# An Assessment of Weather and Climate Monitoring Systems in Colorado

## "Current Systems, Gaps, and Future Needs"

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In collaboration with the, National Weather Service, Colorado's Emergency Management Communities and other users of Colorado's weather and climate data resources

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Finally, thanks to Colorado State University's Samantha Mayhew and Richard Batman for keeping up with the financial management of this project to meet all of the State's many detailed reporting requirements

**Executive Summary**

Colorado State University has completed a two year study assessing weather and climate monitoring systems in Colorado. This effort was undertaken through the Hazard Mitigation Grant Program of the State of Colorado, Department of Public Safety, Division of Homeland Security and Emergency Management, in order to identify and prioritize gaps in observations, data collection and dissemination that create public safety concerns for the citizens of Colorado.

Unmistakable progress has been made in the collection and rapid dissemination of critical weather data since the flash flood disaster in the Big Thompson Canyon in Colorado in 1976 and subsequent extreme localized flash floods such as the Fort Collins Flood of July 28, 1997 and the Pawnee Creek flood of July 29, 1997. The number of weather stations has grown several fold, and the speed of data updates have increased so that weather conditions are often now tracked on a 5 to 15 minute update cycle or faster – compared to the historically traditional update cycle of hourly. Weather Radar systems have expanded and been upgraded to improve severe weather detection and rainfall estimation. Webcams have become a go-to source for verification of developing hazardous weather conditions. Social media now complements weather station data as a means of tracking current severe and dangerous weather. Emergency management providers have profoundly benefitted from the exponential growth in data availability since the turn of the millennium.

While improvements in weather emergency-relevant data and dissemination over the past twenty years have been vast, there are still several critical gaps. Radar coverage remains nearly non-existent in south-central and southwestern Colorado. Real time detection and warning for severe weather events in these areas is difficult. Radar coverage exists in the southeast and northeast corners of the state, but not at an adequate level for detecting low-level rotation (tornadoes), and in some cases, blizzards. While Denver and most of the major urban areas of northern Colorado are served by excellent flood warning systems, such warning systems are not, or are no longer in place in the Colorado Springs, Pueblo, and Trinidad areas – cities with flash flooding risks equal to or greater than Denver.

Furthermore, funding streams for the operation and maintenance of current weather data collection sources are not stable. This poses a significant challenge as these data are relied upon in weather emergencies.

Based on these findings, these high priorities emerged:

1. Fund and implement gap filling radar systems to serve the San Luis Valley and southwestern Colorado including Alamosa, Monte Vista, Durango, Cortez, Pagosa Springs and the National Parks and transportation corridors therein.
2. Develop flood warning systems for Colorado Springs initially and Pueblo and Trinidad later.
3. Make sure that CoAgMET (Colorado Agricultural Meteorological Network) provides data to NWS in real time
4. Maintain existing monitoring networks and make sure agency funders know the importance of networks such as RAWS, CAIC, SNOTEL, COOP, CoAgMET, etc.
5. Maintain and improve precipitation monitoring systems and improve accuracy of snowfall and rainfall data.
6. Convene and maintain the Weather Technical Advisory Group to continue this effort and better connect data collectors, data users, program funders and the public safety communities.

Many other lower priority recommendations were made and are listed in the full report.

**Background**

In 2013, prior to the catastrophic September flooding event, the Colorado Department of Public Safety planned the Weather Technical Assistance Partnership (Weather TAP). Kenneth Brink with CDPS headed up this effort and convened the first meeting at Colorado Parks and Wildlife headquarters. A diverse group of weather data users and providers gathered, representing primarily state and federal agencies. Weather TAP was intended to be a semi-formal coordinating committee to inform CDPS.

The flood of September was a temporary interruption to this developing partnership but also illuminated its importance. By mostly coincidence, the flood of 2013 hit on Colorado's most data rich area the urban and near-urban Front Range region. Even so, some potentially critical gaps were noted

The flood of 2013 triggered a FEMA disaster declaration. With more than $2,000,000,000 in total damages and considerable payout of FEMA disaster recover funds, Colorado Department of Public Safety subsequently received 5% of the FEMA disaster payments to support post-flood hazard mitigation activities. Working through Ken and the Weather Technical Assistance Partnership (Weather TAP), a proposal was drafted to utilize Hazard Mitigation Grant Program (HMGP) funds to advance the work of the partnership by conducting a thorough statewide assessment of weather and climate data resources specific to public safety. Then, after documenting data resources, subsequent gaps and critical needs could be identified. Ken took a new job and left Colorado before the project was finalized, but he deserves credit for paving the way. The proposal was officially submitted in 2014. Notification of selection was received in March 2015. Contractual arrangements were completed in May and work began in July 2015.

**The process and timeline**

- Convene a technical advisory group (summer 2015)
- NWS office visits and staff interviews (fall-winter 2015-16)
- CEMA presentations and outreach efforts (spring 2016)
- Needs and Gaps surveys to forecasters, emergency managers, county officials, water providers (summer-fall 2016)
- Inventory of observing systems, networks and station maps (winter-spring 2017)
- Preliminary findings and presentations (fall 2016 – summer 2017)
- Follow up visits to NWS Offices and prioritization of gaps and needs (spring – summer 2017)
- Completion of summary report and distribution to technical advisory group (summer 2017)
- Final report (Fall 2017)

**Current Data Sources**

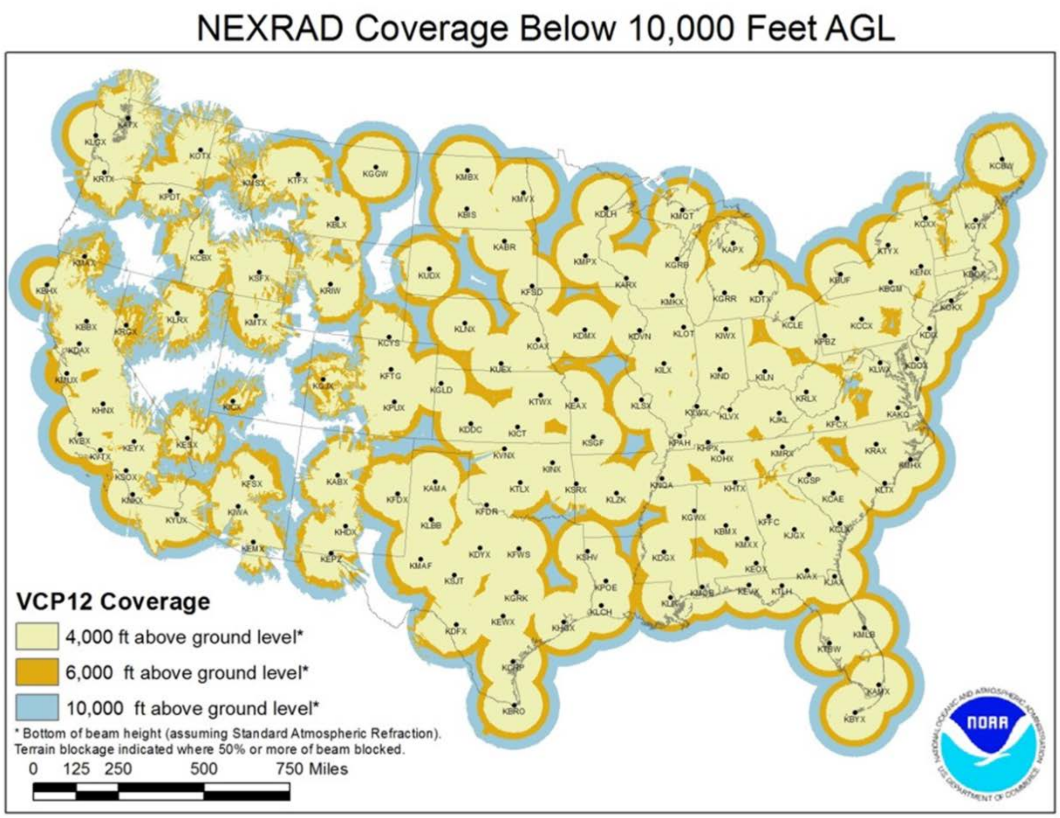
The technical advisory group consisted of Dr. Robert Cifelli with NOAA's Earth Systems Research Lab, Kevin Houck with Colorado Water Conservation Board's Flood program, and Marilyn Gally with the Colorado Department of Public Safety. The group met twice and provided guidance and recommendations on contacting key stakeholders and soliciting input. The group also had the opportunity to review and approve this report before the project was completed.

Information gathering then began in November 2015 with a series of half-day fact finding meetings with the staff and leaders of each of the four National Weather Service Offices serving Colorado (Grand Junction, Pueblo, Boulder and Goodland, KS). Staff availability varied from office to office, but in most cases we were able to interview the meteorologist in charge, the hydrologist, the warning coordination meteorologist, the data acquisition program manager (or staff equivalent) the science and operations officer and one or more senior weather forecasters.

This first round of face-to-face meetings focused on identifying the primary Colorado data sources (not counting satellite data or computer models) used in making weather forecasts, providing and verifying severe weather warnings, and supporting transportation (air and ground) and general public safety.

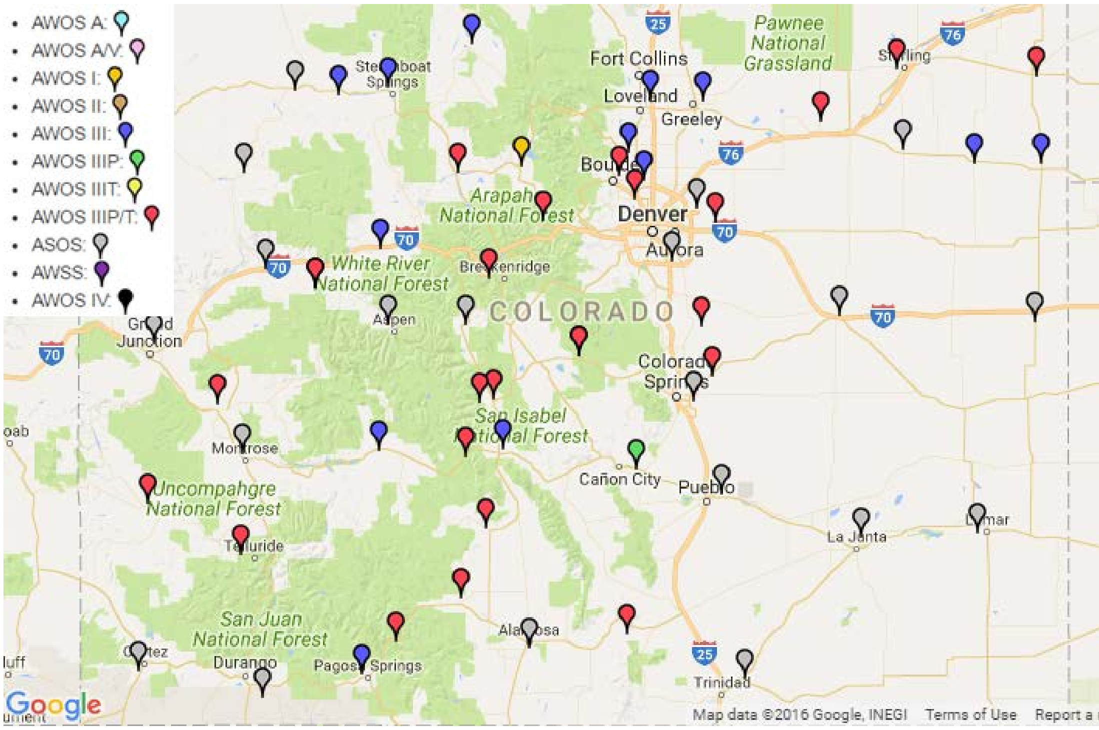
The following data sources were identified. There was some variability from office to office depending on population and geography, but many responses were similar:

- NEXRAD radar system - Radar is the most highly used single source of information using the reflection of microwaves off of precipitation particles to track storms in real time. Radar has many operational advantages but does not provide consistent uniform coverage, especially in mountainous areas and in areas with little radar overlap.



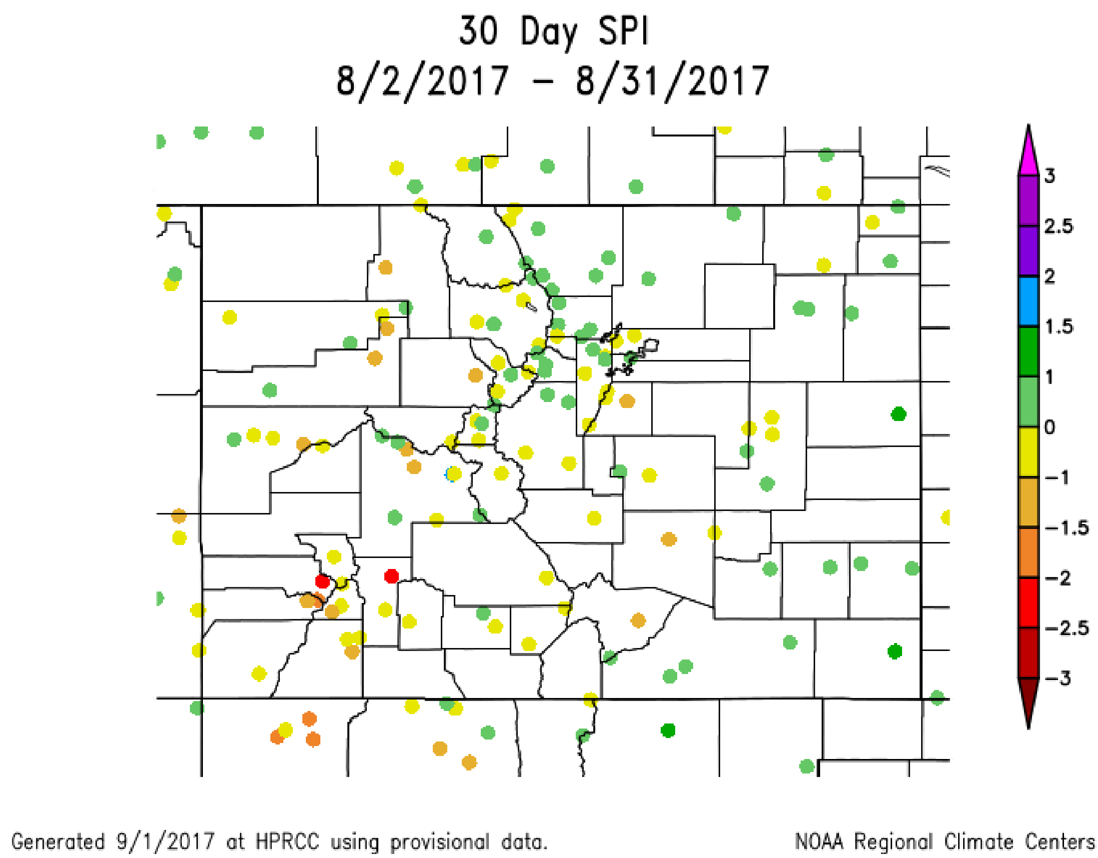

*The United States map above illustrates National Weather Service radar coverage in the United States. Tan-shaded areas are covered by radar beams within 4,000 feet elevation of ground level. Orange-shaded areas are covered by beams within 6,000 feet of ground level. Gray shaded areas are covered by beams within 10,000 feet of ground level. Unshaded areas are not covered by radar.*

- Automated Airport weather station – These stations are FAA-owned and NWS maintained ASOS, other owned ASOS, AWOS (various levels). These stations report temperature, wind speed, visibility, precipitation, and sky condition data in near real time. We learned that the instrumentation, data quality and maintenance can vary considerably depending on ownership.




*The Colorado map above shows the locations of Federal Aviation Administration (FAA) Automated Weather Observation Stations (AWOS). For more information on the different types of AWOS please refer to https://www.faa.gov/air_traffic/weather/asos.*

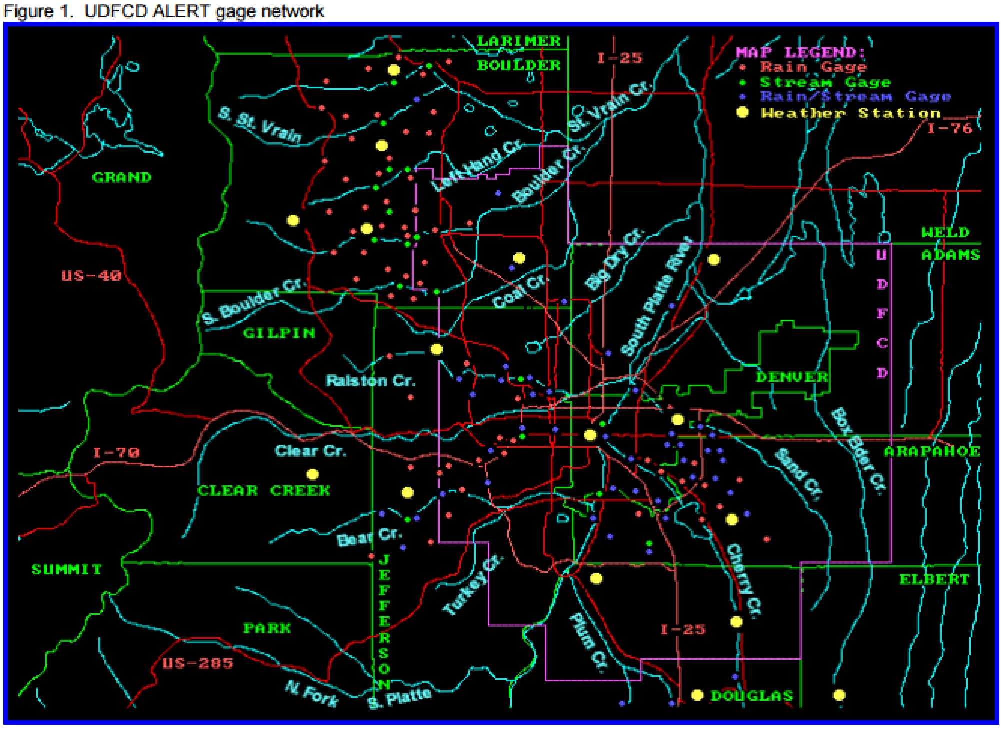
- NWS Cooperative Observer Network (COOP) – COOP is the Weather Service's flagship data source for long-term (since 1880s) temperature and precipitation information. These data are our best shot at accurately measuring long-term climate trends. Operation and maintenance of the COOP network has historically been underfunded.



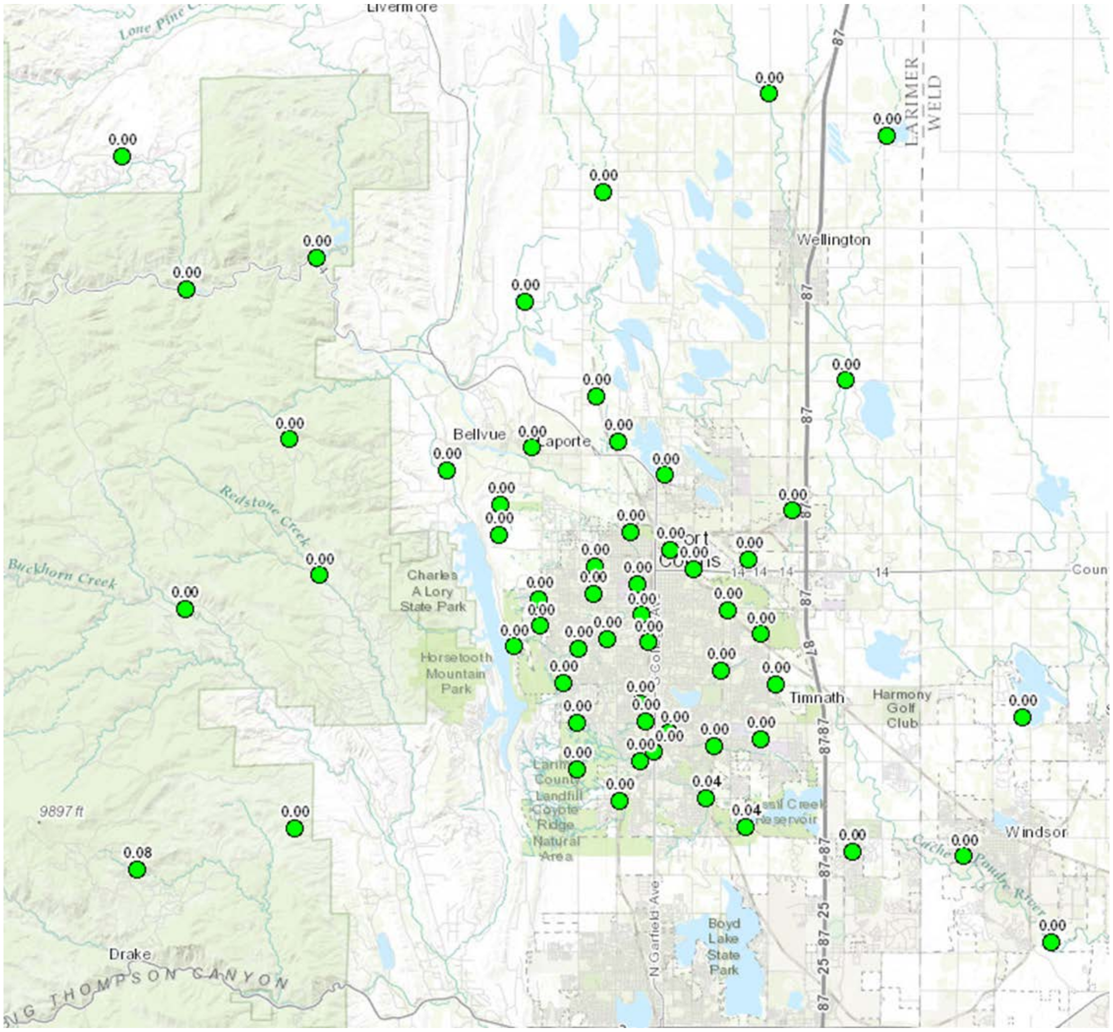

*The Colorado map above shows standardized precipitation index values for Cooperative Observing Networks (COOP) stations from August 2nd, 2017 through August 31st, 2017. This map was added as an indication of how many COOP stations are currently active.*

- Flood Warning Systems (Urban Drainage Flood Control District and Fort Collins ALERT network) – Flood warning systems in the Denver and Fort Collins metro areas couple real-time rainfall and stream gage data. These data are an extremely valuable source for the National Weather Service in issuing timely and accurate flood warnings in highly populated areas.

Figure 1. UDFCD ALERT gage network

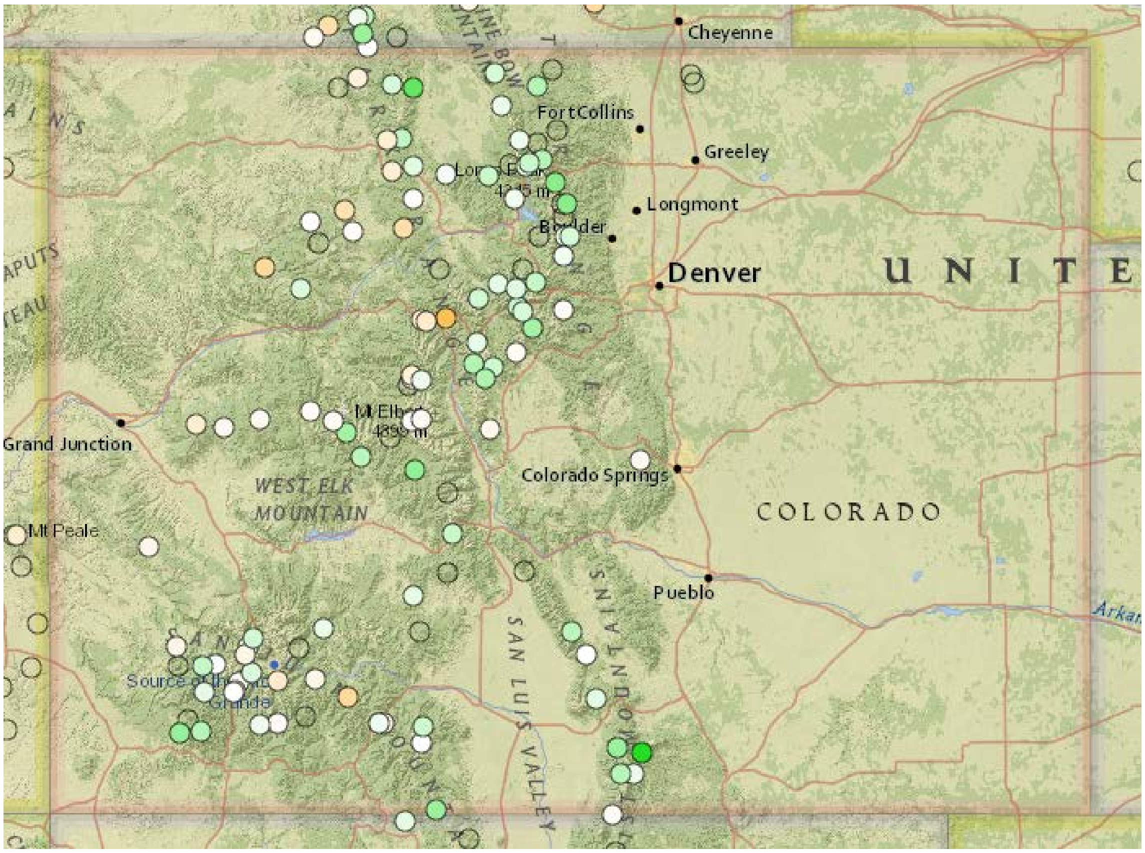



*The map above shows all locations of the Denver metro area's Urban Drainage Flood Control District. Red dots represent automated rain gauges. Green dots represent automated stream gauges. Blue dots represent collocated automated rain gauges and stream gauges. Yellow dots are full automated weather stations.*



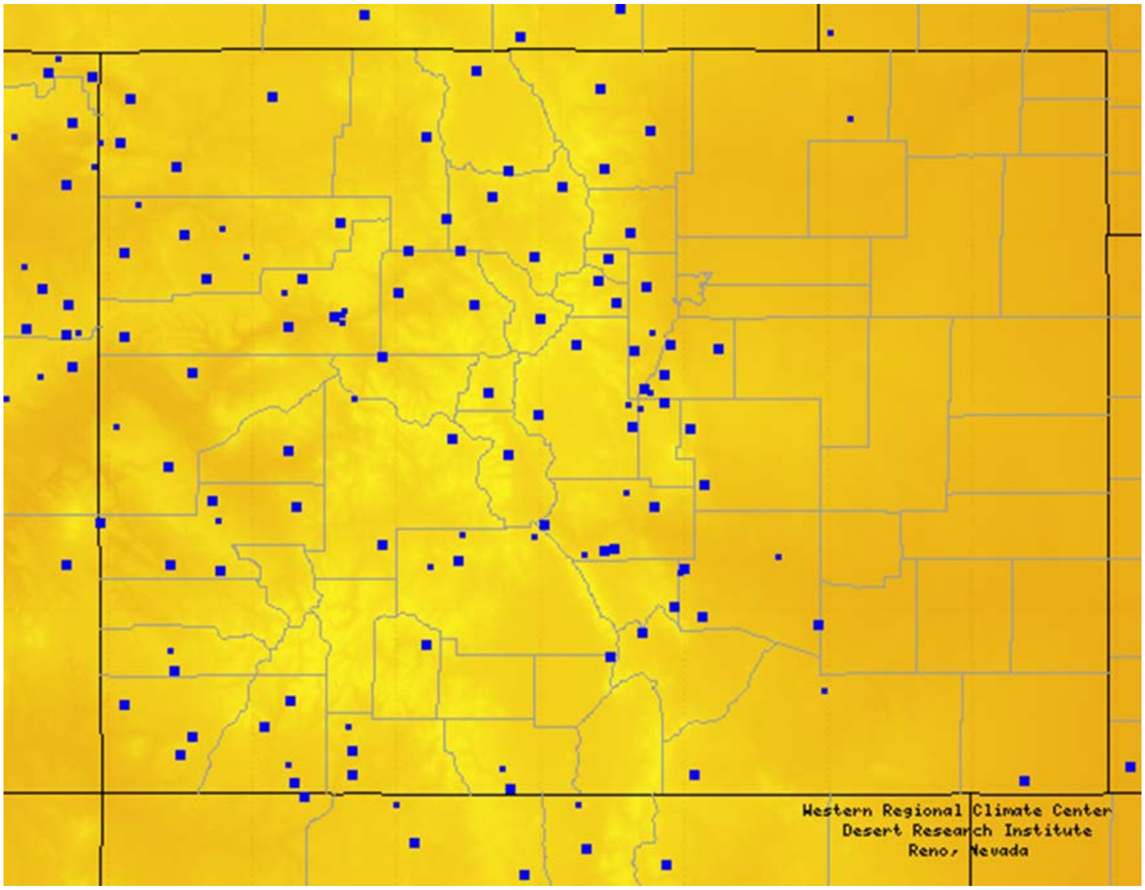

*The map above shows the locations of automated rain gauges in the Fort Collins ALERT network.*

- SNOTEL – This network provides precipitation, snow accumulation, water content and some supporting meteorological information for primarily moderately high elevation in-forest mountain areas typically at elevations between 8,000 and 12,000 feet. New data are available hourly, but are preliminary and subject to additional quality control at that point. SNOTEL stations are located in areas which are otherwise sparsely monitored by radar or other weather networks. SNOTEL data assists NWS Weather Forecast Offices in verifying forecasts.



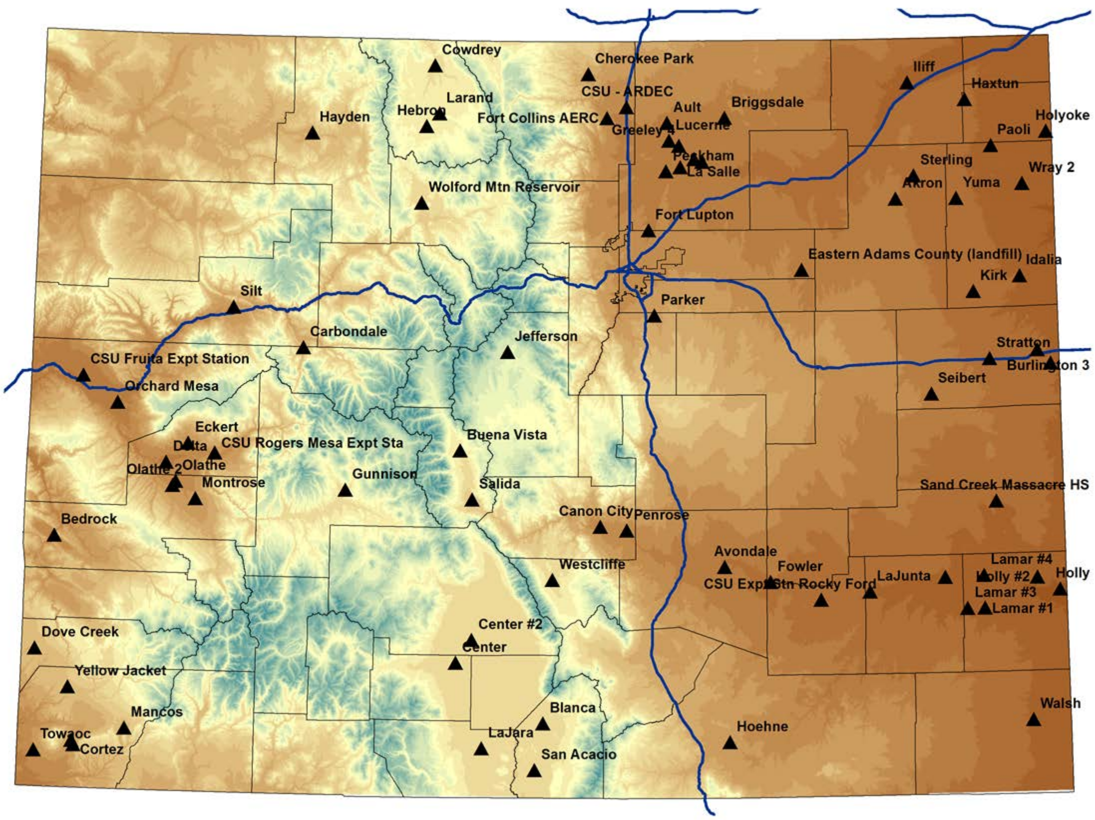

*The Colorado map above shows the locations of Colorado Snowpack Telemetry (SNOTEL) automated weather stations. Each dot represents one station. The dot shading represents percent of normal precipitation for a given time frame, but is not relevant to this report.*

- Remote Automated Weather Stations (RAWS) – These stations provide basic weather data for sparsely populated public lands in support of fire weather prediction and fire management. Communication occurs via satellite and stations are predominately located in western half of Colorado.



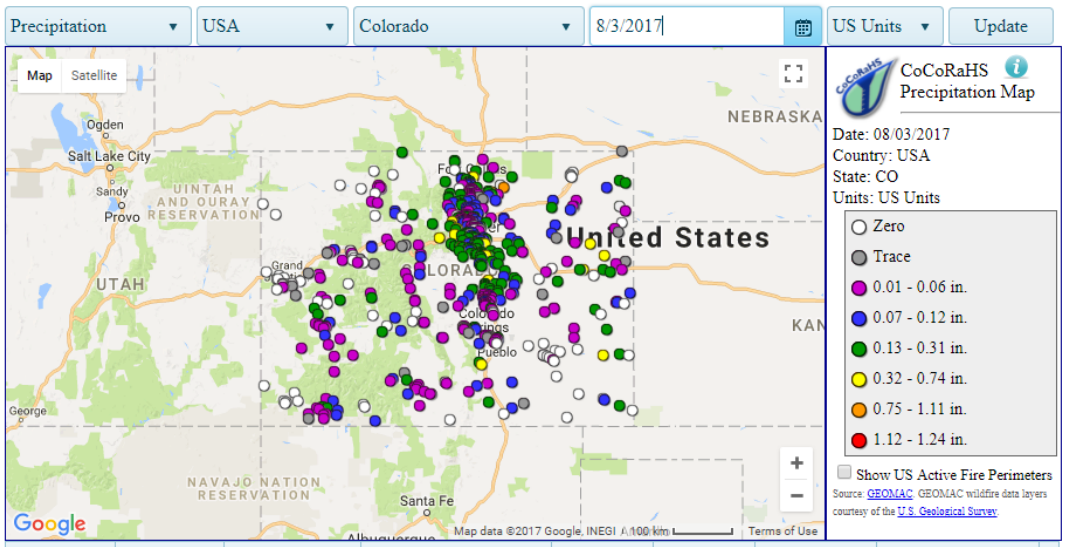

*The Colorado map shown above indicates the locations of Remote Automated Weather Stations (RAWS) . Large blue squares represent currently active stations. Small blue squares represent previously active stations.*

- Colorado State University's Agricultural Meteorological Network (CoAgMET) - This is a network of 75 surface weather stations (and growing) primarily situated in irrigated agricultural areas of the state  with instrumentation mounted closer to the ground (especially wind measurements) to represent plant canopy.  Data communication is being upgraded from hourly intervals to five minute intervals. The National Weather Service are receiving these data in real time as of 2017.



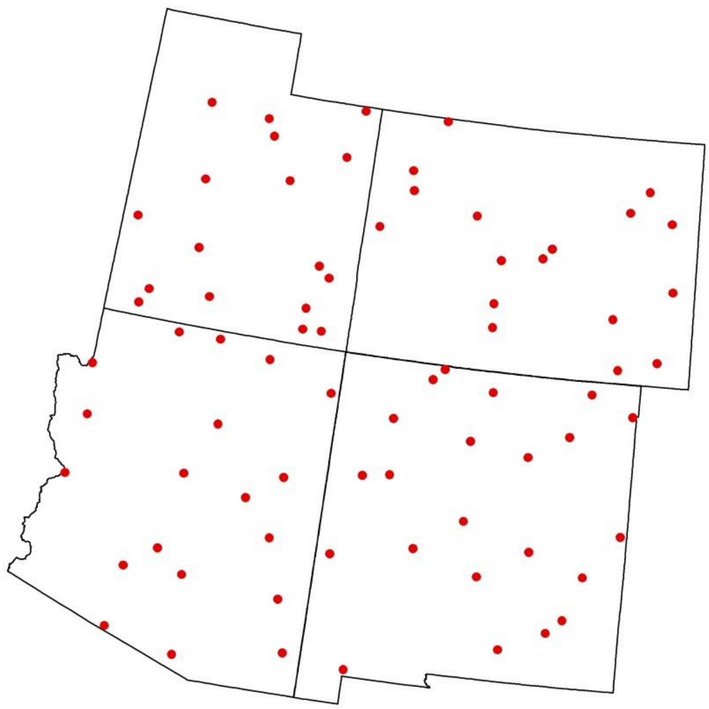

*The Colorado map above indicates the locations of all Colorado Agricultural Meteorological Network (CoAgMET) weather station locations.*

- Community Collaborative Rain, Hail and Snow network (CoCoRaHS) – Citizen scientist take rainfall measurements in their backyards once daily. There are approximately 1100 active observers in Colorado as of September 2017.



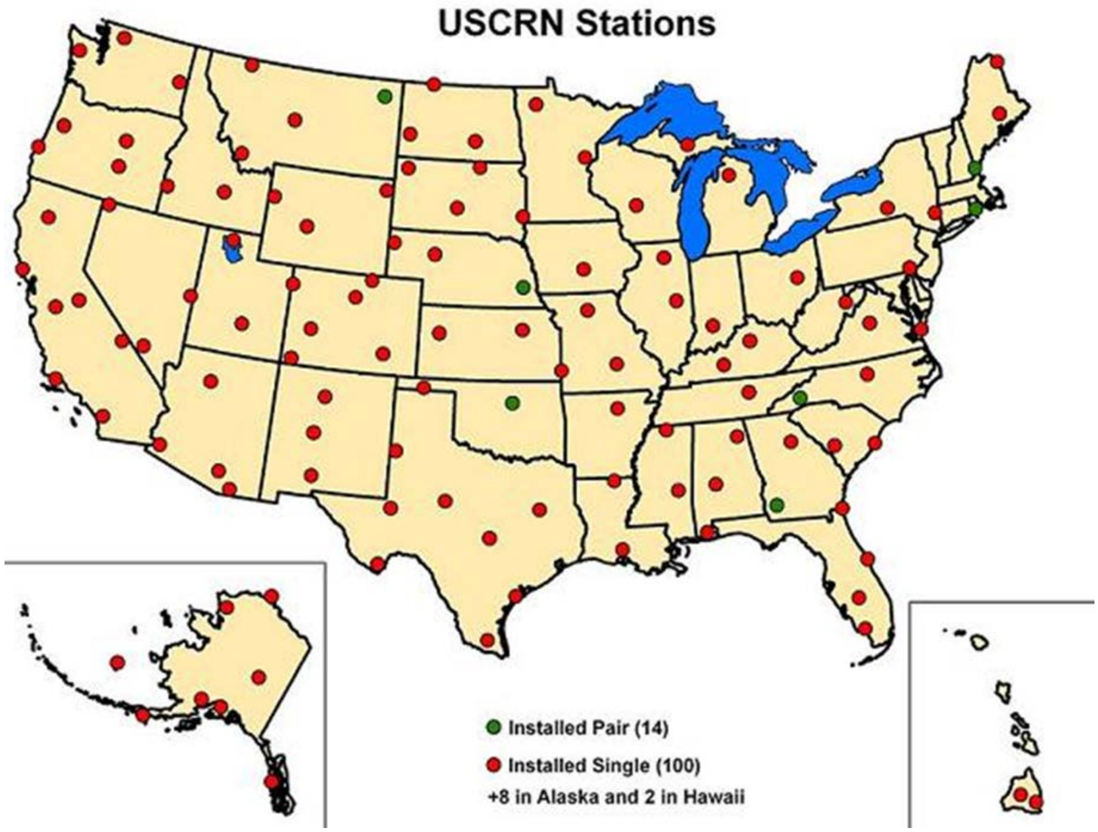

*The Colorado map shown above gives daily rainfall total reports from the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS) for August 3rd.*

- Regional Climate Reference Network - This network consist of 17 high quality temperature and all-weather precipitation measurements communicating via satellite. They were originally installed and operated for the National Weather Service, but defunded and turned over to Colorado State University.



*The map of the Four Corners region above shows the location of Regional Climate Reference Network (RCRN) stations.*

- Climate Reference Network – There are six high quality weather stations in pristine natural environments being operated by NOAA. These stations are designed to be the future state-of-the-art for long-term Climate monitoring. Communications occur via satellite.




*The United States map above shows locations of all United State Climate Reference Network (USRCN) weather stations. Red dots represent single weather station locations. Green dots indicate that a pair of stations have been installed.*

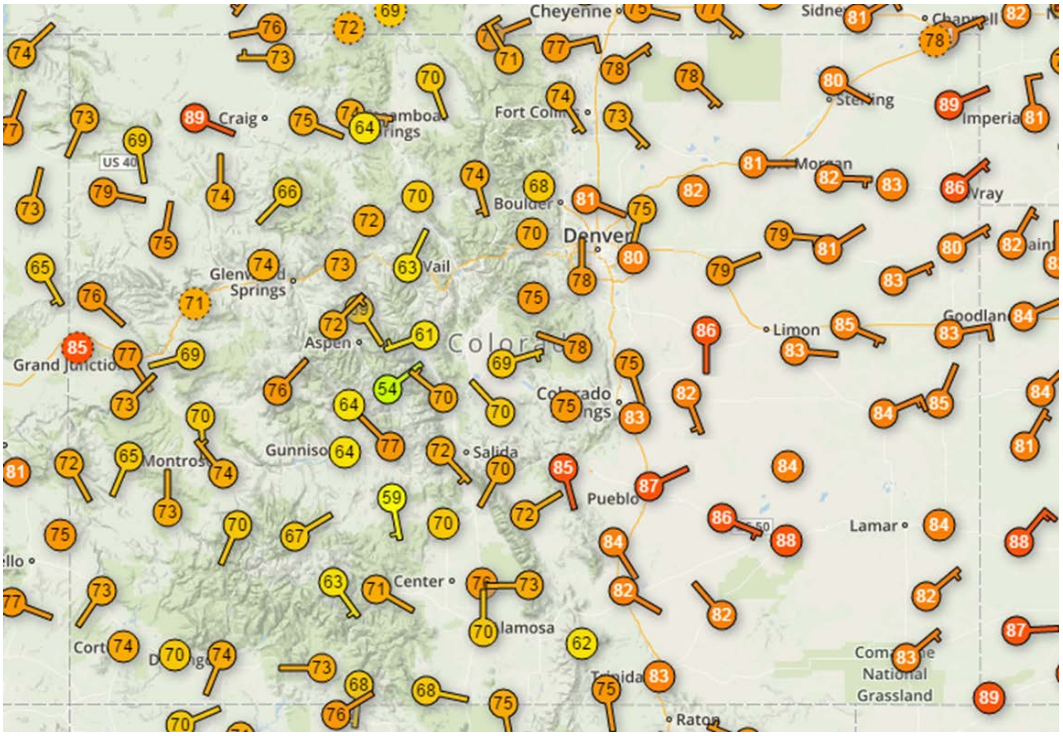
- Hydrometeorological Automated Data System HADS – HADS has a larger role as a data integrator than data collector. HADS has a network of Fischer Porter precipitation gauges primarily in the Upper Colorado River Basin. These stations communicate by satellite and maintained at least partially by NWS.
- Colorado Avalanche Information Center (CAIC)  - This is a specialized network of weather stations from avalanche prone high elevation sites. The Colorado Avalanche Information Center has a larger role in integration of data collected from other sources than in direct data collection, but the network does operate twelve of its own stations. Over half of these are in the San Juans. CAIC weather stations collect an impressive breadth of temperature, humidity, wind, precipitation and snowfall information.
- CDOT roadway weather stations – Automated temperature, wind speed, and precipitation readings are collected at a total of nearly 150 weather stations across Colorado. These stations are collocated with highways to give up-to-date road condition information.
- CDOT aviation mountain pass automated stations – These stations are critical locations for supporting private aviation, but maintenance difficult and sometimes low priority.

- Webcams (CDOT, Ski area, Viaero and many others)  - We learned the reliance NWS forecasters have learned to place on webcam imagery for assessing onset and ending of storms (snow, heavy rain, fog, etc) and accumulation of snow and overall traffic impacts)  All 4 NWS offices had very well developed webcam imagery management systems to streamline access and viewing.

*The image above comes from a Colorado Department of Transportation webcam in January 2017.*

- Railroad observing system – These weather stations are put in place to keep railroad travel safe. Unfortunately only the temperature data are shared with the National Weather Service.
- NWS Skywarn volunteer spotter network – The National Weather Service holds seminars in which members of the public can receive official weather spotter training. These weather spotters call in conditions in their immediate area to the National Weather Service. Their input is used to issue and verify severe weather warnings.

- Consumer-grade home weather stations (WeatherUnderground, Citizen Weather Observer Program, SchoolNet systems etc) - Data resolution from backyard weather stations such as Weather Underground is unbeatable. There are over 250,000 Weather Underground stations reporting online. Quality of the data is highly variable.



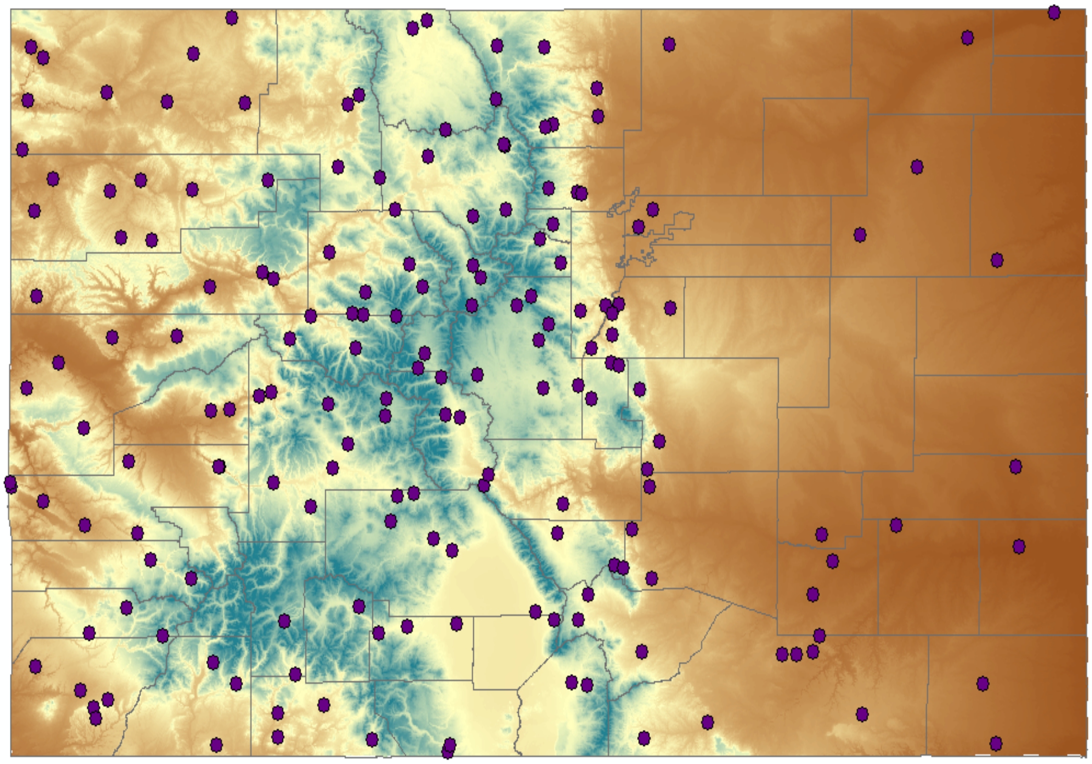

*The image above shows Weather Underground sites on an afternoon in September, 2017. This image does not represent the full resolution of Weather Underground data. Upon zooming in (https://www.wunderground.com/wundermap) one sees more detail.*

- mPING – This data source is a mobile application designed for observers to report the precipitation occurring at their current location. It is easy to use, but reports don't include only information about precipitation type, and not duration or intensity.

Data Integrators

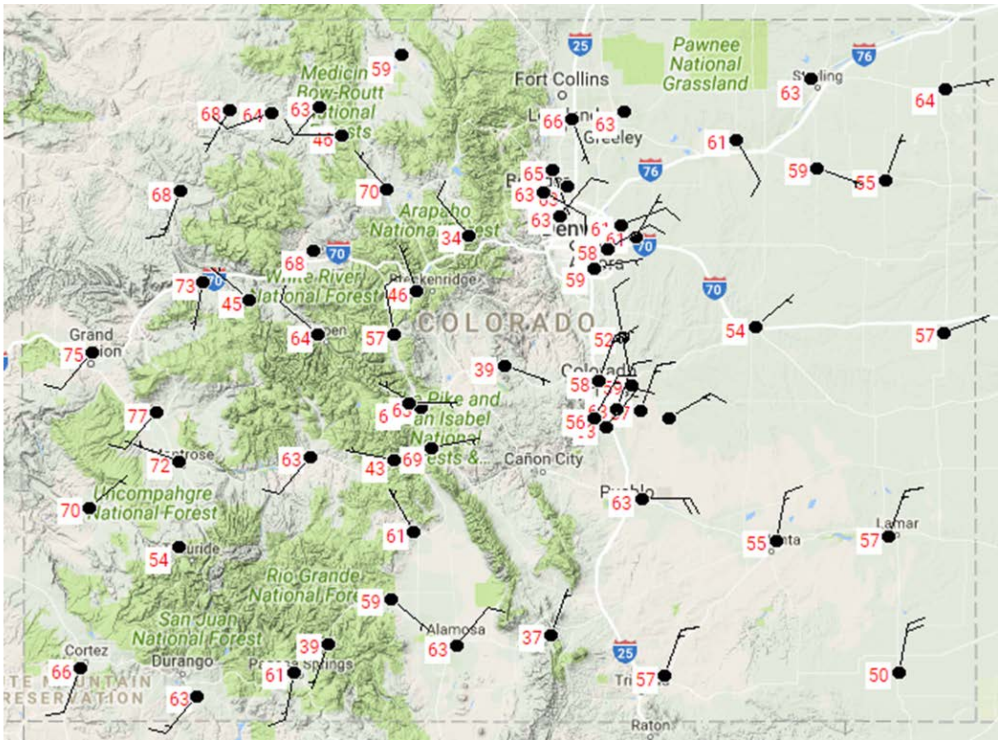
- CAIC – While the CAIC does have twelve of its own stations, its primary role is to use weather stations from a number of networks in order to create the best possible avalanche forecasts. Primary sources for weather data include SNOTEL, RAWS, ASOS, UDFCD, CODOT, and participating private ski resorts.

- HADS – The National Weather Service proclaims HADS a “real-time and near real-time data acquisition, processing, and distribution system operated by the National Weather Service Office of Dissemination. The system exists in support of National Weather Service (NWS) activities of national scope, specifically the Flood and Flash Flood Warning programs administered by the Weather Service Forecast Offices and the operations performed at River Forecast Centers throughout the United States.” This system integrates data from networks such as RAWS, USGS, the State of Colorado Division of Water Resources, Upper Colorado Network, and SNOTEL in Colorado primarily for the purpose of flash flood monitoring.



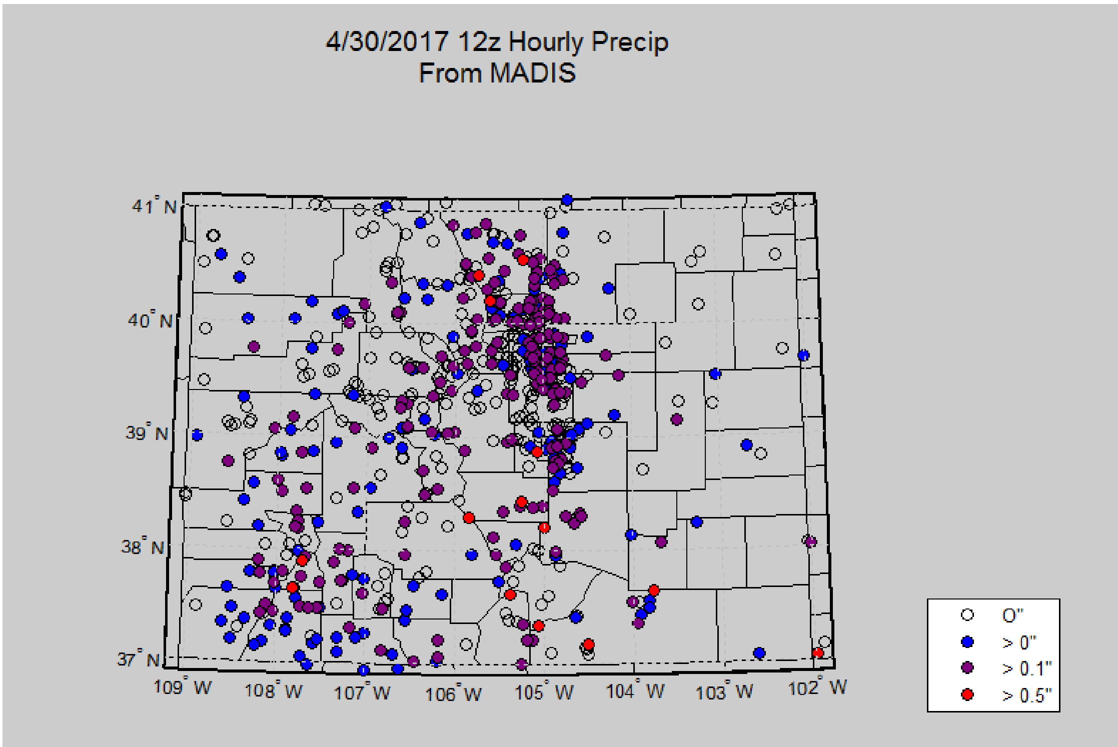
*The map of Colorado above shows the locations of sites in Colorado integrated in HADS (purple).*

- Meso West – Meso West is an operational data integration system with a friendly user interface. This site displays real time temperature, wind, and precipitation data.



*The map of Colorado above is a screenshot from www.mesowest.org. It shows weather station temperatures and wind speeds. Data shown here are actually AWOS stations, but Meso West has additional layers to incorporate other networks such as RAWS and SNOTEL.*

- Meteorological Assimilation Data Ingest System (MADIS) – The National Oceanic and Atmospheric Administration NOAA runs a massive data ingestion, integration, and redistribution system known as MADIS. Many of the data collection networks above, as well as satellite and numerical model data providers, have data funneled through MADIS. The National Weather Service uses this data service extensively.




*The Colorado map above shows an example of the MADIS mesonets product from April 30th, 2017*

**Assessing data needs of the Emergency Management community**

In March, 2016, Nolan Doesken was given a speaking opportunity at the Colorado Emergency Managers Association annual meeting in Colorado Springs. This data assessment project was described, and input from emergency managers on their data gaps and needs was gathered. A shared booth space with the National Weather Service Warning Coordination Meteorologist provided opportunity for follow up one-on-one discussions with emergency managers.

Nolan Doesken and Peter Goble visited the National Weather Service Forecasting Offices in Boulder, Colorado, and in Goodland, Kansas. Nolan Doesken and Peter Goble also participated in conference calls with National Weather Service Forecasting Offices in Pueblo, Colorado and Grand Junction, Colorado. The purpose of these calls was to determine fundamental gaps in weather data collection and dissemination for emergency weather situations. These meetings revealed a wish list of novel means of tracking and disseminating real-time weather information in the state of Colorado. These needs will be listed below in order of priority. The needs will be ranked using a three-tiered system where tier I needs are essentials, tier II needs are optimal, and tier III needs are desired for fully functional emergency management operations. Bear in mind that Needs and gaps are a function of season and situation – winter storms and snowmelt floods are much different than spring dust storms, wild fire, flash floods.

Tier I

1. Radar for real time weather surveillance for southwest Colorado – Lack of radar coverage due to range limitations and beam blockage poses significant challenges to NWS Grand Junction for detecting weather events pertinent to warning decisions. Weather forecasting/nowcasting of serious storms in areas of beam blockage is increasingly dependent of weather spotter reports, which may be limited in information or give little to no early warning. Lack of radar-estimated precipitation may also limit the value of quantitative precipitation forecasts.
2. Radar for real time weather surveillance for the San Luis Valley - Lack of radar coverage poses significant challenges to NWS Pueblo for issuing timely tornado, flash flood, and severe thunderstorm warning. Lack of radar-estimated precipitation may also limit the value of quantitative precipitation analyses and forecasts.
3. Flood Warning Systems for Colorado Springs, Pueblo, Trinidad, and the Big Thompson – The Denver Metro Area and Fort Collins, Colorado both benefit from an array of strategically-placed rain gauges and stream gages that update by the minute. These gauges played a critical role in the emergency management procedures of the September 2013 floods. Colorado Springs and Pueblo are population centers of 455,535, and 108,981 respectively, and both have the potential for flash flooding. Colorado Springs is at climatologically greater flood risk than Denver or Fort Collins, particularly during July and August. These flood warning systems lead to timely, informed decisions with lifesaving potential. Trinidad and the Big Thompson Canyon are home to a smaller population, but are locations of notable deadly flash flooding potential. Steven Kuhr, Manager of Emergency Management Operations in Colorado Springs writes "in Colorado Springs and surrounding communities we have a need for better access to stream/river/rain gauge data to evaluate flood potential, forecasting, and actual conditions. This is critical for life safety-oriented emergency operations planning, evacuation planning and activation, activation of emergency warnings, and impact on critical infrastructure such as electric transmission/distribution, water mains, wastewater mains, and gas mains at creek crossings and alongside stream beds."

Tier II

1. Radar for real time weather surveillance for southeast Colorado – Southeast Colorado is covered by radar, but only above 10,000 ft elevation. This is sufficient for tracking widespread rain and large thunderstorm complexes, but is often times insufficient for detecting winter precipitation, and is absolutely insufficient for properly tracking low-level rotation in tornadic events that may endanger locations such as Springfield, Campo, or Walsh.
2. Radar for real time weather surveillance for northeast Colorado - Northeast Colorado is covered by radar, but only above 10,000 ft elevation. This is sufficient for tracking widespread rain and large thunderstorm complexes, but is often times insufficient for detecting winter precipitation, and is absolutely insufficient for properly tracking low-level rotation in tornadic events that may endanger locations such as Sedgewick and Julesburg.
3. Real time snowfall data – Automation of snowfall measurement is difficult, which makes real-time snowfall measurements regrettably scarce. This often leads to road hazards as snowfall rates are difficult to track in real time, particularly for areas where radar coverage is absent or too high to detect low cloud formations. Upgrading a network such as SNOTEL, CoAgMET, or

RAWS, and feeding that information though MADIS, would go a long way towards making these threats easier to identify.

4. Additional real time precipitation and stream gauges – The NWS has plenty of capability for ingestion of high volumes of data. Because precipitation is often so highly variable in space and time during emergency events, higher resolution automated precipitation and stream gauges are still in demand. This is especially true for population centers.
5. Middle elevation weather stations – ASOS and COOP stations are largely concentrated in population centers, which most sufficiently sample the valleys of mountainous areas. SNOTEL stations are sited with the number one priority of measuring seasonal snowpack. These sites are often placed in subalpine or alpine zones between 9,000 and 11,000 feet. The montane zones that often lie between the mountain valleys and alpine zone are sampled to an extend by RAWS, but are under sampled with respect to lower and higher elevations.
6. High elevation ASOS – The only automated stations that give hour-by-hour snowfall readings are ASOS stations. Again, these stations tend to be around airports, and not on top of mountains. Snowfall in the mountains is difficult to estimate via radar as it is often prevented by beam blockage.
7. Upstream wind profilers – One common weather hazard in Colorado is downslope wind gusts. Impacts from these events are usually benign, but not always. Downslope wind events can lead to dangerous driving conditions, blown down trees and fences, and airborne debris. The National Weather Service in Boulder would be able to make use of upstream (to the west) wind profilers to help forecast and warn these downslope wind events.
8. 10-meter wind towers – Additional 10-meter wind towers would help standardize wind observations. Moving towers to 10 meters moves the sensor out of the surface friction layer of the atmosphere near the ground and would help with tracking high wind events. Data request for 10-meter wind speeds are common. The wind data from sources such as CoAgMet is of very limited value to NWS analysis and forecasting because it is at a nonstandard height. Aside from the unlikely instance of catching a severe wind gust at the shorter level of the instrument, this data is lost. In a similar way, the value of the vast amount of wind data from home weather stations is also compromised, chiefly because of nonstandard exposures due to rooftop installations and blocking from nearby buildings and trees. This gives a low bias and makes the data non-representative of the open air flow and not comparable with standard meteorological observations. They cannot be used for ingest into NWS analysis and forecast operations. Networks such as CoAgMet, which offer good siting and existing communications and data processing, represent a good opportunity to add wind sensors in many areas that lack usable wind observations.
9. Additional SNOTEL stations on the Roan Ridge and Uncompahgre Plateau and west Elk Range– SNOTEL snowpack measurements are used to forecast streamflow and appraise drought conditions. The Roan Ridge and Uncompahgre Plateau regions were cited by NWS Grand Junction as being under sampled relative to other high elevation locations.
10. Enhancements to SNOTEL network – SNOTEL is not currently set up to measure snowfall, or give snowfall and snowpack measurements in real time. Improvements to current SNOTEL infrastructure would benefit Boulder, Grand Junction, and Pueblo offices.
11. Additional RAWS in the Rio Grande National Forest – The Rio Grande National Forest in southern Colorado has less RAWS station coverage than any other national forest in Colorado. Additional RAWS stations in the area would play an important role in fire weather situations.
12. A rain ready reserve of rain gauges to deploy in burn-scarred areas – Soils become nearly impermeable following a fire. Burn scarred regions are at increased risk of flash flooding as a

result. WFOs need some automated gauges on retainer that could be installed following fires. These gauges would be used to improve flash flood watches and warnings.

13. COOPS Sites with Some Automation – There is desire to have standardized data available in real time at existing observation sites, such as COOP stations. These sites are suitable locations with some infrastructure and are visited regularly, but the method of communicating the data in real time is not established. Many of these sites would also be great for wind observations.

Tier III

1. Additional CoCoRaHS participants – One of the greatest sources for improving flood warning and flood analysis during the 2013 floods was the Community Collaborative Rain, Hail, and Snow Network (CoCoRaHS). Hail reports and significant weather reports from CoCoRaHS can be used by the national weather service to issue and confirm watches and warnings.
2. Webcam data – Colorado Department of Transportation webcams have become an essential part of National Weather Service operations in Colorado. Sometimes being able to see current conditions around the state is even more beneficial for forecasting and nowcasting than seeing weather data.
3. NWS COOP for drought/long-term climate and snow documentation – The Cooperative Observing Network is the flagship source of long-term, station-based, climate data in the United States. Some areas in Colorado do not have an operational coop station. It is recommended that coop stations be reinstated for Longmont, CO and Wolf Creek Pass, CO. Other coop-sparse locations in Colorado include eastern Adams and Arapahoe Counties and Moffat County.
4. Additional weather station coverage in National Parks – Rocky Mountain National Park received more visitors in 2016 than any previous year. 4,517,585 people visited the park. Public safety challenges are different for out of state tourists than residents who know the local trouble spots. More weather stations in national parks will help monitor these threats.
5. Colorado Avalanche Information Center sites for the Wet Mountains and Sangre de Cristos – The CAIC's role has been outlined above as a data collection source and an integrator. There is a dearth of CAIC-specific weather stations in the Wet Mountains and in the Sangre de Cristos.
6. Additional ASOS in Cañon City – The National Weather Service in Pueblo has requested an additional ASOS station in Cañon City to meet their operational forecasting needs.

**Opportunities:**

National Mesonet program – Operation and maintenance costs will be a challenge in future years for some, if not all, of the data sources identified above as essential to modern National Weather Service emergency scenario operations. The National Mesonet program does provide funding for operation and maintenance of weather stations provided that these stations be incorporated in the overarching umbrella of the National Mesonet. The Colorado Agricultural Meteorological Network (CoAgMET) has secured some funding through this partnership.

Colorado Water Conservation Board Construction fund – The CWCB provides policy direction for the many water issues that face Colorado. This group puts together a construction fund every year to advance its mission of prudent water resource management in Colorado. Becoming integrated with this construction fund in future years may provide a symbiotic pathway for filling some of the high priority data gaps identified by this report. Flood warning systems in Colorado Springs and Pueblo would fit well with both the missions of the CWCB and FEMA.

A strong, organized, and politically active group in San Luis Valley is working to support Radar there. Similar efforts are needed in southwest Colorado.  Southeast and northeast Colorado would also benefit from additional radar coverage. The CWCB water forecasting partnerships authorization within the CWCB Construction Fund Bill has had funding for data needed for snowpack, hydromodeling, and gap filling data like SNOTEL and SNOTEL lites since 2016.

Colorado Department of Transportation – The Colorado Department of Transportation will have to be partnered with in order to change or upgrade current webcam infrastructure. CDOT will be an important partner in releasing weather information to the public during emergency situations. CDOT's signs on major roadways can be leveraged for communicating important weather safety messages such as "Flash flood potential. Turn around. Don't drown."

Federal Emergency Management Agency Hazard Mitigation Grant Program – A small amount of money from this data gap analysis study may still be available for funding projects that fill data gaps outlined in this report.

**Conclusions:**

The Colorado Climate Center of Colorado State University, in conjunction with partners in the Colorado Department of Public Safety, Colorado Water Conservation Board, and National Weather Service of Boulder, Goodland, Grand Junction, and Pueblo concludes that the state is evolving to better meet the weather-related public safety needs of the citizens of Colorado. Unmistakable progress has been made in the collection and rapid dissemination of critical weather data since the flash flood disaster in the Big Thompson Canyon in Colorado in 1976 and subsequent extreme localized flash floods such as the Fort Collins Flood of July 28, 1997 and the Pawnee Creek flood of July 29, 1997. Despite the level of progress made, the National Weather Service Offices of Boulder, Goodland, Grand Junction, and Pueblo did point to a number of remaining weather data collection gaps. Filling these gaps has life-saving potential.

It is recommended that weather radar coverage gaps in southern and southwest Colorado be filled, and a functional flood warning system for Colorado Springs be implemented first and foremost. It is recommended that a funding source be procured to keep data collection efforts such as ASOS, SNOTEL, RAWS, CoAgMET, and the Urban Drainage Flood Control District afloat in times of scarce operation and maintenance funding. Once these recommendations are met, it is recommended that data gaps addressed in this report be filled in order from tier one to tier three importance.

The Colorado Climate Center once again thanks Kenneth Brink and the Department of Public Safety, The Colorado Emergency Managers Association, and the National Weather Service for their efforts in the completion of this report. The success of this effort will rely on adequate National Weather Service presence closely collaborating with the Emergency Management community.