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Abstract
Chapter 1 is an introductory chapter and provides a foundation for the rest of the report. It provides the reader with a scientific, yet accessible, understanding of drought. This chapter starts by describing drought and providing a functional definition, discussing the degrees of drought severity and how drought is quantified and its severity measured. The climate patterns associated with drought are also reviewed and analyzed. Next, an historical summary of drought in Colorado is presented, describing our knowledge of the past 300 years (with a special section on tree-ring studies), the past approximately 100 years of existing data, and the droughts of the 1930s, 1950s and 1970s. As part of the historical summary, data accuracy, confidence and length of record are reviewed. Information contained in this chapter is presented at a state and major river basin level. The chapter contains a discussion of the recent drought in Colorado (2000-2003), in context with the historical and scientific information presented. The chapter also incorporates a brief review of current drought literature and resources.

Contents:

Introduction

Drought is an insidious hazard of nature. Unlike tornadoes, hurricanes, floods and fires, it sneaks up on the unsuspecting as a series of sunny, hot summer days or a period of mild, breezy weather during winter. Drought builds slowly on itself until it has a major impact on human existence. Water supplies dry up, wells run dry and crops wither. If drought is very severe, cities and states may turn on one another to secure adequate water.

A good place to start in the planning of future Colorado water supplies is in the understanding of what is drought, in general, and what is drought in Colorado: its history and its cycles. The drought of 2000-2003 in Colorado has provided a rude awakening to drought's impacts on modern life. A mandate to respond has been sounded. Decisive but meaningful action requires an appreciation and understanding of nature's power.

> *"If not us, who? If not now, when?"*
> *John F. Kennedy*

What is Drought?

Drought has many different meanings. According to the *Glossary of Meteorology, 2nd edition* (American Meteorological Society 2000), drought is defined as "a period of abnormally dry weather sufficiently long enough to cause a serious hydrological imbalance."

While this may sound like a simple textbook characterization, the definition continues with the following qualification:

> Drought is a relative term; therefore any discussion in terms of precipitation deficit must refer to the particular precipitation-related activity that is under discussion. For example, there may be a shortage of precipitation during the growing season resulting in crop damage (agricultural drought), or during the winter runoff and percolation season affecting water supplies (hydrological drought).

Documents provided by the National Drought Mitigation Center (NDMC 2003) provide further insight into this multifaceted phenomenon.

> Drought is a normal, recurrent feature of climate, although many erroneously consider it a rare and random event. It occurs in virtually all climatic zones, but its characteristics vary significantly from one region to another. Drought is a temporary aberration; it differs from aridity, which is restricted to low rainfall regions and is a permanent feature of climate.

Drought should not be viewed as merely a physical phenomenon or natural event. Its impacts on society result from the interplay between a natural event (less precipitation than expected resulting from natural climatic variability) and the demand people place on water supply. Recent droughts in both developing and developed countries have underscored the vulnerability of all societies to this "natural" hazard.

Clearly, there is no singular expression of the meaning of the term drought. Not only does the meaning vary with the application context, but it is also subject to regional variation.

How is Drought Classified? (Operational Definitions)

The National Drought Mitigation Center (NDMC) classifies meteorological, agricultural and hydrological droughts as "operational definitions of drought." The NDMC (2003) proves to be an invaluable reference, providing four informative operational definitions of drought.

- *Meteorological drought* is usually an expression of precipitation's departure from normal over some period of time. These definitions are usually region-specific, and presumably based on a thorough understanding of regional climatology. Meteorological measurements are the first indicators of drought.

- *Agricultural drought* occurs when there is not enough soil moisture to meet the needs of a particular crop at a particular time. Agricultural drought happens after meteorological drought

> The variety of meteorological definitions from different countries at different times illustrates why it is folly to apply a definition of drought developed in one part of the world to another:
>
> - Great Britain (1936): 15 consecutive days with daily precipitation totals of less than 0.25 mm
> - Libya (1964): annual rainfall less than 180 mm
> - India (1960): actual seasonal rainfall deficient by more than twice the mean deviation
> - Bali (1964): a period of six days without rain

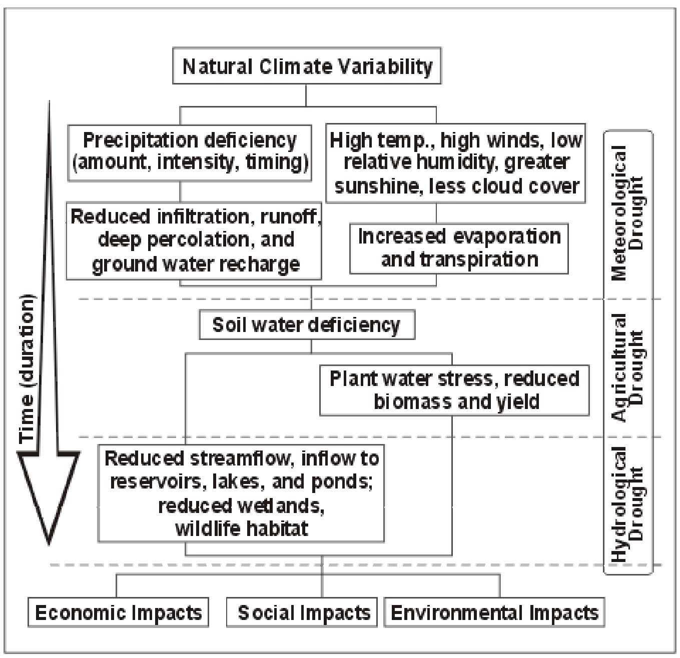
but before hydrological drought. Agriculture is usually the first economic sector to be affected by drought.

- *Hydrological drought* refers to deficiencies in surface and subsurface water supplies. It is measured as streamflow and as lake, reservoir, and groundwater levels. There is a time lag between lack of rain and less water in streams, rivers, lakes, and reservoirs, so hydrological measurements are not the earliest indicators of drought. When precipitation is reduced or deficient over an extended period of time, this shortage will be reflected in declining surface and subsurface water levels.

- *Socioeconomic drought* occurs when physical water shortage starts to affect people, individually and collectively. Or, in more abstract terms, most socioeconomic definitions of drought associate it with the supply and demand of an economic good.

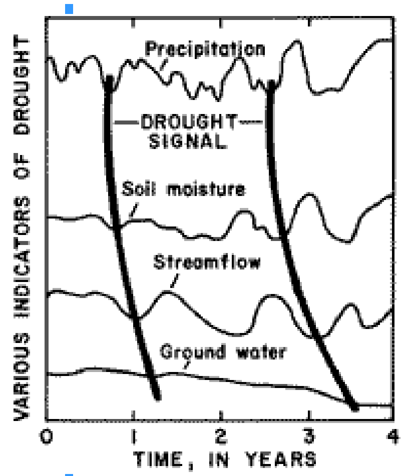
Figure 1-1 illustrates the time lag between meteorological, agricultural, and hydrological drought.

Figure 1-1: Illustration of Operational Drought Definitions (NDMC 2003)



Further, the lag between different components of the hydrology is shown in comparing streamflow and groundwater responses. (Figure 1-2)

Figure 1-2: Time Lag in Hydrologic Drought Response (United States Geologic Survey (USGS) 2003)



Each of the definitions provided above has important contextual implications for the state of Colorado. Taken as a collective whole, these various definitions of drought indicate the variability, complexity, and potential broad-based impacts (e.g., social, economic, etc.) related to the lack of precipitation and the scarcity of water.

Measuring the Severity of Drought: A Difficult Task

In the past 100 years or so, researchers, scientists, and government agencies have established a complex network of instrumentation that is utilized for monitoring climatic variables. The key variables in terms of assessing drought are precipitation, snowpack, and streamflow. McKee *et al.* (2000) state, "these climate observation networks provide important data to analyze current and historic droughts and relate water availability to the observed impacts." Furthermore, years of experience have revealed that the types and levels of drought impacts display a direct relation to the following drought characteristics:

- Magnitude—how large the water deficits are in comparison with historic averages
- Duration—how long the drought lasts
- Severity—combination of the magnitude or "dryness" and the duration of the drought
- Aerial extent—what area is impacted by the drought

Drought Indices

Due to the impossibility of analyzing the voluminous climatic data collected every day in real time, simpler tools are needed to characterize droughts in a manner that can be readily and effectively applied by water supply managers for immediate decision-making and future planning purposes. This necessity has led to the development of a number of drought indices. The NDMC (2003) describes drought indices in a general sense as follows: "Drought indices assimilate thousands of bits of data on rainfall, snowpack, streamflow, and other water supply indicators into a comprehensible big picture. A drought index value is typically a single number, far more useful than raw data for decision making."

A number of computational drought indices, including the Palmer Drought Severity Index (PDSI) and the Standardized Precipitation Index (SPI), have prevalence in the scientific community as means for assessing the severity of a drought. Both of these indices are employed by the state of Colorado for drought monitoring and planning purposes. Other common drought indices include the Palmer Crop Moisture Index (CMI) and the Palmer Hydrological Drought Index (PHDI).

The Palmer Drought Indices

Palmer (1965) developed the first quantitative tools that are widely used to assess the severity of drought. Although the specific details of these indices are quite complex, the NDMC (2003) provides simple explanations of each, as presented below. Note that each index correlates to one of the operational types of drought.

> The *Palmer Drought Severity Index (PDSI),* which relates to meteorological drought, attempts to measure the duration and intensity of long-term drought-inducing circulation patterns. Long-term drought is cumulative, so the intensity of drought during the current month is dependent on the current weather patterns plus the cumulative patterns of previous months. Since weather patterns can change rapidly from a long-term drought pattern to a long-term wet pattern, the PDSI can respond fairly rapidly.
>
> Advantages of the PDSI as an indicator of the severity of meteorological drought, as outlined by Alley (1984) (see Table 1-1), include the following:
>
> 1. It provides decision makers with a measurement of the abnormality of recent weather for a region.
> 2. It provides an opportunity to place current conditions in historical perspective.
> 3. It provides spatial and temporal representations of historical droughts.

Table 1-1: Classifications for PDSI

Value	Meaning
≥ 4.0	Extremely wet
3.0 to 3.99	Very wet
2.0 to 2.99	Moderately wet
1.0 to 1.99	Slightly wet
0.5 to 0.99	Incipient wet spell
0.49 to –0.49	Near normal
-0.5 to –0.99	Incipient dry spell
-1.0 to –1.99	Mild drought
-2.0 to –2.99	Moderate drought
-3.0 to –3.99	Severe drought
≤ -4.0	Extreme drought

> The *Palmer Crop Moisture Index,* which relates to agricultural drought, measures short-term drought on a weekly scale and is used to quantify drought's impacts on agriculture during the growing season.
>
> The hydrological impacts of drought (e.g., reservoir levels, groundwater levels, etc.) take longer to develop and it takes longer to recover from them. The *Palmer Hydrological Drought Index* was developed to quantify these hydrological effects. The PHDI responds more slowly to changing conditions than the PDSI.

An additional means for monitoring drought, the Surface Water Supply Index (SWSI), is designed to complement the Palmer indices in the state of Colorado, where mountain snowpack is a key element of water supply. This index is calculated by river basin, based on snowpack, streamflow, precipitation, and reservoir storage (NDMC 2003).

The Standardized Precipitation Index (SPI)
A more recent drought-monitoring tool, the SPI emerged from research conducted by McKee *et al*. (1993). Again, the NDMC (2003) provides a straightforward examination of this index.

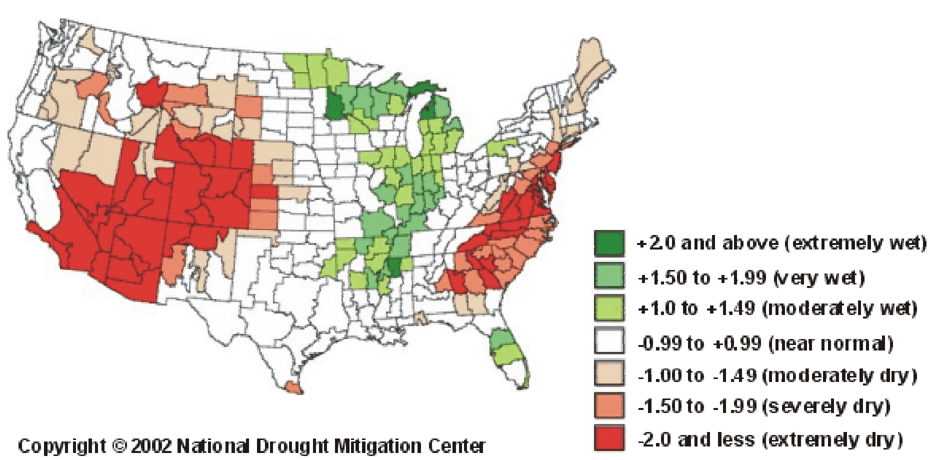
> While Palmer's indices are water balance indices that consider water supply (precipitation), demand (evapotranspiration) and loss (runoff), the *Standardized Precipitation Index* (SPI) is a probability index that considers only precipitation.
>
> The index is negative for drought, and positive for wet conditions (see Table 1-2). As the dry or wet conditions become more severe, the index becomes more negative or positive. The SPI is computed by NDMC for several time scales, ranging from one month to 24 months, to capture the various scales of both short-term and long-term drought.

Table 1-2: Typical SPI Values

Value	Meaning
≥ 2.0	Extremely wet
1.5 to 1.99	Very wet
1.0 to 1.49	Moderately wet
-0.99 to 0.99	Near normal
-1.0 to –1.49	Moderately dry
-1.5 to –1.99	Severely dry
≤ -2.0	Extremely dry

The SPI has been used operationally to monitor conditions across Colorado since 1994 (McKee *et al*. 1995). The nationwide SPI map presented in Figure 1-3 unmistakably illustrates the severity of the 2000-2003 drought across the entire state of Colorado and much of the southwestern United States.

Figure 1-3: 12-month SPI through End of August 2002 (NDMC 2003)



The History and Future of Colorado Drought
A Look at the Past
The history of drought in Colorado can be traced through the analysis of two important data records. First is the modern, or instrumentation,

record consisting of actual measurements of climate variables at various locations throughout the state. This record generally dates from the present back to the late 19th century.

Second is the paleoclimatic record, primarily derived from the analysis of tree rings, and extending backwards through history for several hundred to over a thousand years. This section will begin with a review of the major droughts of the 20th century, followed by a description of paleoclimatic, specifically tree ring, data analyses and a summary of major drought periods throughout the past 2000 years.

Drought is clearly a common occurrence in Colorado, but drought rarely encompasses the entire state at any given time. Key points regarding Colorado drought are as follows:

- The most common droughts are of short duration (6 months or less) with aerial extents that vary with the seasons.
- Multi-year droughts occur infrequently.
- Precipitation data indicate that most weather stations across the state have experienced two or more consecutive years of precipitation less than 80% of average *a few times* during the 20th century.

The most significant droughts of the instrumented period, or since the turn of the past century are listed in Table 1-3. Each drought period is characterized by when it occurred, the worst years of the drought and the portion of the state where the drought was worst.

Table 1-3: Significant Drought Periods of the Modern or Instrumented Era

When	Worst	Major state impact areas
1890-1894	1890 and 1894	Severe drought east of mountains
1898-1904	1902-1904	Very severe drought over southwestern Colorado
1930-1940	**1931-1934, 1939**	**Widespread, severe and long lasting drought in Colorado**
1950-1956	1950, 1954-1956	Statewide, worse than the 1930s in Front Range
1974-1978	1976-1977	Statewide, driest winter in recorded history for Colorado's high country and Western Slope
1980-1981	Winter 1980-1981	Mountains and West Slope; stimulated writing of the "Colorado Drought Response Plan" and the formation of the Water Availability Task Force
2000-2003	**2001-2002**	**Significant multi-year statewide drought, with many areas experiencing most severe conditions in Colorado instrumented history**

Early Turn of the Century Drought

A severe but brief drought occurred in 1890, particularly east of the mountains, followed by a very wet year in 1891. Drought returned in 1893 with severe drought occurring in 1894, again most pronounced over eastern Colorado. This statewide drought preceded a sustained and very severe drought over southwestern Colorado. The worst drought on record occurred in the Durango area during this time.

The Dust Bowl of the 1930's

The major drought of the 20th century in terms of duration and spatial extent is considered to be the 1930s Dust Bowl drought that lasted up to 7 years in some areas of the Great Plains. The Dust Bowl drought, memorialized in John Steinbeck's novel, *The Grapes of Wrath*, was so severe, widespread, and lengthy that it resulted in a mass migration of millions of people from the Great Plains to the western U.S. in search of jobs and better living conditions.

Severe drought developed in 1931 and peaked in 1934 and early 1935, which was interrupted by heavy spring rains in 1935 and more widespread heavy rains in 1938. The decade culminated with one more extremely dry year in 1939 when several stations along the Front Range recorded the driest year in (20th century recorded) history.

...Now the wind grew strong and hard, it worked at the rain crust in the corn fields.

Little by little the sky was darkened by the mixing dust, and the wind felt over the earth, loosened the dust and carried it away.

...from **The Grapes of Wrath**, written by John Steinbeck.

The Visionary Drought of the 1950's

With the Dust Bowl of the '30's a vivid memory, the statewide drought of the 1950's spurred major development of water storage facilities across the state. The development of the Front Range water supply system may have been a product of the fact that this drought was more severe along the Front Range than the drought of the 1930's. Its severe impact on the Colorado Front Range and only light to moderate impact on mountain precipitation may have overly influenced water supply planners into using it as a model of sorts since water supply planners developed infrastructure based on drought in the plains and ample mountain snow pack.

The Severe Mountain Drought of the 1970s

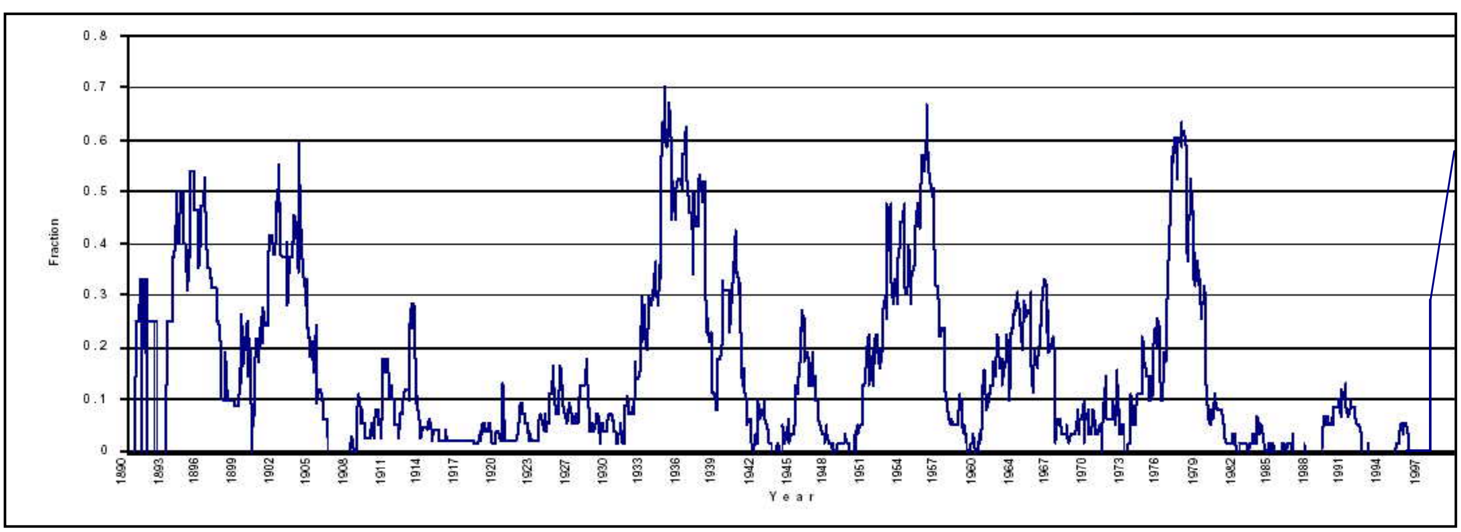
Colorado's last period of sustained multi-year drought in the 20th century occurred from 1974-1981. The record-breaking winter drought of 1976-1977, the driest winter in recorded history for much of Colorado's high country and Western Slope, culminated this drought. Statewide weather modification activities were launched during the winter seasons with hopes of increasing the mountain snow pack. Only limited success was reported before snows briefly returned to the mountains for 1979-1980.

Associated Press/Mike Orlowski

An extreme, but brief, drought period returned for the fall of 1980 into the summer of 1981. This drought most dramatically impacted Colorado's high country and ski industry, and initiated a huge investment in snow making equipment. It also stimulated the writing of the "Colorado Drought Response Plan" and the formation of the Water Availability Task Force, which has been meeting at least once a quarter each year since 1981.

Many of the drought dates presented in the preceding discussion and table are mirrored in the time series plot shown in Figure 1-4. The plot shows the fractional percent of Colorado immersed in at least moderate drought from 1890 to 2002. It is clear that the most prominent droughts in recorded history, those with the longest time-span and largest aerial extent, occurred at the turn of the twentieth century (1890s-early 1900s), the 1930s, the early- to mid-1950s, the mid- to late-1970s and the recent 2000-2003 drought.

Figure 1-4: Fraction of Colorado in Drought Based on McKee et al. 2000 (with est. for 2000-2003)



Drought of 2000-2003

The severity of the 2000-2003 drought eclipsed many of the records established during 20th century droughts, including those of the 1930s, 1950s, and late 1970s.

The comparative magnitude of this drought to other Colorado droughts is represented graphically in Figure 1-5. The 2000-2003 drought produced the lowest Palmer Hydrologic Drought Index seen during the modern (instrumental) period of record.

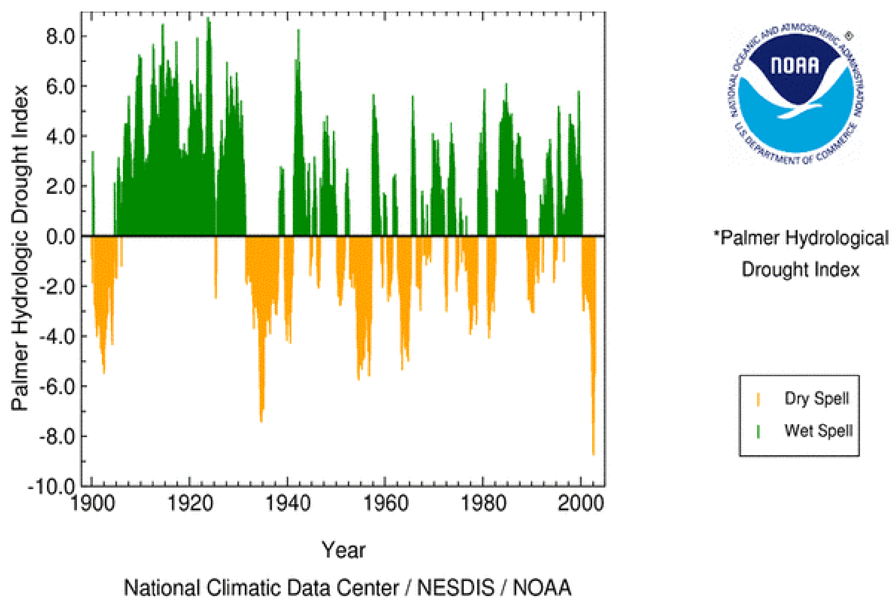


Figure 1-5: Colorado statewide PHDI*, January 1900 - December 2002 (NCDC 2003)

During the drought of 2000-2003, scientists at Hydrosphere and the National Atmospheric and Oceanic Administration (NOAA) collaborated to identify several tree ring records that correlate well with natural flows in Boulder Creek. From these tree ring records, they were able to generate estimates of stream flows in Boulder Creek that extend back as far as 1703.

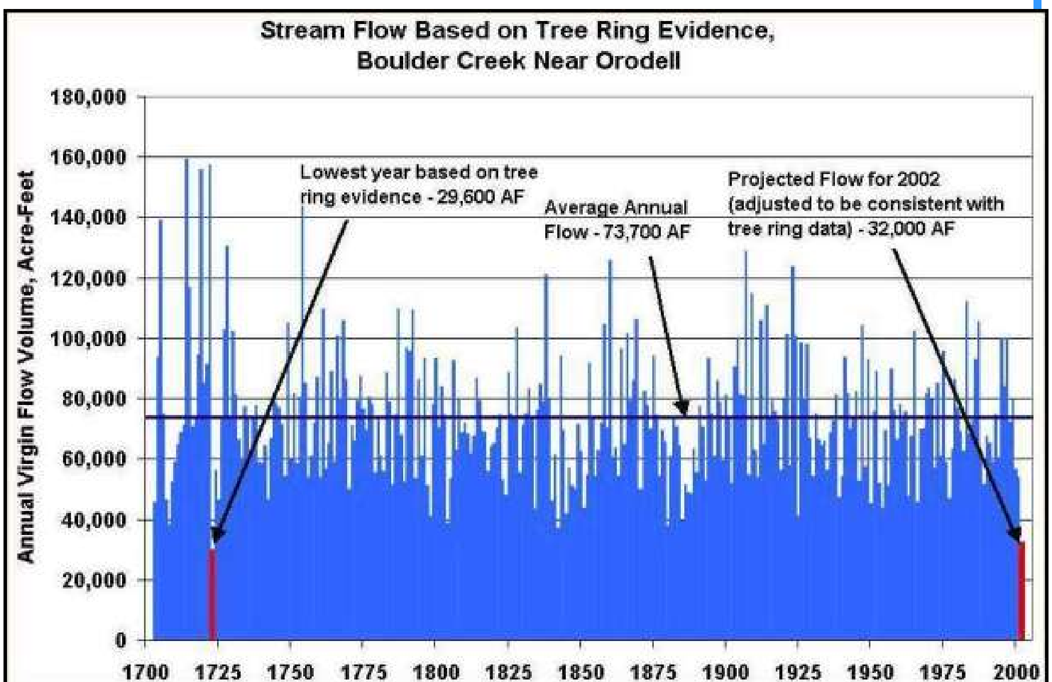
The data depicted in Figure 1-6 show that the 2002 stream flows are the lowest that have occurred since 1725. Not only that, but the data analyzed in that droughts lasting more than 15 years have occurred several times within the past 300 years (Hydrosphere 2002).

Hydrosphere qualified the regional significance of the study, saying, "Boulder Creek is fairly representative of most of the northern Front

Range and most of the tributaries into the Colorado-Big Thompson [system] as well" (Associated Press 2002).

More than half the state has been in moderate drought during the droughts of the 1890's, 1930's and the current drought of 2000 – 2003. However, short-term droughts (3-month duration) have previously covered as much as 80% of the state, and longer-duration droughts (2-4 years) have encompassed as much as 70% of the state.

Figure 1-6: Streamflow on Boulder Creek Based on Tree Ring Analysis near Ordell, Colorado that Shows the Comparative Impact of Droughts since 1700.



The question remains how this drought compares to historical droughts of the past 300 to 500 years. Paleo-climatology may provide that insight.

Paleo-Climatology of Colorado Droughts

Investigation of droughts that pre-date the instrumentation period falls within the realm of paleo-climatology. Tree rings can be utilized to reconstruct records of past climate, including precipitation, drought, stream flow, and temperature. Trees at mid- to high-latitudes, such as those found in Colorado, grow one ring per year, and the most recent ring is formed inside the bark.

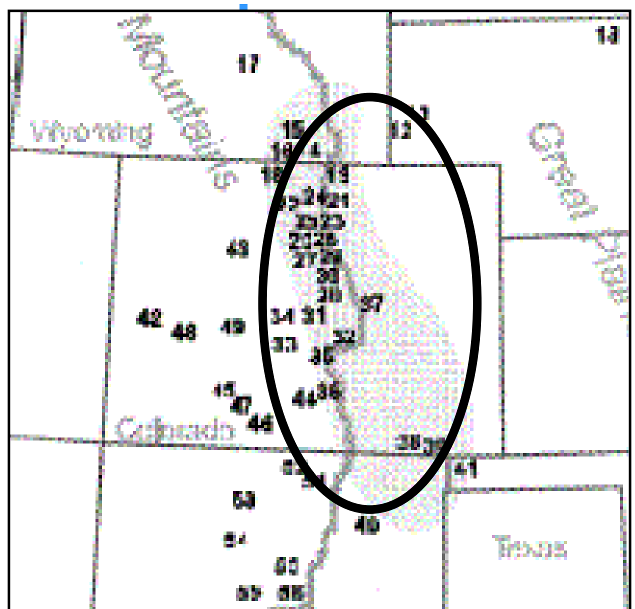
A wealth of long-lived, moisture-sensitive trees in this state make possible the generation of high-quality stream flow reconstructions that extend 300 to over 500 years into the past. Variations in ring widths that

Trees can grow to be hundreds to thousands years old and can contain annually-resolved records of climate for centuries to millenia.

are common from tree to tree reflect droughts and other anomalies in climate (Woodhouse 2003).

As depicted in Figure 1-7, the identified core area (the shaded region) of the 1845-1856 drought encompassed much of southeastern Colorado and the Front Range.

Figure 1-7: Core area of 1845-1856 Drought (Woodhouse *et al.* 2002)



Were a drought of this severity and duration to occur here today or in the future, it would have, Woodhouse warns us, "considerable impacts now that the area now includes a major, rapidly expanding metropolitan area as well as large-scale crop and livestock production." These impacts would have widespread significance for Colorado's society, economy, and ecology.

In their review of Great Plains droughts over the past 2000 years, Woodhouse and Overpeck (1998) summarize, saying "the paleo-climatic data suggest a 1930s-magnitude Dust Bowl drought occurred once or twice a century over the past 300-400 years, and a decadal-length drought once every 500 years."

Elaborating on these conclusions, the authors report the following:

> Historical documents, tree rings, archaeological remains, lake sediment, and geomorphic data make it clear that the droughts of the twentieth century, including those of the 1930s and 1950s, were eclipsed several times by droughts earlier in the last 2000 years, and as recently as the late sixteenth century. In general, some droughts prior to 1600 appear to be characterized by longer duration (i.e., multidecadal) and greater spatial extent than those of the twentieth century (Woodhouse and Overpeck 1998).

Table 1-4: Occurrences of Wet/Dry Decades from 1500-1995 based on Tree-ring Growth Index at Colorado Data Points

Millennia	Wet	Decade	Very Dry	Decade	Total Events
1500's	3	20's, 60's, 90's	2	00's, 70's	5
1600's	3	20's, 40's, 60's	2	30's, 70's	5
1700's	2	10's, 50's	2	10's, 30's	4
1800's	2	20's, 30's	2	50's, 60's	4
1900's	2	10's, 20's	2	30's, 50's	4
Totals	**12**		**10**		**22**

The data in Table 1-4 are based on an analysis of the occurrence of wet and dry decades based on the tree-ring PDSI of four data points in Colorado (Henz and Badini, 2002). The four data points were used to analyze the occurrence historically of droughts in the northeastern, southeastern, southwestern and northwestern areas of the state.

Analyses of the Colorado sites produced depictions of wet and dry decades. However, a number of dry decades that affected only the western or eastern half of the state were evident. It should be noted that at least one dry decade affects the entire state each millennia.

From this historical perspective it appears that the current drought of 2000 – 2003 likely has been exceeded in duration, intensity and coverage by historical droughts of the past.

> ***"the paleoclimatic data suggest a 1930s-magnitude Dust Bowl drought occurred once or twice a century over the past 300-400 years, and a decadal-length drought once every 500 years"..***
>
> ***Woodhouse and Overpeck (1998)***

Water Availability: Where Does the Precipitation Come From?
To better appreciate the forces at work during a period of drought in Colorado, the variability in precipitation across the state from both the perspective of location and time must first be examined. Figure 1-8 depicts the annual precipitation found across the state; observe that annual precipitation and elevation are well correlated. By simply examining this figure and Figure 1-9 immediately below it, one can infer the locations of the highest terrain in Colorado. The topography of Colorado has a major influence on the distribution of precipitation across the state.

Figure 1-8: Colorado Average Annual Precipitation (WRCC 2003)

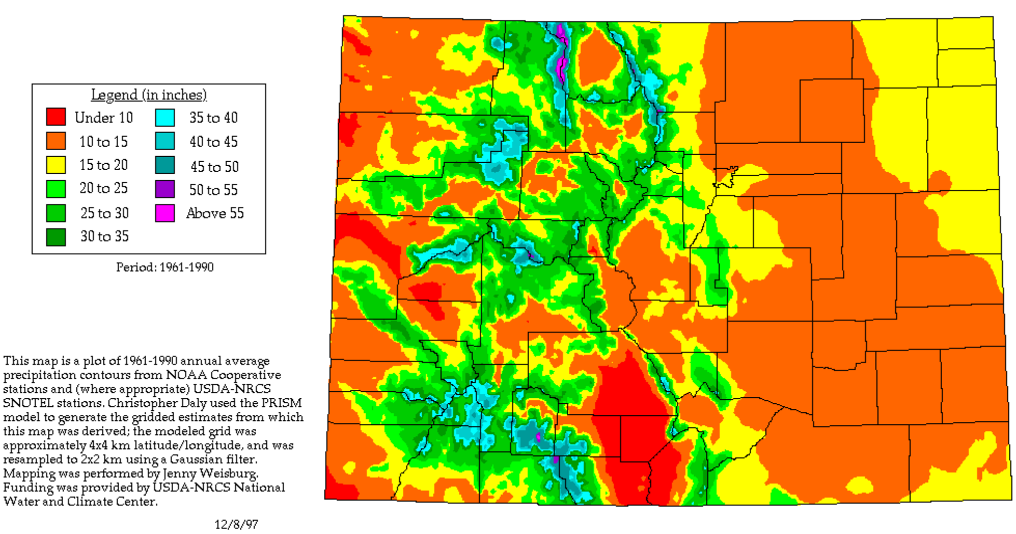
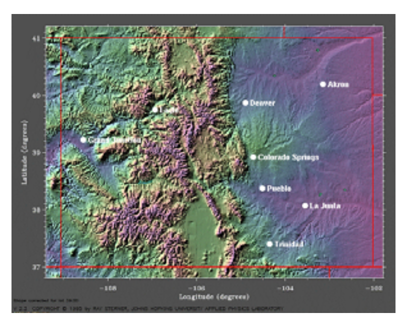


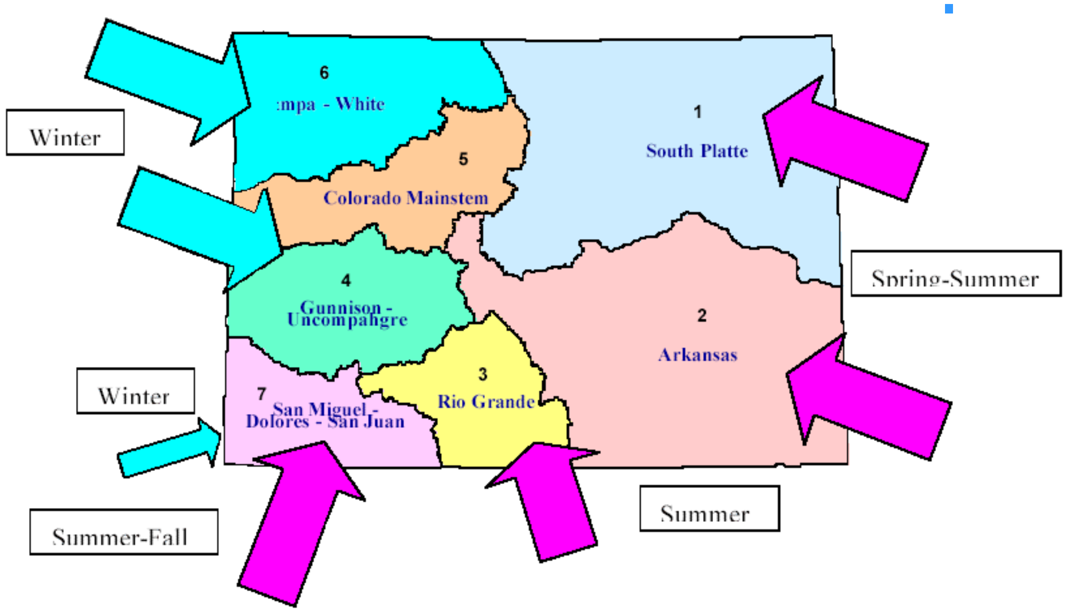
Figure 1-9: Colorado Topography



Wind, Topography and Precipitation

The sources of atmospheric moisture are depicted in Figure 1-10. Clearly the mountainous areas of the state are affected by moisture bearing winter winds from the west to northwest. The southwestern mountains favor wet winds from the southwest from summer into fall and winter. Upslope easterly winds from spring into summer bring green fields to the eastern half of the state and the southern mountains. Thus weather factors that influence the seasonal frequency and moisture content of these winds have a major impact on Colorado's precipitation.

Figure 1-10: Sources of Atmospheric Moisture in Colorado (McKee *et al.* 2000)



A majority of the seasonal snowpack that accumulates across the higher mountain ranges of Colorado is produced between late fall and early spring. This time period is of particular interest because it is estimated that up to *80% of Colorado's surface streamflow* originates from snowpack that accumulates during this period before melting in the April to July time frame.

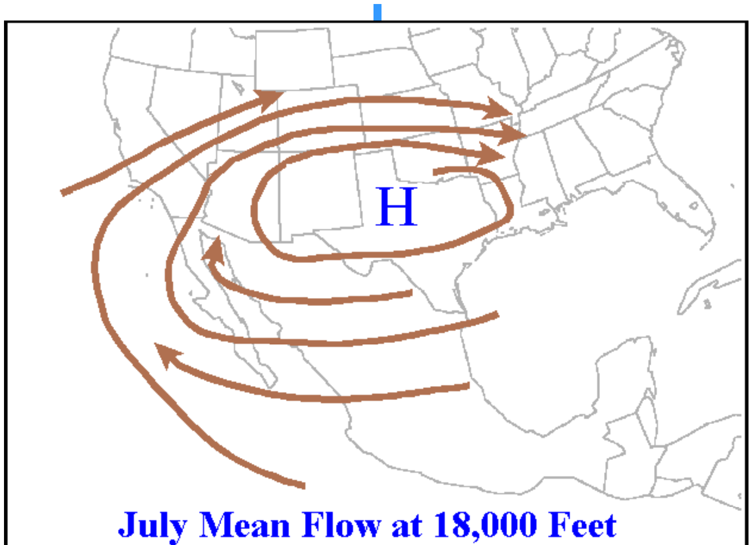
During the summer and early fall, the jet stream becomes notably weaker, if not absent, and convective (i.e. thunderstorm) activity becomes the primary source of precipitation. The moisture for this thunderstorm activity derives largely from the pattern commonly referred to as the Southwestern Monsoon. The monsoon area is defined by a general area of high pressure, or ridge, in the mid levels (~7,000-20,000 ft. above sea level) of the atmosphere that develops over southern New Mexico/western Texas (see Figure 1-11). The inflow of monsoon moisture is determined by this flow. The clockwise flow of moisture around this area of high pressure introduces moisture into Colorado from both the Gulf of California and the Gulf of Mexico.

The data in the Figure 1-11 are analogous to an area of high pressure at approximately 18,000 feet above sea level. Droughts that have occurred during the summer and early fall period are typically associated with an unseasonable northward migration of this area of high pressure resulting in two physical impacts.

The first impact would effectively funnel the rich sub-tropical moisture to areas further west of Colorado in the direction of California, Arizona, and Utah. The second impact is that a more local presence of this mid-level ridge over the state can result in relatively warmer temperatures at these levels.

Unseasonably warm air (between 10,000 and 20,000 ft above sea level) can act as "a lid on the atmosphere," acting to suppress the strength of convective activity across the region, which reduces the occurrences of summer thunderstorms. The longer-term persistence of this ridge over Colorado can result in below-normal amounts of precipitation on a more widespread basis.

Figure 1-11: Long-term Average of the 500 MB Height Field for July (from Douglas 1993)



Jet streams, Storm Tracks, El Niños and La Niñas

The production of precipitation across the state is attributed to the general positioning and strength of the jet stream, which typically traverses the state in a west-to-east direction during winter and spring. A majority of the moisture that falls across the state originates from the Pacific Ocean. This moisture is essentially transformed into precipitation by the following mechanisms, either singularly or in combination:

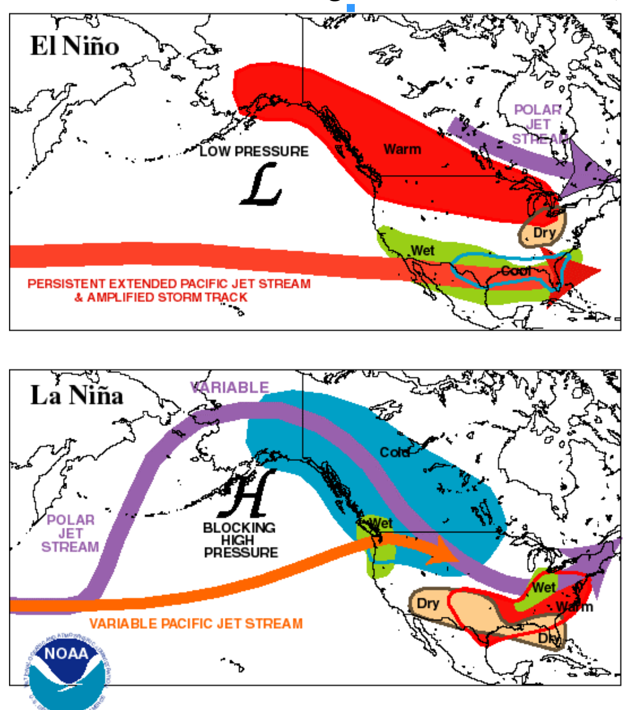
1. Strong lifting by individual storms traveling along the jet stream, and
2. The forcing of air across the mountains barriers, which also provides the lift needed to cool and condense water vapor in the air and produce precipitation.

In early spring, Pacific-based storm systems can effectively draw in low-level moisture from the Gulf of Mexico and generate exceptionally high amounts of precipitation east of the Continental Divide (a fine example of this scenario is the mid-March blizzard of 2003 across the northern Front Range).

To assess the impacts of drought during the late fall to early spring period, one should look at the longer-term positioning of the jet stream at this time of year and the factors that may influence it. The dominant cause of wintertime jet stream variability over western and central North America is the El Niño/Southern Oscillation (ENSO), which is essentially a shifting of relatively warm and cold surface waters and subsequent wind patterns across the equatorial Pacific Ocean. The general effects of El Niño and its counterpart La Niña can be found in Figure 1-12.

In general, El Niños are typically associated with conditions of higher moisture over Colorado while La Niñas have been typically been associated with drier than average conditions over the state during winter. These relationships tend to be more robust in the southern regions of the state. However, it should be noted that the extreme, nearly statewide drought during the winter of 2001-2002 ENSO was not in a conclusive El Niño or La Niña state. Regardless of the state of ENSO or other climatic factors that are currently being examined, either a lack of Pacific moisture, a lack of storms with the jet stream (in strength or numbers), or both can be linked to periods of wintertime drought.

Figure 1-12: Typical January-March Weather Anomalies and Atmospheric Circulation during Moderate to Strong El Niño & La Niña (CPC 2001)



Climate Prediction Center/NCEP/NWS

In La Niña years, the Pacific storm track tends to migrate further to the north and is already in a less-than-ideal position to bring an adequate amount of storms in terms of numbers and intensity for precipitation generation. La Niña years have had a greater tendency to produce drier-than-normal springs across the Front Range.

Note that in Grand Junction and Denver, El Niño years tend to produce more precipitation than in La Niña years. In Grand Junction the impact is more noticeable as a reduction of late summer and fall precipitation during La Niña years with lesser winter and spring impacts noticeable. In Denver both winter and summer precipitation is higher during El Niño periods. The heaviest El Niño precipitation in Denver is evident from late February into early June. The recent Saint Patrick's Day snowstorm of March 17-20, 2003 is an excellent example of an El Niño-assisted major precipitation event.

El Niño tend to create wet years statewide.

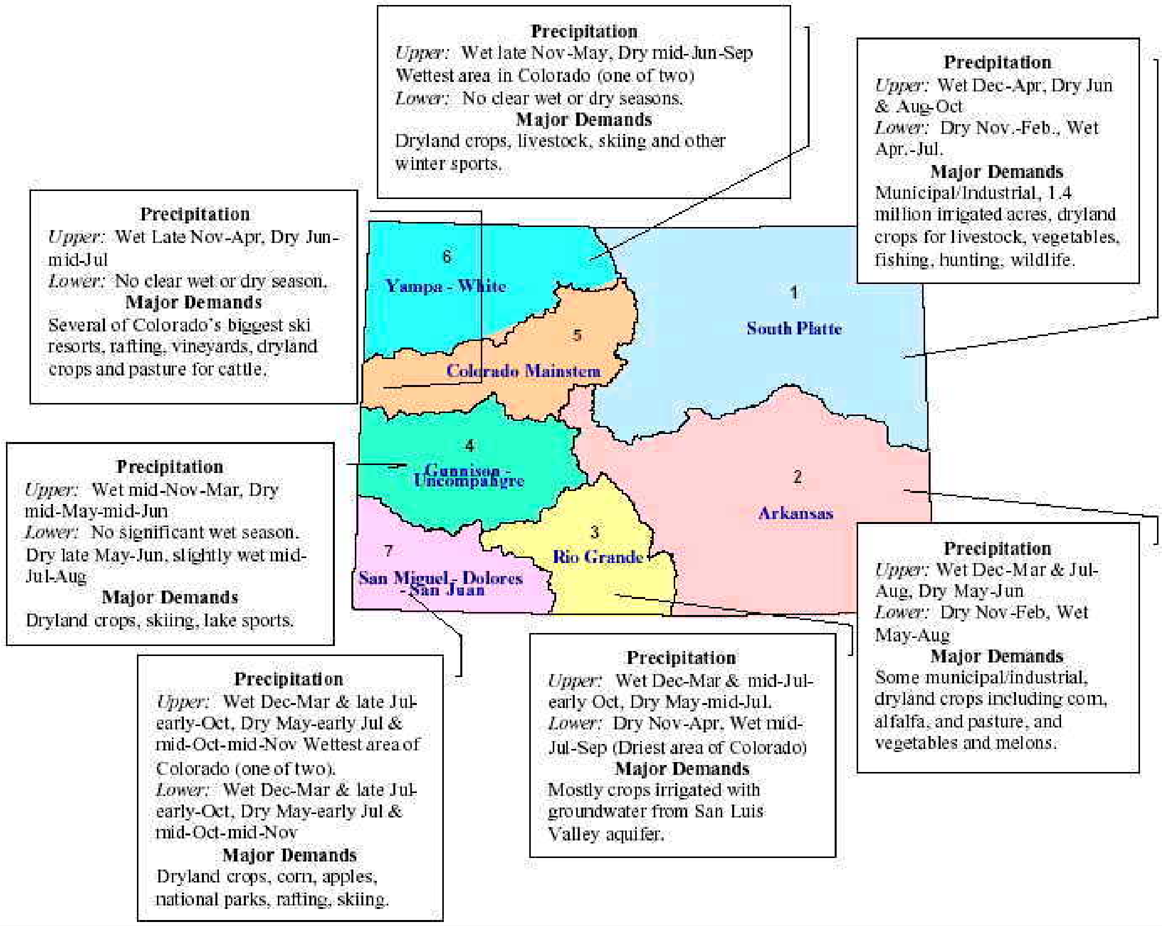
La Niñas tend to create multi-year dry periods that can accelerate into extended droughts.

Precipitation Variability across Colorado's Major River Basins

Due to the variability in climate and topography that define Colorado's landscapes, it is important to have an understanding of drought at a watershed level. "For many water management and planning

Figure 1-13: Major Water Demands in the Seven Colorado Water Divisions (McKee *et al.* 2000)

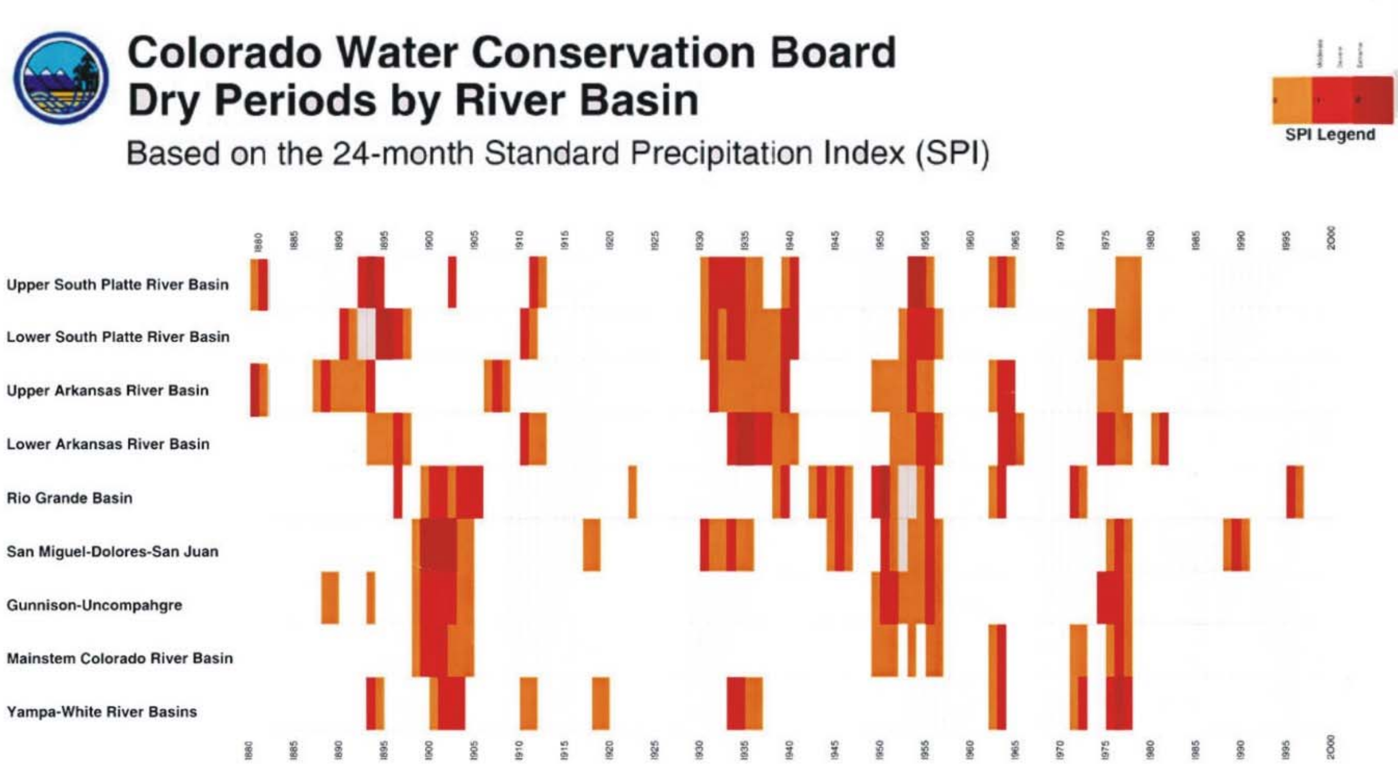
The figure below shows the State of Colorado divided into the seven Water Divisions that are used for water right administration and management purposes by the Colorado Division of Water Resources. These Water Divisions correspond with the major river basins in the state, with some of the smaller river basins lumped together into a single division (e.g. the San Juan and Delores Rivers in the southwestern corner of the state, and the North Platte with the Yampa-White). Additional information on major water demands by basin available in *Water, Colorado's Precious Resource, 2nd Edition.*



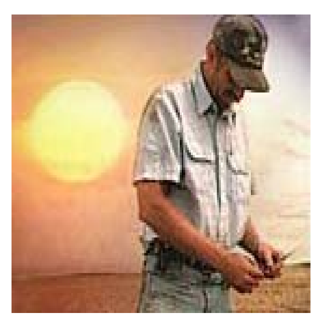
applications," reports McKee *et al.* (2000), "Colorado is divided into seven water divisions. Each of these basins originates in high mountain environments and descends through mountain valleys and eventually drops to much lower elevations. Thus, we can roughly divide each basin into an upper and lower basin based on approximate elevation and mountain proximity." A general picture of typical wet and dry periods in Colorado, as well as the principle demands in each water division, is provided for each of the seven major Colorado River basins (Figure 1-13). Note the great variability in precipitation across different seasons and different regions. An understanding of the various regional demands is important in order to determine the impacts of drought on a particular area of the state.

Figure 1-14 was prepared by the Colorado Water Conservation Board (CWCB) and presents the periods of moderate, severe, and extreme drought by basin since the late 1800s. The figure shows that major droughts rarely impact all of Colorado's major river basins simultaneously. When they do, as noted in the 1890's, the 1930's, the 1950's and the 1970's, the impacts are significant. On the other hand, many regional droughts occur almost every decade that impact only one or two basins for periods of one to two years.

Figure 1-14: Plot of Drought Severity by Year for Major Colorado River Basins based on 24-Month Standard Precipitation Index (created by CWCB, Stanton and Busto, 1997)



Drought is a very frequent visitor to Colorado. Single season droughts with precipitation of 75% or less of average for one to three months in a row occur nearly every year in Colorado. Based on long-term weather station records, it was observed that at least 5% of the state is experiencing drought on 3- to 24-month timescales almost all of the time (McKee *et al*. 2000).



Drought Cycles: What Goes Around, Comes Around

Many drought observers insist that drought cycles exist. Some suggest that the sunspot cycle of 11 years or a "double sun spot cycle" of 22 years controls Colorado's drought patterns. Others claim that a 3- or a 7-year cycle exists in local or regional drought occurrence. An extensive review by the Colorado Climate Center to identify drought cycles was inconclusive.

An example of how new information can be developed through "database mining" can be seen in Table 1-5. Table 1-5 shows a comparison from 1900 to 1999 of decadal occurrences of basin-specific annual precipitation that is 2 inches or more above or below average. The base annual precipitation information was derived from the Western Regional Climate Center database.

Table 1-5: Comparison of the Number of Annual Basin Precipitations +/- 2" of Average/Decade

Basin	00's		10's		20's		30's		40's		50's		60's		70's		80's		90's		Totals		100 year Results
Above/Below	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	**A**	**B**	
Platte	0	0	3	0	2	0	1	5	1	0	0	2	1	5	0	1	0	0	3	1	11	14	-3
Colorado	1	4	3	0	4	1	0	3	1	0	2	4	0	3	0	2	5	1	3	1	19	19	0
Arkansas	2	0	3	0	4	0	1	3	3	0	1	5	2	4	0	4	0	0	2	0	18	16	2
Rio Grande	0	4	1	0	2	0	0	9	1	1	0	5	1	0	1	4	2	0	6	2	14	25	-11
Total	**3**	**8**	**10**	**0**	**12**	**1**	**2**	**20**	**6**	**1**	**3**	**16**	**4**	**12**	**1**	**11**	**7**	**1**	**14**	**4**	**62**	**74**	**-12**
Difference	**-5**		**10**		**11**		**-18**		**5**		**-13**		**-8**		**-10**		**6**		**10**		**-12**		

In Table 1-5, the droughts of the 1930's, 1950's and the 1970's show up as significant decades of below average precipitation in Colorado's major river basins (as indicated by the negative number in the "Difference" row). Wet periods are indicated by the positive numbers in the "Difference" row. Note that the two wet periods of the past century (the 1980's and 1990's) appear to provide less durational impact than the entire extended dry period of the 1930s through the 1970s.

A = Years with annual basin precipitation of equal to or greater than 2" above average.

B = Years with annual basin precipitation of equal or greater value than 2" below average.

Impacts of Drought: What Might the Future Hold?

Drought will be a continuing unwelcome aspect of Colorado's climate. Despite all the good science applied to understanding drought, considerable uncertainty exists in trying to anticipate its arrival, duration, severity and departure. The only thing certain is that drought will come again.

Henz and Badini (2002) attempted to take a bold look into the future of Colorado's climate from 2000 to 2075. Their look ahead, shown in Table 1-6, predicts several periods of statewide drought in the future. Of particular concern, an extended period of drought appears likely within the next 50 years. This result should not be considered unrealistic given the paleo-climate research results reported earlier.

Table 1-6: Trend Analysis of a Blended Climate Data Set for Average Precipitation in the Major Colorado River Basins from 2000 to 2075

Time	Precipitation/ weather factors outlook
2000-2009	An "average" decade marked by an early drought and wet El Nino
2010-2019	**Significant multi-year drought likely due to extended La Nina**
2020-2029	Drought gives way to a "mildly wet" strongly El Nino decade
2030-2065	**Extended period of drought possible as La Nina is enhanced**
2065-2069	El Nino returns to bring a wet end to the decade
2070-2079	An extended period of above average precipitation returns
	Note: This outlook is experimental

An extended drought may have chased the ancient Anazazi Indians from their dwellings in the Mesa Verde area. If a similar strong and protracted drought were to occur over the next 100 years it would cause major impacts on Colorado residents and their way of life. The drought of 2000-2003 has shown that major impacts on our quality of life and water supplies can be inflicted by short-term drought.

"Those who do not remember the past are doomed to repeat it."

George Santayana (1863 – 1952) American Philosopher The Life of Reason, Volume 1, 1905

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