(b) No Flood / Flood	4
(c) Flood / No Flood	28
(d) No Flood / No Flood	108
Total Days	154
Hit %	79%
POD	78%
FAR	21%
Miss %	22%

3) CHARACTERIZATION OF FORECAST PERIOD WEATHER

Overview

The 2018 operational season can be best characterized as warm and dry with the exception over the eastern plains where precipitation was at or above normal (Figure 8). Dry conditions were present over the bulk of the state with parts of western Colorado (20-40% of normal locations) logging their driest year on record. Temperature records were also broken with record warm for the majority of western Colorado and portions of the high country. Grand Junction recorded 90 days of 90°F+ temperatures for 2018, which is about a full months worth of days above normal (climatology of 90°F days is 59 days). Denver recorded just over 50 90°F+ days, which about 40% greater than average. Overall, the 2017-2018 Water Year was the warmest ever and second driest (second to 2002).

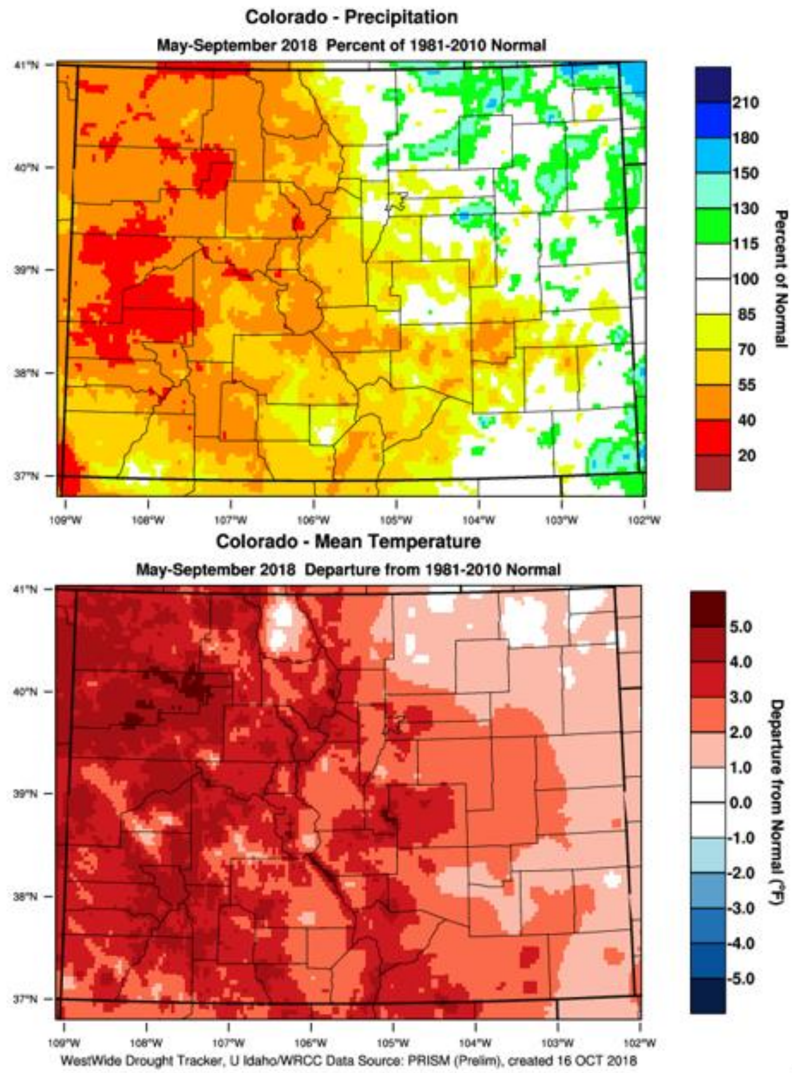


Figure 8: Precipitation (top) and temperature (bottom) anomalies for May-September 2018 using PRISM data. Source: Desert Research Institute.

Over the 154-day operational season, heavy rainfall activity took a large downturn in comparison to previous seasons. Table 7 shows that 50 Flood Days were observed this season, which is about 60% below the 2012-2017 average of 79.5 days. Looking at Appendix D, a visual was created that shows the number of flood threats issued for a given locale. Notably, the 416 and Spring Creek burn areas stand out as very active due to their freshness and, therefore, low rain rate flooding thresholds. 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 dropped significantly from 2016 and 2017. Western Colorado was less active as well, which likely had to do with the anomalously strong ridge over the West, which prevented the typical monsoon pattern from setting up.

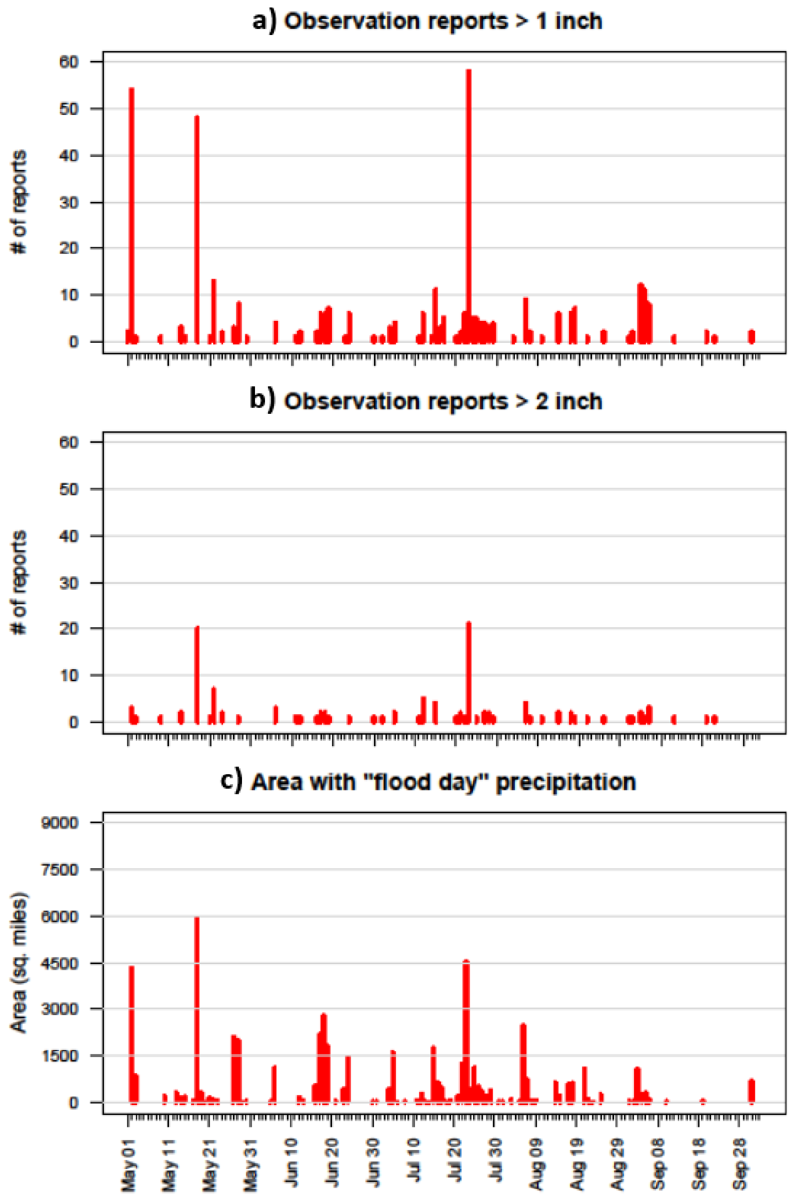


Figure 9: The number of daily observation reports exceeding (a) 1 and (b) 2 inches, and (c) the coverage of Flood Day precipitation, in sq. miles, from the gridded precipitation product. For reference in (c), the total area of Colorado is about 104,000 sq. miles

Figure 9 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 76 days where at least 1 station measured a qualifying precipitation amount (see “NStats” column in Appendix A). There were 54 days where at least two stations measured qualifying amounts, and 24 days where at least 10 stations measured qualifying precipitation. There were only two days (May 2 and July 23) where over 100 gages measured qualifying precipitation, though it should be noted that the May event was associated with snow and low intensity rainfall. The July 23rd widespread heavy rainfall event will be dicussed below in greater detail.

In terms of Flood Day area (panel c), there were 17 days where over 1,000 sq. mi. recorded rainfall greater than 1.50 inches (1 inch) east (west) of the 1,600 meter contour. However, there was one day where Flood Day area exceeded 5,000 sq. mi., indicative of widespread heavy precipitation: May 18th. This was an overnight into the morning event where NOAA Stage IV rainfall data indicated 3.3 inches fell over the Northeast Plains with widespread amounts in the 1.5 to 2 inch range. The realtively rural location of the heavy rainfall explains why this event did not show up in the 100 gage metric above. Compared to previous seasons, the 2018 season had below normal Flood Days at a statewide-level.

Detailed Summary

With low snowpack to start the season and the drying trend continuing throughout the summer, drought conditions quickly worsened. At the beginning of May, the southern third of Colorado was experiencing Extreme Drought conditions, while the southwest corner and southeast mountains were categorized under Exceptional Drought conditions. By the end of the operational season, nearly all of western Colorado and the Southeast Mountains were under Extreme Drought conditions with the Southwest Slope, Grand Valley and San Juan Mountains undergoing Exceptional Drought conditions (16.21% of the state; Figure 10). The lack of moisture sparked an active fire season across the state, as well as over the entirety of the western United States. In Colorado, it was one of the worst wildfire seasons on record with more than 450,000 acres burned and 96 named fires (geoMAC). The High Resolution Rapid Refresh (HRRR)-Smoke experimental numerical model was incoporated into FTB forecasts due to the increased smoke pollution over the state from fires across the West.

As mentioned, snowpack for the 2017-2018 Water Year was at 64% of normal (statewide) at the start of the warm season, with snowpack over southern Colorado at less than 50% of the median. This translated to low and early peaks in the streamflow during Spring 2018, along with major riverine flooding being completely avoided. Fortunately, reservior storage was at or above 100% for all basins in May. However with the dry conditions, by the end of the operational season, statewide reservior storage was at 81% of average (38% lower than 2017) and 44% of capacity. Blue Mesa Reservior (Gunnison River Basin) was at 37% of normal capacity by the end of August, which was the lowest water level since 1987.

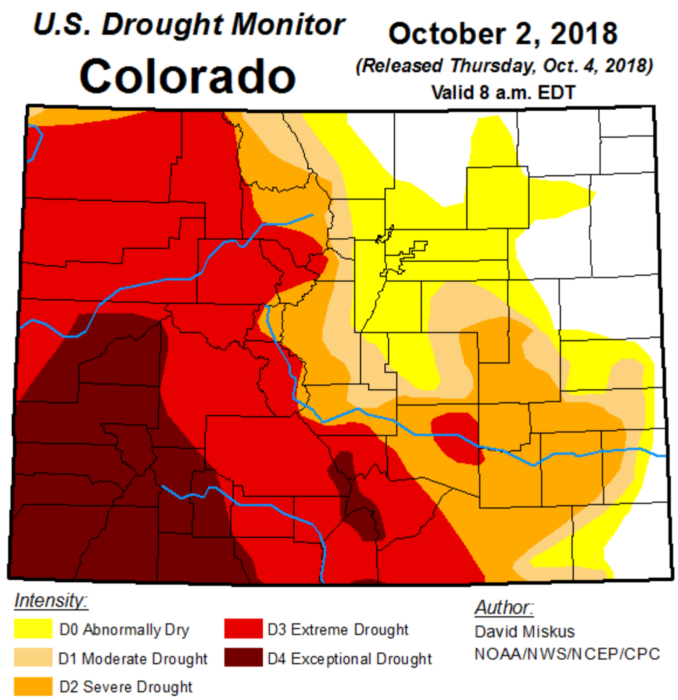


Figure 10: US Drought Monitor for Colorado ending on October 2nd, 2018. A large area of the state (16.2%) was experiencing Exceptional Drought conditions. Source: UNL Drought Monitor

Another highlight of the 2018 operational season were two tropical cyclones near Baja California whose remanent tropical moisture was advected into Colorado. Normally, the remnants of a tropical cyclone or tropical storm are swept into the easterly winds as they form over the warmer waters along the central Mexico coast. By the time they are swept back into the westerlies, they are west of the North American coast by hundreds of miles. However, about 10% of Pacific tropical cyclones avoid the easterly winds and their remnants are swept into the westerlies as they move north up Mexico's coast, which causes heavy rainfall over the southwest US (Corbosiero et al., 2009). The anaomalous high PW values associated with tropical storm remnants rarely reach Colorado; however, this occurred twice during the 2018 operational season.

The first of these events took place in mid-June when the remnants of tropical storm Bud moved into the Four Corners region. While this would normally only be an Elevated Threat in the FTO, PW values greater than 1 inch were forecast to advected over the recent/ongoing 416 and Burro burn areas. This made the burn areas highly susceptible to flash flooding, mud flow and debris slides, so a High Threat was issued for surrounding communities. As stated earlier, a special FTO was produced on June 14th, which highlighted potential rainfall rates, timing for the core of the event and storm motion information. On Saturday (June 16th), the only High Impact Threat of the season was issued for the 416 and Burro burn areas. The FTB focused on specific locations for flooding, timing for the core precipitation, flooding threats and rain rates. At 5:40AM on the 17th, the forecast was verified when a rock and debris flow was reported near Iron Horse. Rain rates were measured in the 0.25-0.50 inch range for the event, which was lower than guidance suggested. Some models failed to properly incorporate ongoing cloud cover during the day on the 16th, which kept instability from building and helped lower rain rates. The lower rain rates likely helped advert major flooding, though observations showed 24-hour totals reaching over 1 inch.

The second tropical-related event extended the FTB season as late season Tropical Cyclone Rosa moved into the Californian Baja at the end of September. While PW values were not projected to reach as high of values as Bud, values would still be in a range that could produce max 1-hour rain rates near 0.50 inches over the recent burn areas and pockets of 24-hour totals exceeding 1 inch. Throughout the season, these rain rates and totals had produced flooding issues over the burn areas, so a Moderate flood threat was issued for all recent burn areas over southwest Colorado. Flooding was averted as early morning rainfall on October 2nd limited the chance for embedded convection as the main wave moved through during the afternoon and evening hours. While 24-hour totals in the area exceeded 1 inch, rain rates remained below 0.50 inches per hour and the dry soils helped soak up the rainfall. While the precipitation totals from the event were still impressive for the beginning of October, they did little to help improve the ongoing drought.

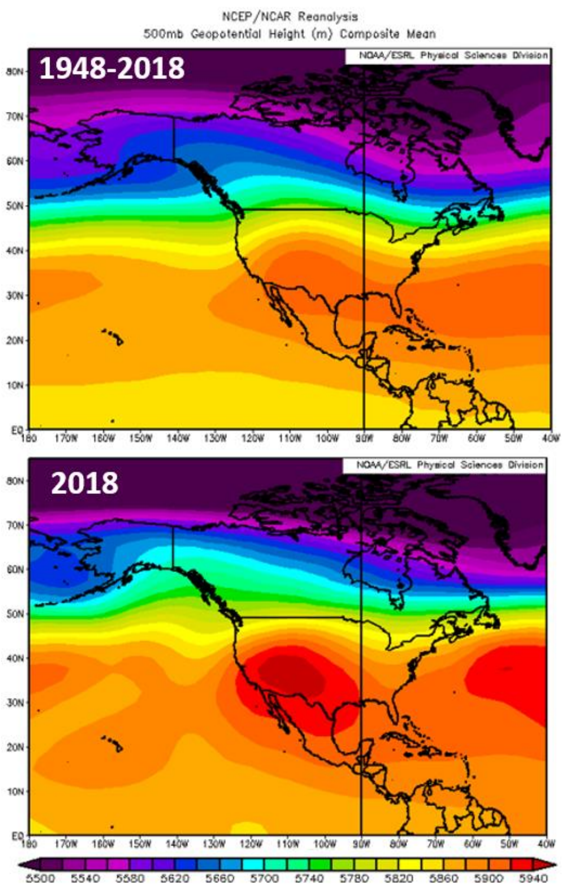


Figure 11: Mid-Level (500mb) Geopotential Heights for July 1948-2018 (top) and July 2018 (bottom). Source: NOAA/ESRL

Overall, the 2018 monsoon season was quieter than usual with very few traditional atmospheric monsoon patterns setting up. While high PW events ususally occur uniformaly across the state or start west of the Continential Divide then move east, most events in 2018 set up solely east or west of the Continential Divide. Reanalysis data of the July 500mb geopotential heights show the axis of the subtropical ridge extending further west and stronger than climatology (Figure 11). The anomalously strong mid-level ridge particularly shielded western Colorado from the typical monsoon setup and limited tropical moisture advection northward.

High PW events were also short-lived when compared to climatology. The longest stretch of threats in a row occurred from July 21st to July 29th and flooding occurred on 8 of those 9 days. During the period 4 Low threats, 3 Moderate threats and 1 High threat were issued. This is quite the contrast to 2017 where the period of July 11 through August 13 marked a 33 day stretch of incredibly active weather over eastern Colorado. Flood threats were issued on 30 out of those 33 days, with 5 High threats and 15 Moderate threats amongst them.

One of the most active days of the year, not surprisingly, occurred during the height of the monsoon on July 23rd after the passage of a weak cold front. This even was the lone (non-burn) High threat of the season. The 500mb high pressure center spun over New Mexico and southeasterly/easterly low-level winds allowed for high PW values to pool over eastern Colorado. Denver's 12Z sounding indicated PW values in the 90th percentile and 0.1 inches below the daily max PW value. While upper-level winds provided decent storm motion, back-building thunderstorms (perpendicular low-level flow to the mountains) and upper-level disturbances rotating around the high pressure center helped enhance lift for multiple rounds of afternoon thunderstorms.

Several debris flows were reported in the mountains including a debris slide outside Bailey, CO on Highway 285. A large debris flow on High 24 (El Paso County) temporarily shut down the highway, and the flood sirens (added post-2012 Waldo Canyon Fire) were sounded in Manitou Springs evacuating low-lying areas. As far as observations, a CoCoRaHS gage north of Fountain, CO (El Paso County) recorded 4.12 inches with a nearby station reaching 3.88 inches for the duration of the event. A trained spotter just northwest of Colorado Springs recorded 1.8 inches in 20 minutes! Further north in Denver, an ALERT gage recorded 2.76 inches in an hour, which was the second highest recorded 1-hour rainfall value since Dewberry started collecting data in 2015. The storms eventually moved east and formed into a mesoscale convective system (MCS) that brought late night flooding to Lamar and La Junta as well. The validation figure with the overlaid threats can be seen below (Figure 12).

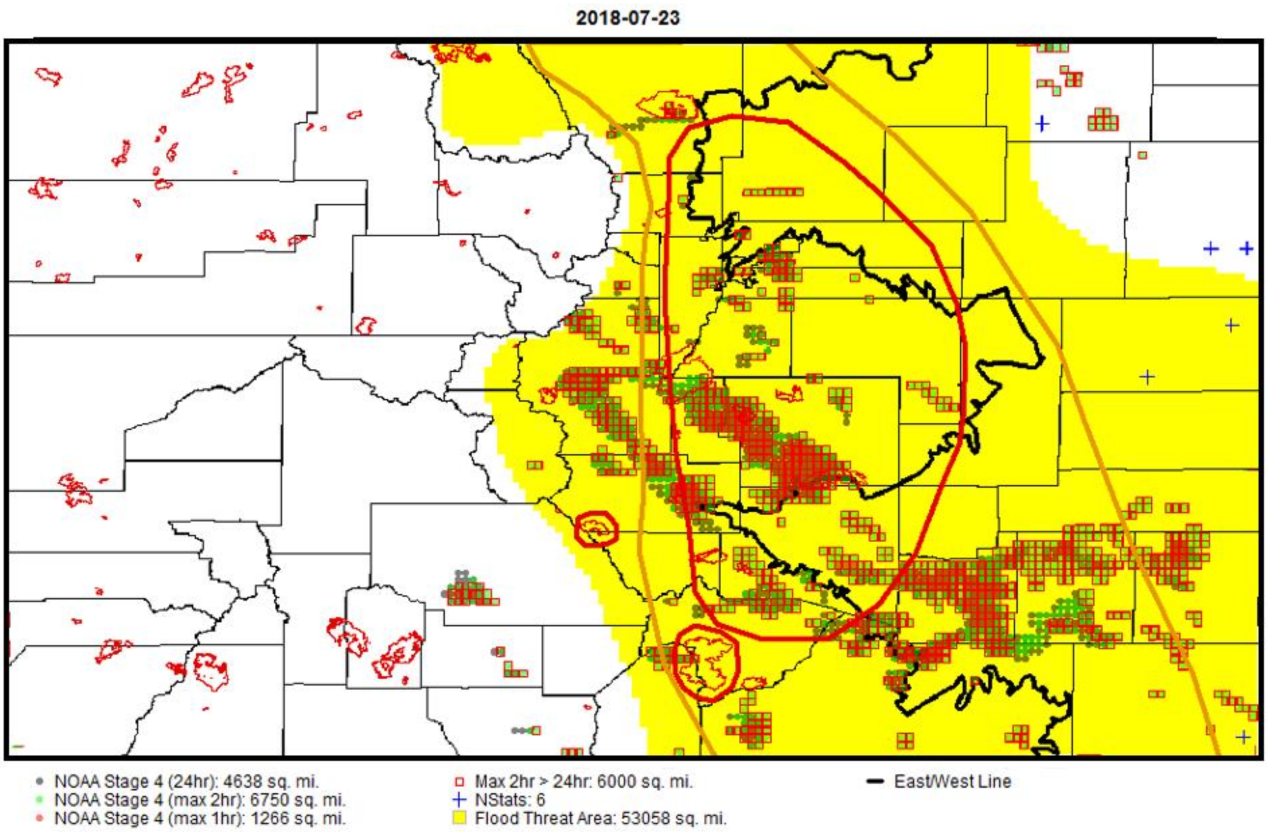


Figure 12: Rainfall observations over 1 inch for Stage IV and CoCoRaHS data on July 23rd, 2018. The total threat area is in yellow with the Moderate Threat outlined in orange and High Threat outlined in red. The Weston Pass and Spring Creek burn areas also had their own individual High threat.

After the event on the 23rd, Dewberry was contacted by the chief meteorologist at the NWS Boulder office, Nazette Rydell. They were interested in the FTB products and also indicated some confusion with the FTB threat definitions and thresholds. It was decided that prior to the 2019 season, Dewberry and CWCB will join the local NWS offices for a spring colloquium to share flood forecast techniques and objectives. It was also agreed that in order to avoid public confusion, especially when forecasts differ, Dewberry will contact the NWS office on days either a High or High Impact flood threat will be issued. On the reverse, Dewberry made a conscious effort to better highlight the flood threat timeline and possible impacts in a more concise and forward matter.

August into September, a much quieter weather pattern was observed. The number of threats decreased by 50% from the 2017 season with only 12 threats issued over the two month span (including the October 2nd special edition FTB). Decent moisture returned, post cold front passage, and gave way to heavy rainfall on September 5th, which was the last elevated flood threat for the season. Dew points in Denver were in the mid-50°Fs during the morning, and with slow steering winds and a passing vorticity maximum, afternoon storms were widespread and nearly stationary. As is common this time of year, the low-top supercells produced abundant small hail and helped clog gutters causing street flooding around Denver. Only light to moderate rainfall was observed post September 6th, bringing the 2018 flood threat season to a close.

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 2018, 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 message. Third, we added a 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 2018 (green) overlaid with the previous two seasons. As has been seen in the past, average daily site visits continue to be highest on days flood threats are issued. During 2018, website usage continued to grow and the number of users increased by ~80% from the previous season (+1,491 users; 3,382 total). Interestingly, website usage was up from 2017 and 2016, even though the number of flood threats decreased (60 in 2018; 74 in 2017; 91 in 2016). There may be a few reasons to account for the increase. One, on Thursday, June 14th (special FTO for Bud), the average daily user count reached an all-time high of 175 users. The following Saturday (event peak), the site reached 141 Users, which is ~80% retention of the audience reached on Thursday. This event likely brought more users into the fold for the remainder of the FTB season as Figure 13 also shows a large increase in overall users after this date. The event may have even helped to diversify the FTB audience as the flood threat was burn scar focused. Secondly, increased social media exposure could have brought more users to the site than previous years since a link to the FTB product discussions were almost always included with the social media posts. Whatever the case may be, the user increase is encouraging, and it indicates the FTB is continuing to gain traction as a successful early detection flood tool.

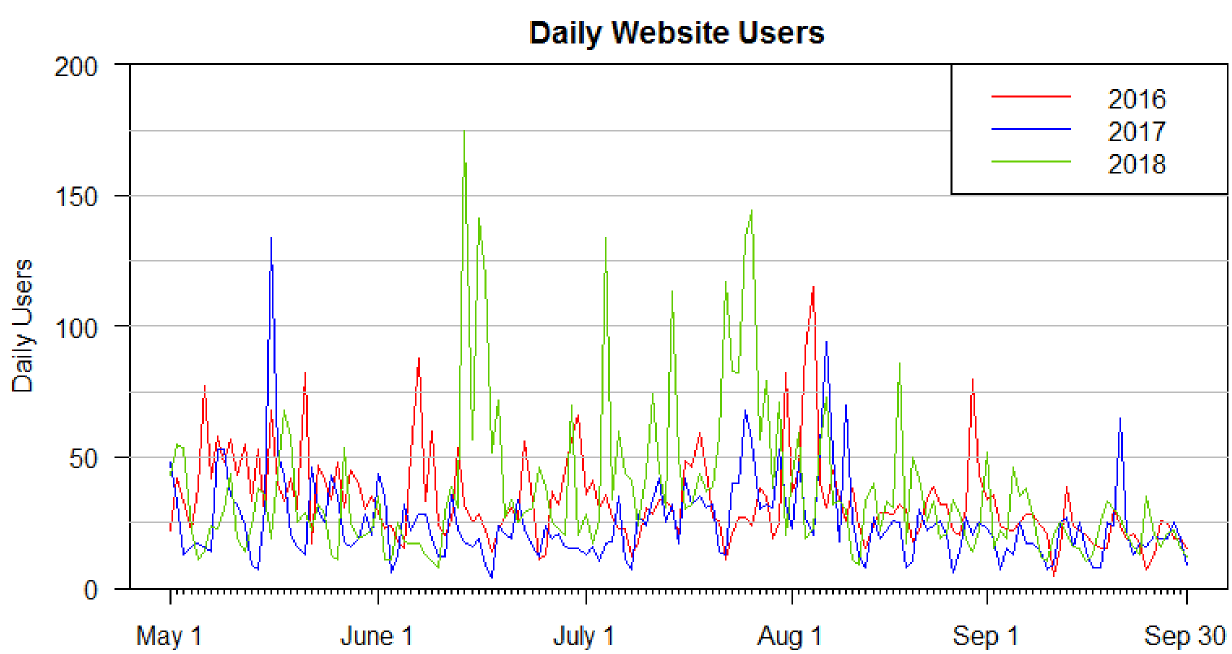


Figure 13: Daily website users during 2016 (red), 2017 (blue) and 2018 (green).

Social Media

During the historic floods of September 2013, we 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 we 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, we expanded our social media strategy to maximize the way this data is leveraged. For example, Figure 14 shows a Tweet that highlights the special FTO created for Bud as tropical moisture moved over the recent 416 and Burro burn areas. Messages such as those have shown their value by being well received by social media users through ample retweets and impressions.

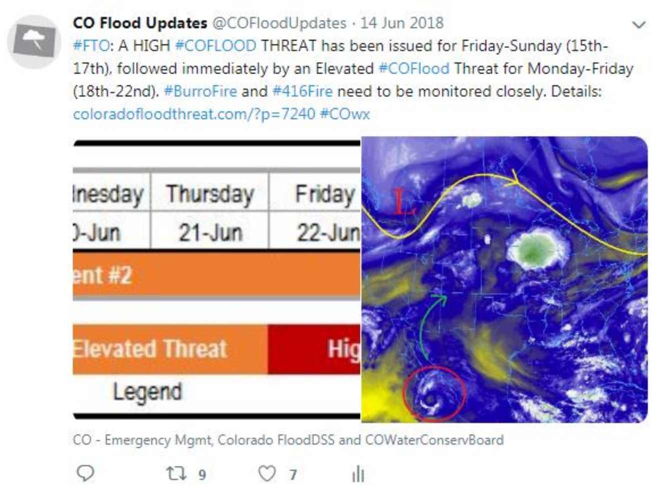


Figure 14: Example of a tweet that received significant user interaction for the 2018 season. This tweet was related to the special FTO created for Bud event that brought abundant tropical moisture to the state on June 16^{th}.

The FTB's Twitter account, **@COFloodUpdates**, continued to gain usage since its inception with the total number of followers up to 1,183 by the end of the 2018 season (an increase of 147 compared to the end of the 2017 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 51.1K Twitter followers. @COFloodUpdates continues to be featured in the 9NEWS Local Market science section and mentioned by their associated twitter account (17.7K 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 2018 (green line) as well as those for the 2016 and 2017 seasons. There is a slight increase in the number of daily impressions from the 2016 and 2017 seasons. During the 2018 season, we disseminated 230 Tweets (about 80 less than 2017) and received a total of about 313K impressions (up from 293K in 2017). Of the 154 operational days, during 94 of them, our Tweets received over 1,000 impressions. The largest impression occurred on May 22^{nd}, though the tweet had little to do with the typical FTB posts. Dewberry posted a reminder of the annual flush of Cherry Creek, since it would close down parts of the Cherry Creek bike trail. The Tweet gained over 21K impressions with 16 retweets including 9NEWS (425K followers) and the Denver Office of Emergency Management (4.7K followers).

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, Colorado Wildfire Info 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.

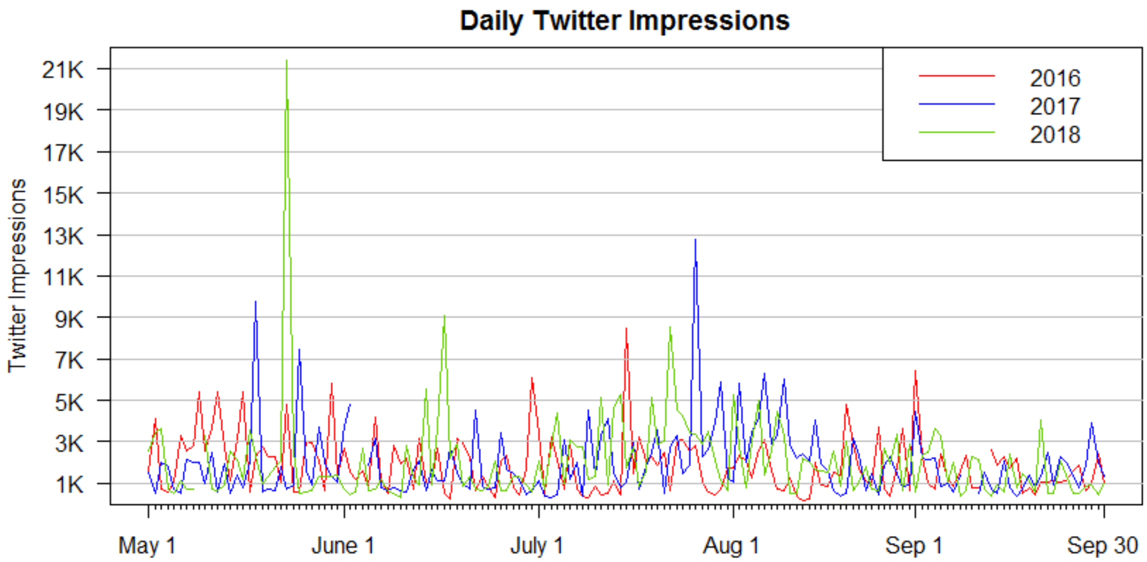


Figure 15: Daily Twitter impressions during 2018 (green) 2017 (blue) and 2016 (red).

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 for 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. Over its first season, the Facebook account gained 142 likes and 155 followers, which is the equivalent of Twitter followers. While this number is quite a bit lower than the Twitter account, it is relatively new and there is still added value. For one, 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.

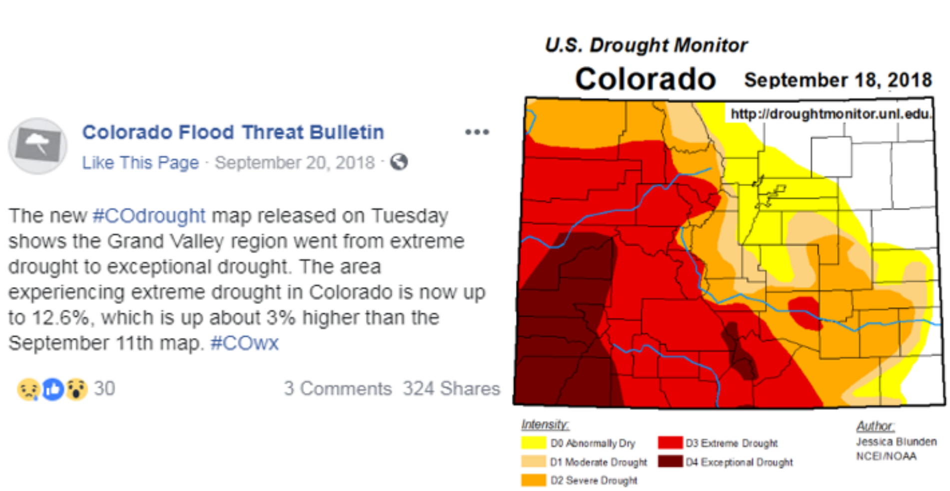


Figure 16: Example of a Facebook post on September 20th, 2018 that received significant user interaction. This post highlighted the increased area under Extreme Drought conditions over the Grand Valley region.

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 931. On average for the 2018 season, we had 871 reaches per day with a range from 25 to 5,162. The largest of the reaches was achieved on September 20th after the latest Colorado drought map was released. The post highlighted the 3% increase in area size of the Exceptional Drought conditions over the Grand Valley Region (Figure 16). This post had 324 shares, 5,162 reaches and 30 reactions. It also likely facilitated +15 likes to the page. While it's hard to determine which posts will be the most popular among users, no climatology related tweet was ever this successful on the Twitter platform. This also suggests that the viewership and types of users between Twitter and Facebook are quite different from one another.

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 and we need to continue to monitor and reassess whether Twitter and Facebook are the most effective platforms they can be for the FTB service. It can also valuable to note the similarities and difference between the social media platforms for optimal success. 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 (placed on every post) was only clicked once 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 September 30, there were 25 active subscribers, which is an additional 14 users from last season. Unlike last season, there was no one case 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. While the number of subscribers may be low, one of the key objective from the program's standpoint 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, such as a pre-season notification to all Colorado emergency manager groups.

5) CONCLUSIONS

- Statewide, 2018 was the quietest year on record since the Program began with only 50 Flood Days and 52 (non-burn) threats issued. This is about 35% below the 2012-2017 average of 76.5 days, and much lower than 2017's 74 days. New to 2018, a burn area threat validation was attempted. There were 18 Burn Area Flood Days and 42 burn-specific threats issued. Despite a quieter season, the eastern plains was at or near normal precipitation. Conversely, some parts of western Colorado (due to an anomalously strong mid-level ridge) logged their driest year on record and moved into Exceptional Drought conditions. The longest stretch of active weather occurred during the height of the monsoon season from July 21st to July 29th where a Flood Day occurred on 8 of the 9 threat days. It was during this period one of the most notable flood events of 2018 occurred. On July 23rd, PW values were in the 90th percentile and back-building storms helped drop several inches of rain in a short period of time along the Front Range and Urban Corridor. Several debris flows were reported over the Front Range and Highway 24 in El Paso County was closed through the evening. A High flood threat was posted that day.

- The State Precipitation Map was also improved by MetStat, Inc. when they added a bias correction to the MetStorm Live QPE 24-, 48- and 72-hour accumulations (June 11th). 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 improves 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.

- Forecast accuracy during 2018 was on par with prior seasons. The overall "Hit" rate was 87%, with the Probability of Detection (i.e. of detecting a Flood Day) at 82%. These are both above the Program targets of 75%. The False Alarm rate decreased to 11% (4% below the target), with the Miss Rate slightly increasing to 18% (3% over the target). The validation process was expanded this year with the addition of a burn area threat verification to evaluate the usefulness of burn specific threats in forthcoming operational seasons. The Hit Rate was 79% with the Probability of Detection at 78%. Both the False Alarm and Miss Rates were under 25%, which is satisfactory given the small forecast area. Burn areas are a fraction of the ~250 sq. mi. at which current forecasts begin to show skill.

- Website viewership continued to grow with +1,491 more users than last season. The June 14th Bud event likely helped increase traffic on the website as the average daily user count reached an all-time record of 175 users. Days with threats continued to show more usage when compared to days with no threat.

- The Program's Twitter account (@COFloodUpdates) continued to expand with 1,183 followers. Total "Impressions" from the Program's Tweets now exceed 300,000, which is about 6% higher than 2017 even though the flood season was much quieter. A Facebook account was added to diversify the user community and had over 100 likes in its first season. Twitter is driving a significant amount of day-to-day website usage, while Facebook does a better job highlighting more climatology-based posts. 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.

- The Email Alert subscription continued to be issued each morning when the FTB is posted, although the service only added an additional 14 users for 2018 (25 subscribers total). Due to the low effort of maintenance for the service, it is recommended the Email Alert subscription continues. During the off-season it will be important to assess the content and quality of the information provided in the email. We must continue to learn and adapt to user preferences for flood information dissemination. Dewberry will consider methods on how to better advertise the email subscription option, such as a pre-season notification to all Colorado emergency manager groups.

6) REFERENCES

Corbosiero, K. L., M. J. Dickinson, and L. F. Bosart, 2009: The contribution of eastern North Pacific tropical cyclones to the rainfall climatology of the southwest United States. Mon. Wea. Rev., 137, 2415–2435.

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

APPENDIX A – FORECAST VERIFICATION WORKSHEET

Table 10 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 10 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 10: 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	0.98	1.88	0.85	1.60	1.03	0.59	0	0.41	1.6	18	0	0			None		
2-May	0.56	1.10	0.76	1.30	1.97	2.02	4324	1.95	2.43	193	0	0			Low	LI	False Alarm
3-May	1.11	1.96	1.12	2.13	1.29	1.29	849	1.05	3.1	6	0	0			None	SNOW	
4-May	0.18	0.34	0.15	0.28	0.00	0.11	0	0.18	0.34	0	0	0			None		
5-May	0.07	0.12	0.09	0.16	0.07	0.10	0	0.01	0.1	0	0	0			None		
6-May	1.13	2.23	0.04	0.08	1.18	0.08	0	0.27	0.32	0	0	0			None		
7-May	0.87	1.69	0.01	0.04	0.00	0.02	0	0	0.2	0	0	0			None		
8-May	0.05	0.07	0.01	0.04	0.05	0.00	0	0	0.3	0	0	0			None		
9-May	0.81	1.48	0.17	0.32	1.04	0.19	0	0.08	3.4	1	0	0			None		
10-May	0.96	1.89	0.71	1.36	2.16	0.76	206	0.06	0.2	0	0	0		YES	None		Miss
11-May	1.40	2.76	0.43	0.86	0.54	0.68	0	0.36	0.4	0	0	0			None		
12-May	0.49	0.88	0.53	1.05	1.13	0.67	0	0.07	1.05	2	0	0			None		
13-May	0.85	1.70	0.47	0.84	1.79	1.50	307	1.48	1.22	1	0	0		YES	Low		Hit
14-May	1.20	2.23	1.00	1.81	1.44	1.40	171	1.35	2.7	8	0	0		YES	None		Miss
15-May	1.45	2.57	0.97	1.77	1.67	1.50	177	1.21	1.7	3	0	0	YES	YES	Low		Hit
16-May	1.07	2.11	1.08	2.05	0.90	0.10	0	0.01	0.5	0	0	0			None		
17-May	0.79	1.53	0.31	0.42	1.84	0.37	48	0.02	0.6	0	0	0		YES	Low		Hit
18-May	1.37	2.54	1.44	2.81	3.33	2.46	5946	2.8	2.77	57	3	0	YES	YES	Mod		Hit
19-May	2.85	5.27	0.98	1.95	1.29	1.42	283	1.46	1.29	1	0	0	YES	YES	Mod		Hit
20-May	0.25	0.50	0.52	1.01	0.86	1.01	6	0.14	0.51	0	0	0	YES		None		
21-May	0.78	1.40	1.01	1.88	1.62	2.11	142	0.06	2.38	1	0	0		YES	None		Miss
22-May	0.98	1.90	1.31	2.60	1.57	1.26	100	2.86	1.49	14	0	0		YES	None		Miss
23-May	1.16	2.29	1.02	1.99	1.03	1.31	35	0.07	0.2	0	0	0			None		
24-May	0.92	1.79	0.82	1.48	1.39	0.82	0	3.66	0.1	2	0	0			None		
25-May	1.35	2.39	0.02	0.04	1.22	0.03	0	0	0.4	0	0	0			None		
26-May	0.62	1.09	0.20	0.38	0.00	0.10	0	0	0.3	0	0	0	YES		None		
27-May	1.26	2.47	0.77	1.41	2.50	1.59	2112	1.55	0.4	3	0	0		YES	Low		Hit
28-May	1.49	2.90	1.17	2.16	3.59	1.63	1982	3.15	1.5	8	3	0	YES	YES	Mod		Hit
29-May	1.83	3.49	0.94	1.82	1.30	1.05	6	0.48	0.2	0	0	0	YES		None		

	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					
30-May	0.99	1.95	1.04	2.04	1.27	1.18	35	1.53	1.06	2	0	0	YES		Low		False Alarm
31-May	0.91	1.80	0.44	0.76	0.01	0.08	0	0.17	0.1	0	0	0			None		
1-Jun	0.02	0.04	0.04	0.08	0.04	0.04	0	0.01	1.3	2	0	0			None		
2-Jun	0.04	0.07	0.01	0.04	0.00	0.38	0	0	0.6	0	0	0			None		
3-Jun	0.14	0.28	0.37	0.67	0.25	0.95	0	0.03	0.64	0	0	0			None		
4-Jun	0.24	0.44	0.28	0.50	0.29	0.21	0	0	0.3	0	0	0			None		
5-Jun	0.39	0.74	0.09	0.17	1.68	0.66	12	0.03	0.1	0	0	0			None		
6-Jun	2.07	3.92	0.65	1.23	4.34	2.02	1109	2.76	0.5	4	1	0	YES	YES	None		Miss
7-Jun	1.50	2.99	1.64	3.20	0.88	0.88	0	0.18	0.3	0	0	0			Low		False Alarm
8-Jun	0.96	1.81	0.85	1.60	1.14	0.72	0	0.01	0.5	0	0	0			None		
9-Jun	0.94	1.87	0.53	1.05	0.98	0.69	0	0	0.01	0	0	0			None		
10-Jun	0.09	0.18	0.01	0.04	0.10	0.04	0	0	0.2	0	0	0			None		
11-Jun	0.02	0.04	0.00	0.04	0.00	0.00	0	2.74	0.3	1	0	0			None		
12-Jun	0.02	0.04	0.50	0.97	2.18	1.60	171	1.6	2.46	6	0	0		YES	Low		Hit
13-Jun	1.82	3.51	1.21	2.31	1.21	1.20	53	0.96	0.7	0	0	0		YES	Low		Hit
14-Jun	1.09	2.10	0.44	0.84	0.56	0.51	0	0.13	0.6	0	0	0			None		
15-Jun	0.86	1.65	0.74	1.48	1.03	0.84	0	0.02	1.4	9	0	0			None		
16-Jun	1.25	2.23	1.48	2.64	1.46	2.00	507	1.02	2.98	16	2	0		YES	Low		Hit
17-Jun	1.13	2.15	0.94	1.78	1.70	2.10	2188	1.35	2.51	40	0	0	YES	YES	Mod		Hit
18-Jun	0.86	1.53	1.18	2.26	6.68	2.46	2802	4.84	1.57	21	2	0	YES	YES	Low		Hit
19-Jun	2.02	3.81	1.26	2.44	3.12	1.98	1805	2.2	1.74	13	3	0	YES	YES	Mod		Hit
20-Jun	2.81	5.49	0.95	1.84	0.38	0.37	0	0.48	0.24	0	0	0			None		
21-Jun	0.21	0.42	0.41	0.71	0.73	1.27	35	0	0.5	0	0	0			None		
22-Jun	0.79	1.56	0.68	1.34	1.24	0.45	0	0.49	0.3	0	0	0			Low		False Alarm
23-Jun	0.71	1.42	0.80	1.59	2.08	0.99	436	1.62	1.25	2	0	0		YES	Low		Hit
24-Jun	2.56	4.91	1.02	2.00	2.81	1.36	1469	1.75	2.4	7	0	0		YES	Low		Hit
25-Jun	1.67	3.07	0.85	1.69	0.04	0.00	0	0.01	0.17	0	0	0			None		
26-Jun	0.00	0.04	0.00	0.04	0.00	0.00	0	0	0.1	0	0	0			None		
27-Jun	0.05	0.09	0.11	0.20	1.09	0.19	0	0.03	0.01	0	0	0			None		

	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					
28-Jun	0.80	1.57	0.84	1.64	0.93	0.88	0	0.15	0.26	0	0	0			None		
29-Jun	0.63	1.23	0.18	0.30	0.69	0.21	0	0.11	0.1	0	0	0			None		
30-Jun	0.97	1.77	0.51	0.99	1.75	0.97	12	2.45	0.31	1	0	0			Low		False Alarm
1-Jul	1.59	2.96	0.53	0.98	0.06	1.16	12	0	0.6	0	0	0			None		
2-Jul	0.77	1.48	0.61	1.16	1.21	0.92	0	2.42	0.38	1	0	0			None		
3-Jul	0.81	1.52	0.80	1.38	1.35	0.93	0	0.02	1.4	1	0	0			None		
4-Jul	1.27	2.17	0.80	1.52	2.93	1.77	419	1.92	1.4	8	1	0	YES	YES	None		Miss
5-Jul	1.61	3.18	2.15	3.86	2.83	3.09	1604	2.57	2.27	11	4	0	YES	YES	Mod		Hit
6-Jul	0.86	1.65	1.56	3.07	0.38	1.02	6	0	1.3	1	1	0			Low		False Alarm
7-Jul	0.21	0.30	0.75	1.38	0.42	0.68	0	0.02	0.5	0	1	0			Low		False Alarm
8-Jul	0.29	0.50	0.69	1.36	0.62	1.59	12	0	0.7	0	0	0			Low		False Alarm
9-Jul	0.38	0.58	0.59	1.14	0.00	0.49	0	0	0.7	0	0	0			None	BURN	
10-Jul	0.00	0.04	0.71	1.37	0.27	0.74	0	0	1	1	0	0			None	BURN	
11-Jul	1.09	1.96	1.59	2.88	1.99	1.29	59	0.21	3.44	3	3	0	YES	YES	Low		Hit
12-Jul	0.94	1.83	1.38	2.46	2.26	1.77	277	2.38	2.31	10	0	0	YES	YES	Low		Hit
13-Jul	1.25	2.39	0.46	0.79	1.09	1.33	12	0	0.9	0	4	0			Low		False Alarm
14-Jul	0.68	1.15	1.03	1.97	0.69	1.10	6	1.05	1.7	2	0	0			Low		False Alarm
15-Jul	0.78	1.48	1.88	3.59	2.05	3.39	1758	2.34	2.53	30	7	0	YES	YES	Mod		Hit
16-Jul	1.88	3.36	2.26	4.45	2.25	1.93	649	1.55	1.76	11	1	0	YES	YES	Mod		Hit
17-Jul	1.79	3.43	1.03	2.01	1.95	1.47	454	1.46	1.98	17	1	0	YES	YES	Mod		Hit
18-Jul	1.46	2.77	1.09	2.11	0.00	1.07	18	0	0.5	0	0	0			None		
19-Jul	2.40	4.61	0.48	0.94	3.83	0.69	53	0	0.44	0	0	0			None	AREA	
20-Jul	0.79	1.50	0.49	0.95	0.88	0.66	0	0.04	2.36	1	0	0			None	BURN	
21-Jul	1.10	1.63	1.34	2.52	1.96	1.96	212	2.64	2.21	4	1	0	YES	YES	Low		Hit
22-Jul	1.14	2.27	1.36	2.53	3.67	1.56	1250	2.75	0.8	6	4	0	YES	YES	Low		Hit
23-Jul	2.07	4.10	3.02	5.91	3.74	4.19	4506	2.71	4.12	114	10	1	YES	YES	High		Hit
24-Jul	2.39	4.69	1.71	3.05	2.12	1.83	413	1.42	1.96	24	10	0	YES	YES	Mod		Hit
25-Jul	1.43	2.72	1.36	2.63	2.52	1.84	1115	2.33	1.63	18	4	0	YES	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					
26-Jul	1.73	3.38	1.47	2.70	2.48	2.89	501	1.66	1.65	14	6	1	YES	YES	Mod		Hit
27-Jul	1.81	3.48	2.03	3.81	3.53	1.29	348	2.82	1.39	9	4	0	YES	YES	Low		Hit
28-Jul	2.11	4.15	0.73	1.38	2.43	1.14	201	2.95	1.02	4	3	0	YES	YES	Low		Hit
29-Jul	1.71	3.16	0.98	1.85	2.13	1.19	389	2.15	0.83	4	1	0		YES	Mod		Hit
30-Jul	1.64	2.90	0.76	1.42	0.28	0.49	0	0.1	0.3	0	0	0			None		
31-Jul	0.00	0.04	0.44	0.83	0.00	1.19	29	0.01	0.5	0	0	0			None		
1-Aug	0.14	0.25	0.69	1.18	1.25	1.16	12	0.07	0.7	0	1	0			None		
2-Aug	0.66	1.27	0.81	1.61	0.03	0.89	0	0	0.88	0	0	0			None	BURN	
3-Aug	1.44	2.79	0.73	1.39	2.02	1.19	100	1.64	0.5	1	0	0		YES	Low		Hit
4-Aug	1.26	2.41	0.49	0.94	0.81	0.82	0	1.05	0.63	0	0	0			None		
5-Aug	0.54	1.05	0.63	1.23	1.36	1.08	12	0.16	0.42	0	0	0			None		
6-Aug	1.11	2.14	1.29	2.57	7.35	5.07	2448	1.86	2.55	16	3	0	YES	YES	Mod		Hit
7-Aug	1.86	3.38	1.66	3.30	3.01	1.48	743	1.27	2	3	0	0	YES	YES	Low		Hit
8-Aug	1.42	2.72	1.31	2.58	1.19	1.18	24	0.27	1.05	1	2	0			None	BURN	
9-Aug	0.41	0.57	1.01	1.85	0.96	1.44	65	0.04	0.25	0	0	0			None	BURN; AREA	
10-Aug	0.73	1.38	0.59	0.86	0.92	0.71	0	2.47	0.5	1	1	0			None	BURN	
11-Aug	0.02	0.04	0.22	0.42	0.00	0.07	0	0	0.2	0	0	0			None		
12-Aug	0.00	0.04	0.44	0.84	0.00	0.64	0	0	0.4	0	1	0			None	BURN	
13-Aug	0.48	0.93	0.34	0.59	0.77	0.56	0	0.12	0.36	0	0	0			None		
14-Aug	1.04	1.78	1.02	1.99	2.07	1.86	631	1.94	2.08	34	4	0	YES	YES	Mod		Hit
15-Aug	2.07	4.00	1.67	3.10	0.92	1.77	206	0.04	0.7	0	2	0	YES	YES	None		Miss
16-Aug	0.77	1.48	0.71	1.37	0.69	0.81	0	0.09	1.1	1	1	0			None	BURN	
17-Aug	1.19	2.34	1.63	3.15	2.30	1.91	572	2.64	1.8	17	3	0	YES	YES	Mod		Hit
18-Aug	2.05	3.78	1.14	2.22	4.39	1.55	608	3.12	1.82	19	0	0		YES	Low		Hit
19-Aug	2.50	4.97	0.66	1.22	0.35	0.25	0	0.06	1.1	3	0	0			None		
20-Aug	0.04	0.07	0.11	0.21	0.51	0.75	0	0.01	1.01	1	0	0			None		
21-Aug	0.51	1.00	1.10	2.12	2.82	1.81	1068	2.92	1.27	4	2	0	YES	YES	Mod		Hit
22-Aug	1.43	2.75	1.06	2.02	0.56	1.29	100	0.05	1.02	1	2	0	YES	YES	Low		Hit
23-Aug	0.38	0.76	1.31	2.52	0.15	1.04	6	0	0.6	0	0	0			None		

	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					
24-Aug	0.18	0.36	0.43	0.80	0.19	0.19	0	0.02	0.5	0	0	0			None		
25-Aug	1.14	2.10	0.84	1.41	2.27	1.05	254	2.19	1.31	3	1	0		YES	None	BURN	Miss
26-Aug	1.16	2.20	0.59	1.00	0.88	0.82	0	0.05	0.23	0	0	0	YES		None		
27-Aug	0.58	1.08	0.61	1.12	0.06	0.14	0	0	0.3	0	0	0			None		
28-Aug	0.00	0.04	0.02	0.04	0.04	0.02	0	0	0.2	0	0	0			None		
29-Aug	0.04	0.06	0.03	0.06	0.08	0.03	0	0	0.1	0	0	0			None		
30-Aug	0.16	0.17	0.30	0.53	0.16	0.30	0	0	0.8	0	0	0			None		
31-Aug	0.55	1.04	0.29	0.57	0.62	0.60	0	2.66	0.5	1	0	0			None		
1-Sep	1.38	2.57	1.13	2.13	1.54	1.31	53	2.72	1.57	5	0	0			None	AREA	
2-Sep	0.87	1.72	0.62	1.12	0.98	1.01	12	0.04	1.1	1	0	0			None	BURN	
3-Sep	1.94	3.23	1.30	2.36	3.29	1.67	1074	2.52	1.59	15	0	0		YES	Low		Hit
4-Sep	2.34	4.30	0.69	1.06	2.33	1.91	271	1.95	2.14	29	0	0		YES	None	BURN	Miss
5-Sep	1.59	3.14	1.50	2.83	0.66	2.26	313	0.24	2.25	20	0	0	YES	YES	Mod		Hit
6-Sep	0.77	1.47	1.66	2.84	1.12	2.15	71	0.14	1.29	3	3	0	YES	YES	Low		Hit
7-Sep	0.49	0.89	0.70	1.21	0.49	0.43	0	0.01	0.1	0	0	0			None		
8-Sep	0.02	0.04	0.16	0.31	0.72	0.51	0	0.03	0.14	0	0	0			None		
9-Sep	0.66	1.31	0.61	1.17	0.66	0.74	0	0.01	0.15	0	0	0			None		
10-Sep	0.85	1.55	0.16	0.27	1.74	0.36	12	0	0.1	0	0	0			None		
11-Sep	0.33	0.61	0.22	0.39	0.60	0.23	0	0	3	1	0	0			None		
12-Sep	0.31	0.56	0.03	0.06	0.09	0.07	0	0	0.36	0	0	0			None		
13-Sep	0.00	0.04	0.00	0.04	0.00	0.00	0	0	0.1	0	0	0			None		
14-Sep	0.00	0.04	0.00	0.04	0.00	0.00	0	0	0.1	0	0	0			None		
15-Sep	0.00	0.04	0.41	0.77	0.00	0.43	0	0	0.36	0	0	0			None		
16-Sep	0.00	0.04	0.05	0.08	0.01	0.08	0	0	0.2	0	0	0			None		
17-Sep	0.26	0.44	0.18	0.31	0.46	0.18	0	0.01	0.7	0	0	0			None		
18-Sep	0.43	0.84	0.06	0.11	0.00	0.02	0	0	0.5	0	0	0			None		
19-Sep	1.14	2.10	0.55	0.98	1.72	0.76	18	2.21	1.44	9	0	0			None		
20-Sep	0.87	1.63	0.75	1.32	0.79	0.33	0	2.45	0.2	1	0	0			None		
21-Sep	0.10	0.16	0.96	1.81	0.09	0.98	0	2.44	0.2	1	0	0			None		
22-Sep	0.00	0.04	0.51	0.99	0.00	0.17	0	0	0.6	0	0	0			None		

	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					
23-Sep	0.00	0.04	0.01	0.04	0.00	0.54	0	0	0.23	0	0	0			None		
24-Sep	0.32	0.56	0.31	0.61	0.47	0.33	0	0.15	0.36	0	0	0			None		
25-Sep	0.17	0.32	0.09	0.17	0.11	0.10	0	0	0.2	0	0	0			None		
26-Sep	0.08	0.15	0.06	0.10	0.00	0.07	0	0	0.4	0	0	0			None		
27-Sep	0.00	0.04	0.01	0.04	0.01	0.00	0	0	0.3	0	0	0			None		
28-Sep	0.02	0.04	0.01	0.04	0.03	0.00	0	0.01	0.2	0	0	0			None		
29-Sep	0.01	0.04	0.01	0.04	0.00	0.00	0	0.01	0.2	0	0	0			None		
30-Sep	0.00	0.04	0.01	0.04	0.02	0.19	0	0.03	1.7	6	0	0			None		
2-Oct	0.38	0.71	0.36	0.71	0.46	1.78	0	0	0.4	0	0	0			Low	LI	False Alarm

APPENDIX B – BURN AREA VERIFICATION WORKSHEET

Table 11 is a daily verification worksheet documenting heavy precipitation and flash flooding over burn areas, along with whether a Burn Area Flood Threat was issued. The columns of Table 12 are described below. Also included is a list of Burn Areas the National Weather Service (NWS) issued at least one Flood Advisory or Flash Flood Warning for over the course of the 2018 season as well as the same list for Dewberry. Work will be completed with the NWS during the offseason to rectify differences prior to May 2019 (Table 11).

Table 11: Forecast Burn Areas

Burn Areas	
NWS	**Dewberry**
416/Burro	416/Burro
Beaver Creek	Beaver Creek
Hayden	Bull Draw
High Park	Cabin Lake
Junkins	Chateau
Lake Christine	Hayden
Spring Creek	Junkins
Starwood	Lake Christine
Waldo	Plateau
Chateau	Spring Creek
Royal Gorge	Waldo
Weston Pass	Weston Pass

Threat: Highest category of the Burn Area Flood Threat.

Burn Area Flood Day: Denotes whether or not the day qualified as a Burn Area Flood Day (Local Storm Report or Flash Flood Warning).

Outcome: Classification of Flood Threat into the following two categories. Note that a blank implies a correct forecast.

False Alarm: A Burn Area Flood Day was forecasted, but a non-Burn Area Flood Day was observed,
Miss: A Burn Area Flood Day was observed but not forecasted.

Table 12: Daily Burn Area Verification Worksheet

Date	Threat	Burn Area Flood Day	Outcome
1-May	None		
2-May	None		
3-May	None		
4-May	None		
5-May	None		
6-May	None		
7-May	None		
8-May	None		
9-May	None		
10-May	None		
11-May	None		
12-May	None		
13-May	None		
14-May	None		
15-May	None		
16-May	None		
17-May	None		
18-May	Low		False Alarm
19-May	None		
20-May	None		
21-May	None		
22-May	None		
23-May	None		
24-May	None		
25-May	None		
26-May	None		
27-May	None		
28-May	None		
29-May	None		
30-May	None		
31-May	None		
1-Jun	None		
2-Jun	None		
3-Jun	None		
4-Jun	None		
5-Jun	None		
6-Jun	None		
7-Jun	None		

Date	Threat	Burn Area Flood Day	Outcome
8-Jun	None		
9-Jun	None		
10-Jun	None		
11-Jun	None		
12-Jun	None		
13-Jun	None		
14-Jun	None		
15-Jun	None		
16-Jun	Vhigh	YES	
17-Jun	Mod	YES	
18-Jun	None		
19-Jun	None		
20-Jun	None		
21-Jun	None		
22-Jun	None		
23-Jun	None		
24-Jun	None		
25-Jun	None		
26-Jun	None		
27-Jun	None		
28-Jun	None		
29-Jun	None		
30-Jun	None		
1-Jul	None		
2-Jul	None		
3-Jul	None		
4-Jul	None		
5-Jul	High	YES	
6-Jul	High		False Alarm
7-Jul	High		False Alarm
8-Jul	Mod		False Alarm
9-Jul	Low		False Alarm
10-Jul	Mod		False Alarm
11-Jul	Mod		False Alarm
12-Jul	High	YES	Miss
13-Jul	Mod		False Alarm
14-Jul	Mod		False Alarm
15-Jul	High	YES	
16-Jul	High	YES	
17-Jul	Mod	YES	

Date	Threat	Burn Area Flood Day	Outcome
18-Jul	None		
19-Jul	None		
20-Jul	Low		False Alarm
21-Jul	None		
22-Jul	Low		False Alarm
23-Jul	High	YES	
24-Jul	High	YES	
25-Jul	Mod	YES	
26-Jul	Mod	YES	
27-Jul	Mod	YES	
28-Jul	None	YES	Miss
29-Jul	Low		False Alarm
30-Jul	None		
31-Jul	None		
1-Aug	None		
2-Aug	Low	YES	Miss
3-Aug	Mod		False Alarm
4-Aug	None		
5-Aug	None		
6-Aug	None		
7-Aug	Mod		False Alarm
8-Aug	Low		False Alarm
9-Aug	Low		False Alarm
10-Aug	Low		False Alarm
11-Aug	None		
12-Aug	Low		False Alarm
13-Aug	None		
14-Aug	Mod	YES	
15-Aug	None	YES	
16-Aug	Low		False Alarm
17-Aug	Low		False Alarm
18-Aug	Low		False Alarm
19-Aug	None		
20-Aug	None		
21-Aug	Mod		False Alarm
22-Aug	Low		False Alarm
23-Aug	None		
24-Aug	None		
25-Aug	Low		False Alarm
26-Aug	None		

Date	Threat	Burn Area Flood Day	Outcome
27-Aug	None		
28-Aug	None		
29-Aug	None		
30-Aug	None		
31-Aug	None		
1-Sep	None		
2-Sep	Low		False Alarm
3-Sep	Low		False Alarm
4-Sep	Low		False Alarm
5-Sep	Mod	YES	
6-Sep	Mod	YES	
7-Sep	None		
8-Sep	None		
9-Sep	None		
10-Sep	None		
11-Sep	None		
12-Sep	None		
13-Sep	None		
14-Sep	None		
15-Sep	None		
16-Sep	None		
17-Sep	None		
18-Sep	None		
19-Sep	None		
20-Sep	None		
21-Sep	None		
22-Sep	None		
23-Sep	None		
24-Sep	None		
25-Sep	None		
26-Sep	None		
27-Sep	None		
28-Sep	None		
29-Sep	None		
30-Sep	None		
2-Oct	Mod		False Alarm

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 17 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 20 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 17: 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 18, 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.

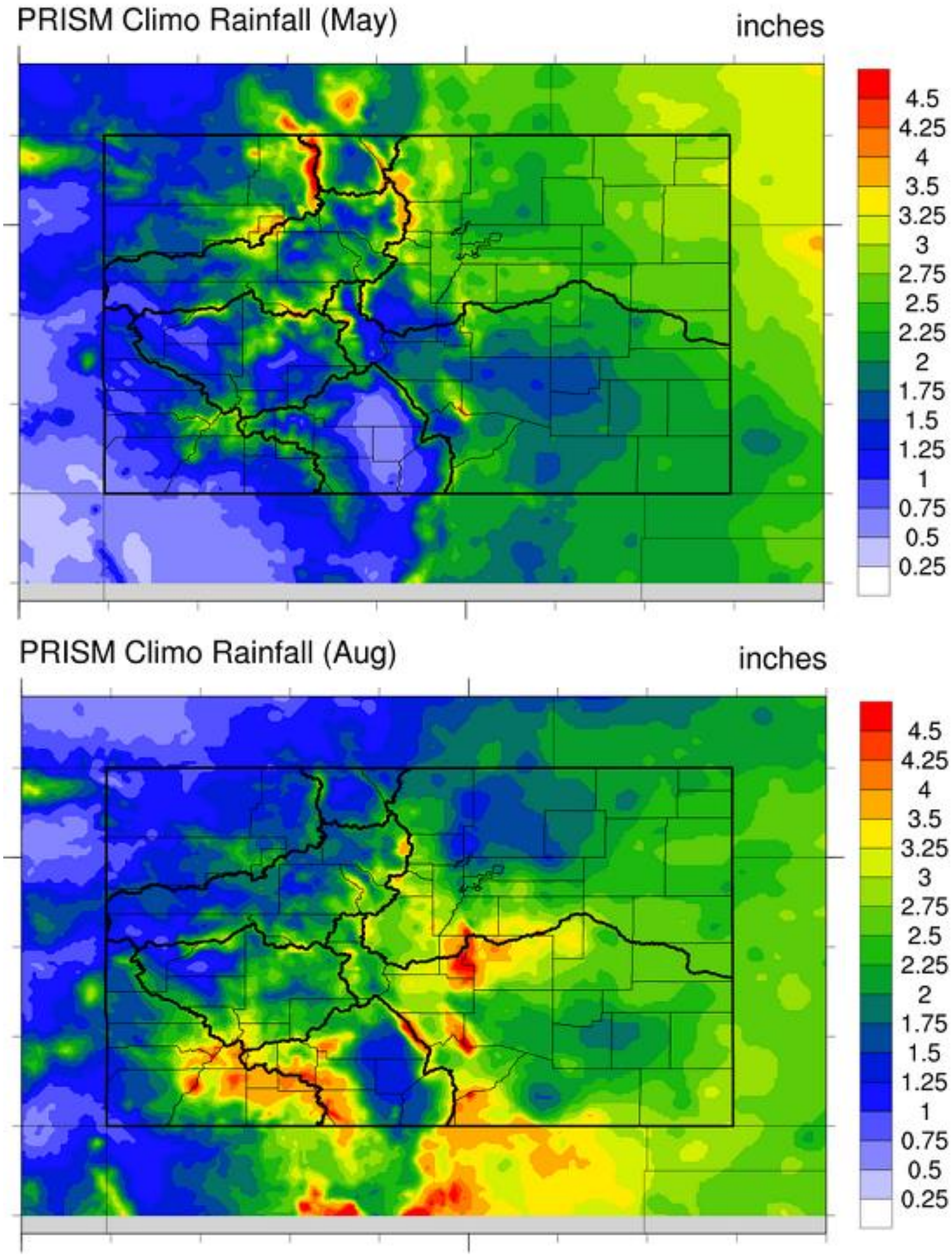


Figure 18: Monthly average precipitation for (top) May and (bottom) August. Source: Oregon State University PRISM group.

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 19 shows the 1-hour Flash Flood Guidance (FFG) for central and eastern Colorado. This product is updated daily by 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 2.75 inches, while over the San Juan Mountains, 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. Surface characteristics play an integral role in the translating the heavy rainfall threat to a flooding potential.

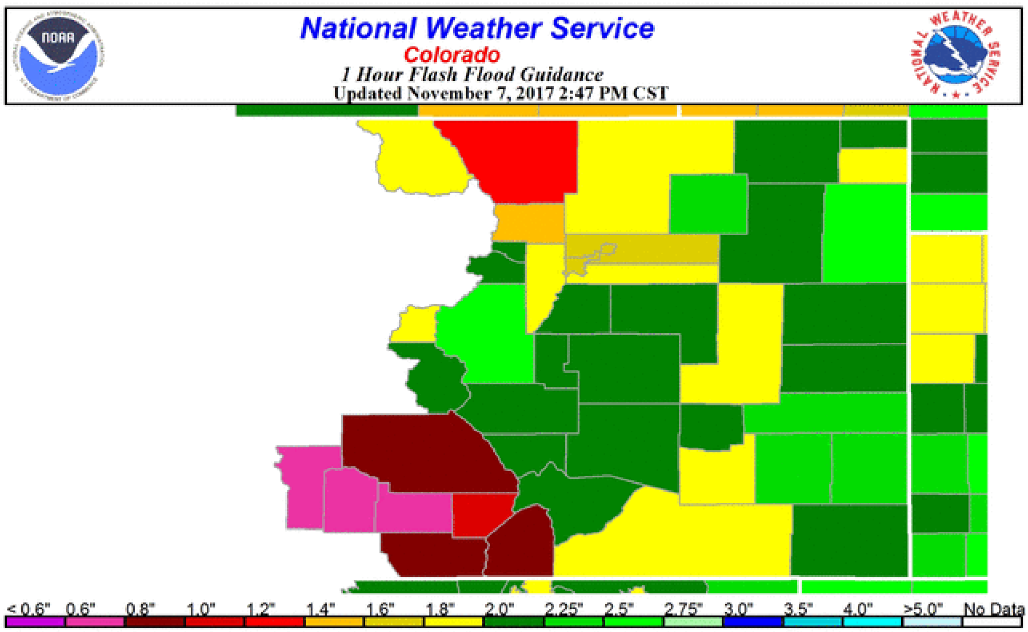
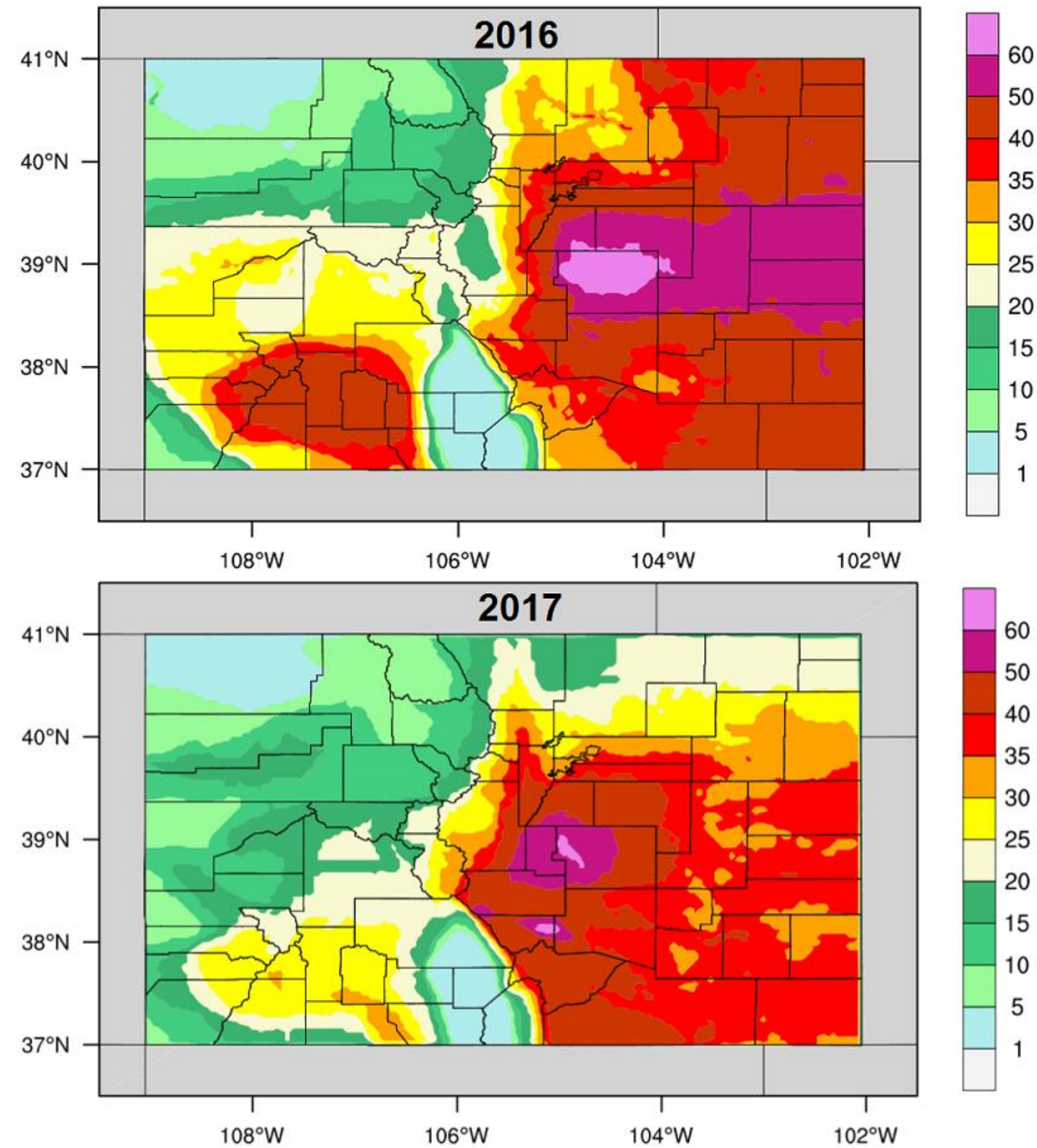


Figure 19: 1-hour Flash Flood Guidance for central and eastern Colorado, valid November 7, 2017. Source: National Weather Service River Forecast Centers.

APPENDIX D – FLOOD THREATS ISSUED

Figure 20 shows the total number of days when a given location was under a flood threat during the 2016 and 2017 (top, middle; for reference) and 2018 (bottom) operational seasons. Note that this does not distinguish the type of flood threat (e.g. low versus moderate). For reference, there are normally 153 days during the forecast season with 154 days during 2018.



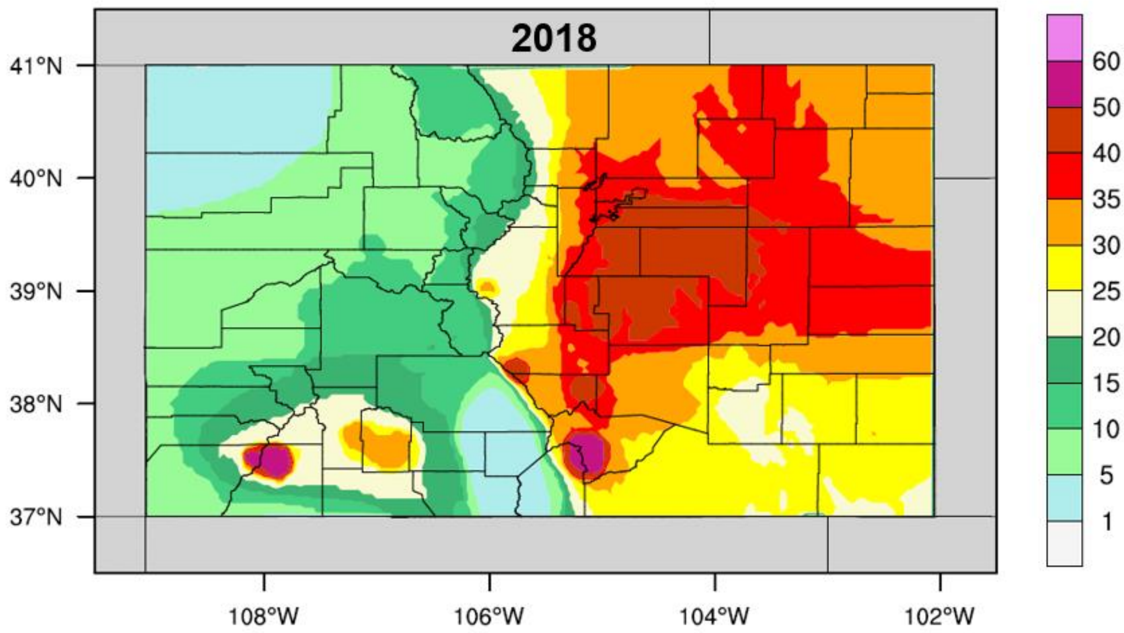


Figure 20: Number with days with a flood threat during (top) 2016, (middle) 2017 and (bottom) 2018.