DROUGHT MONITORING INDICES

ANNEX D TO THE DROUGHT MITIGATION AND RESPONSE PLAN

August 2018

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1 INTRODUCTION

Colorado’s diverse needs for timely and reliable water resources results in a broad spectrum of stakeholders who hold different definitions of what constitutes drought. The great spatial variation in precipitation and temperature regimes across the state presents a unique challenge to state drought monitoring and planning. For these reasons, Colorado must apply a robust system of drought monitoring tools to ensure drought conditions are adequately tracked for water user groups throughout the state. To help new users become familiar with the drought monitoring tools currently available and provide existing users with an up-to-date summary, this annex is designed to provide a comprehensive outline of the most pertinent drought indices and their intended applications.

This annex replaces what was in Annex D in the 2013 and 2010 updates of the Colorado Drought Mitigation and Response Plan (Drought Plan or Plan). The annex to the previous versions of the Plan included an analysis of the Palmer Drought Severity Index (PDSI) and its applicability to Colorado, and discussed the modernization of the Surface Water Supply Index (SWSI). This update of the annex in 2018 provides a synopsis of the current state of the art in drought indices. Included is a discussion of their applicability in monitoring drought and activation of Annex A of the Colorado's Drought Mitigation and Response Plan. Strengths and limitations of drought indices are discussed. Other indices or remote sensing methods are discussed that, in the future, could play a more formal role in drought monitoring and Plan activation. In addition, the monitoring and reporting of drought impacts is also discussed.

The United States Drought Monitor (USDM), SWSI, PDSI and the Standardized Precipitation Index (SPI) make up the key drought tracking products defined in the Plan. Guideline index values for the SWSI, PDSI, and SPI and drought classifications from the USDM have been developed and documented within previous versions of the Plan and are actively used in the decision-making processes for the activation and deactivation of Plan Phases and Impact Task Force (ITF) groups. These index guidelines attempt to provide a comprehensive estimate of drought conditions (magnitude, duration, areal extent), while drought impact reports provide an essential observation-based verification component necessary for the local and regional activation, mitigation, and response decisions. The drought monitoring structure defined within the Plan is centered around the professional judgment of the WATF to evaluate current and projected drought conditions using drought index data and drought impact reports (Figure 1.1). By employing this convergence of evidence approach, the Plan allows decision makers to examine a wealth of data to make timely and informed drought mitigation and response decisions.

Figure 1.1 Workflow summary of the drought monitoring and response progression outlined in the Plan

While the USDM, SWSI, PDSI, and SPI indices represent the most widely applied drought tracking index tools, there are numerous other drought indices that have provided added benefit to the state's ongoing drought monitoring practices as well as several newer indices that may soon provide further enhancements to drought monitoring in Colorado. A literature review of recent publications provided the framework for a brief overview of the indices commonly applied within the state and regional drought monitoring community. The Colorado Climate Center (CCC) and National Drought Mitigation Center (NDMC) also provided expert knowledge regarding index development and application for drought monitoring in Colorado. Each index summary includes a breakdown of documented applications as well as some of the most relevant strengths and weaknesses of the indices in their current state. By providing this information in an organized and detailed manner, future updates to the Plan may continue to evaluate the list of indices and focus efforts on linking local drought impact response/mitigation to the most appropriate drought indices and index values.

This annex also presents a synopsis of the 2012-2013 drought conditions in southeastern Colorado through a series of timeline plots. This high-level case study evaluation is intended to help illustrate the drought progression and decision-making processes performed via the Plan. This analysis also provides a simplified proof of concept example of a post-event evaluation that can be generated for future Plan updates to further refine indices and threshold values for improved localized monitoring.

The drought index "thresholds" outlined in Table 1.1 below were defined in previous drought Plans (Annex A in the 2013 Plan) and are actively incorporated as the set of guidelines for drought response activation and mitigation used by the WATF. The table includes a summary of the data inputs to each index, time frame coverage, update frequency, and intensity scale range for the four main drought indices along with the index value range guidelines for the defined drought phases. This table was developed as a supplement to Table 1 in the Colorado Drought Response Plan Annex A (2013).

Table 1.1 Outline of the primary drought indices currently documented in the 2013 Colorado Drought Plan

Drought Index	Primary Inputs	Calculated or Effective Time Frames	Update Frequency	Intensity Scale Typical Range	Index Value Range Guidelines (2013 Plan)				Link to Data Access/View
					Normal	Phase 1	Phase 2	Phase 3	
USDM	40-50+ indicators and indices; flexible for future input/indices to be implemented	1 month to 12 months	every week	D0-D4	D0 Abnormally Dry	D1 Moderate Drought	D2 Severe Drought	D3-D4 Extreme to Exceptional Drought	NDMC UNL
PDSI	Precipitation, Temperature	9 months	every month	-4.0 to +4.0 (can exceed these bounds)	> -1.0	-1.0 to -2.0	< -2.0	-2.0 to -3.9	WRCC WWDT
SWSI	Streamflow, Reservoir Storage, Forecasted Runoff (snowfall and precipitation)	3-6 months to several years	every month	-4.2 to +4.2 (can exceed these bounds)	+2.0 to -1.9	-2.0 to -2.9	-3.0 to -3.9	-4.0 to -4.9	CO DWR
SPI	Precipitation	Selectable; 1 month to 48 months+	daily	-3.0 to +3.0 (can exceed these bounds)	> -0.5 (six month)	-0.6 to -1.0	< -1.0 (six month)	< -1.0 to -1.99 (six month)	HPRCC

A list of some of the most prominent and comprehensive drought toolboxes/dashboards and drought impact reporting/tracking resources are provided below. Note that this list is just a sample of the many resources available for drought planning and monitoring.

Drought Indices Toolboxes and Dashboards

- CO DWR CDSS SWSI Mapper
- ESRI Living Atlas Drought Tracker
- High Plains Regional Climate Center Map Generator
- NDMC U.S. Drought Risk Atlas
- NIDIS Drought Portal Data Search
- NIDIS Summary of Drought Outlook & Forecast Products
- NIDIS/CCC Intermountain West DEWS
- NRCS Interactive Map
- USDM Current Conditions Products
- WRCC WestWide Drought Tracker Dashboard
- WWA Intermountain West Climate Dashboard
- NRCS Colorado Snow Survey
- CBRFC Water Supply Forecasts

Drought Impacts Reporting and Tracking

- CoCoRaHS Condition Monitoring Reports
- NDMC Drought Impact Reporter
- USDA National Agricultural Statistics Service (Colorado)

The general classification of each drought indicator/index is typically a direct reflection of the best application of each drought monitoring product. It is important for users to have a basic understanding of the purpose and limitations of each drought index before evaluating the output. As a basic starting point, the drought research community commonly groups indicators and indices into the following classifications:

- Meteorology (e.g. Standardized Precipitation Index)
- Soil moisture (e.g. Soil Moisture Deficit Index)
- Hydrology (e.g. Surface Water Supply Index)
- Vegetation (e.g. VegDRI)

The emergence of the term "flash drought" has gained substantial momentum within the drought research community as well as the drought monitoring community. Otkin et al. (2017) recently proposed a formalized definition of a "flash drought" to focus on the rate of rapid drought intensification rather than the duration of drought conditions. By formalizing a clearer definition, stakeholders who are susceptible to flash drought conditions can potentially be alerted to the initial warning signs and forecasts for rapid drought intensification.

The next section of this annex provides a brief overview of the typical application of each index for drought monitoring in Colorado.

1.1 Overview of Strengths and Limitations of Drought Indices for Colorado Drought Monitoring

The following subsections summarize the applicability of each drought monitor as well as a brief summary of the strengths and weaknesses identified in the literature review of recent publications and discussions with drought monitoring experts. The index summaries are intended to provide a high-level overview of the index purpose and application within the context of drought monitoring in Colorado. Effective drought monitoring in Colorado requires a robust set of tools. While each of the indices and monitoring products described below have valuable applications, it's also important to note where there is overlap between how indices are generated. When applying a convergence of evidence approach to drought monitoring is important to understand how individual index products are similar (e.g. precipitation input) and how they differ. Note that the USDM is also an important component of drought monitoring in Colorado, but since it is a mixture of other indices and drought impact monitoring products, it is discussed in Section 4 Drought Impact Reporting and Conditions Data.

1.1.1 Standardized Precipitation Index (SPI)

Developed at the CCC, this index is broadly used to track and quantify conditions related to meteorological drought. SPI uses historical precipitation records to calculate a probability of precipitation accumulation at timescales ranging from 1 month to 48 months or longer.

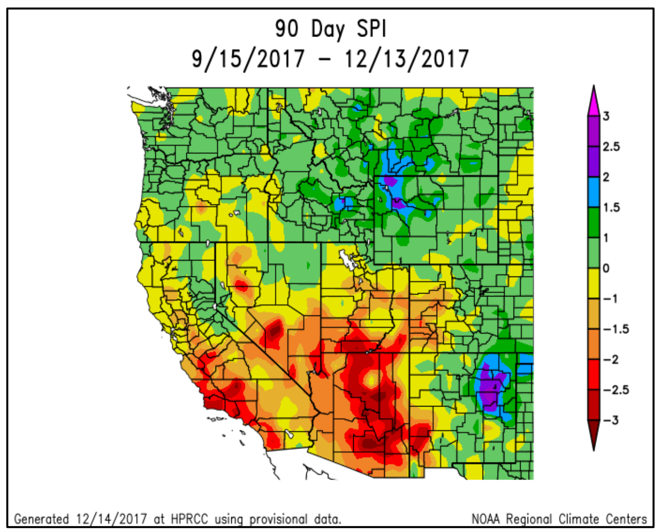

Figure 1.2 SPI image obtained from: https://hprcc.unl.edu/maps.php?map=ACISClimateMaps#

1.1.1.1 Colorado Application

The range of SPI timescales makes the SPI a robust product for evaluating meteorological drought onset, intensity, and duration for agriculture, water resources, and other sectors. The shorter-timeframe SPI data can provide an early indication of drought emergence which can be useful for implementing drought mitigation measures in a timely manner. Drought experts in Colorado typically use the 60- and 90-day SPI to look at more consistent patterns emerging and to make initial recommendations to the USDM while the 6-month SPI is frequently used to look at longer term patterns. It is also important to note that negative SPIs may carry more weight when monitoring drought during a wet season vs. a dry season.

1.1.1.2 Strengths

- SPI values for a range of timescale can be applied for multiple applications relating to the type of drought impacts in question (e.g. shorter timeframe for agricultural drought and longer timeframe for hydrologic drought).
- SPI is one of the easier indices to calculate and uses only precipitation data making it an ideal index for regions with sparse data coverage.
- SPI values can also be compared across widely varied climates.

1.1.1.3 Weaknesses

- There is no temperature component in SPI so it does not directly account for evaporative demand, an important component of the overall water balance. Drought events with similar SPI may have different impacts because of differences in evaporative demand.
- The calculation can be sensitive the quantity and quality of the underlying historical precipitation data used to generate the probability distribution (30+ years of historical data is recommended).
- Selecting the appropriate time scale of SPI (e.g. 3-month vs. 6-month) can be challenging for users when attempting to evaluate a range of potential drought vulnerabilities and impacts.

1.1.2 Palmer Drought Index (PDSI)

This prominent index was developed in the 1960s and has been widely applied to drought monitoring practices. PDSI is designed to use a simple supply and demand water balance approach with inputs of precipitation, temperature, and soil water capacity estimates. There are also two modified PDSI products commonly used within drought monitoring practices:

- Self-Calibrated PDSI: uses a mathematical calibration of model coefficients to represent local climate and soil properties
- Palmer Z: a measure of the relative wetness/dryness anomalies of a region evaluated against the full record at each location; often preferred for its normalized approach and better spatial comparison attributes

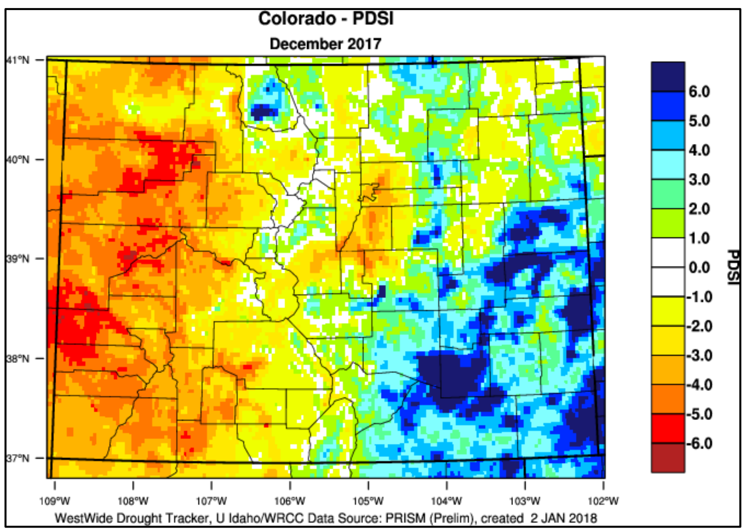

Figure 1.3: PDSI image obtained from: https://wrcc.dri.edu/wwdt/index.php?folder=pdsi

1.1.2.1 Colorado Modified Palmer Drought Severity Index

Using the same water balance approach (temperature and precipitation inputs) as the PDSI, the CMPDSI was designed to evaluate drought conditions at a finer spatial scale across Colorado. The CMPDSI expanded on the original PDSI by enhancing the spatial resolution of the index from the original 5 sub-regions (climate divisions) to 26 sub-regions to better represent the range of topography and climate conditions within Colorado (Doesken et al. 1983). CCC discontinued the generation of the CMPDSI in 2016 in favor of using similar products operationally available (e.g. Western Regional Climate Center's West Wide Drought Tracker PRISM PDSI). The newer products use gridded climate data to provide a much higher resolution depiction of PDSI conditions.

1.1.2.2 Colorado Application

PDSI considers both evapotranspiration as well as the moisture deficit within the soil column making it a useful tool for detecting and quantifying meteorological and agricultural drought conditions. This index was primarily developed for identifying drought conditions impacting the agricultural sector, but its use has been expanded to other sectors (e.g. water supply). Within Colorado, PDSI is primarily used for the eastern plains as its performance in the mountains is largely inadequate.

1.1.2.3 Strengths

- PDSI is commonly applied around the world and has been extensively evaluated under a range of conditions and has been thoroughly documented within the drought community literature.
- The application of soil properties and water balance methodology allow for a comprehensive analysis of drought conditions compared to many other indices.
- As noted by Doesken & Ryan (2010), the CMPDSI has shown promising results for prediction of winter wheat harvest as well as streamflow across various areas of the state.

1.1.2.4 Weaknesses

- PDSI has a relatively long memory (about 9 months) and does not respond quickly to emerging dry conditions compared to other indices and is not ideal for short term evaluations of drought conditions.
- It does not have a flexible multi-timescale calculation feature.
- The time lag between snowfall and snowmelt is not directly accounted for, all precipitation is assumed to be immediately available.

1.1.3 Surface Water Supply Index (SWSI)

This index attempts to quantify the amount of surface water available in streams and reservoirs across the state of Colorado. SWSI is calculated for the seven major intrastate basins as well as the HUC 8 basins throughout Colorado ("Revised SWSI"). NRCS originally developed this index in 1981 and modernized the SWSI for Colorado as part of the Drought Plan update effort in 2010. This update included an improved spatial resolution calculation (using the HUC-8 statewide basins). The Colorado Department of Water Resources (DWR) hosts a database of current and historical SWSI statistics (included non-exceedance probabilities) for HUC8 basins in Colorado.

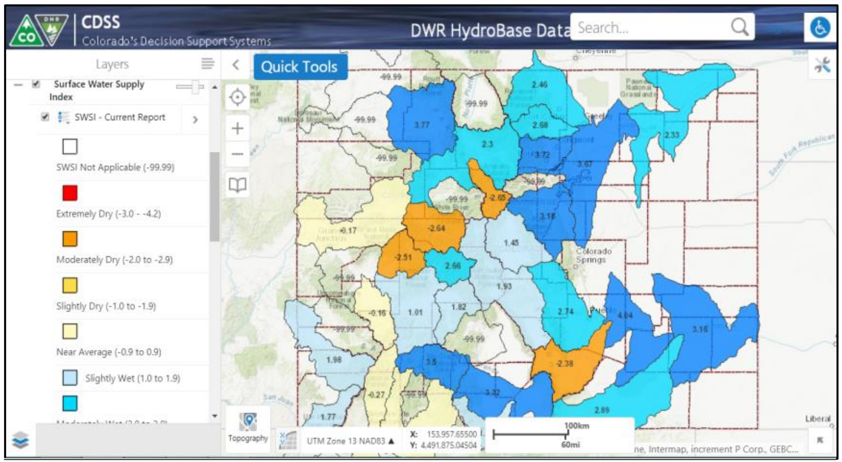

Figure 1.4: SWSI image obtained from: https://gis.colorado.gov/dnrviewer/Index.html?viewer=dwrhydrobaseviewer

The Index uses the following inputs based on the time of year:

- January-June: SWSI = Streamflow Forecast + Reservoir Storage
- July-September: SWSI = Reservoir Storage + Previous Month's Streamflow
- October-December: SWSI = Reservoir Storage

1.1.3.1 Colorado Application

This index is especially applicable for monitoring hydrologic drought conditions and month-to-month fluctuations for water supply planning. SWSI was specifically designed to quantify drought severity where water availability is driven by winter snow accumulation and ensuing snowmelt. During the 2018 update of the Drought Plan, a member of the Colorado Water Availability Task Force noted that SWSI has become decreasingly referenced in recent years; this could be the result of the SWSI acronym confusion (the SWSI acronym also represents the Statewide Water Supply Initiative).

1.1.3.2 Strengths

- SWSI takes into account the primary water supply components including snow accumulation, snowmelt/runoff, and reservoir contents. This calculation provides a comprehensive evaluation of the overall water balance of a given basin while accounting for manmade storage impacts (reservoirs).

- Several Colorado water supply organizations have implemented localized SWSI calculations into their monitoring system, making SWSI a relatively familiar index.

1.1.3.3 Weaknesses

- The index must be recalculated anytime there are underlying changes to the input data (e.g. reservoir capacity changes, diversion/return flow modifications, etc.).
- SWSI user's have noted some basin-to-basin irregularities likely influenced by differing reservoir and water supply management practices (at the Colorado HUC-8 scale). This may lead to confusion or added uncertainty when attempting to evaluate conditions or trends between neighboring basins.

1.1.4 Colorado Monthly Precipitation and Percent of Normal Maps

These indicators involve a simple statistical formula to generate using precipitation data as the only input. This index can be applied quickly to evaluate meteorological drought conditions by comparing recent precipitation values to mean historical data.

1.1.4.1 Colorado Application

Total precipitation and percent of normal precipitation data is primarily used for simple evaluations of meteorological drought conditions. These variables are relatively simple to understand and evaluate compared to other indices.

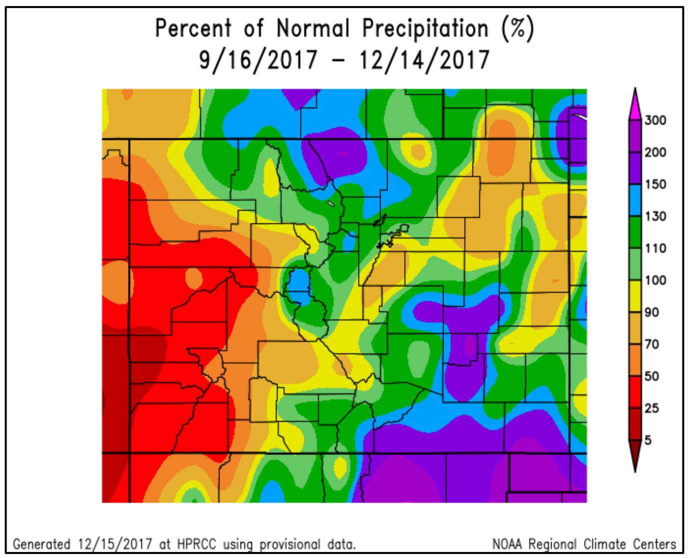

Figure 1.5: Percent of normal precipitation image obtained from: https://hprcc.unl.edu/maps.php?map=ACISClimateMaps#

1.1.4.2 Strengths

- These statistics can be easily generated to cover a range of time periods in order to evaluate a range of drought conditions.

1.1.4.3 Weaknesses

- Percent of normal values can be difficult to compare among different climate regimes (differing precipitation climatology).
- "Normal" precipitation can be misunderstood when there are sizeable differences between the median and mean for a given period.

1.1.5 Colorado Snowpack Accumulation and Ablation

Mountain snowpack in Colorado is a critical component of the hydrologic cycle. Higher elevation snowfall and subsequent melt is a key driver of the overall water supply for many of the water demands for both in-state and out-of-state users. Snow Telemetry (SNOTEL) instrumentation stations provide a relatively dense network of data points to monitor snowpack conditions. The Natural Resources Conservation Service (NRCS) and National Water and Climate Center provide current and historical data access for real time evaluation of snowpack conditions.

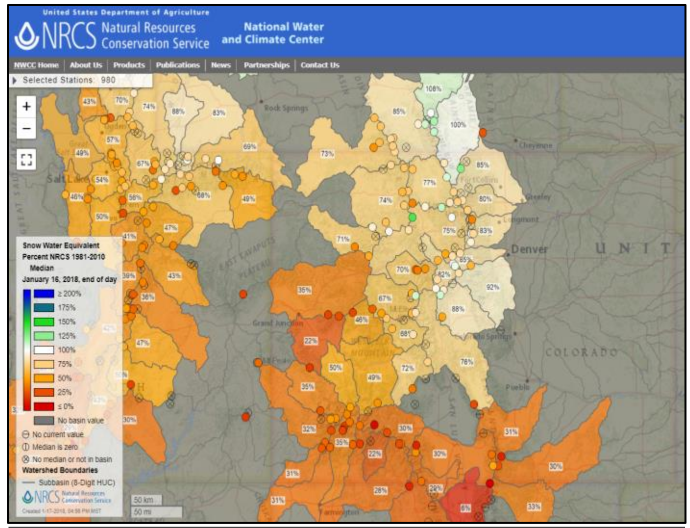

Figure 1.6: Snow water equivalent percent of normal image obtained from: https://www.wcc.nrcs.usda.gov/snow/snow_map.html

The National Weather Service's National Operational Hydrologic Remote Sensing Center (NOHRSC) SNOw Data Assimilation System (SNODAS) is also routinely used by water supply managers and drought monitoring systems. SNODAS produces high-resolution (1km) gridded snowpack estimates through a modelling and data assimilation system. This data product merges ground observations (e.g. SNOTEL point measurements) with satellite/airborne measurements, and model estimates of snow cover.

1.1.5.1 Colorado Application

Maps and timeseries plots of the snowpack can be generated for SNOTEL stations as well as basin-scale estimates via online tools. This data provides water supply managers and drought planners with valuable estimates of the magnitude and timing of the snowmelt.

1.1.5.2 Strengths

- Snowpack data can provide and early indication of water shortages and potential drought conditions.
- Daily to hourly temporal resolution of observed and modeled data products.
- Percent of normal snowpack information is a relatively easy product to understand for drought planners and the public.

1.1.5.3 Weaknesses

- SNOTEL observations are point samples of an often complex and spatially variable snowpack which may lead to an over or under estimate of true basin-wide snowpack.

- Snowpack data should also be interpreted with reservoir storage levels and capacity to better understand the expected water availability for downstream users.
- Gridded products like SNODAS have a limited history, therefore it's difficult to assess how far from "normal" the snowpack is at a given time when there is not a long enough record to calculate a "normal".

1.1.6 Crop Moisture Index (CMI)

This index was developed as a compliment to the PDSI in an attempt to address some of the shortcomings of PDSI. CMI is intended to be a quick responding index that evaluates the soil column moisture deficit using estimates of available moisture and potential evapotranspiration.

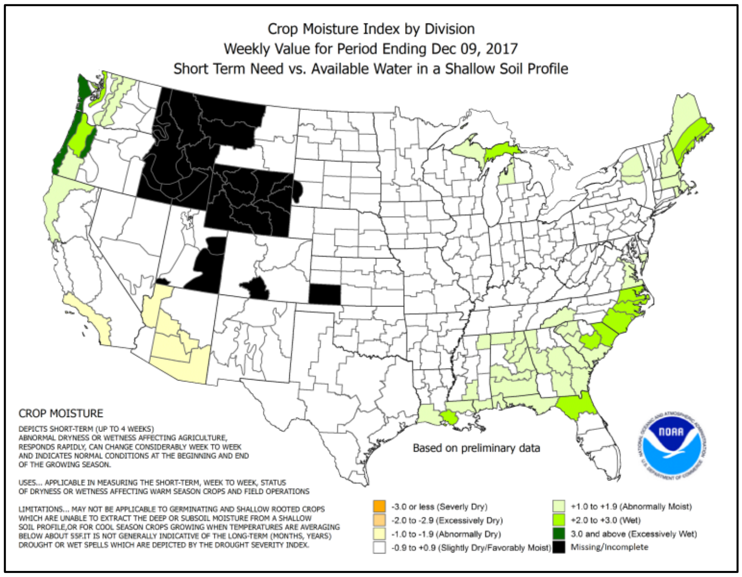

Figure 1.7: CMI image obtained from: http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/regional_monitoring/cmi.gif

1.1.6.1 Colorado Application

Mainly used for agricultural purposes, the CMI gives a short-term status of a purely agricultural drought which can change rapidly. It is applicable in measuring drought on a week to week basis for warm season crops.

1.1.6.2 Strengths

- CMI is especially suited to evaluating drought conditions in relation to agriculture impacts.

1.1.6.3 Weaknesses

- As CMI is sensitive to quickly developing drought conditions, it may also produce a false sense of drought recovery if longer-term moisture deficits are important.
- CMI may not be applicable for cool season or shallow rooted crops.
- Current spatial resolution is limited for Colorado (five climate divisions)

1.1.7 Keetch-Byram Drought Index (KBDI)

KBDI was developed by the United States Fire Service (USFS) as a fire risk index for fire control managers. The index calculates the moisture deficiency in duff and the upper soil layers which is designed to evaluate the flammability of organic material on the ground. This measure is especially useful when examining wildfire conditions and potential drought stress on vegetation and crops.

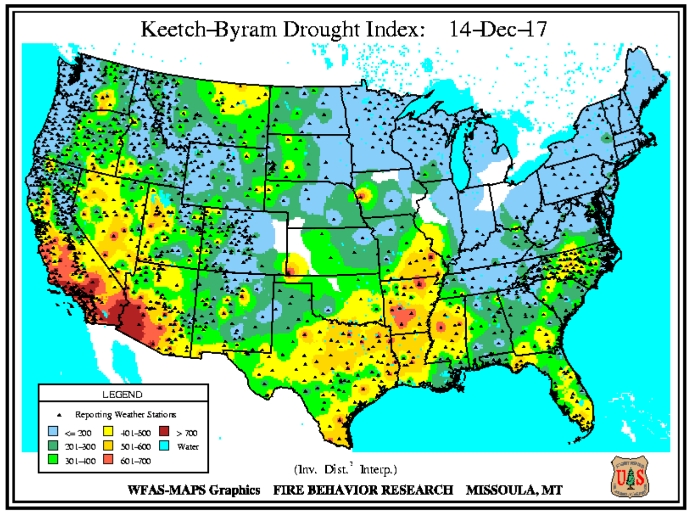

Figure 1.8: KBDI image obtained from: http://www.wfas.net/index.php/keetch-byram-index-moisture--drought-49

1.1.7.1 Colorado Application

KBDI estimates the amount of precipitation necessary to return the soil to full field capacity, with values ranging from 0 to 800 units (corresponding to 0 to 8 inches of water in the soil). Wildfire potential is divided into four levels based on KBDI values (0 to 800): low, moderate, high, and extreme contribution to fire intensity. These levels correspond to typical seasonal variations.

1.1.7.2 Strengths

- The KBDI calculation is relatively simple index relying on daily maximum temperature and daily precipitation as inputs.

1.1.7.3 Weaknesses

- The calculation assumes a limit of available moisture based on regionalized climate estimates which may not be sufficient for every location.

2 Drought Indices for Future Consideration

The following sections discuss some of the newer indices that have been the focus of recent drought monitoring research and development. While these indices have started to gain attention among Colorado drought monitoring experts, these products are still being tested and evaluated in regards to operational capabilities. For this reason, the following indices are not included in the formal drought monitoring guidelines; however, these indices can still provide a valuable resource while the vetting process continues. Future updates to the Plan should reevaluate these indices for updated information.

2.1.1 Evaporative Demand Drought Index (EDDI)

EDDI is an experimental drought monitoring tool specifically designed to capture the early warning signs of water stress through the emergence and/or persistence of anomalous evaporative demand. The EDDI calculation relies on North American Land Data Assimilation System (NLDAS) for gridded climate input data. The CCC routinely examines the EDDI products as part of their drought monitoring toolbox. While the application of EDDI to operation drought monitoring is in an early stage at this point in time, confidence is growing in that EDDI can be a very useful tool for future drought plans and early warning activation.

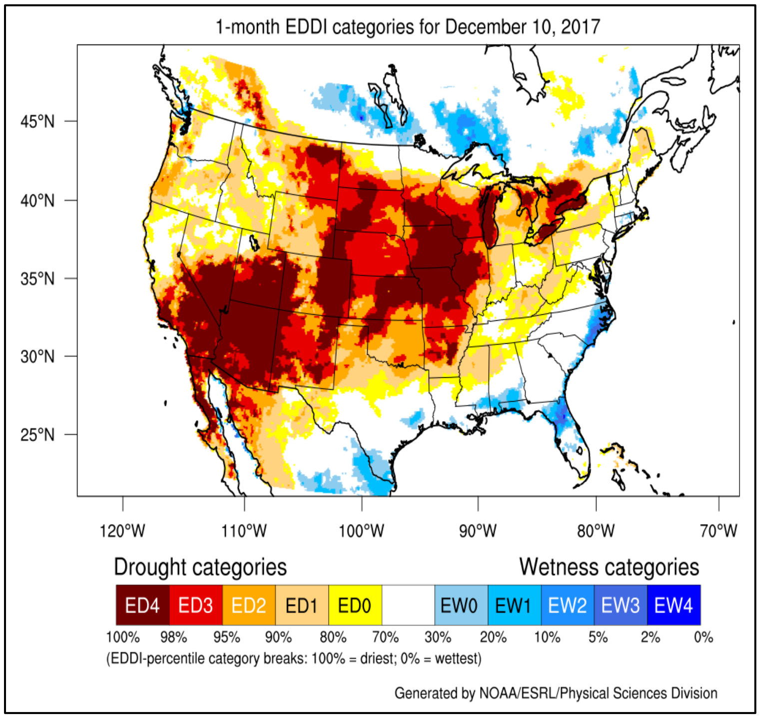

Figure 2.1: EDDI image obtained from: https://www.esrl.noaa.gov/psd/eddi/

2.1.1.1 Future Colorado Application

EDDI is designed to be applicable for all land-cover types, which is especially useful for Colorado's diverse needs. The daily output (5-day lag) from EDDI provides a much-needed tool for monitoring "flash drought" conditions which can have substantial impacts to the agricultural sector in Colorado. EDDI can also be used as a fire-weather monitoring tool throughout the state.

2.1.1.2 Strengths

- Quick response time drought tool has long been a need for drought monitoring
- Capable of detecting "flash drought" conditions earlier than most other indices
- Drought category display colors can sharply highlight regions of drought concern
- EDDI model data have been validated using surface observations in Colorado
- EDDI is generated on the same range of timeframes as SPI

2.1.1.3 Weaknesses

- Still needs additional expert review and additional testing to fully understand and document strengths and limitations
- Colored display of drought categories can be over emphasized under some conditions and require user insight to fully evaluate (e.g. winter vs growing season anomalies)
- EDDI does not include any water supply information

Figure 2.2 below plots the 1-month to 12-month EDDI values (standardized anomalies in reference evapotranspiration) for the 2010-2015 period. The data were extracted for the southeastern quadrant of Colorado (spatially averaged output). This plot shows the early onset of dry conditions starting in late 2010 and persisting into 2014 (positive index values). For perspective, plots the EDDI timeseries for the 1990-2015 period. Note the anomalously dry conditions (magnitude and duration) during the 2011-2014 drought period. Note that unlike other drought indices, raw EDDI values are positive in dry conditions, and negative in wet conditions.

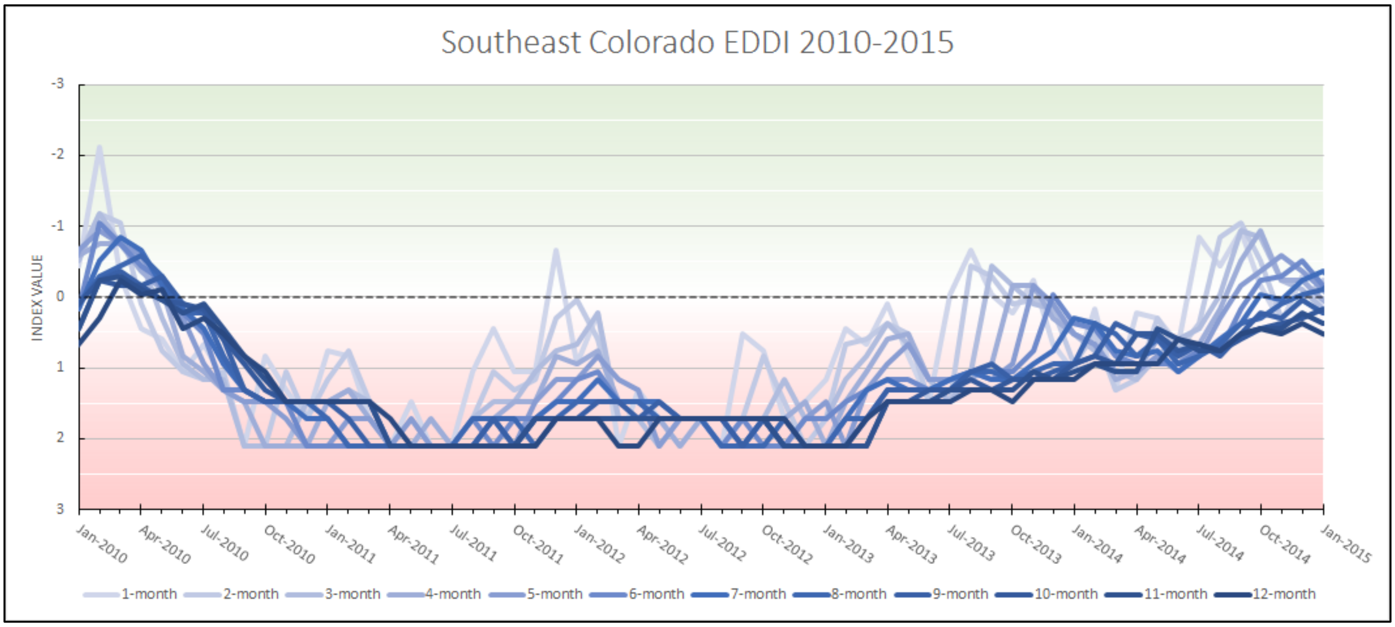

Figure 2.2: EDDI timeseries for southeastern Colorado for the 2010-2015 period (data obtained from: https://www.esrl.noaa.gov/psd/eddi/)

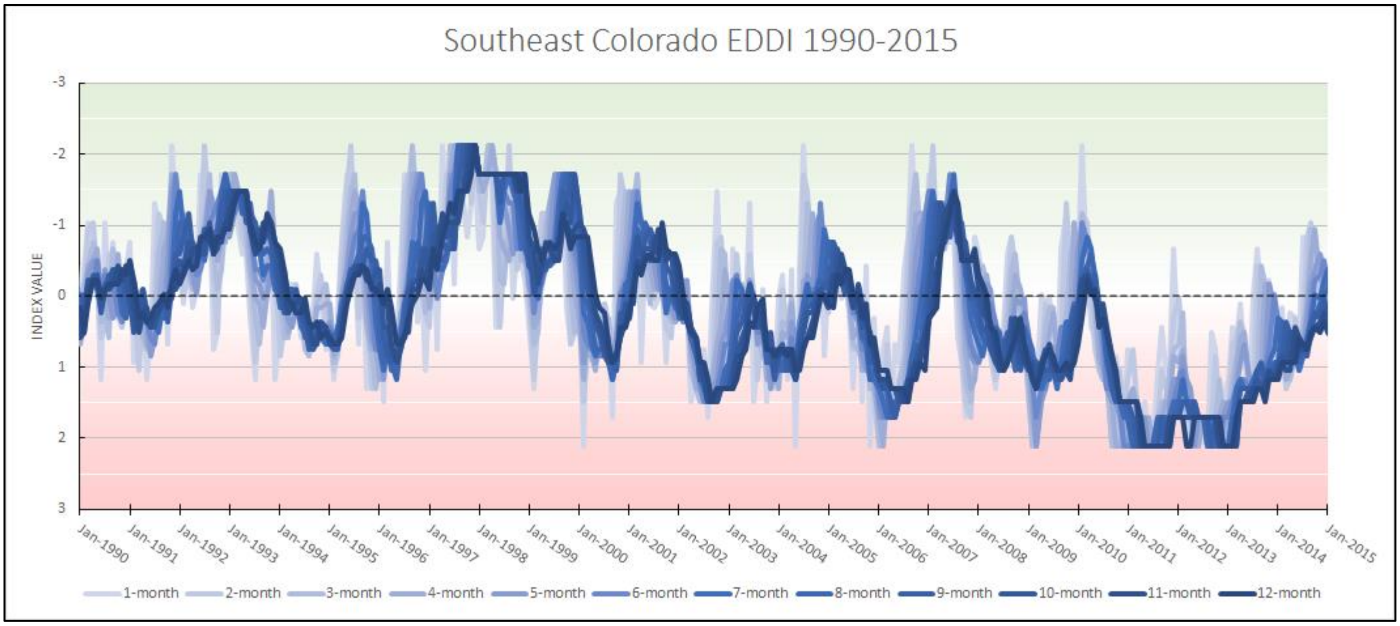

Figure 2.3: EDDI timeseries for southeastern Colorado for the 1990-2015 period (data obtained from: https://www.esrl.noaa.gov/psd/eddi/)

2.1.2 Standardized Precipitation-Evapotranspiration Index (SPEI)

This index is an extension of the SPI and incorporates temperature data to account for potential evapotranspiration in a basic water balance calculation. SPEI aims to improve the representation of drought duration and magnitude resulting from trends in potential evapotranspiration change.

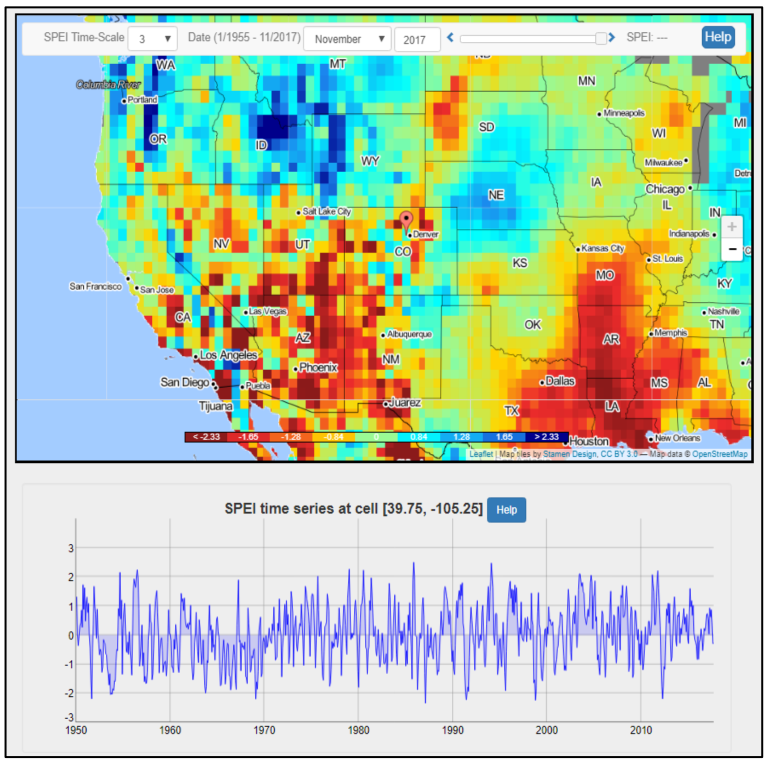

Figure 2.4: SPEI Global Drought Monitor image obtained from: http://spei.csic.es/map/maps.html

2.1.2.1 Future Colorado Application

This index can be applied in all instances where SPI is currently used while providing a more reliable estimate of drought conditions resulting from air temperature influences.

2.1.2.2 Strengths

- Expected to be a more reliable estimate over the traditional SPI product especially when accounting for warming climate scenarios

- Available on the same range of timeframes as SPI (<1-month to > 48-months+)

2.1.2.3 Weaknesses

- Real-time SPEI output is currently based on the Thornthwaite equation for potential evapotranspiration (temperature-based estimate) which can have limited reliability in western US applications
- Output is highly sensitive to the method used to calculate the PET product (e.g. Thornthwaite vs. Penman Monteith) especially in regions where wind can play a big role in varying evapotranspiration
- Not yet extensively tested and evaluated by the drought monitoring community

2.1.3 VegDRI and QuickDRI

The Vegetation Drought Response Index (VegDRI) and the Quick Drought Response Index (QuickDRI) and have been developed by the U.S. Geological Survey (USGS), Earth Resources Observation and Science (EROS) Center and the National Drought Mitigation Center (NDMC). These hybrid modeled drought indices incorporate satellite-based observations of vegetation properties, climate data, and other biophysical data products to quantify the current vegetative state. VegDRI has a seasonal time horizon for characterizing drought conditions, while QuickDRI is designed for detecting early onset and rapidly developing drought conditions on a roughly 1-month timescale (i.e. flash drought conditions).

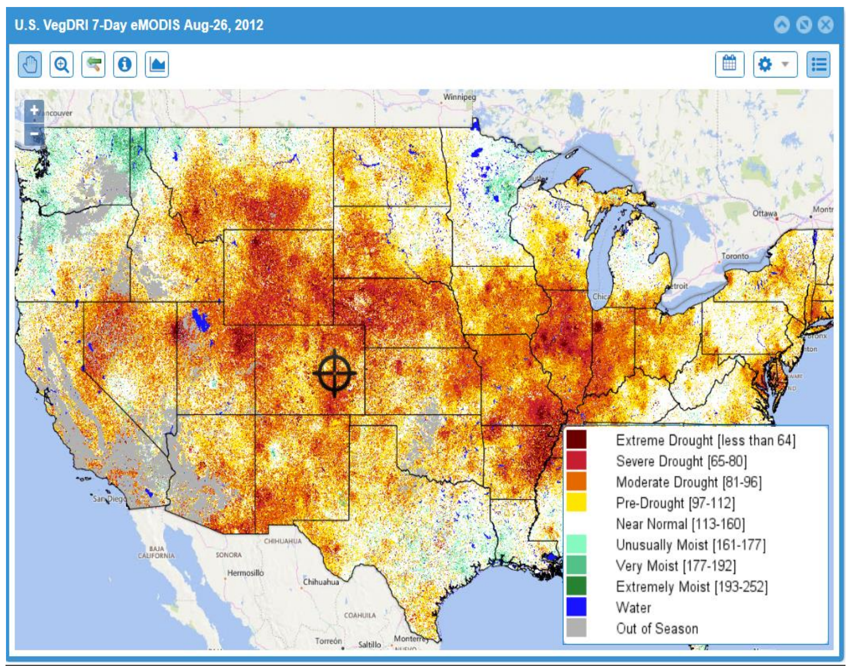

Figure 2.5: VegDRI image obtained from: https://vegdri.cr.usgs.gov/viewer/

2.1.3.1 Future Colorado Application

These two indices provide a high-spatial resolution (1km) drought indicator specifically designed for vegetation stress and agricultural applications. VegDRI has provided valuable updates on the mid to late summer vegetation health within Colorado whereas the early growing season output is largely just a function of the input SPI blend. (personal communication with CCC, Jan 2018).

2.1.3.2 Strengths

- Both indices are a weekly product
- 1km spatial resolution
- Both indices are a hybrid index – incorporating numerous variables representing the hydrologic cycle and drought-related vegetation stress

2.1.3.3 Weaknesses

- Only applicable in areas with vegetation cover and during the growing season
- Relies on precipitation as an input which may lead to redundancies in output with other precipitation driven indices (e.g. SPI & PDSI)

3 Drought Impact Reporting and Conditions Data

Comprehensive drought impact assessments are a well-known shortcoming within the drought monitoring community. Drought management decisions are ultimately focused on mitigating and responding to a range of drought related impacts; however, localized impact assessments are often complicated by a multitude of socioeconomic and physical factors relating to drought vulnerability and exposure. Aligning projected drought conditions with known impacts remains a critical link to developing a localized drought mitigation and response system.

While historical records of drought-related impacts have typically focused heavily on agricultural impacts, several drought impact reporting systems and databases have emerged in recent years to help meet the growing need for a comprehensive record of current and historical drought impacts across a range of sectors. Three resources are described in the following sections in an effort to continue to build usership and emphasize their application for continued improvements to drought mitigation efforts in Colorado.

3.1.1 United States Drought Monitor (USDM)

The USDM was the first operational composite-based drought monitoring product used in the US. While it is primarily based on a handful of key indicators (SPI at multiple time scales, PDSI, modeled soil moisture, weekly streamflow) it uses a flexible framework to incorporate up to 50+ inputs from a variety of sources with capabilities to continuously incorporate newly developed

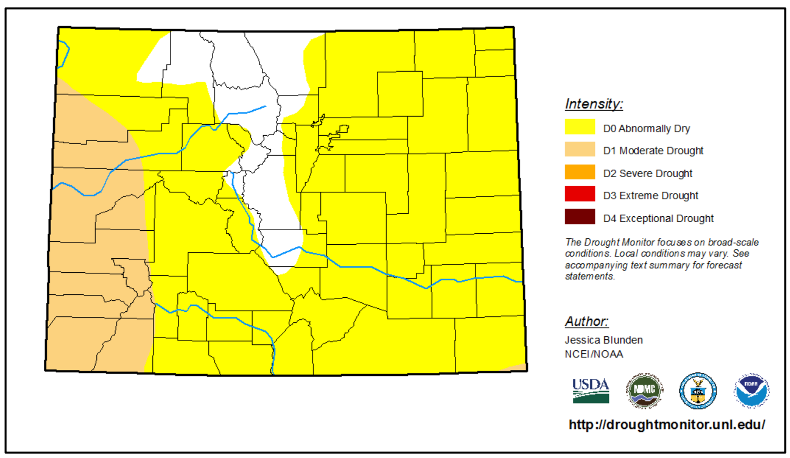

Figure 3.1: USDM image obtained from: http://droughtmonitor.unl.edu/CurrentMap.aspx

data/indices as they become available. For example, snow-water equivalent is incorporated in the wester US in the winter. The weekly map generation process also relies on human observations and impact reports. The Colorado Climate Center continues to provide and coordinate drought monitoring data and information input from Colorado water experts to the USDM on a weekly basis.

3.1.1.1 Colorado Application

The USDM is often a key focal point of drought monitoring efforts covering a wide range of applications throughout the state of Colorado. The USDM is not limited to seasonal interpretation (e.g. wet season or growing season) and can be consistently evaluated throughout the year. The WATF includes the percent coverage of drought categories at all monthly meetings.

3.1.1.2 Strengths

- USDM incorporates numerous indicators and indices covering a range of timescales to produce a robust drought identification and intensity classification.
- The five-scale drought intensity classifications are widely used throughout the country and familiar to stakeholders, the media, and the public. Other indices attempt to apply the same general intensity scale for data displays.

3.1.1.3 Weaknesses

- Very localized drought conditions may not be sufficiently represented within the USDM resolution
- Drought can only be depicted where the actual water shortage is present, not necessarily where the area of impacts is greatest. For example, a drought over the mountains (where the majority of the water resources reside) can have major implications over many other regions, including other states, but the USDM does not provide that information.

3.1.2 NDMC Drought Impact Reporter

The Drought Impact Reporter (DIR) was initially released in 2005 as one of the first nationwide drought impact databases. This data catalog incorporates drought-related reports from a wide variety of sources including media reports, user-submitted reports, CoCoRaHS reports, NWS Drought Information Statements, and state agency reports. DIR documentation notes that media reports of drought-related news stories make up the largest contribution to

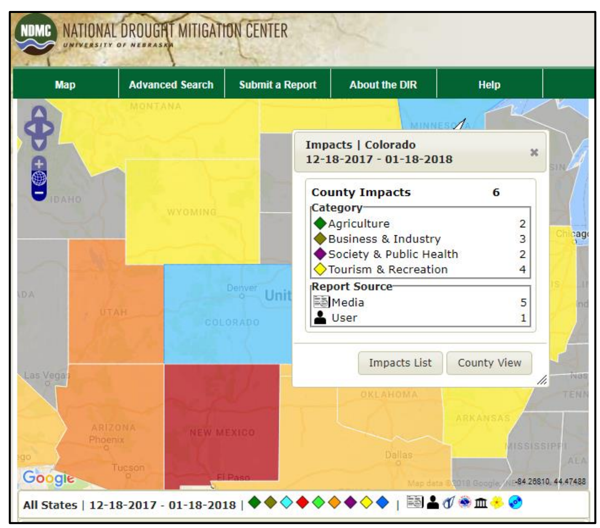

Figure 3.2: Drought Impact Reporter map interface (http://droughtreporter.unl.edu/map/)

the database; however, user-submitted reports from the public are also an essential component of the database. The DIR is also designed to group drought impacts by relevant characteristics such as the drought category (e.g. agriculture, water supply/quality, tourism/recreation), drought duration, and affected locations.

3.1.3 CoCoRaHS Condition Monitoring Reports

Community Collaborative Rain Hail and Snow (CoCoRaHS) is a network of community volunteers who provide detailed measurements and observations of daily weather conditions nationwide (and international). Started in Fort Collins in 1998, the network has grown to include thousands of active daily reports that provide a valuable database of localized weather observations. While initially designed to primarily record precipitation observations, the CoCoRaHS reporting system has adapted a condition monitoring reporting system. The condition monitoring reports submitted by CoCoRaHS volunteers are designed to provide a constant stream of qualitative reports regarding the status of wet or dry conditions and the localized impacts. Condition monitoring reports provide date stamped observations with a relative conditions scale bar (ranging from severely dry to near normal to severely wet) as well as a description of the impacts affecting the reporter. The condition monitoring reports also include a classification structure similar to the DIR to help streamline the categorization of impacts by sectors (e.g. agriculture, fire, business etc.). Processed reports can be viewed through an interactive map interface or by a database search query.

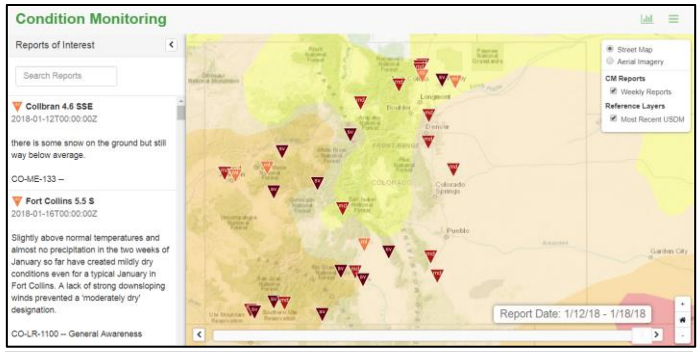

Figure 3.3: CoCoRaHS Condition Monitoring map interface (https://www.cocorahs.org/Maps/conditionmonitoring/#)

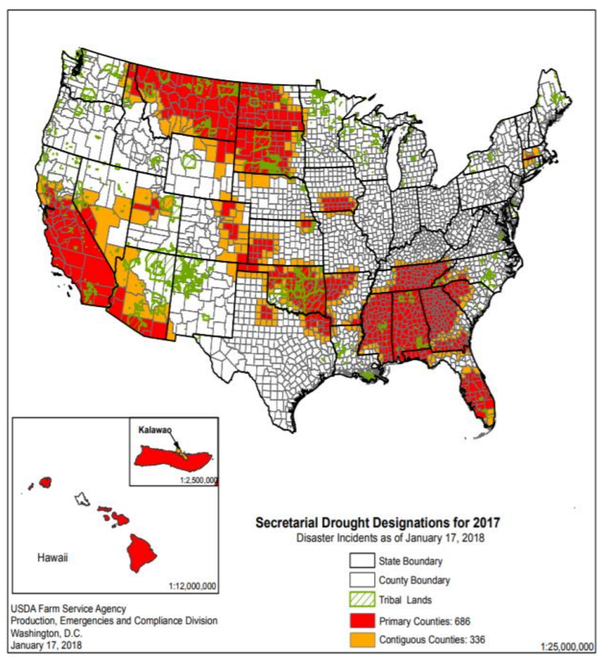

Figure 3.4: Secretarial county drought designations for 2017 (https://www.usda.gov/sites/default/files/documents/usda-drought-fast-track-designations.pdf)

3.1.4 USDA National Agricultural Statistics Service

The United States Department of Agriculture (USDA) National Agricultural Statistics Service (NASS) maintains a detailed record of crop, livestock, pasture, and range conditions relating to drought impacts. With water availability playing such a significant role in the agricultural sector, crop conditions are routinely documented for large portions of the country through annual, monthly, and weekly reports. County and statewide crop progress reports provide records regarding commodity conditions, soil moisture conditions, and crop yields. The USDA also maintains a record of Secretarial Drought Designations by county.

3.2 2012-2013 Case Study of Drought Monitoring for the Arkansas River

The 2011-2013 drought conditions impacted the entire state of Colorado, but conditions were especially severe in the southeast quadrant of the state which includes most of the Upper Arkansas River basin. A simple case study re-analysis was developed for the 2011-2015 period to help illustrate the drought progression and subsequent drought mitigation and response actions applied throughout the state. Figure 3.5 is a snapshot of the USDM during the week of February 18, 2013 showing the widespread drought conditions over Colorado with exceptional drought conditions over a large portion of the eastern part of the state.

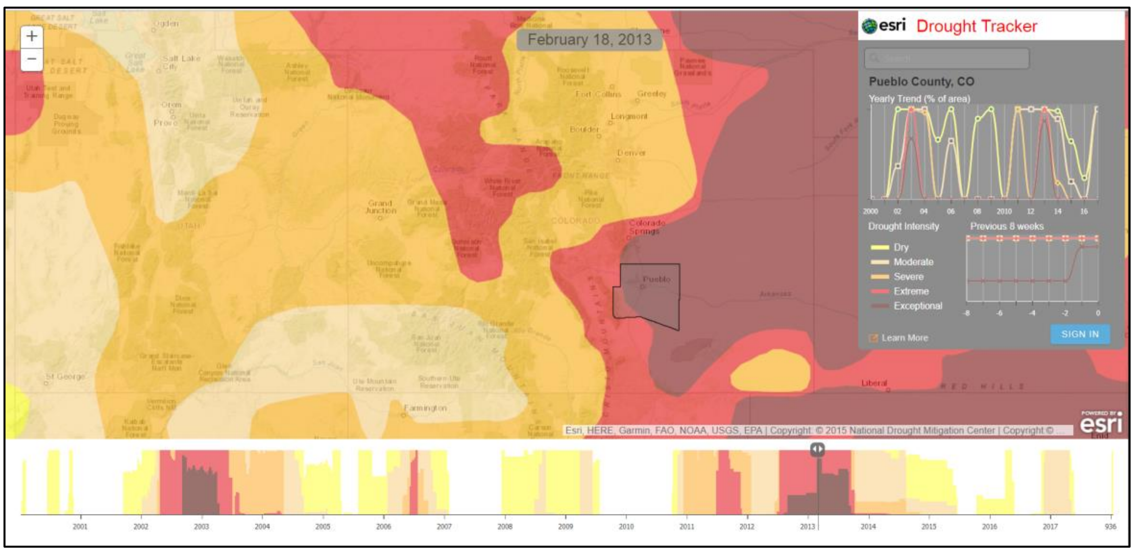

Figure 3.5: ESRI Drought Tracker showing the USDM drought severity in early 2013.

This case study aims to provide a simple synopsis of the drought conditions by plotting the historical drought indices timeseries along with a timeline of the documented drought mitigation/response actions, and drought impact reports. Figure 3.6, Figure 3.7, and Figure 3.8 outline the evolution of drought conditions evident by the USDM, several drought index timeseries, and a timeline of the drought Plan actions.

For simplicity, the drought indices datasets focus on the spatial average for the Upper Arkansas River basin (HUC 110200). The USDM drought index percent coverage time series plot for the

Upper Arkansas basin was obtained from the [USDM webpage](). The historical timeseries of PDSI, Palmer Z, SC-PDSI, SPI (1-month), and SPEI (1-month) were obtained from the WRCC [WestWide Drought Tracker]() (Abatzoglou et al., 2017). The WestWide Drought Tracker dataset applies the monthly gridded PRISM data products as the foundation for the calculation of the monthly historical index timeseries. Recall that the range of typical index values may differ from one index to the next, and the user should give special attention to the magnitude of each index when quantifying the overall drought signal. The SWSI timeseries data for the Arkansas basin were obtained from the Colorado DWR Information Marketplace. Drought Plan activation/deactivation dates and descriptions were mostly attained from monthly WATF Drought Update Reports and the Governor's Memorandum documents (all archived files are available on CWCB Laserfiche WebLink database).

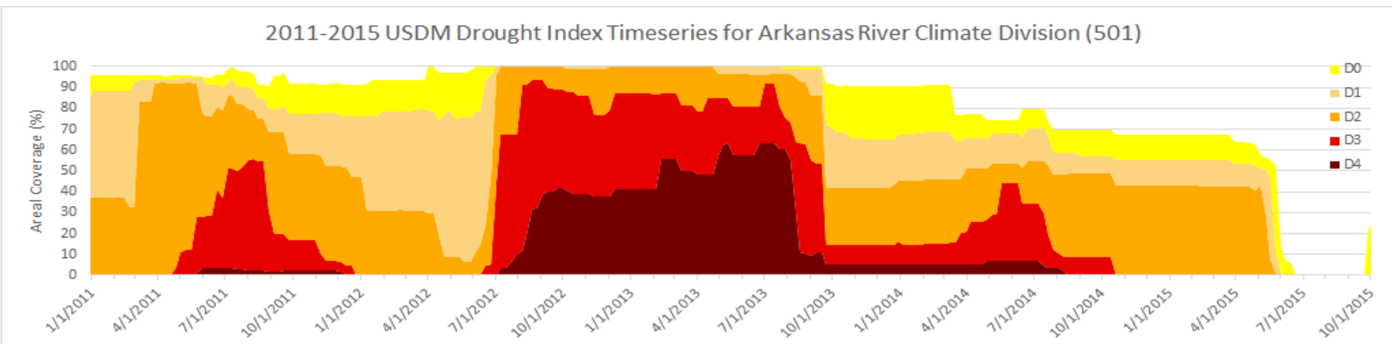

Figure 3.6: USDM Drought categories percent coverage for the Upper Arkansas (Climate Division 501) for the 2011-2015 period (data obtained from http://droughtmonitor.unl.edu)

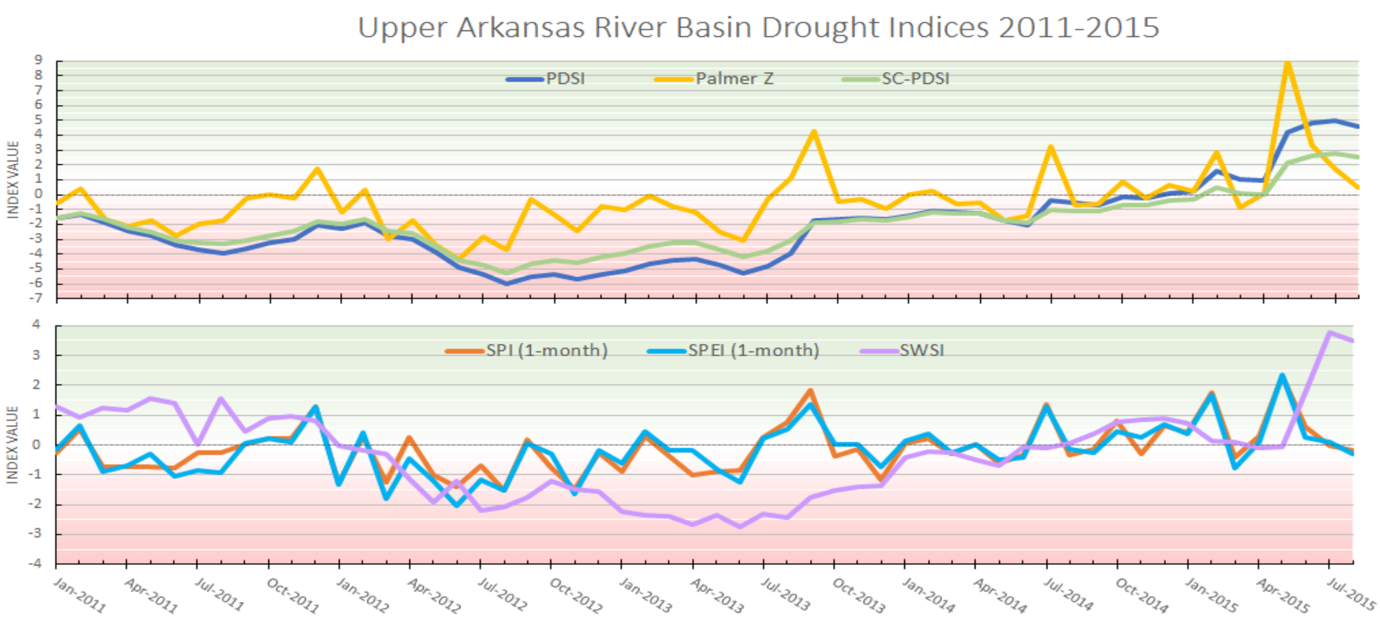

Figure 3.7: Monthly time series plots of drought index values for six drought indices during the 2011-2015 period (data obtained from the West Wide Drought Tracker and the Colorado DNR)

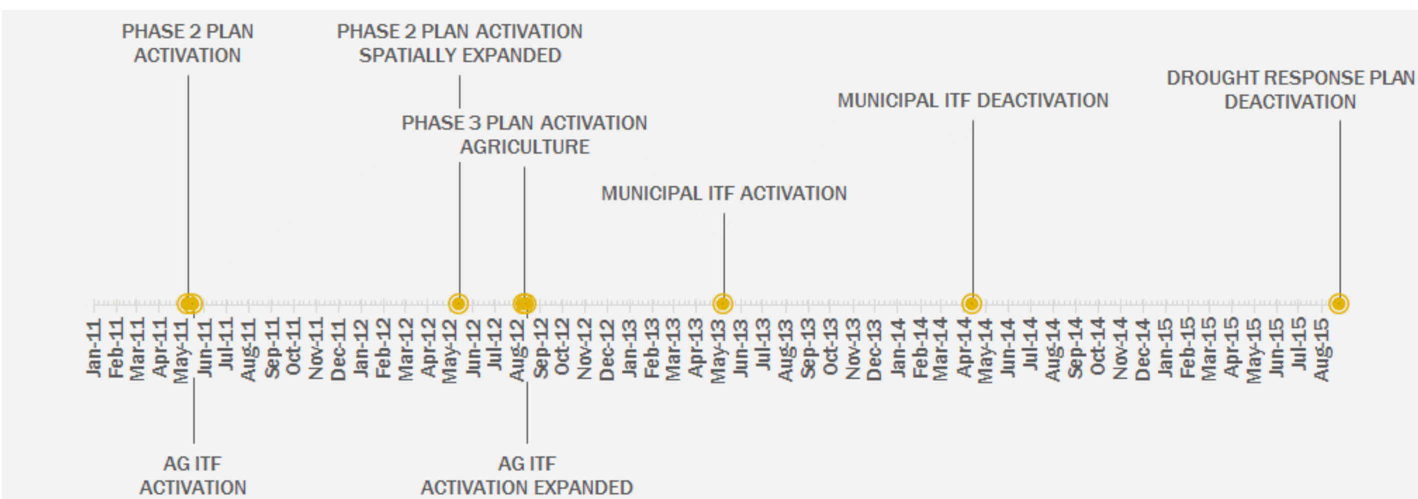

Figure 3.8: Timeline of drought Plan actions/phases including ITF activation and deactivation

By incorporating a variety of drought indices, a “convergence of evidence” approach can be applied for sound drought decision making. The USDM and drought indices timeseries data plots above attempt to illustrate the quantitative data available to the WATF and drought decision makers as the drought progressed; however; qualitative data sources are also important for identifying and validating drought impacts. Qualitative data includes information such as drought impact observations from a variety of sectors. These observations are essential for focusing drought mitigation and response resources prior-to and during a drought while also providing an invaluable dataset to evaluate drought indices and refine future drought planning resources at a localized scale.

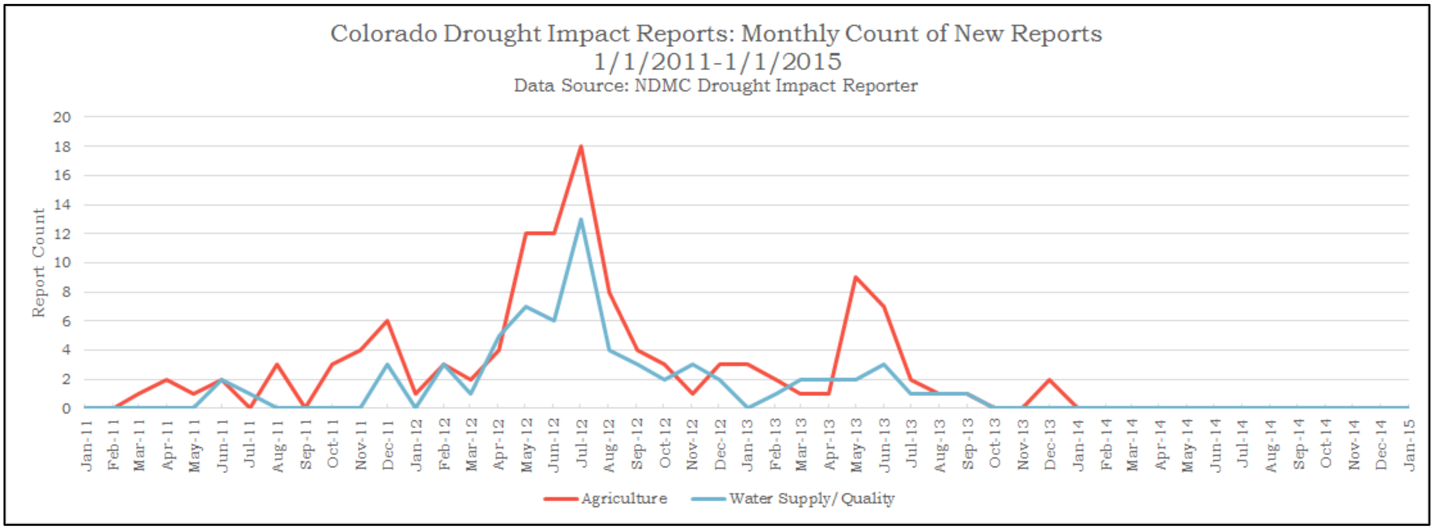

Figure 3.9: Summary of the 2011-2015 drought impact reports for Colorado

Figure 3.9 summarizes the monthly count of new drought reports categorized into agricultural and water supply/quality impacts. Impact data were obtained from the NDMC Drought Impact Reporter for the entire state of Colorado. Individual impact reports include a description, start and end date, and category classification tag(s). The data search yielded 213 reports that have a start date, end date, or timespan that occurs within the 2011-2015 period. It's important to note that the figure above represents the start date of each report and drought impacts may have extended months to years into the future. Numerous reports (78) did not include an ending date to fully examine the temporal component of drought impacts, and this finding further illustrates the continued need for comprehensive condition monitoring impact reporting prior to, during, and after drought periods. For added spatial reference, Figure 1.23 is a web map screenshot of the NDMC Drought Impact

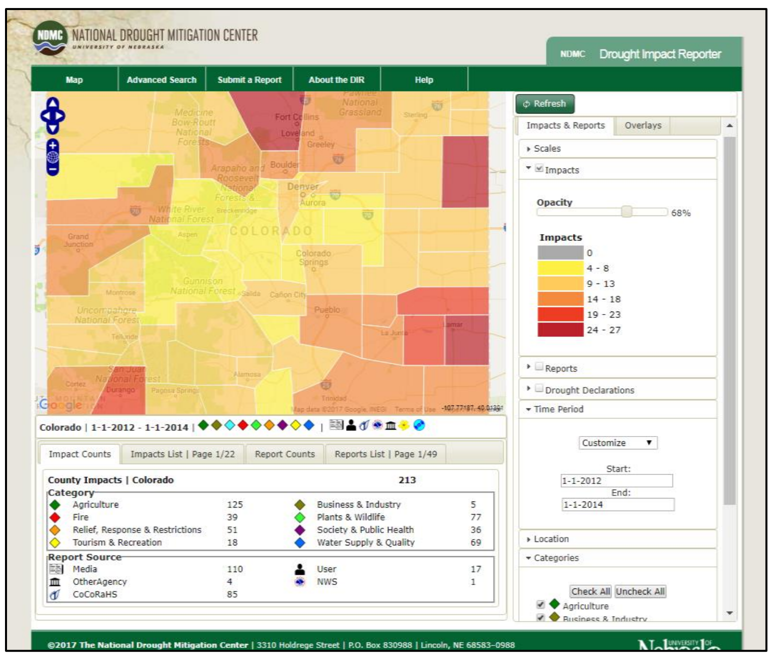

Figure 3.10: NDMC Drought Impact Reporter summary of county impact counts for the 2012-2014 period.

Reporter showing the total drought impact report counts by Colorado County for the 2012-2014 period.

4 RECOMMENDATIONS

After extensive discussions with leading experts in the drought monitoring field as well as representatives from the Colorado Impact Task Forces a list of key recommendations for continued development and improvement to the Colorado Drought Plan was developed.

1. Recommend the Water Availability Task Force and each individual Impact Task Force expand efforts to document drought impacts throughout Colorado as well as any mitigation actions or response measures put in place. Comprehensive records of dates, locations, and drought-related impact descriptions are difficult to come by but are extremely valuable for continued improvement to understanding drought vulnerabilities at a localized scale. A robust drought impact database can be combined with archived drought index data to provide a foundation for a future validation and refinement of drought monitoring practices and responses. Results of future validation efforts can be used to focus future drought Plan updates on linking drought vulnerabilities to specific drought indices (and index values) by location and stakeholder groups. Drought Plan Appendix B Actions Taken to Reduce Drought Impacts in Previous could be used as a starting point and should be updated periodically during future droughts.

2. Continue to monitor/evaluate EDDI and other newer indices currently being tested for future Plan implementation as they mature.

3. Consider future implementation of drought index guidelines as a function of both index values and index percentile ranking to allow for a streamlined comparison among the different indices.

4. Update and modernize the CWCB Drought Planning Toolbox website by providing newer resources to data hosting portals and dashboards.

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