Montana Drought Management Plan
- Guide for Drought Monitoring & Assessment -

1.0 Introduction

This guide is intended to offer direction in the application of drought metrics in Montana and identifies some common pitfalls in drought assessment resulting from these extremes.
Drought monitoring and assessment in both the near and long-term is complicated and nuanced. In Montana, extreme geographic and climatologic diversity makes this task even more difficult. Variability resulting from climate change and an increase in the incidence of extreme weather events add additional complexity. Droughts in Montana are highly variable, and can be characterized in terms of their severity, location, impacts, duration and timing. No two droughts are ever completely alike. Given this variability, there are a variety of drought indicators and drought indices that help to assess drought extent and severity. Furthermore, the impacts of various forms of drought are often as different as the causes. The drought indicators discussed in this plan offer a guideline for identifying the severity, location, duration onset and cessation of drought conditions in Montana.

1.1 The importance of seasonality for assessing Montana's drought conditions

Much of Montana has a semi-arid climate, where drought is a recurring, natural and cyclical feature that presents in a variety of forms and intensities. Drought arises from a range of weather processes that can suppress precipitation, increase snowmelt rates, increase evaporative water loss and contribute to declines in soil moisture, surface water and groundwater availability. Montana's topography and mix of continental and maritime climates contribute to significant variability in seasonal meteorological conditions that lead to drought. Precipitation amount, precipitation phase (e.g. rain versus snow), air temperature, humidity and wind speeds all vary significantly, and all have important ramifications for drought onset and intensification. For example, during the summertime, extended heat waves, exceptional aridity and lack of wetting rains can cause rapid intensification of drought conditions resulting in "flash drought" (exemplified during the spring and summer of 2017 and again in June of 2021). However, slowly evolving deficits in the winter snowpack accumulation can result in "snow drought" conditions that have serious implications for springtime hydrological drought and ecological drought. These seasonally dependent meteorological conditions and the degree of departure from "normal" are the variables (e.g. intensity of abnormality) that set the stage for drought development and characterization.

Since the U.S. Drought Monitor (USDM) started in 2000, the longest duration of drought (D1-D4) in Montana lasted 307 weeks (5.9 years). This long-term drought began on May 16, 2000 and ended on March 28, 2006. The most intense periods of drought occurred in the weeks of September 12, 2017, and November 23, 2021, where D4 (exceptional drought) affected 26% and 33.1% of Montana's land area (Fig. 1).

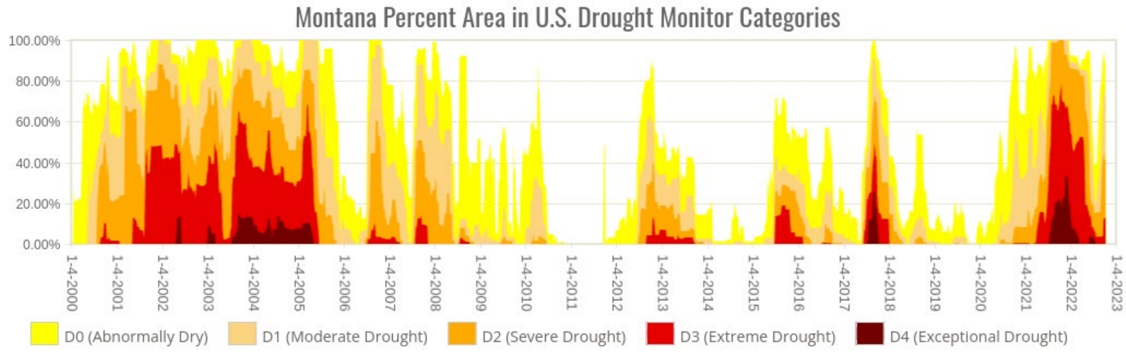


Figure 1: *Time series of land area within different drought categories January 2000 to Present. Attribute USDM.*

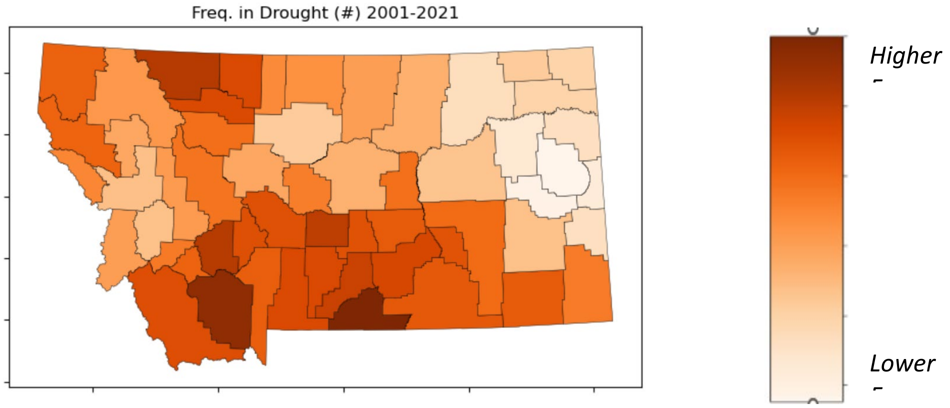


Figure 2:*. Map of drought exposure by county as represented by the USDM*

As illustrated in the figures above, historically, drought has appeared most frequently in the south central and southwestern portions of Montana (Madison and Carbon counties; fig. 2). However, it is also a relatively frequent phenomena along the northern portions of the Rocky Mountain front (Glacier County; fig. 2). Over the last 20 years, northeastern Montana has experienced the least time in drought, however severe droughts in 2017, 2021, and 2022 have disproportionately impacted this region.

1.1.2 Seasonal Conditions: Winter (December, January, February)

Winter conditions in Montana vary widely across the state. Wintertime is typically the wettest season in western Montana averaging about 10 inches of precipitation. In contrast, winter east of the Continental Divide is a climatologically dry period representing an average of 2.3 inches of precipitation. Most of Montana's winter precipitation falls as snow with accumulations upwards of 75 inches of snow water equivalent in western MT's mountains. The accumulated snowpack in western Montana is critically important to Montana's surface water supply, and snowpack is a primary indicator of hydrological drought during the transition from spring into summer. Chinook Winds can contribute to periods of mild temperatures and windy conditions east side of the Continental Divide and these can have significant impacts on winter snowpack accumulation and retention. Further east, the extent of rangeland snow abundance is also an important contributor to soil moisture recharge - the lack of prairie snowpack or an "open winter" can foreshadow terrestrial and agricultural drought conditions.

1.1.3 Seasonal Conditions: Spring (March, April, May)

Temperatures warm during Montana’s spring (statewide average of 41.7 degrees Fahrenheit) and the accumulated winter snowpack in both mountainous regions to the west and the plains in the east begins to melt. The peak prairie snowpack usually occurs by March 15. In the mountains, peak snowpack typically occurs near April 15th although late season storms may boost snowpack into late May. Spring and early summer are also periods of significant precipitation in Montana and can set the stage for normal water supply conditions or drought. Much of the precipitation and snowmelt contributes to the recharge of soil moisture and groundwater that is critical for progression into summer water supply and growing conditions. Western Montana tends to have cooler springs (~39.5 degrees Fahrenheit) which help prolong the melting of higher elevation snowpack during “normal years”. Western Montana typically receives an average of 8.8 inches of precipitation in the spring, in addition to water released from accumulated mountain snowpack. Given eastern Montana’s small winter precipitation totals, the anticipated 5.4 inches of average spring and early summer precipitation is critical for soil moisture recharge and adequate summer growing conditions. East of the continental divide, June is the most important precipitation month. In 2021, cooler and wetter than normal conditions in April and May were not enough to overcome the record heat and dryness that arrived in June resulting in the rapid onset of extreme drought conditions.

1.1.4 Seasonal Conditions: Summer (June, July, August)

Summer precipitation is more evenly distributed across the state - ranging from 5 to 6 inches for west and east of the continental divide respectively. Precipitation is often highly localized due to the occurrence of strong thunderstorms that originate from both the subtropical Pacific and Atlantic. Highly localized drought events can occur due to absence of these storm events in the summer. While these events are valuable for critical moisture, they can also produce crop damaging hail. Temperatures during the summer vary significantly due to elevation and proximity to the continental divide. Average summer temperatures vary between 59 and 65 degrees Fahrenheit west and east of the continental divide respectively. Temperatures across Montana typically peak in July and August when daily highs can reach above 100 degrees Fahrenheit. The number of days above 90 degrees can have a significant impact on declines in soil moisture, crop damage and declines in groundwater and streamflow. High temperatures in conjunction with dry atmospheric conditions promote significant moisture loss due to evapotranspiration. These dry atmospheric conditions can cause drought conditions to emerge quickly and amplify dry soil moisture conditions if recharge was not realized during the spring. During this time, paying close attention to precipitation, temperature and evaporative demand is critical to monitor terrestrial drought conditions that impact agriculture, range and forest ecology, soil moisture, surface water and groundwater.

Rapid increases in temperature and declines in precipitation in late spring and early summer can offer an early signal for the onset of cascading drought impacts affecting soil moisture, streamflow and groundwater. Higher than normal temperatures and precipitation deficits in the later spring and early summer have the potential to trigger the early onset of plant dormancy across the lower elevations, bottomlands, and prairie.

1.1.5 Seasonal Conditions: Fall (September, October, November)

Fall in Montana is met with increased precipitation across the state, ranging from 8 in to 3.6 in for west and east of the continental divide respectively. Precipitation during this period is critical for soil moisture recharge across the state and should be monitored closely. Temperatures vary considerably during the fall season with relatively warm conditions dominating in September, and cool to cold conditions dominating in November. Daily average temperatures during the fall are in the low to mid 40 degrees Fahrenheit. Most vegetation in Montana goes dormant by mid to late October in response to freezing temperatures and the reduction in daylight hours. Precipitation falls as a mix of rain and snow during this period Antecedent precipitation accumulations following the growing season and prior to the winter freeze can be critical to soil moisture recharge that could determine water availability the following spring. The snow accumulation season in the mountains generally starts mid-late October.

1.2 The Future Climate of Montana

Future changes to Montana's climate are expected throughout the next several decades due, in part, to anthropogenic climate change. These changes are also expected to impact the character of drought events with respect to historical frequency and intensity. Montana has experienced significant warming trends over the last several decades. Based on an analysis presented in the Montana Climate Assessment (MCA, Whitlock et al., 2017), Montana is projected to continue to warm in all geographic locations, seasons, and under all carbon emission scenarios throughout the 21st century (Fig. 3).,Depending on the emission scenario, Montana temperatures are projected to increase by approximately 4.5-6.0°F (2.5-3.3°C) by 2050 , and. 5.6-9.8°F (3.1-5.4°C) by the end of the century.

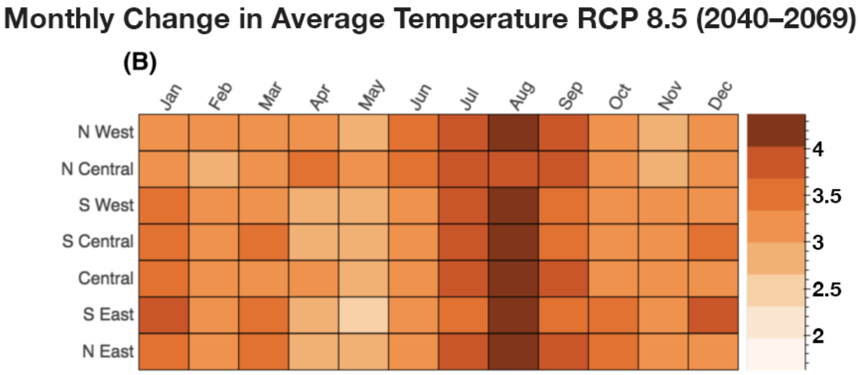


Figure 3: *Projected changes to Montana's future climate with respect to temperature. Warming is expected for all regions and seasons across Montana. Figure from the Montana Climate Assessment (MCA,Whitlock et al., 2017).*

Changes to Montana's future precipitation regime are less certain than expected trends in warming temperatures. With this uncertainty in mind, the MCA (Whitlock et al., 2017) projects that precipitation will likely increase in winter, spring, and fall. However, more importantly for drought conditions in Montana, precipitation is projected to decrease in summer (Fig. 4). The largest increases are expected to occur during spring in the southern part of the state. The largest decreases are expected to occur during summer in the central and southern parts of the state. Overall, increases in precipitation variability are expected across Montana.

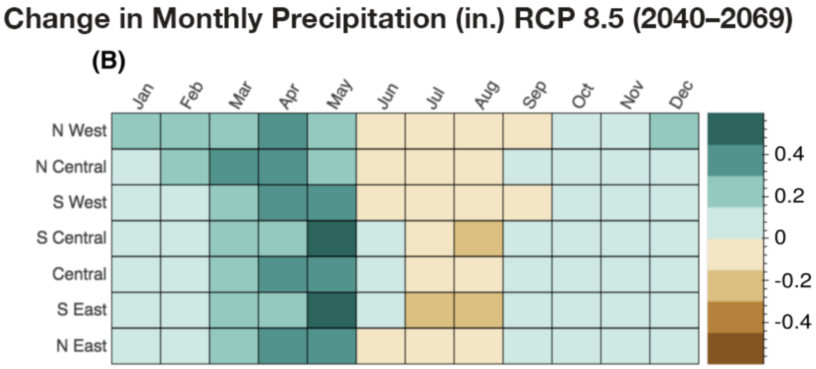


Figure 4: *Projected changes to Montana's future climate with respect to precipitation. Precipitation is expected to increase in the winter, spring and fall, but decrease in the summer. Figure from the Montana Climate Assessment (Whitlock et al., 2017).*

1.3 Implications for future droughts

Changes to Montana's future climate have major implications for the character of future droughts across the state. Warmer atmospheric temperatures are of particular concern because they result in air that can hold more water. Furthermore, warmer temperatures cause rates of evapotranspiration to increase, resulting in greater atmospheric demand for moisture. The combination of these two elements suggests that in the future Montana will experience greater depletions of water from snowpack, surface water and soil moisture. The impact of increasing atmospheric demand is also a major driver of rapid drought onset and "flash drought" events (Christian et al., 2021). The negative impact of increasing atmospheric demand for moisture may be amplified by a decrease in summertime precipitation, setting the stage for more severe summer droughts in Montana

Projected warming temperatures across all seasons will impact Montana's hydrological cycle, water storage dynamics and future drought events. For example, warmer wintertime conditions will impact the persistence of snow water resources and is projected to shorten the "snow season." As a result, moisture stored in the snowpack will release earlier in the season and have less opportunity to help sustain water availability during the spring and summer seasons. Warming temperatures are also projected to impact the phase of precipitation falling, with a shift towards greater proportions of rain versus snow (Marshall et al., 2019) and a greater number of rain on snow events (Musselman et al., 2020). Warmer springtime conditions will promote greater moisture loss to the atmosphere following melt, further reducing the availability of snow-melt derived moisture later in the season.

The historical impacts of drought and projected changes to Montana's drought character underscore the importance of accurate assessment frameworks and monitoring networks across Montana. In addition, strong, consistent and reliable communication between local, state and federal entities is critical for timely action in response to drought. The importance of these monitoring networks and assessment frameworks will only become more critical as the climate continues to change and drought events occur more frequently.

2.0 Montana's Drought Indices and Indicators:

The purpose of this section is to cover some of the most used drought indicators and indices for assessing drought extent and severity in Montana. **Drought Indicators** are variables used to describe drought conditions. Examples include measured precipitation, snowpack, temperature, soil moisture, groundwater, streamflow and reservoir levels. **Drought Indices** aim to measure the quantitative state of drought on the landscape for a given timeframe and are typically computed numerical representations of drought severity, assessed using climatic or hydrological inputs, including the indicators listed above. Examples of drought indices include precipitation percentiles and the Standardized Precipitation Index (commonly referred to as the SPI). Drought indices leverage historical information to contextualize the degree of abnormality which directly relates to drought severity (see **Table 1**). Historical information is defined using a "reference period" to define the distribution of expected conditions for a given location/season. Montana uses a 30-year period of record as the foundation for drought indices. The choice of this reference period is very important in defining drought severity (following Hoylman et al., 2022). Descriptions of Montana's drought metrics (e.g. both drought indicators and indices) are outlined below. The indicators and indices discussed in this plan offer a guideline for identifying the severity, location, duration onset and cessation of drought conditions in Montana. The process and approach described here will evolve and integrate new metrics as they are developed in the future.

2.1 Montana's Drought Metrics:

No single indicator or index can describe the extent or intensity of all types of droughts. Instead, the preferred method is to use many drought indicators in a "convergence of evidence approach" (described in greater detail below) to obtain a holistic assessment of drought extent and severity. The U.S. Drought Monitor requires that the assessment of drought severity be supported by quantitative data derived from drought metrics, indices, and documented impacts.

Drought metrics are computed using differing time periods or "timescales" to evaluate drought duration and seasonality. The time periods used typically range from days to years. For example, precipitation anomalies can be computed for a 30-day timescale (representing more recent anomalies) and for a 1 or 2-year time scale (representing long term precipitation deficits). Importantly, the most appropriate metrics and/or timescales to use for assessing drought in Montana are seasonally dependent (discussed in greater detail below). The indicators and indices listed in Table 1 are those that are generally implemented by Montana's Drought Assessment group but are not intended to represent an exhaustive or exclusive list. They are grouped into the following classifications: (a) meteorology, (b) soil moisture, (c) hydrology and (d) vegetation:

Table 1: Drought metrics and required data for their calculation

a. Meteorology	**Description**
Precipitation Percentile	**Input data: Precipitation** Precipitation percentiles describe the amount of precipitation received relative to what is expected over a timescale of interest. Percentiles are calculated against a historical record (reference period) to estimate expected precipitation amounts.
Percent of Normal Precipitation	**Input data: Precipitation** Percent of normal precipitation describes precipitation anomalies with respect to the climatological average defined by the reference period. While more easily interpretable to some, percent of normal indices cannot describe how a particular anomaly compares to observed variability (which is a strength of percentile indices). This metric is more valuable at longer timescales 90+ days especially during dry periods where one event could appear unduly beneficial. E.G. 1" in a month like August that typically accumulates only 0.5" is 200% but depending upon the location may not be insignificant.
Temperature Percentile (daily maximum or minimum)	**Input data: Temperature** Temperature percentiles describe the average daily maximum (or minimum) temperature experienced relative to what is expected over a timescale of interest. Percentiles are useful as they provide a historical context of any particular anomaly with respect to how it compares to observed variability.
Snow Water Equivalent (SWE) Anomaly	**Input data: Snow Water Equivalent (typically SNOTEL or SNODAS)** Snow water equivalent (SWE) is an important indicator of liquid water stored as snow. SWE anomalies describe the observed SWE measured (or estimated) at a site relative to what is expected for a day of interest.
Basin-Scale Snow Water Equivalent (Hypsome-SWE)	**Input data: SNODAS and Digital Elevation Model** Hypsome-SWE represents a method to evaluate the distribution of snow water equivalent (SWE) across watersheds. It evaluates the cumulative SWE that occurs across elevation bands within Montana's HUC 8 watersheds and calculates a percentage of normal. This metric is useful to evaluate high vs low elevation snow water accumulation.

Standardized Precipitation Index (SPI)	**Input data: Precipitation** The Standardized Precipitation (SPI) was designed to standardize precipitation time series across a reference period in order to normalize precipitation anomalies in both time and space. SPI is advantageous because it does not assume a normal distribution- SPI generally assumes that precipitation follows a distribution that can account for the fact that small precipitation events are much more common then big ones (e.g. non-normal). SPI is different from precipitation percentiles as it explicitly models the probability of observing a specific amount of precipitation over a time scale of interest.
Standardized Precipitation Evapotranspiration Index (SPEI)	**Input data: Precipitation and Reference Evapotranspiration** The Standardized Precipitation Evapotranspiration Index (SPEI) accounts for both precipitation (P) and reference evapotranspiration (ET_r) to describe the wetness or dryness of a time period. Similar to SPI it was designed to standardize the difference between P and ET_r ($P - ET_r$) over various timescales During warmer times of the year, SPEI is advantageous to SPI as it accounts for atmospheric demands on moisture as well as precipitation inputs. Therefore, an SPEI value of -2 represents a value that is ~98% drier than the rest of the distribution.
Evaporative Demand Drought Index (EDDI)	**Input data: Reference Evapotranspiration** The Evaporative Demand Drought Index (EDDI) is similar to SPI and SPEI in its formulation, however EDDI only accounts for reference evapotranspiration (ETr). Therefore, EDDI describes anomalies in ETr over a timescale of interest with respect to a historical reference period.
b. Soil Moisture	**Input Data**
Soil Moisture Percentile	**Input Data: Soil Moisture** Soil moisture percentiles describe the amount of soil moisture in the soil reservoir relative to what is expected for period of interest. Soil moisture percentiles are typically calculated with respect to a day of interest (assuming adequate record lengths) or using a 31 day centered moving-window approach (citation). This drought index can be computed using a variety of data sources (both point and spatial grids), some of which are listed below. Potential Sources of Data: NASA Soil Moisture Active Passive (SMAP), U.S. Forest Service TopoFire Soil Moisture, MT Mesonet, NRCS SCAN, NRCS SNOTEL
Soil Moisture Anomaly	**Input Data: Soil Moisture** Similar to soil moisture percentiles, soil moisture anomalies describe the amount of soil moisture in the soil relative to what is expected for a time period of interest. Soil moisture anomalies are typically calculated with respect to a day of interest (assuming adequate record lengths) or using a 31 day centered moving-window approach (Ford et al., 2016). Anomalies are typically computed assuming a Gamma distribution which accounts for non-normal data distributions. Similar to SPI and SPEI above, a soil moisture anomaly value of -2 represents a value that is ~98% drier than the rest of the distribution. This drought index can be computed using a variety of data sources (both point and spatial grids), some of which are listed below. Potential Sources of Data: NASA Soil Moisture Active Passive (SMAP), U.S. Forest Service TopoFire Soil Moisture, MT Mesonet, NRCS SCAN, NRCS SNOTEL

Plant Available Water/ Wilting Point	**Input Data: Soil Water Potential (MT Mesonet)** Soil texture can strongly determine soil water stress to vegetation. The MT Mesonet has developed soil water retention curves for Mesonet sites which allows for the conversion of soil water content to soil water potential (or tension). This is perhaps the most biologically meaningful measure of soil water availability to plants and can be used to estimate where soils are beyond the wilting point and drought stress is all but likely to occur.
c. Hydrology	**Input Data**
Streamflow Percentile	**Input Data: River Discharge (USGS, DNRC)** Streamflow is an important indicator of hydrological drought. Streamflow percentiles represent streamflow deviation from normals and can be computed over various timescales.
Groundwater Percentile	Input Data: Water Table Depth (MBMG, GRACE) Groundwater is an important indicator of longer timescale hydrological drought. Groundwater table height percentiles represent water table deviation from normals and can be computed over various timescales. This metric is important to understand the availability of stored subsurface water but must be used in conjunction with storage characteristics of the aquifer.
d. Vegetation	**Input Data**
Greenness Anomaly	**Input Data: Normalized Difference Vegetation Index (NDVI)**

2.2 Thresholds for drought indices as an indicator of drought severity

Standardized thresholds allow for more effective dataset comparisons and implementation of the “convergence of evidence” (discussed more below), and aids in communication of potential drought impacts and severity assessments to inter-state and national partners. Thresholds represent specific values of an index that indicate different drought severity classifications and Montana’s associated mitigation or emergency management responses. Importantly, the thresholds outlined here are consistent with national drought assessment frameworks. The drought classes that are “triggered” by different index thresholds include: 1. D0 - Abnormally Dry; 2. D1 - Moderate Drought; 3. D2 - Severe Drought; 4. D3 - Extreme Drought; and 5. D4 - Exceptional Drought. These classifications have been adopted from the U.S. Drought Monitor (USDM, link).

Table 2: A summary of recommended drought triggers for different drought levels.

Category	**Description**	**Percentile Ranges** e.g. precipitation, soil moisture, streamflow, snowpack	**Drought Index Values** e.g. SPI, SPEI, EDDI
D4	**Exceptional Drought**	0 to 2	-2 or less
D3	**Extreme Drought**	2 to 5	-1.6 to -2.0
D2	**Severe Drought**	5 to 10	-1.3 to -1.6
D1	**Moderate Drought**	10 to 20	-0.8 to -1.3
D0	**Abnormally Dry**	20 to 30	-0.5 to -0.8

2.3 Drought Metric Timescales – Some Guidelines

Timescale is a key consideration when calculating and assessing drought severity. Timescales (also referred to as lags or aggregation periods) represent the period over which a drought metric is calculated. For example, a 30-day timescale represents a 30-day aggregation period over which a variable of interest is analyzed. Monitoring drought indices and indicators at various timescales enables the identification of short-term wet periods within long-term droughts or short-term dry spells within long-term wet periods. The appropriate timescale also depends upon the specific drought stage under consideration. As drought severity increases, the timescale applied for evaluating the aggregation of drought metrics typically increases. For example, the transition from D0 (abnormally dry conditions) to D1 (moderate drought) can occur in a matter of days or weeks. But a transition from D2 (severe) to D3 (extreme) typically (but not always, as in the event of a Flash Drought) usually takes more time and therefore requires an assessment with a longer timescale (30 to 90 days or more). This increase in the timescale is necessary to diminish and compensate for the effects of short-term weather variability. As a result, the transition and appropriate timescale for making changes between drought categories typically increases as drought severity increases. The same applies to the determination of drought recovery.

Choosing the right timescale to describe drought and its causes by a process of interest (e.g. precipitation shrotage, soil moisture decline, groundwater or surface water) can be challenging. Furthermore, drought timescales will sometimes include or exclude specific short-term events (such as a major precipitation event, a week with high temperatures, or an unusual out of season event) which may dramatically change the depiction of drought severity in the relevant drought metrics and indices. Inclusion of these types of extreme, short-term events into drought metrics and indices is not wrong, but it can unduly influence drought severity assessments. Practitioners must be aware of the effect of these events on the associated drought metrics.

The use of averages in drought assessments is particularly susceptible to misinterpretation in the evaluation of anomalous weather events. For example, April and May of 2021 in Montana were colder than average followed by the 2nd warmest June on record. In this case, the application of a 90-day timescale to assess temperature indicates relatively average conditions because the colder than normal conditions offset the hotter than normal conditions. In this case, the unusually cool April and May suppressed green-up across Montana, while the unusually hot June caused plant growth to move into dormancy prematurely. The combination of these two temperature driven events greatly increased the severity of the drought across Montana that summer.

The evaluation of data and weather events at a variety of timescales is a core concept of the "convergence of evidence" approach (described below) that must be at the forefront of drought assessment practitioners' consideration in the application of drought metrics in Montana.

2.4 Seasonality of Drought Indicators

The purpose of this section is to outline the key drought indicators and indices for different seasons in Montana and discuss a few theoretical drought evolution scenarios to help describe how different metrics and timescales may be used depending on the seasonal context. This section is intended to share knowledge gained by members of Montana's drought monitoring subcommittee to aid in future assessment efforts.

Montana's climate is one of strong seasonal variability. Conditions change dramatically from cold, snowy winters to hot, dry summers every year. This strong annual cycle means that different drought metrics become more or less useful depending on the season. Moreover, it is important to consider current conditions with respect to the recent past, which in some cases requires the evaluation of metrics over 12 to 24 months or more, to provide a holistic assessment of drought conditions. Drought indices also fail to account for the importance of seasonality or precipitation timing in the aggregation of data. For example, June, east of the continental divide in Montana, is the most important precipitation month. Failure of June precipitation is generally a harbinger for summer drought on the east side of Montana. While those precipitation deficits will show up quickly in the appropriate index, an out of season weather event in mid to late July or August could erase that deficit in the SPI, SPEI or precipitation percentiles. Even though the combination of temperature and precipitation deficit that will likely result in the onset of plant dormancy and associated drought impacts by mid-July, the precipitation indices may suddenly indicate near normal or even above normal conditions. The maps below (Figures 5 & 6) offer a 90-day timescale and illustrate the effect of a rare August storm in the summer of 2021. That year, an unusual 3-day weather event in the third week of August dropped 1.5 to 3 inches of precipitation across much of Montana. That is about twice the normal precipitation in August. Although slightly different in timescale, the maps below show the effect of that one storm on SPEI.

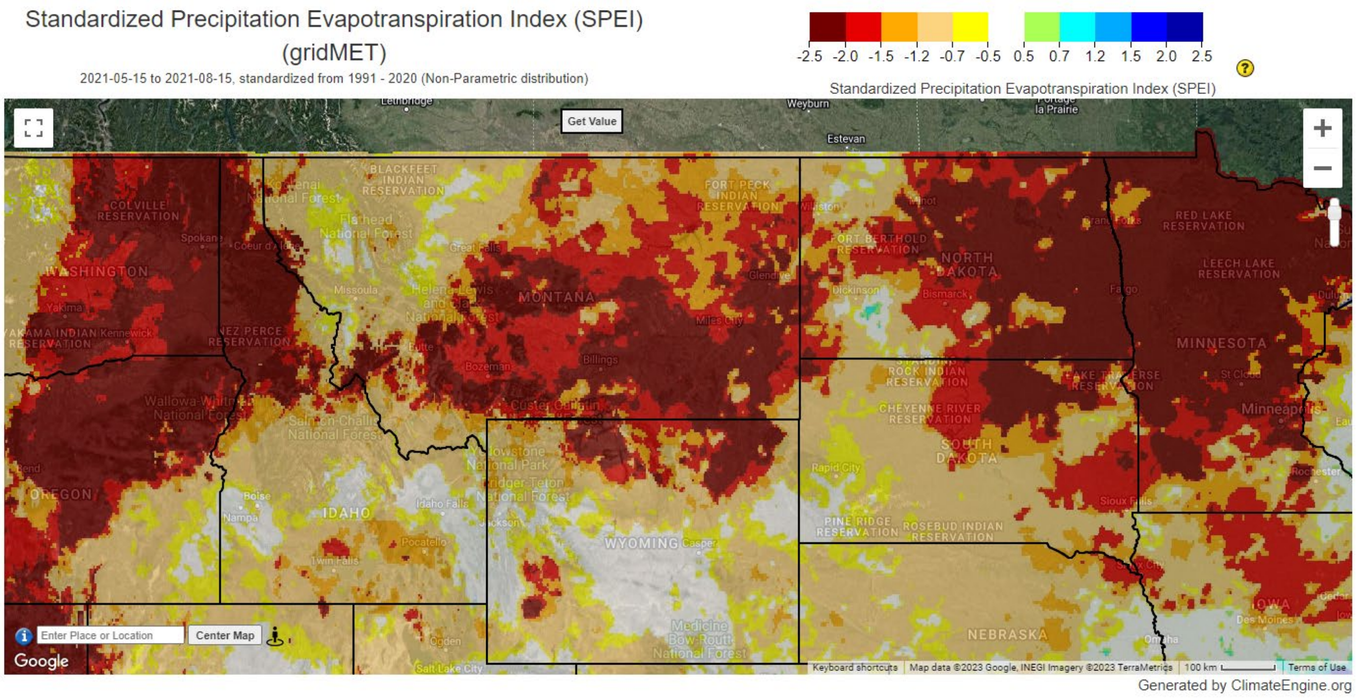


Figure 5: *SPEI – May 15, 2021 thru August 15, 2021*

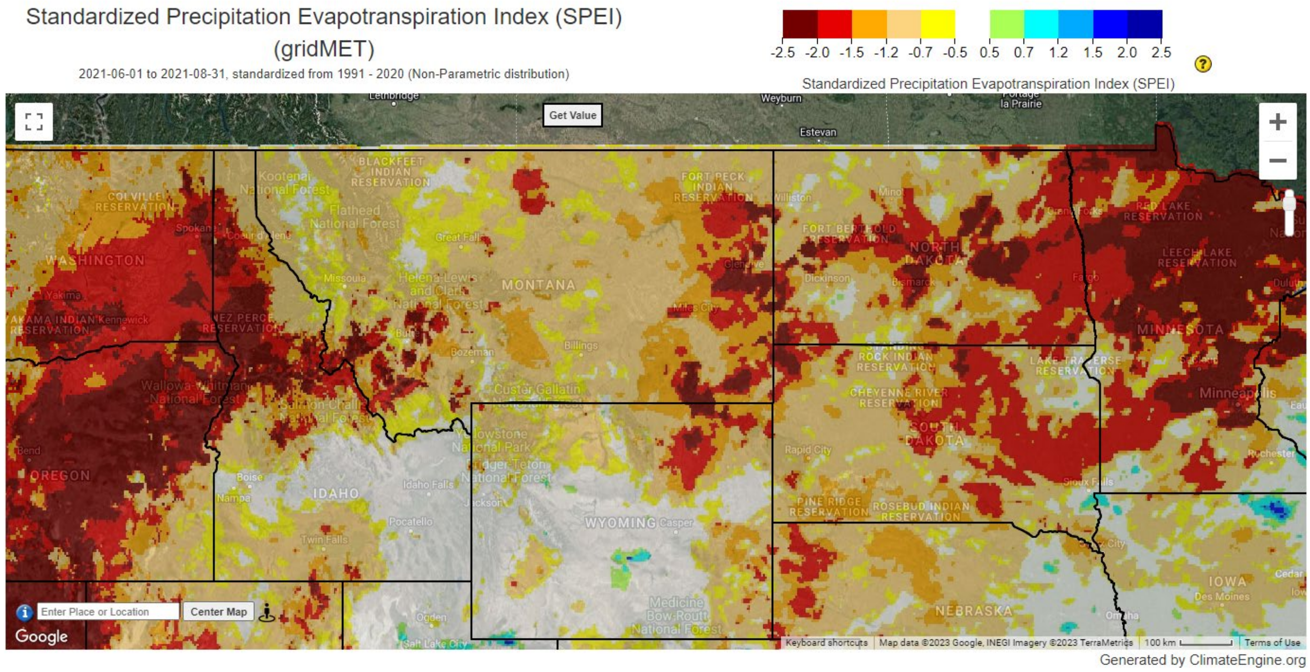


Figure 6: *SPEI – June 1, 2021 Thru August 31, 2021*

The example above illustrates the pitfall of assessing drought conditions absent the consideration of event seasonality or timing.. Despite the index showing substantial improvement in drought conditions, three inches of precipitation in the second week of August of an exceptionally dry and hot summer in Montana could be virtually meaningless with respect to the effect on soil moisture depending on the location (see figures 11and 12). This example also illustrates the importance of a convergence of evidence approach to drought assessments that utilizes multiple metrics, indices, drought impacts and knowledge of local conditions in the assessment of drought severity.

2.4.1 Seasonality of Drought Indicators - Winter (Snow Accumulation Phase)

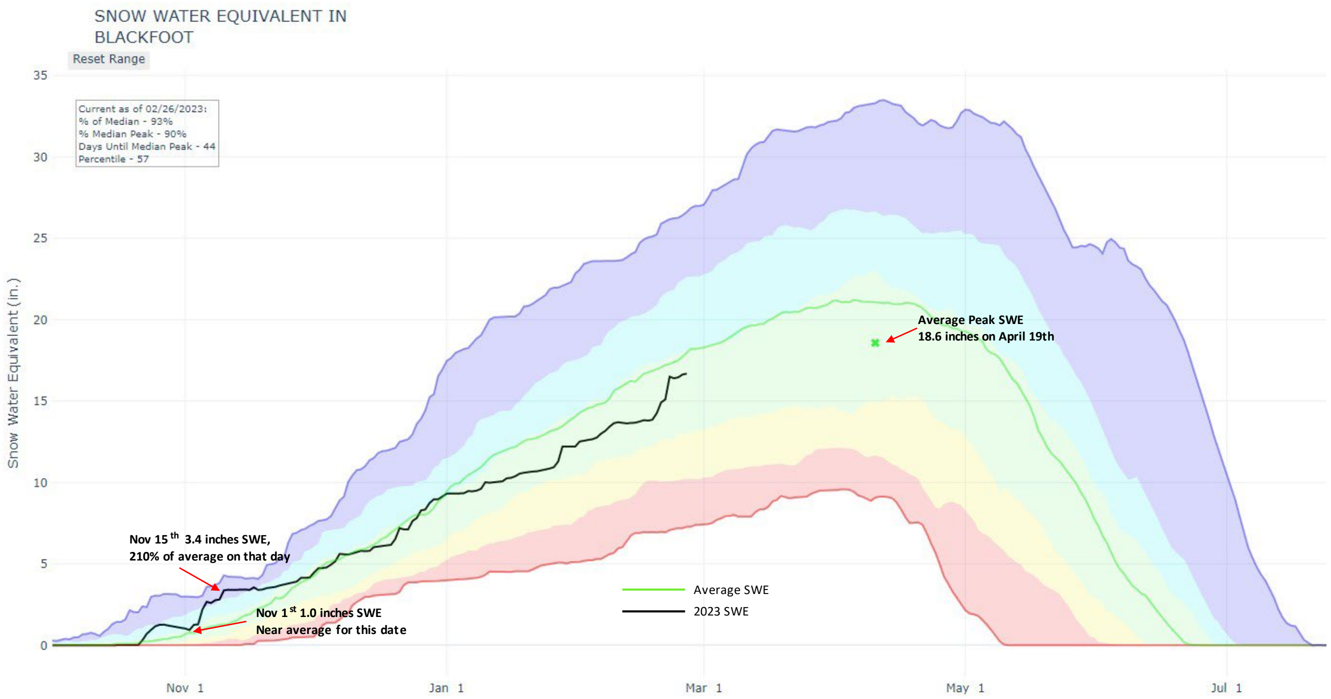
Winter in Montana is often typified by cold air temperatures, with the majority of precipitation falling as snow. Precipitation based metrics like SPI, for example (Table 1), measure the precipitation falling to be immediately beneficial to soil moisture, vegetation, surface water, etc. However, in the case of snow, the precipitation captured by metrics like SPI is not immediately available. It may become available later in the season as melt water or it might be lost to sublimation and not provide the level of benefit indicated by the metrics and indices.

Direct SWE measurements from the USDA Natural Resources Conservation Service Snow Telemetry Network (SNOTEL) are extremely valuable during the cold winter months to monitor water stored in the snowpack. In evaluating the effect of snow on drought conditions, meteorological metrics that are dependent on estimates of liquid precipitation (i.e. SPI, SPEI, precipitation percentiles, etc) are less useful to describe conditions on the ground. Instead, direct measures of snow water equivalent (SWE) or modeled estimates of the spatial distribution of SWE are more important metrics to consider. Of particular importance is the timing and magnitude of peak SWE across basins. These data should be strongly considered in drought assessments during the winter but also recognized as point observations. While very important, SNOTEL stations are distributed at relatively high elevations, and they do not represent the full range of elevations across Montana's watersheds nor are they distributed in every watershed across Montana. Snowpack at these high elevations can have significantly different responses to warm winter temperatures and pre-season melt dynamics. In recent years, warmer than average temperatures for weeks at a time during winter has resulted in increased sublimation (the transformation of snow or ice directly into water vapor) greatly reducing Montana's low and mid-elevation snowpack. As a result, SNOTEL and other precipitation observations may not be indicative of the relative SWE accumulated at lower and mid elevations.

For a more complete watershed scale approach it is important to also consider spatially distributed (gridded) measures of SWE in wintertime assessments. Currently, data assimilation and modeling approaches such as Snow Data Assimilation System (SNODAS, Table 1) are particularly useful to contextualize point-based measures of SWE. Using these data it is possible to generate maps of standardized SWE (Table 1) and models that compute elevational profiles of the snowpack (such as Hypsome-SWE; Table 1) to better understand how snow water is distributed across the landscape and when it is lacking or exceeding expectations. Snowpack is a unique moisture reservoir in Montana that acts as a critical storage system. It is unique in that seasonal accumulation is often one of the most important considerations along with the rapidity and timing of melt (discussed further in the "spring" section below). This means that snowpack deficits during the early snow accumulation season can be balanced by a few large storms late in the season.

Snow is not the only consideration during wintertime drought assessments. Annual temperature and wind are also critical to consider, especially in the plains of eastern Montana. In these regions, warm temperatures during the wintertime can cause "open" conditions that decrease snowpack retention, increase sublimation from the snowpack (causing atmospheric losses that do not improve soil moisture) and remove the thermal buffering provided by the snowpack needed for certain agricultural practices. Streamflow is often in "baseflow" conditions during this time and low flows are the norm. In this case, percentiles of streamflow can offer a useful indicator of surface water supply before the snowmelt season, although ice jams and cold temperatures can cause erroneous readings that must be taken into consideration. Finally, precipitation metrics at longer timescales (~180 days) are useful to put snowpack accumulation into a seasonal context and describe places more likely to have experienced soil moisture recharge in the fall prior to freeze-up.

In evaluating snowpack as represented by SWE, the indices typically represent SWE as a measure of available SWE for that particular day. As a result, this indicator should be used with some caution as it can be misleading in both the early and late stages of the snow season. For example, the average peak SWE in the Blackfoot River subbasin is 18.6 inches (Figure 7, below). On November 1st the average accumulation is 0.7 inches. In 2022, three large storms in late October and early November had deposited 3.4 inches of SWE by November 15. Even though there is still 15 inches of SWE to accumulate in the basin, the data and associated maps indicate that the basin is holding more than 200% of normal on that date. That is an encouraging number, however, snowpack early in the season is largely aspirational. The timing is so early that this number is virtually meaningless with respect to water availability for snowmelt in the spring.



Nov 15th 3.4 inches SWE, 210% of average on that day

Nov 1st 1.0 inches SWE Near average for this date

Average Peak SWE 18.6 inches on April 19th

Figure 7: *Early Season SWE in the Blackfoot River Basin 2023 WY*

This same principle applies at the end of the season when a relatively minor delay in snowmelt or a late season storm can have an outsize impact on the representation of SWE for that day. For example, the cool April and May of 2022 delayed snowmelt. In addition, some late season snowstorms added more SWE to the accumulation. As a result, in a year when most basins failed to reach peak SWE, a map of SWE in mid-June indicated most basins at more than 1,000 percent of normal at a time when many rivers in Montana were setting all-time record lows. As the graph in figure 9 shows below, despite falling far short of peak SWE, the delayed snowmelt produced the high basin SWE percentages in mid-June. This example is another good illustration of the importance of the convergence of evidence approach and the need to evaluate multiple metrics and indices.

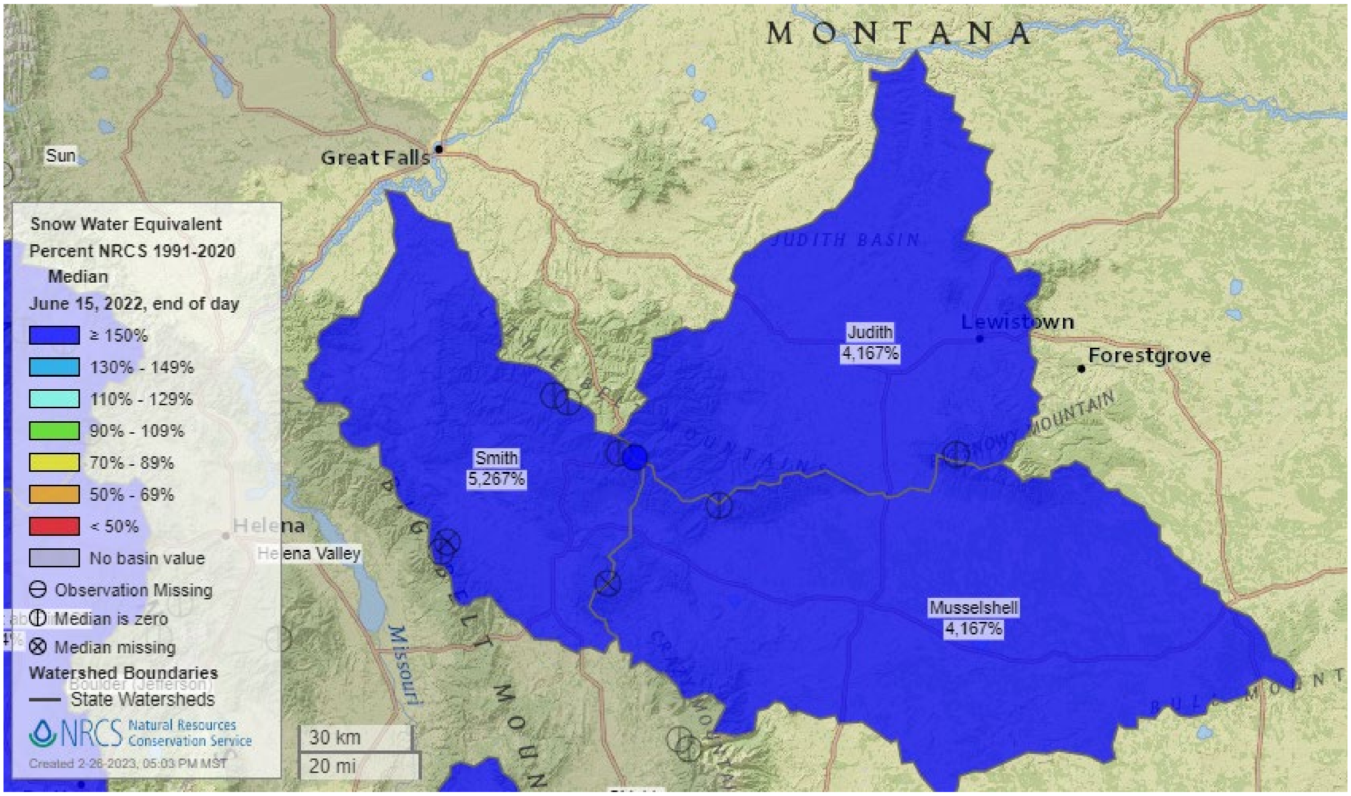


Figure 8: *SWE as measured in the Smith – 5,267%, Judith and Mussellshell, 4,167%, basins on June 15, 2022.*

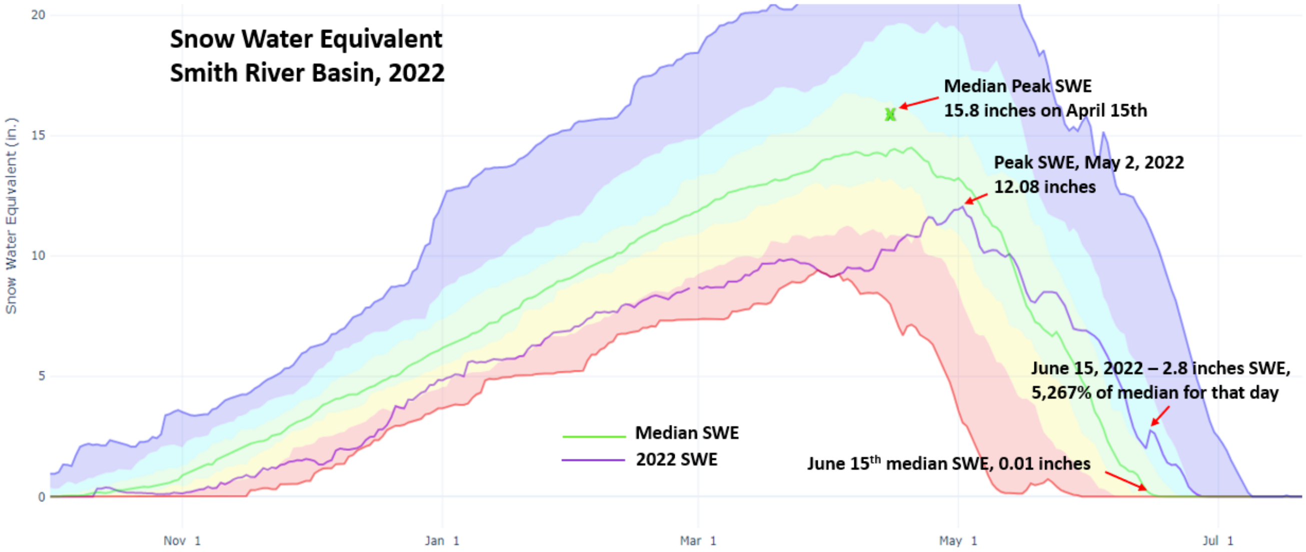


Figure 9: *a plot of historic SWE in the Smith River Basin*

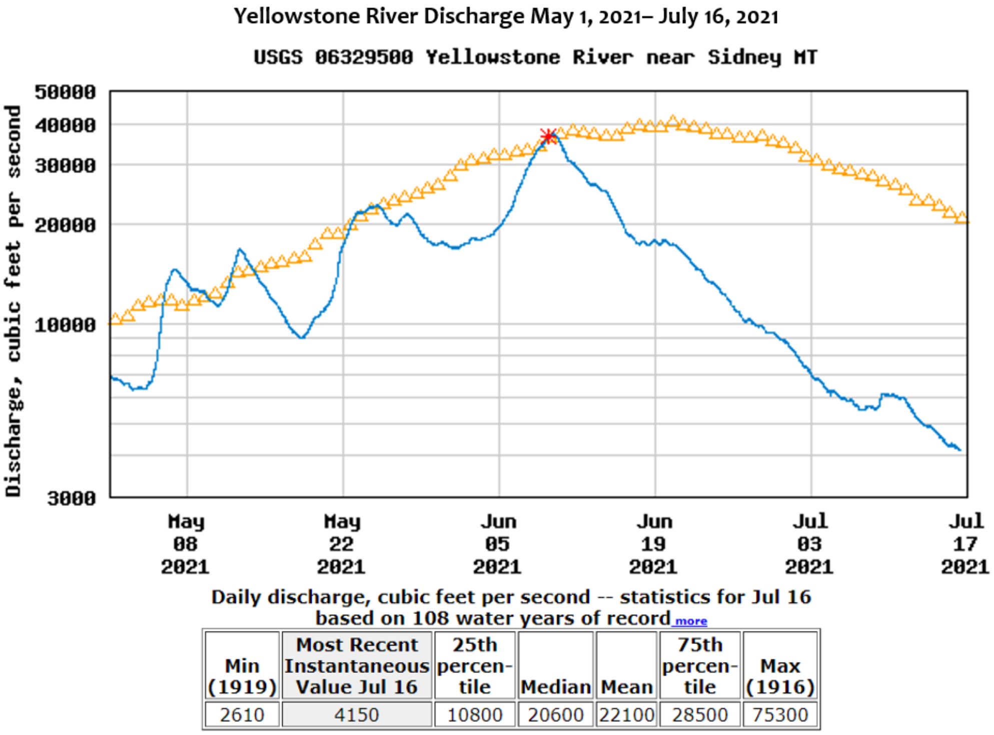
2.4.2 Seasonality of Drought Indicators - Spring (Snowmelt and spring moisture)

Spring in Montana brings the snowmelt and seasonal rains. This period represents a critical time of moisture recharge across the state. Moisture released from the snowpack infiltrates into the soil and groundwater reservoirs to support vegetation and feeds rivers for months to come. This recharge is an important indicator of conditions during the warm and dry summer and can offer a useful “early warning” indicator of future conditions. If no soil moisture recharge occurs during this period, it is more likely that soil water reserves will be inadequate for summertime demand. Timing and rate of snowmelt is of critical importance in the mountains, while precipitation accumulation, timing and onset of higher temperatures is of critical importance on the prairies. For example, early melt events diminish water availability later in the season for streamflow and late season soil moisture. In contrast, late melt events can prolong water abundance into the early to mid-summer, especially if seasonal spring rains amplify melt water stores (rainfall is much more likely to infiltrate moderately wet soils).

Springtime also brings seasonal rains back to Montana. SPI, and precipitation percentiles are key indicators for determining the recharge of soil moistureand groundwater and surface water run-off. Temperature and evaporative demand indexes (e.g. SPEI, EDDI, temperature percentiles) help to describe depletion of moisture to the atmosphere. During the spring, shorter timescales (30 to-90 days) that capture the post-winter season deserve the greatest attention.

Measures of vegetation greenness can provide a useful indicator of soil water recharge and temperature dynamics across the state. Vegetation indices with adequate periods of record (to allow for proper standardization) are useful for evaluating vegetation emergence and development. However, it should be noted that the timing of vegetation emergence is a function of both water availability and temperature, both of which can have a negative (delaying) effect on vegetation for different reasons. Measures of vegetation greenness as a drought indicator is most useful early in the season (late April to late May as an indicator for the onset of green-up).

Streamflows are typically at the highest levels between May 1st and June 15th. Flooding is common during this timeframe, but flooding is not always indicative of excess water availability across the terrestrial landscape and can occur in the midst of a drought. Meteorological conditions that moderate and prolong high flows later into the melt/runoff season are generally advantageous for sustaining late season streamflow. ***The rapid decline of streamflow shortly after peak flow (for example, the Smith and Yellowstone rivers in 2021) is a good indicator of the onset of hydrologic drought as was observed in central and southwest Montana that year .***



Daily discharge, cubic feet per second -- statistics for Jul 16 based on 108 water years of record more

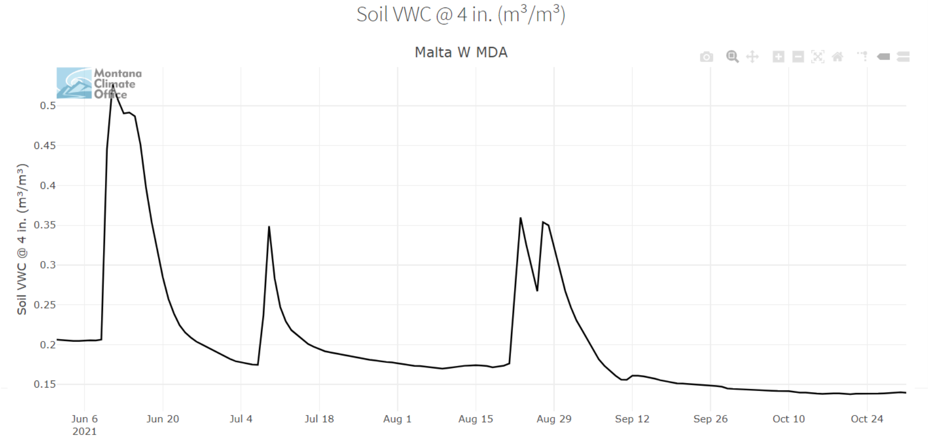
Min (1919)	Most Recent Instantaneous Value Jul 16	25th percen- tile	Median	Mean	75th percen- tile	Max (1916)
2610	4150	10800	20600	22100	28500	75300

Figure 10: *Yellowstone River discharge spring of 2021*

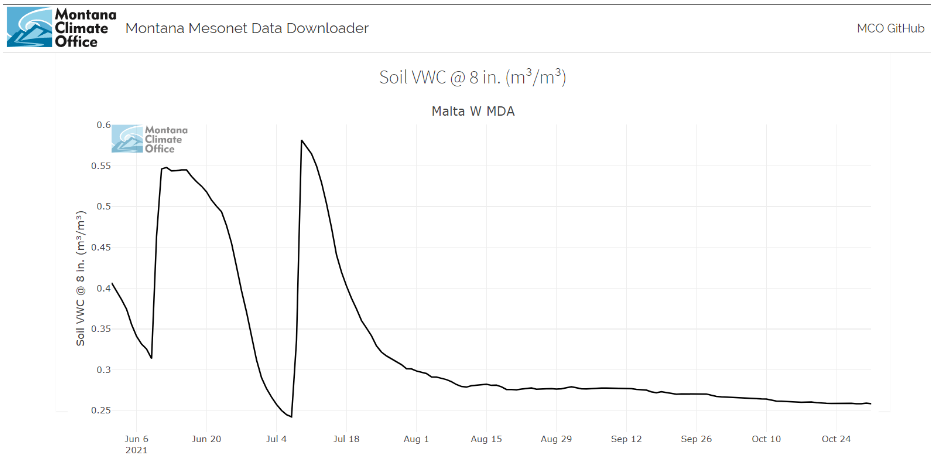
2.4.3 Seasonality of Drought Indicators - Summer (Drydown and evaporation demand)

During the summer, unusually hot, dry and windy conditions can amplify high rates of evaporative demand, extracting soil moisture from the subsurface. The strong impact of evaporative demand on rapid onset droughts (flash droughts) is of special importance to consider during this period. Drought metrics like SPEI (30-180 day), EDDI (30-180 day), soil moisture anomalies/percentiles and streamflow percentiles are critical for these assessments. Timescale is a critical consideration during this time period, where 30-to-90 day metrics tend to best describe moisture recharge or depletion related to this season specifically. However, due to the importance of springtime moisture, 90-to-180 day timescales can help to describe longer term drying trends that capture seasonal spring moisture. Many ecosystems are driven by seasonal variations in precipitation delivery. In this scenario, even excess annual precipitation may lead to drought conditions driven by the seasonality of precipitation accumulation. ***In Montana, it is very unlikely that unseasonably wet conditions in late July or August will be enough to overcome unseasonably hot and dry conditions in June.***

Leveraging soil moisture data during this period is helpful as it incorporates the integrated effect of precipitation and evaporative demand on water availability. Furthermore, soil moisture observations help drought assessment practitioners differentiate “effective” precipitation from non-beneficial precipitation (e.g. precipitation that immediately returns to the atmosphere via evapotranspiration). Dry soils impede the infiltration of moisture into the subsurface diminishing the relative efficacy of any precipitation events. Therefore, a 0.5 inch to 1 inch event may not relieve soil water deficits as greatly as expected if this precipitation falls on dramatically dry soils. Soil type is another important consideration when evaluating the effect of precipitation events. The extremely tight, high clay soils found in the eastern half of Montana are unable to effectively absorb water as efficiently as the more loamy and cobbly soils more prevalent on the west side. This effect can be especially problematic during short duration, high intensity precipitation events that may result in surface flow but have little effect on soil moisture due to soil physics. For example, the figures below show the effect on soil moisture at a Montana Mesonet station following the mid-August precipitation event described in figures 5 & 6. Despite receiving 3 inches of precipitation between August 5 and August 29th, improvements in soil moisture at 4” only lasted about a week and there was no discernible improvements at 8 inches. Drought indices like SPI, SPEI, and precipitation percentiles can be prone to overstating the benefits of these types of precipitation events, especially those occurring in mid to late summer when soils are driest. Drought assessments should contextualize precipitation in the context of both antecedent and current conditions and must consider the role of soil characteristics when evaluating the potential for improvements in drought classification resulting from precipitation events.



Figures 11 &12: *Graphs of Soil Water Content at 4” and 8“ following a mid-August rain event, 2021, Malta, MT.*



Summertime surface water and streamflow dynamics (reservoir levels, stock water availability, streamflow and temperature) are also important metrics to consider during summertime assessments. This period is critical for ecological impacts (algae blooms, salmonid thermal and low flow stressors, etc.) and economic impacts (outfitting, surface water supply for agriculture, etc). Recent droughts in the southwestern and central portions of Montana strongly impacted ecosystems and the recreation industry due to wide-reaching fishing closures and restrictions. Stream temperature (where available) is also a useful indicator of ecosystem stress in fluvial systems (see Fish, Wildlife and Parks temperature thresholds for restrictions on the recreation sector) and should be considered as an ecological impact in drought assessments.

Vegetation based drought metrics should also be considered in the summertime. Drought metrics that incorporate remotely sensed measures of vegetation stress are especially useful as they capture actual vegetation response and can be independent measures of drought conditions from meteorologically based metrics (Table 1). June is typically Montana’s greenest month, and greatly diminished levels of greenness at this time can offer an early signal for drought onset. This metric is also especially useful after July 15th with the onset of warmer and drier conditions when available soil moisture is the primary source of water for vegetation. This analysis can be useful in a similar context to soil moisture data in differentiating “effective” precipitation from specific rain events. These metrics are also useful when considering range and pasture conditions important to the livestock producer community and rangeland ecosystems. Figure 12 and 13 below are maps of the Vegetative Health Index – VHI for mid-June of 2021 compared to the VHI for the same week one year previously. The severely degraded vegetative health in mid-June that year offered a good indicator for the early onset of drought conditions.

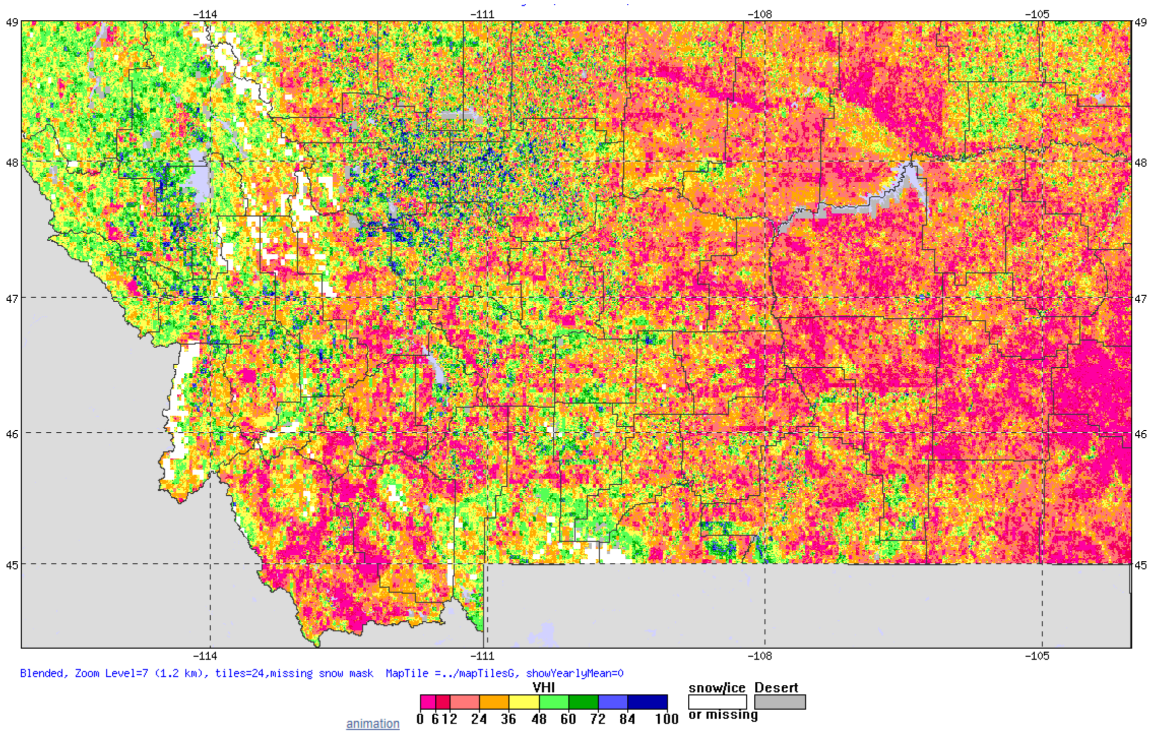


Figure 13: *Vegetative Health Index – June 17, 2021 (week 24)*

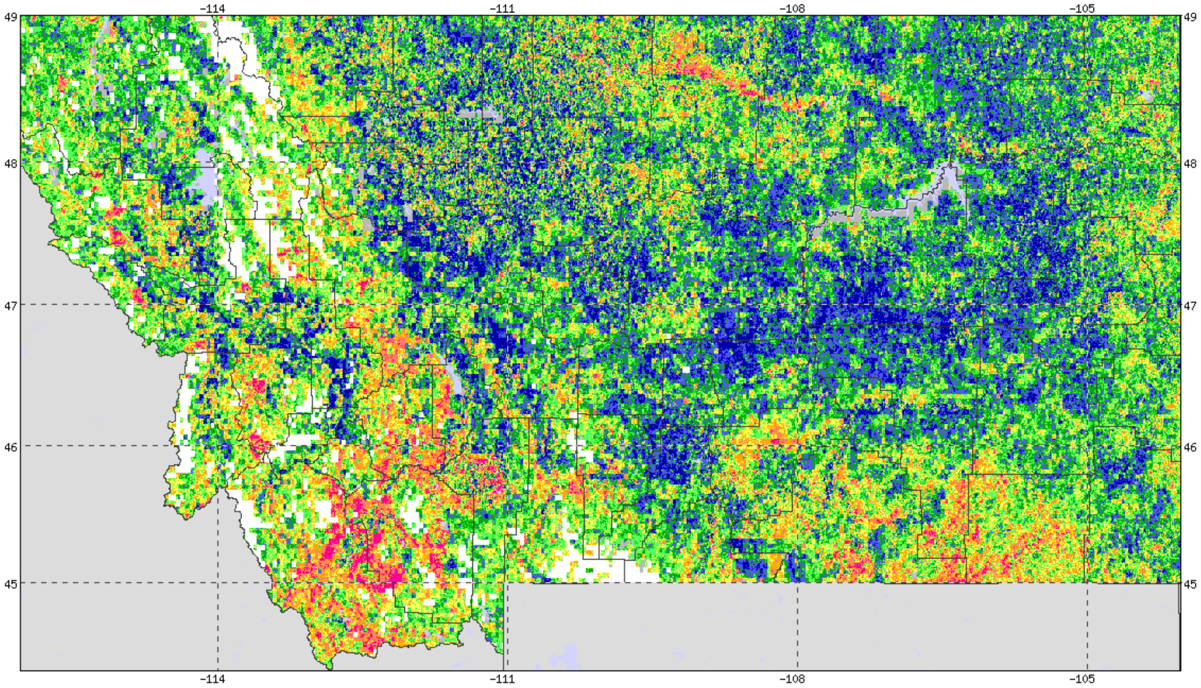


Figure 14: Vegetative Health Index – June 17, 2020 (week 24) – 2020 was the onset of the drought in SW MT. June that year was mostly average for the remainder of the state.

2.4.4 Seasonality of Drought Indicators - Fall (Soil moisture recovery, freeze up)

Following the hot, dry summer conditions, soil moisture reservoirs and streamflow are typically low. The fall provides a time for soil moisture recharge that is critical prior to the “freeze up” (e.g. when soils freeze and soil moisture uptake is severely reduced until melt). Conditions can remain hot and dry during this period, especially prior to November. Therefore, drought assessment practitioners should consider both SPI and SPEI for meteorological indices at short to medium time scales (30-180 days). Soil moisture data should also be used during this period to differentiate effective precipitation as soils are likely to be very dry prior to recharge. Streamflow is expected to remain low during this period but may respond to precipitation events. In this case it is important to use longer timescales of streamflow percentiles (e.g. 28-day streamflow metrics from USGS duration hydrograph toolkit, link) in order to avoid overestimating the effect of improving streamflow conditions due to a short and transient rise in the hydrograph resulting from an isolated precipitation event.

2.4.5 Special Cases: Multi-annual events

Drought conditions in Montana can persist for several years. In the event of multi-annual drought events, short term (e.g. 30-to-180 day) metrics may not fully describe conditions on the ground, especially in the spring, summer and fall seasons. This is because long periods (1+ year) of below normal precipitation can have significant impacts on groundwater and surface water availability - impacting streamflows, lake systems, stock water ponds, wetlands and vegetation. These long periods of abnormal dryness also result in extremely dry soils that impede the infiltration of moisture which would normally provide beneficial recharge. During these conditions it is important to consider short term metrics within the context of multi-annual dryness.

Near term observations of soil moisture serve as indicators of plant water availability and offer valuable point data for evaluating precipitation inputs and their influence on soil moisture conditions. However, precipitation accumulation is not always indicative of actual improvements in soil moisture. Alternatively, surface water deficits may persist despite improvements in soil moisture recharge. Here it is especially useful to analyze drought impact reports (described below) as an indication of the geographic extent and timescales that most accurately describe current conditions as reflected by the metrics. The accurate assessment of precipitation events offers a host of challenges, and impact assessments leverage the collaborative network and experience of individuals on the ground.

2.4.6 Special Cases: Extreme Events

Drought metrics are used to distinguish a divergence from the median, mean or calculate a percentile for a timescale of interest as compared to an established period of record (POR). Montana uses a 30 year POR record to calculate anomalies similar to other natural resource agencies like the USGS, NRCS and others. While the POR provides a solid comparable for the calculation of current anomalies, it can also complicate the evaluation of extreme weather events in both the near term and long term. For example, in 2017 a fast-evolving flash drought across the northern great plains was devasting for agriculture, recreation, wildlife and resulted in the most severe wildfire season in Montana since 1910. Figure 14, below, is a map of SPEI from June 15, 2017, through September 15, 2017 (90 day SPEI), during which time much of Montana experienced D2 (severe) to D4 (exceptional) drought.

Figure 15 is a map of SPEI from January 1, 2017, through December 31, 2017 (1 year SPEI). In this map, it appears to indicate that the western half of Montana received relatively normal precipitation for the calendar year. Despite a crippling drought and the worst fire season in more than 100 years, SPEI indicates that conditions were mostly normal in northwestern Montana in 2017. The reason for this disparity is that the aggregation period does not distinguish when the precipitation accumulates- all precipitation during the aggregation period is treated equally. This example highlights the importance of a convergence of evidence approach that applies a variety of metrics, timescales and knowledge of local conditions for an accurate drought assessment. In this case, shorter timescales (Figure 15) can help to identify severe short term dryness within relatively normal long-term conditions (Figure 16).

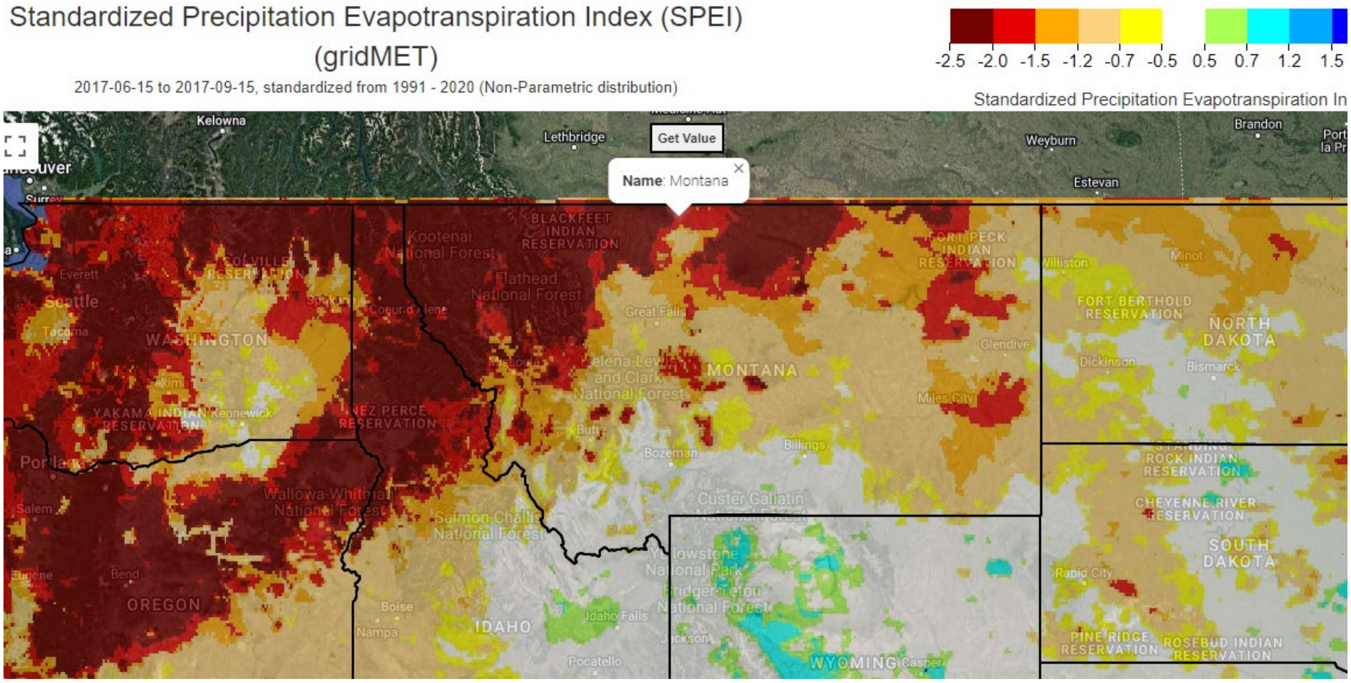


Figure 15: *SPEI – June 15, 2017, through September 15, 2017*

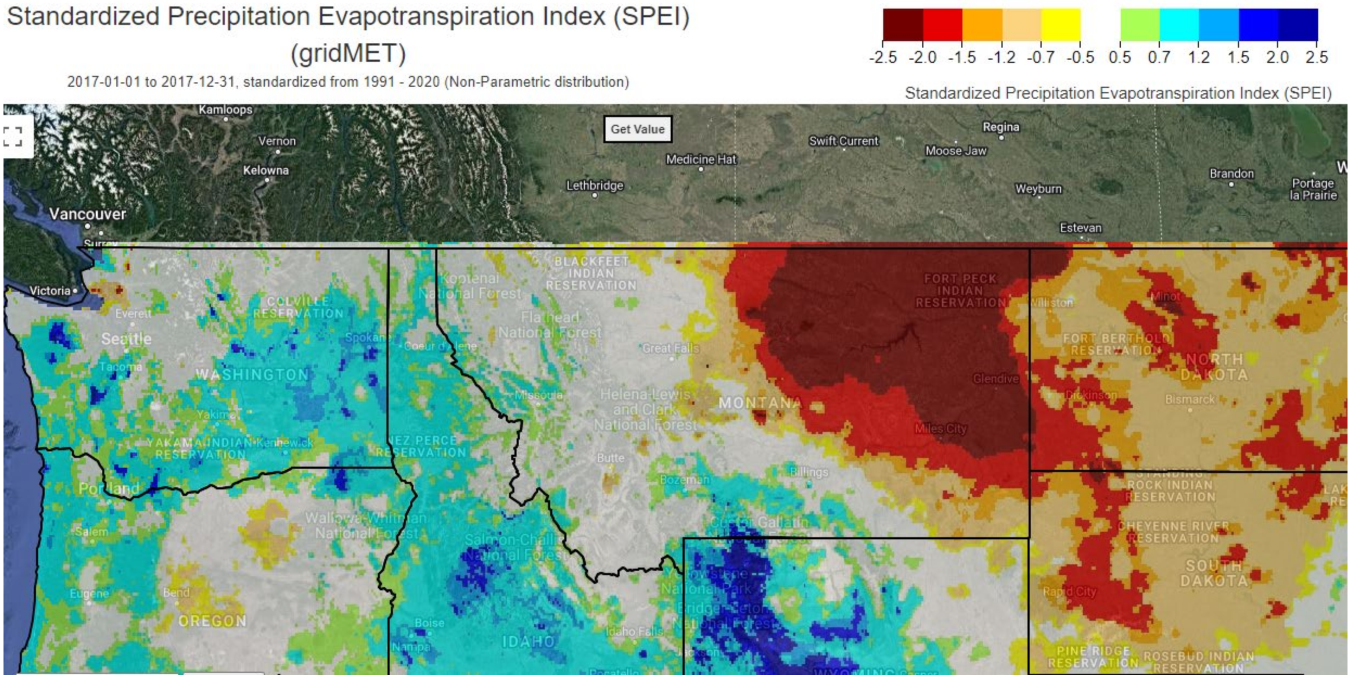


Figure 16: *SPEI – January 1, 2017, through December 31, 2017*

2.4.7 Drought onset and recovery

The determination of drought onset and recovery is complex. It requires the analysis of conditions at a variety of timescales with close attention given to precipitation seasonality and extreme events that might otherwise misrepresent the importance of an indicator depending upon the aggregation period. It is also important to keep in mind that the assessment of drought impacts and associated recovery is not simply an accounting exercise that measures the level of water deficit. Other metrics like temperature, soil type, vegetative cover, the influence of pests like grasshoppers, and others are integral to the evaluation of both drought onset and recovery. Furthermore, the longer the timescale that is applied, the more variables that come into play.

Drought recovery typically occurs over a longer period of time than drought onset, and absent extreme conditions, increases in drought severity usually occur more quickly than recovery. The increased timescale necessary for drought recovery occurs for a variety of reasons. As discussed earlier, dry soils are more difficult to rehydrate than moist soils. Lack of vegetative cover associated with long term drought diminishes the water holding capacity of the affected area. Ecologically, feedback loops like this are common in which the longer an area is in drought, the longer it takes for the area to recover. Also, as the length of drought duration increases, it usually takes more consistent moisture over a longer period to relieve those conditions. Hence, the move from D1 to D0 often takes less time and less of a increased moisture anomaly than a move from D3 to D2 which requires the evaluation of precipitation over a longer timescale.

2.5 Drought Impacts

Drought impacts nearly all of Montana in various ways, including impacts to agriculture (e.g., reduced yield), livestock (e.g., shortage of feed and culling herds), recreation and tourism (e.g., closures), fisheries and wildlife (e.g., water supply and quality), human health (e.g., air quality from smoke and mental health), forestry (e.g., wildfire), and other sectors important to Montana's economy and livelihoods. Table 3 and Table 4 provide a summary of common drought impacts in Montana.

One of the most visible impacts of drought is the effect on producers, such as failed crops, limited water for irrigation, demand for new water sources (especially increased groundwater development), and increased plant stress, pests, and disease. Livestock production is also challenged by drought. Reduced pasture and forage lead to animal stress and decreased stock weights. Supplemental hay and feeding may become necessary and crops, such as spring wheat and barley, may be harvested to make up for poor rangeland conditions. Culling and shipping cattle to market early is also seen in drought years.

The impacts of drought can arise rapidly or build gradually. Ill-timed dry spells can bring rapidly deteriorating conditions and impacts, especially in eastern and north-central Montana where spring rains are crucial for dryland farming. The flash drought of 2017 is a prime example. That year, moisture conditions looked positive until May; then, much below precipitation in late May and June coupled with high temperatures prevented crop germination and led to diminished range and other forage resources. Slower developing and prolonged droughts have a greater impact on water supply. Stock ponds are common across the state, especially in eastern Montana. Dry years can lead to empty ponds or poor water quality and require the development of alternative water sources or hauling.

Drought years often mean increased fire activity. The lack of moisture causes vegetation to become dry and highly flammable, providing fine fuels for fires. Drought-stressed trees may die, and their dry branches and leaves can become kindling for fires. Dry conditions can cause lightning strikes to ignite fires more easily, and high winds can quickly spread fires through dry vegetation. These factors contribute to the increased likelihood and severity of wildfires during times of drought. The 2017 drought contributed to the largest Montana fire season in more than 100 years.

Table 3: Common drought impacts in Montana

Category	**Potential Impact**
Crop Production	• Reduced yield • Crop disease • Plant stress • Increased irrigation demands • Changing sources of water (esp. increased groundwater use and wells)
Livestock Production	• Reduced pasture, forage • Supplemental feed • Animal stress and mortality • Decreased stock weights • Hauled water • Culling and shipping to market early
Water Supply	• Low or dry well • Water quality issues and algal blooms • Moving pumps, intakes • Voluntary or mandatory conservation
Community Health	• Poor air quality (esp. smoke and dust) • Mental health and stress
Household	• Dry lawn and garden • Increased power bill • Low or dry well • Landscaping changes
Recreation and Tourism	• Closures • Ski season shorter • Hunting or fishing reduced • Less-appealing landscape • Reduced sales • Reduced workforce
Fire	• More fires, intense fires • Property damage • Smoke • Closures • Burn or fireworks ban
Forest	• Change in timing of plant growth • Leaves/needles discolored, shriveled, burnt, dropping • Dead trees • Change in fruit, nut, berry production • More pests, invasive species, diseases
Fish and Wildlife	• Less food and water • Increase in invasives • Disease and mortality • Fishery closures • Wildlife foraging near people • Warm water temperature • Water quality change • Low flows

Table 4: Common drought impacts in Montana associated with differing drought severity classes.

Potential Impacts	
D0 **Abnormally Dry**	● Soil moisture is low; dryland crop germination is poor; pastures are dry ● Fire danger is increasing ● streamflows are lowering and stream temperatures are rising, affecting recreational fishing
D1 **Moderate Drought**	● Producers feed livestock supplemental hay; crops are stressed and growth is poor ● Fire restrictions are implemented
D2 **Severe Drought**	● Hay and crop yields are low; hay quality is poor; subsoil moisture content is nonexistent ● Fire count and danger are high; air quality is poor with dust and smoke ● Livestock ponds are low or dry; water quality is monitored; groundwater wells are stressed
D3 **Extreme Drought**	● Crops are not harvestable; winter pasture is opened for grazing; soil has cracks and fields are bare ● Cattle have very little water; producers are hauling water and buying supplemental feed, culling cattle and selling early ● Fire restrictions increase
D4 **Exceptional Drought**	● Pasture loss is widespread; crops are destroyed ● Property is closed for hunting, streams are closed for fishing ● Fire risk is extremely high; fires are widespread and air quality is poor.

2.6 Limitations of Drought Metrics

Drought metrics are not perfect representations of conditions on-the-ground. This disparity results because drought metrics are generally based on meteorological datasets that do not account for the many complex physical processes driving watershed scale moisture dynamics. As discussed above, the amount of precipitation that ultimately infiltrates into soil water reservoirs depends on antecedent moisture conditions (e.g. dryness prior to an event) the character of the precipitation event itself (e.g. rapid, high intensity event versus long, low intensity event) in addition to many other factors like geographic variability, soil properties, vegetation conditions, phase of precipitation, etc. As a result, drought index values like the SPI, SPEI, EDDI and others will not always accurately represent moisture characteristics for a specific geographic extent. Practitioners must acknowledge the limitations of these resources, recognizing that effective assessments will incorporate both data driven metrics and observational tools that may be grounded in professional opinion and expertise. That said, drought metrics and indices provide the backbone of drought monitoring and assessment in Montana.

3.0 Montana's Drought Assessment Process

3.1 Convergence of evidence

Drought monitoring is a multi-faceted and complex process.. There is no formula or algorithm that can produce a perfect drought assessment. Many of the examples discussed above highlight some of the limitations and pitfalls of drought metrics and indices as they relate to season, timescale, mode (rainfall vs snowfall) and gaps in the monitoring network. As a result, practitioners in Montana rely on a convergence of evidence approach to complete the weekly drought assessment. This approach represents an effort to evaluate many lines of inference (for example many drought metrics at varying timescales) and determine where the data is converging. This approach enables drought assessment practitioners to account for the many drivers, forms and impacts of drought into a single drought assessment. As illustrated above, various drought metrics (and/or the same drought metric calculated over different timescales) will depict drought conditions quite differently. This is because various drought metrics account for different drivers of drought that may or may not accurately describe current conditions on the ground.

This process is subjective by design, partially because drought is not a solely physical phenomena and is implicitly tied to impacts that will affect some sectors and not others. Furthermore, drought metrics are not perfect representations of current on-the-ground conditions and often do not account for complex processes such as soil water physics. Finally, the word "drought" has various meanings depending on individual circumstances and therefore impacts people and places differentially. Meteorology and subsurface hydrology act as the physical driver of landscape dryness, but human interactions with physical dryness determine some of droughts' impacts to the communities, and ecologies of Montana. The convergence of evidence approach considers both quantifiable and non-quantifiable variables that are at the core of drought assessments and provides a comprehensive and defensible method to define drought severity across Montana.

3.2 Weekly Drought Monitoring Process - Collaborative Drought Assessment

The drought monitoring process in Montana is supported by a collaborative network of scientists, land and watershed managers, drought specialists, extension agents and interested public members from a suite of federal, state, tribal and local entities. Active and open communication between the interested parties is critical to this effort. This network provides a mechanism to help develop and appraise Montana's weekly evaluation of drought conditions. This process has been developed and adjusted over the last several years and is currently viewed nationally as an excellent example of collaborative drought assessment practice within a particularly challenging setting (e.g. diverse state).

Montana's drought assessment process provides weekly recommendations to the U.S. Drought Monitor [USDM] located within the National Drought Mitigation Center [NDMC] at the University of Nebraska Lincoln. It is the primary role of Montana's collaborative drought network to provide accurate drought assessments to the USDM to ensure that the state's conditions are as accurate as possible in this national assessment.

Drought assessment is initiated weekly by the drought "lead" or "author" responsible for providing an initial assessment of drought conditions. Currently, five state drought leads serve Montana's collaborative drought network representing various state and federal entities. Using the convergence of evidence approach, the drought lead evaluates a suite of physical drought metrics and indicators (see the Upper Missouri River Basin Drought Dashboard in the "Tools" section, table X) and reviews recent drought impact reports (see Montana's Drought Impact Reporter in the "Tools" section). This initial analysis provides the basis to make recommended changes to the previous week's USDM drought map.

Once the state drought lead has concluded an initial assessment, the draft recommendation is distributed to Montana's collaborative drought network via a federally supported drought "ListServ". The ListServ acts as a communication conduit to facilitate collaborative drought assessments across the state. Direct feedback from the network is used to validate and adjust the recommendation based upon local expertise and knowledge of local conditions. This verification step is critical to Montana's drought assessment process since it provides a ground-truthing system to help the drought lead render the most accurate drought assessment possible. Recommended changes to the USDM map are always accompanied with justification supported by drought metrics, indices and drought impact information that follow the convergence of evidence approach.

The drought assessment feedback process between the weekly drought lead and the collaborative network is iterative, providing a space to modify the initial assessment made by the drought lead. Once a consensus is achieved, a final recommendation is prepared by the drought lead to send to the USDM. In the event that a consensus cannot be met across the collaborative network, the weekly author has the discretion over the details of the weekly recommendation. The final recommendation in the form of a graphical summary of changes (e.g. a map) accompanied by supporting information and justification is then sent to the national drought author. This recommendation is typically sent by midday on Tuesday to allow time for discussion with the national drought author. A second round of iteration is then initiated between the national drought author and Montana's state lead to incorporate the state recommendations into the USDM. The final USDM is released on Thursday morning.

4.0 Montana's Drought Assessment Toolkit:

4.1 MT Drought Impacts Reporter

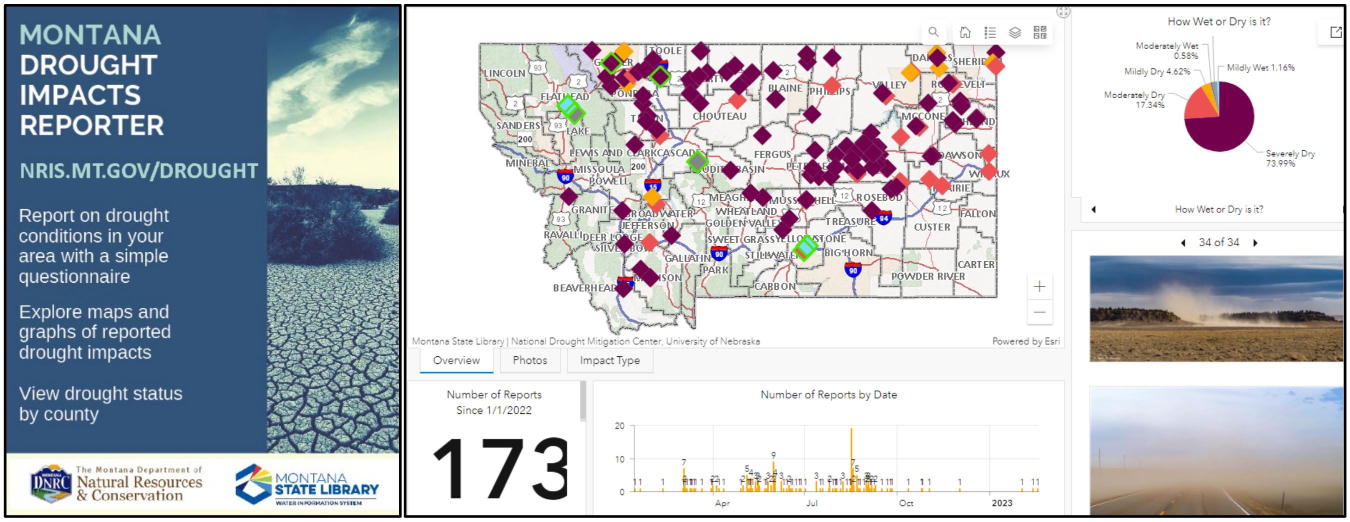
The Montana State Library and the Montana Department of Natural Resources and Conservation released the Drought Impacts Reporter (DIR) in July 2017 in response to the flash drought that occurred that summer. The DIR is a web-based tool for collecting feedback about moisture conditions (dry or wet) and the impacts of these conditions. Producers, recreationalists, landowners, field workers, water and natural resources professionals, anyone interested, can submit surveys about moisture conditions for the lands they know best. Photos can also be submitted through the portal. Reports are stored in a GIS database and the information is mapped in various ways, such as by moisture status (e.g., mildly wet, normal, moderately dry) and by impact type (e.g., crop production, livestock production, municipal, or fish and wildlife). An online "dashboard" allows users to search and view the where, when, and what of drought impacts across Montana.

Since the DIR relies on crowd-sourcing, the reliability of results generally increases with the number of reports submitted for a county or other area of interest. The reports serve as an "initial alert"– a first indication that more attention and supporting data may be needed to accurately depict drought conditions. Used in conjunction with drought metrics, the impact reports can provide local knowledge and reveal changing conditions in areas lacking weather stations and other observations.

The Montana Drought Impacts Reporter is integrated with a national drought reporter, known as the Condition Monitoring and Observer Reports (CMOR) and managed by the National Drought Mitigation Center (NDMC). The development of CMOR used ideas from the Montana DIR and vice versa. Currently, the two systems are one and the same, built off the same survey and feeding the same GIS database. Reports submitted to either the national CMOR or the state DIR appear in both. This collaboration provides for increased marketing and public outreach for each system.

The MT DIR is a valuable resource for stakeholders and decision-makers who need to better understand the extent of drought and severity of impacts in different counties, regions, and sectors.

Submit and view Montana drought impact reports at https://nris.mt.gov/drought


MONTANA DROUGHT IMPACTS REPORTER

NRIS.MT.GOV/DROUGHT

Report on drought conditions in your area with a simple questionnaire

Explore maps and graphs of reported drought impacts

View drought status by county

Figure 17: An example handout (left) promoting the Montana Drought Impact Reporter and a screenshot (right) of drought reports received in 2022.

4.2 The UMRB Drought Indicators Dashboard

The Upper Missouri River Basin (UMRB) Drought Indicators Dashboard (https://drought.climate.umt.edu/) is an open-source, interactive tool developed by the Montana Climate Office andcomputes and displays a multitude of common drought indices and indicators on a daily basis and at various timescales (table X). Importantly, this dashboard was co-produced and developed iteratively through meetings and critique by the Montana's drought monitoring and assessment group, state, tribal and federal partners. As discussed above, drought monitoring in Montana is a collaborative process that relies upon many entities and personnel. The development of the dashboard has followed this tradition of collaboration and has matured following the guidance and perspective of this diverse network. Importantly the dashboard was designed to incorporate new tools, indices indicators and models as the group identifies needs and efficacy of these new tools and their applicability in Montana.

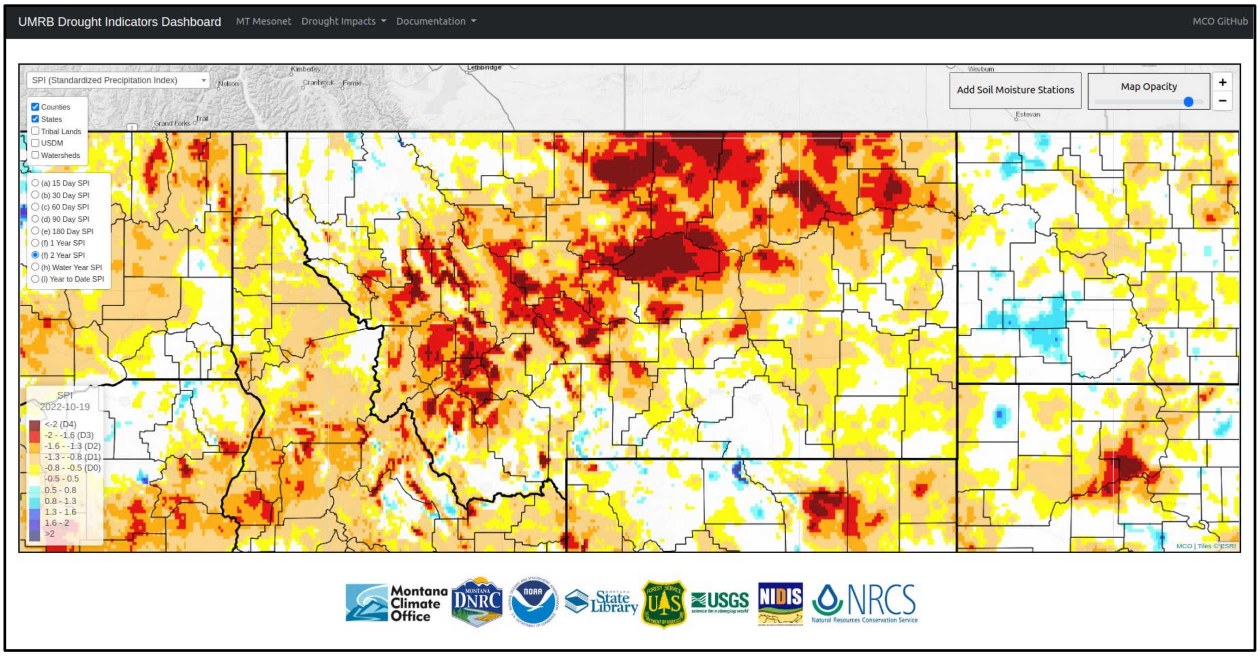


Figure 18: A screen shot from the UMRB Drought Indicators Dashboard, available at https://drought.climate.umt.edu/.

The dashboard provides reliable, timely and scientifically robust data for operational drought assessment in Montana. Importantly, this tool was developed using open-source software; all code is publicly available (https://github.com/mt-climate-office/mco-drought-indicators) for scrutiny and/or application in alternative locations. Many of the datasets presented in Table 1 are displayed on the dashboard. Further, many of the common indicators used in drought monitoring, such as SPI, SPEI and EDDI, are presented in a format that follows the color scaling and thresholds utilized by the USDM presented in Table 3. Datasets computed daily within the drought dashboard include meteorological anomalies and drought metrics; watershed and station scale snow monitoring and analysis; modeled, remotely sensed and station-based soil moisture anomalies; satellite-based measures of vegetation health, vigor and trends. Where possible, station-based information and analysis are presented alongside gridded model estimates, promoting a convergence of evidence approach to drought monitoring as is encouraged by the USDM. For example, the drought dashboard also allows for easy access to data collected by the Montana Mesonet and provides convenient “quick plotting” functions to evaluate recent (last 3 months) soil moisture responses to recent meteorology.

The UMRB drought dashboard is an ever-evolving piece of software that seeks to apply the best available drought science and tools to drought assessment in Montana. As new tools, models and metrics become available, scientists at the Montana Climate Office will work with drought monitoring practitioners to integrate these tools into the dashboard. A key component to this process is validation of new tools to assess their efficacy and accuracy in Montana. In other words, new tools should be properly vetted by drought assessment practitioners in Montana before they are used for operational assessment. This process goes both ways; as new science becomes available dis-crediting the efficacy of certain models/metrics, they will be removed from the dashboard to avoid confusion and misinterpretation. This flexibility and within-state origin of the dashboard provides Montana with a unique opportunity to dictate what information is used within Montana’s state drought assessments.

5.0 Next Steps

Given the shortcomings of traditional drought metrics, some of which were introduced in the 90’s (McKee et al., 1993), it is important to consider “next steps” in drought assessment tools. In many cases, drought assessment practitioners use meteorological information over different timescales to describe hydrological and ecological processes of interest. However, this approach is undermined by the current era of rapid climate change. In light of this, it will be important to leverage new tools for drought assessment as they become available and are validated. Leveraging physically based, fully distributed and coupled hydrological and ecosystem models show great promise in better describing actual conditions on the ground. Furthermore, these models can be applied retrospectively to compute estimates of observed variability, providing a means to convert raw outputs to standardized drought indices applicable to the thresholds described above. Currently computation limitations hinder the practicality of this approach. However, recent advances in remote (cloud) computing and new approaches in machine learning promise a new age of ecohydrological models that may revolutionize drought assessment frameworks.

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