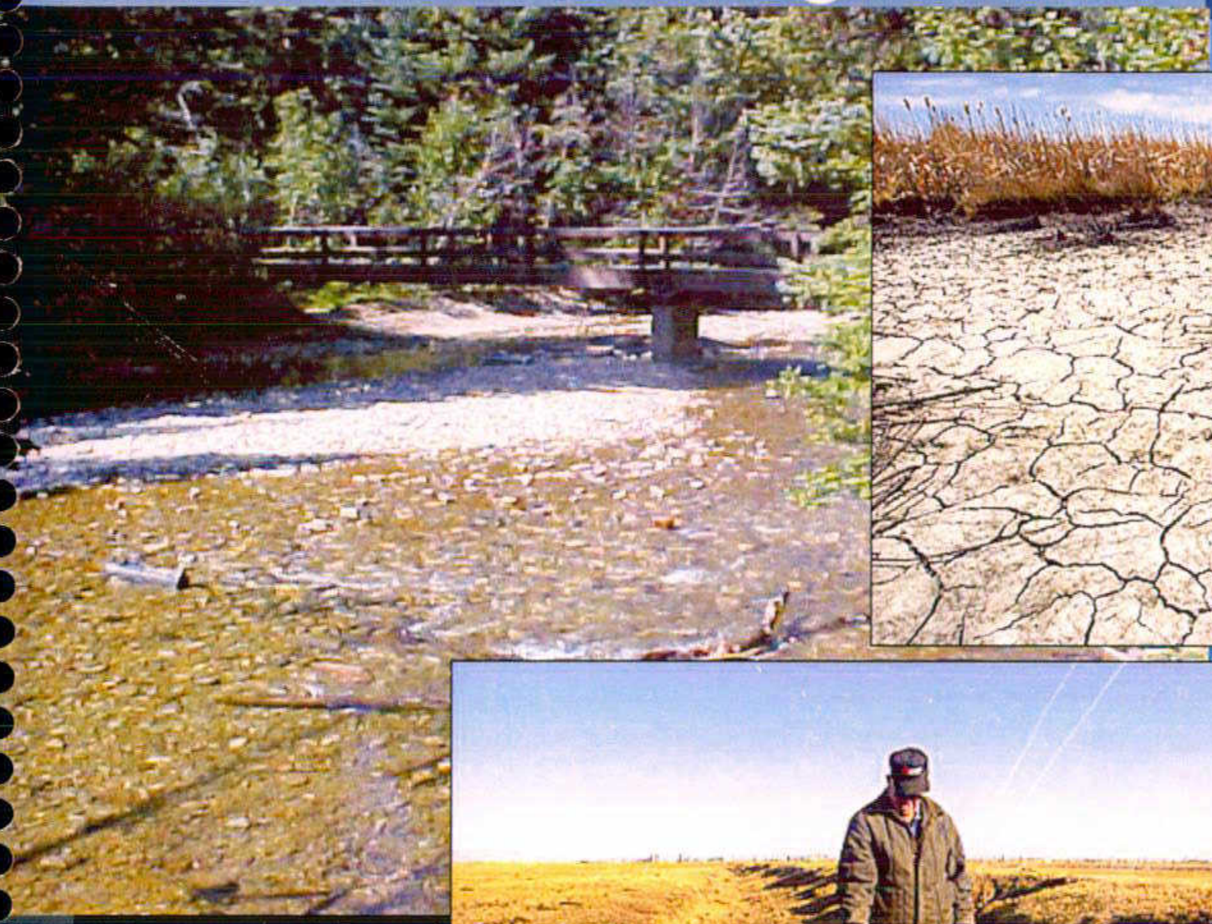
Historical Perspectives on Colorado Drought



HDR

December 1, 2003

Historical Perspectives on Colorado Drought

The Fight for the Waterhole, Frederic Remington, 1897

The History and Future of Colorado Drought

What is drought: not everyone agrees?

Measuring Drought's Severity: A difficult task.

Water availability: where does precipitation come form?

Drought cycles: what goes around, comes around.

Impacts of drought: what might the future hold?

John Henz, Seth Turner, William Badini and Jerry Kenny
HDR Inc, Denver, Colorado

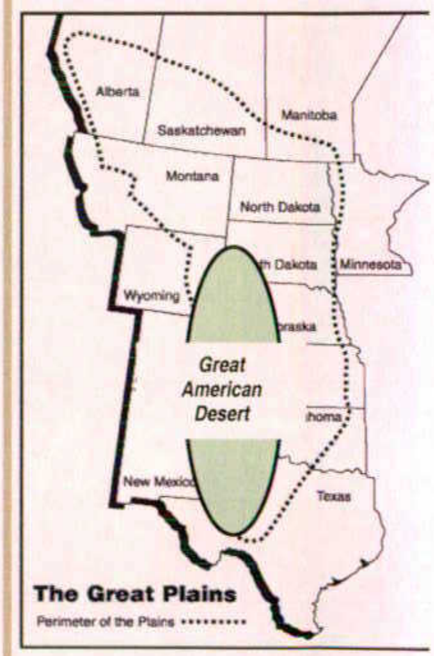
Look deep, deep into nature, and you will understand everything better.
Albert Einstein

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 our very existence. Water supplies dry up, wells run dry and crops whither. If it is very severe, cities and states turn on one another to secure it.

Frederic Remington, the artist and Western historian, understood the importance of water to the West. His famous painting, The Fight for the Waterhole, embodies the very essence of water's importance to the Western way of life.

Stephen Long, a U.S. Army lieutenant who passed through Colorado in 1822, giving his name to the most visible peak in Rocky Mountain National Park, wrote off the entire block of real estate that included Kansas, eastern Colorado and the Texas panhandle as ``the great American desert." His assessment was much the same as Pike, who preceded him, even as to the limiting factor of the plains:

> The Great Plains region is almost wholly unfit for cultivation, and of course inhabitable by a people depending upon agriculture for their subsistence. Although tracts of fertile land considerably extensive are occasionally met with, yet the scarcity of wood and water, almost uniformly prevalent, will prove an insuperable obstacle in the way of settling the country.



The Great American Desert covered the Great Plains from eastern Wyoming to the Texas Panhandle including all of Colorado east of the Continental Divide.

If we are to plan water supplies of Colorado's future, a good place to start is in the understanding of Colorado drought: its history, its cycles, how we measure it, where it comes from and how we might plan for its occurrence in the future. The Drought of 1999-2002 in Colorado has provided a rude awakening to drought's impacts on modern life. A mandate to respond has been sounded. The time for decisive but meaningful action requires that we humbly appreciate and understand nature's power.

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

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. We will begin this section 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 droughts rarely encompass 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. 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 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	Most widespread, severe and longest lasting drought in Colorado instrumented history
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"
1999-2003	2001-2002	Significant multi-year state-wide drought

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

Woody Guthrie once sang,

"This old world is a hard world, for a dust bowl refugee."

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 in1894, again most pronounced over eastern Colorado. This statewide drought produced a sustained and very severe drought over southwestern Colorado. Worst drought on record occurred in the Durango area during this time.

The Dust Bowl of the 1930's

Most widespread and longest lasting (and most famous) drought in Colorado recorded history. Severe drought developed in 1931 and peaked in 1934 and early 1935. Interrupted by heavy spring rains in 1935 and more widespread heavy rains in 1938. Culminated with one more extremely dry year in 1939 when several stations along the Front Range recorded the driest year in [20^{th} 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 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 1930s 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.

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 in the 1930's. Its

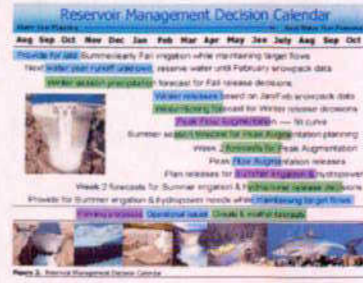
severe impact on the Colorado Front Range and only light to moderate impact on mountain precipitation may have overly influenced water supply planners into using it as a model of sorts. Unfortunately, severe drought can simultaneously impact the entire state and negate a strategy based on plains drought but ample mountain snows.

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.

An extreme but brief drought period returned for the fall of 1980 into the summer of 1981. This drought again took aim at the Colorado 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 below. 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 1999-2002 drought.



Colorado Drought Plan prompted by 1970's drought

Associated Press/Mike Orlowski

Snow-making equipment in operation

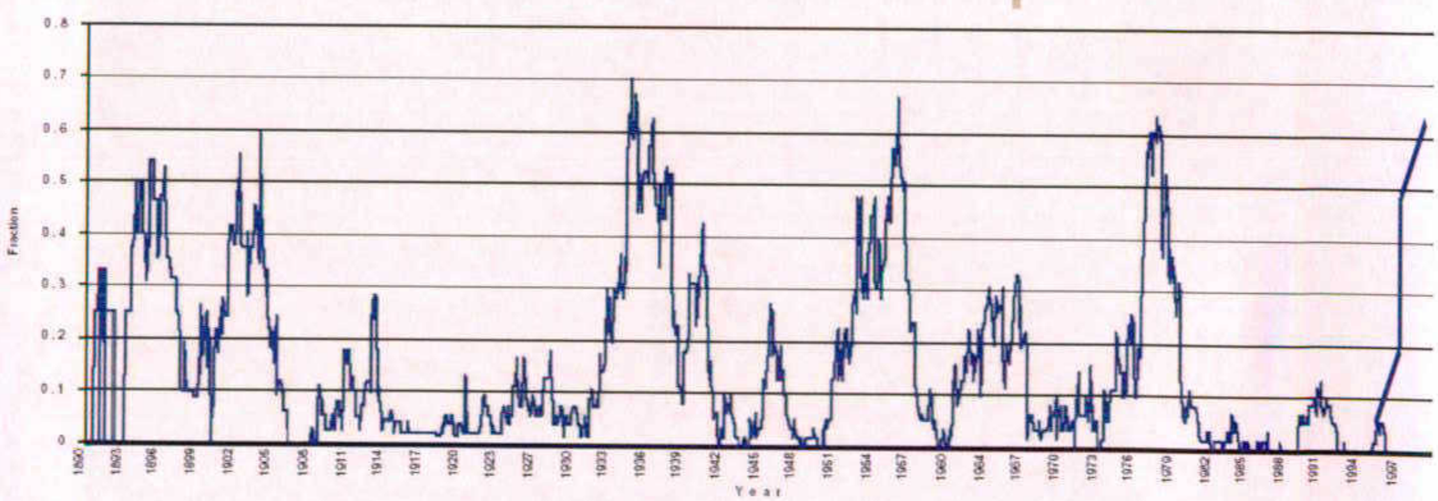


Figure 1. Fraction of Colorado in drought based (McKee *et al.* 2000) with est. 1999-2002.

Drought of 2002

Having considered the full extent of recorded droughts in the past 110 years, how does the Colorado drought of 2002 compare with past droughts? The severity of the 2002 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 2. The 2002 drought produced the lowest Palmer Hydrologic Drought Index seen during the modern (instrumental) period of record.

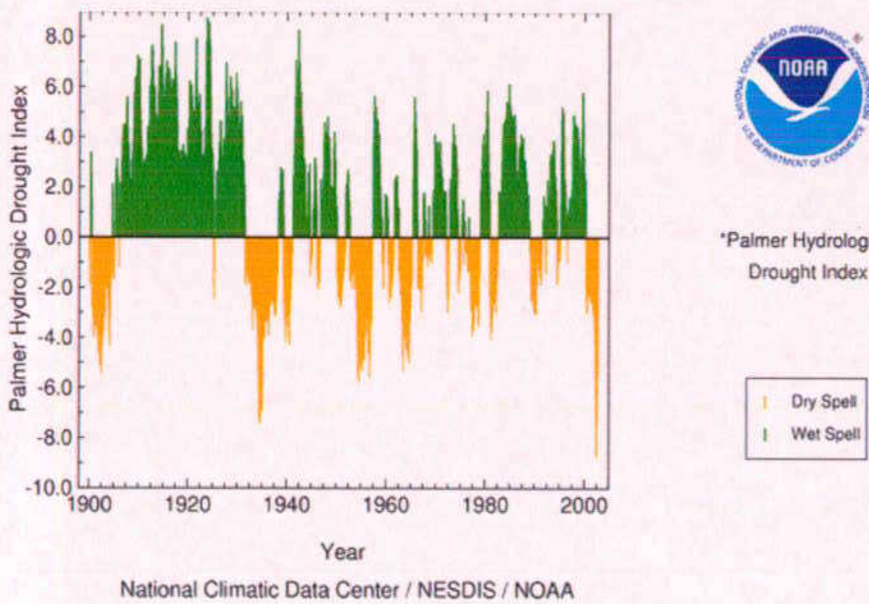


Figure 2. Colorado statewide PHDI*, January 1900 - December 2002 (NCDC 2003)

During the drought of 2002, scientists at Hydrosphere and the National Atmospheric and Oceanic Administration 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 Figure3, show that the 2002 stream flows are probably the lowest that have occurred since 1725. **Not only that, but the data analyzed in the study suggest that droughts lasting more than 15 years have occurred several times within the past 300 years (Hydrosphere 2002).**

Tree ring records can be compared to instrumented periods to develop estimated Palmer Drought Severity Index records for hundreds of years into the past

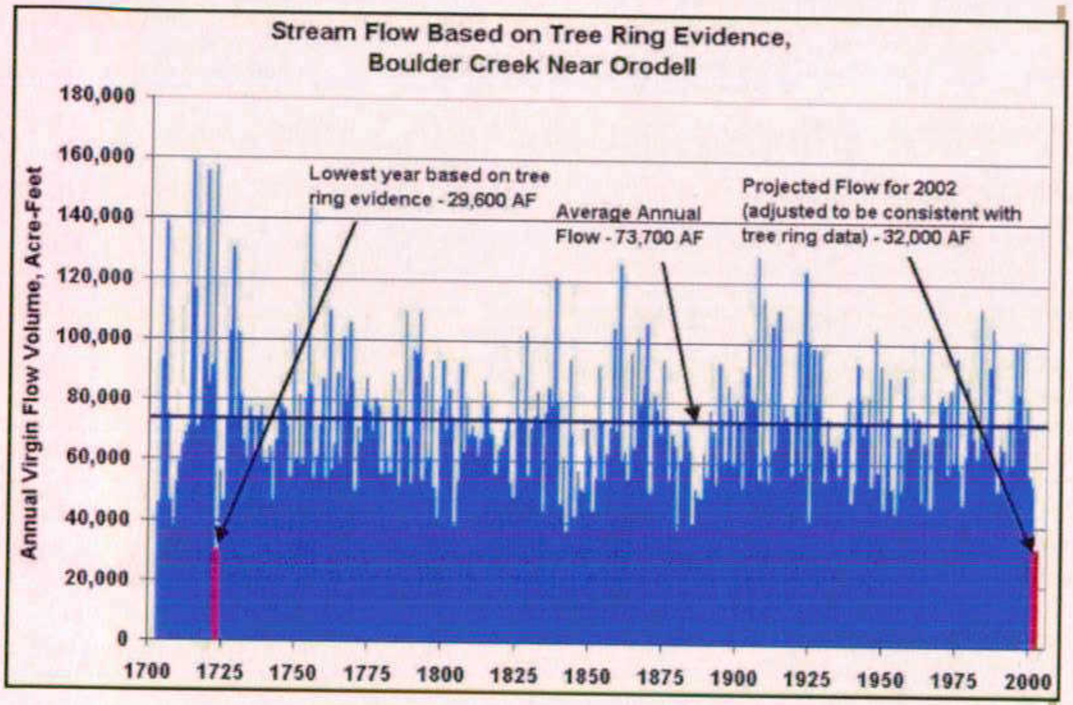


Figure 3 Streamflow on Boulder Creek based on tree ring analysis near Ordell, Colorado that shows the comparative impact of droughts since 1700.

Tree ring analysis of streamflow suggests that the 2002 drought is the severest to impact northeastern Colorado in almost 300 years!

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 1999-2003. 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.

The data in Table 2., edited from a table in McKee *et al*. (2000), "shows the periods during which **at least 60% of Colorado was dry, as determined by the Standardized Precipitation Index (SPI) values for 24-month periods."** Note that the dates are not identical to those discussed above, as they were determined using a different methodology, namely the SPI instead of water year precipitation totals. However, it is clear that the 1999-2002 drought ranks as one of the most severe to affect the state during the instrumented period of record. The question remains how this drought compares to historical droughts of the past 300 to 500 years. Paleo-climatology may provide that insight.

Table 2. Dry periods in Colorado based on 24-month SPI

Date	Duration
1893-1905	12 years
1931-1941	10 years
1951-1957	6 years
1999-2002	4 years+
1963-1965	2 years
1975-1978	3 years

Paleo-climatology of Colorado Droughts

Investigation of droughts that pre-date the instrumentation period falls within the realm of paleo-climatology. One of many options, 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 are common from tree to tree reflect droughts and other anomalies in climate (Woodhouse 2003).

Having established a general understanding of tree ring analysis, we can now look at some examples of the application of tree ring studies to determine historical drought periods in Colorado. Woodhouse *et al.* (2002) provide a detailed account of the impacts and implications of a drought in the western Great Plains from 1845-1856. Tree-ring based reconstructions of streamflow and Palmer Drought Severity Index (PDSI) have been developed and clearly show the extensive magnitude and duration of this mid-19th century drought.

As depicted in Figure 4, the identified core area (the shaded region) of the 1845-1856 Drought encompassed much of southeastern Colorado and the Front Range.

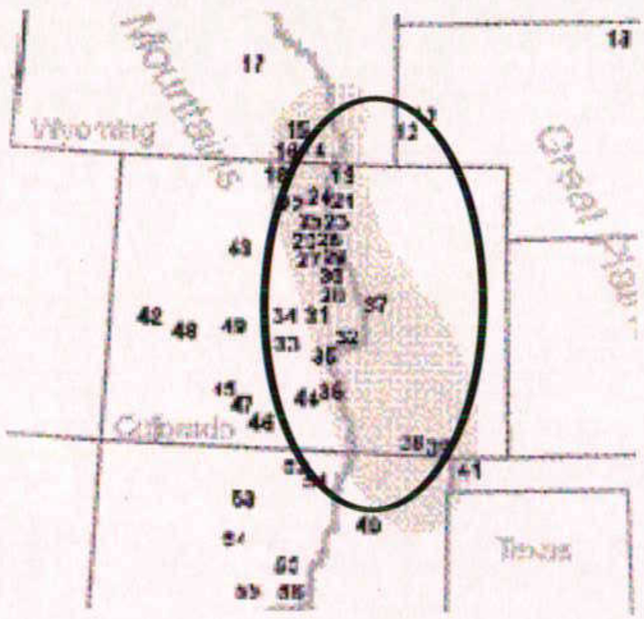
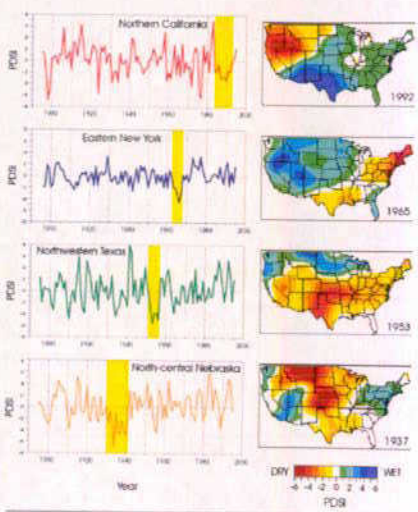


Figure 4 Core area of 1845-1856 drought (Woodhouse *et al.* 2002)

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

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



A national tree ring data base was used to re-construct a number of historical drought from around the United States.

The yellow bars indicate the drought periods in the tree ring estimated PDSI charts. The red areas on the accompanying maps show the areas of observed drought 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).

"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)

The United States map below (Figure 5) was prepared by NOAA using a national tree ring data base that was used to prepare a standardized set of tree ring values of the Palmer Drought Severity Index (PDSI). Henz and Badini,2002 prepared a detailed comparison of the tree-ring growth index at the four points shaded within Colorado. A comparison of tree ring derived and instrumented SPI and PDSI values for the important Colorado drought periods during the past 100 years was developed. Special attention was given to recent period droughts of the 1930s and 1950s to insure that the drought periods correlation with tree ring derived drought periods.

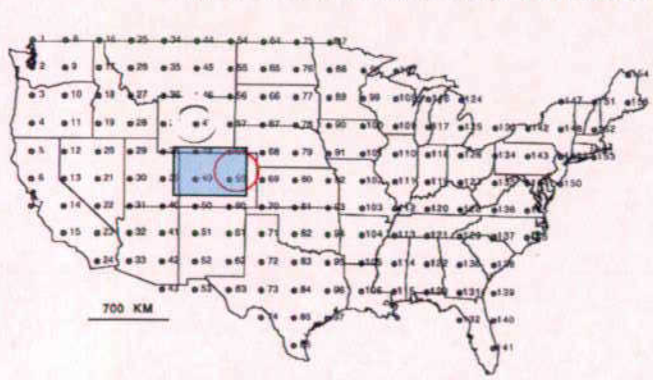


Figure 5

The data in Table 3 is based on an analysis of the occurrence of wet and dry decades based on the tree-ring PDSI of four data points in Colorado shown in the shaded area in Figure 5 above. The four sites were used to analyze the occurrence historically of droughts in the northerneastern, southeastern, southwestern and northwestern areas of the state.

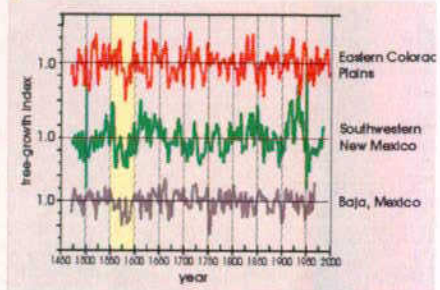
Analyses of the Colorado sites produced similar depictions of wet and dry decades. However, a number of dry decades that affected only the western or eastern half of the state were evident. It should be noted that at least one dry decade affects the entire state each millennia.

Table 3: Occurrences of wet/dry decades from 1500-1995 based on tree-ring growth index at Colorado data points in Figure 5.

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

From this historical perspective it appears that the current Drought of 1999-2002 likely has been exceeded in duration, intensity and coverage by historical droughts of the past. Consider the occurrence of coincident droughts such as the one apparent in the yellow bar on the graph to the right. The eastern plains of Colorado, southwestern New Mexico and Baja, Mexico all experienced a multi-decade drought simultaneously. Winter and spring drought conditions appear to have been particularly severe in the Southwestern U.S. and northwestern Mexico, where this drought appeared to have lasted several decades (1625-1655). In other areas, drought conditions were milder, suggesting drought impacts may have been tempered by seasonal variations.

The non-traditional database of historic tree-ring analyses reported by Woodhouse, 2001, provides new opportunities for an in-depth look at the past that could open doors into the future of Colorado drought occurrence, while linking the information to state stream flow and water supply.



In the graph tree ring derived Palmer Drought Severity Indices were calculated from trees across Southwestern New Mexico, eastern Colorado and Baja Mexico.

The solid yellow bar indicates a coincident severe drought in all three locations in the mid-1500s

What is drought: not everyone agrees?

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).

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. 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 defining drought is a multi-faceted problem.

How is drought classified? (Operational definitions)

The National Drought Mitigation Center 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. Figures 6-8 illustrate the causes and effects associated with these definitions.

> *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. 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

Meteorological measurements are the first indicators of drought.

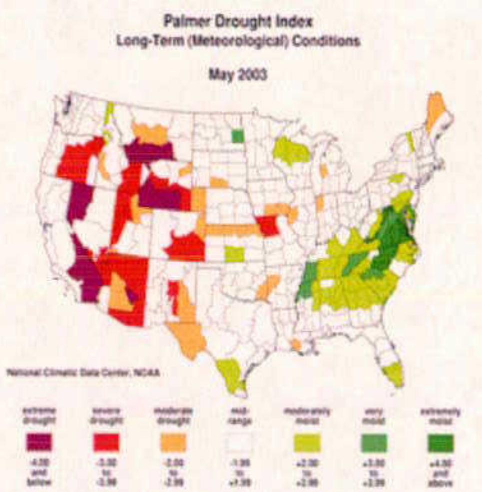


Figure 6. Map of meteorological drought conditions (NOAA-NCDC 2003)

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

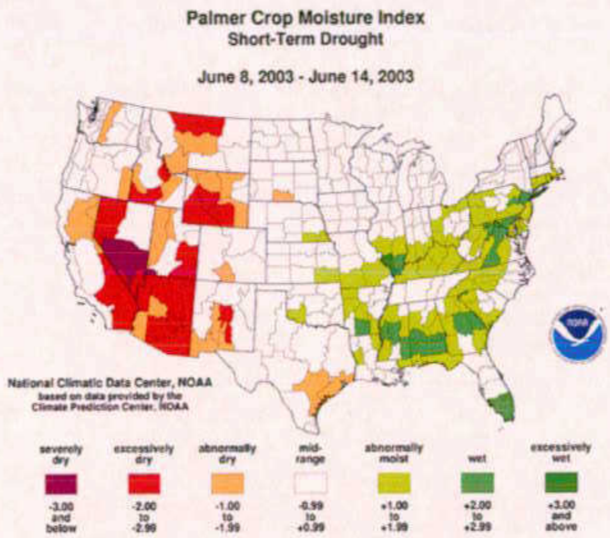


Figure 7. Map illustrating agricultural drought conditions (NOAA-NCDC 2003).

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.

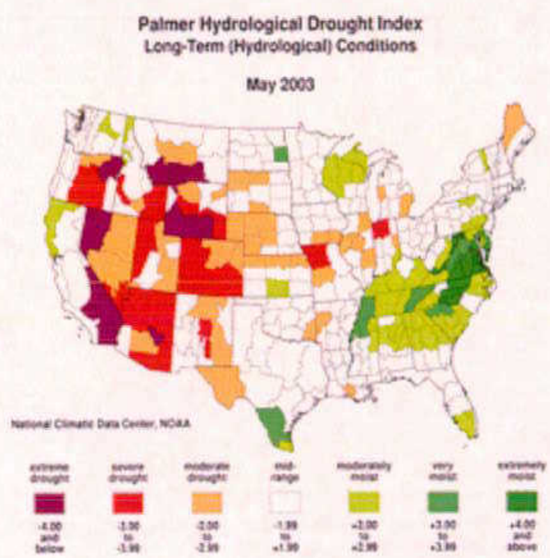


Figure 8. Map of hydrological drought conditions (NOAA-NCDC 2003)

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 9 illustrates the time lag between meteorological, agricultural, and hydrological drought.

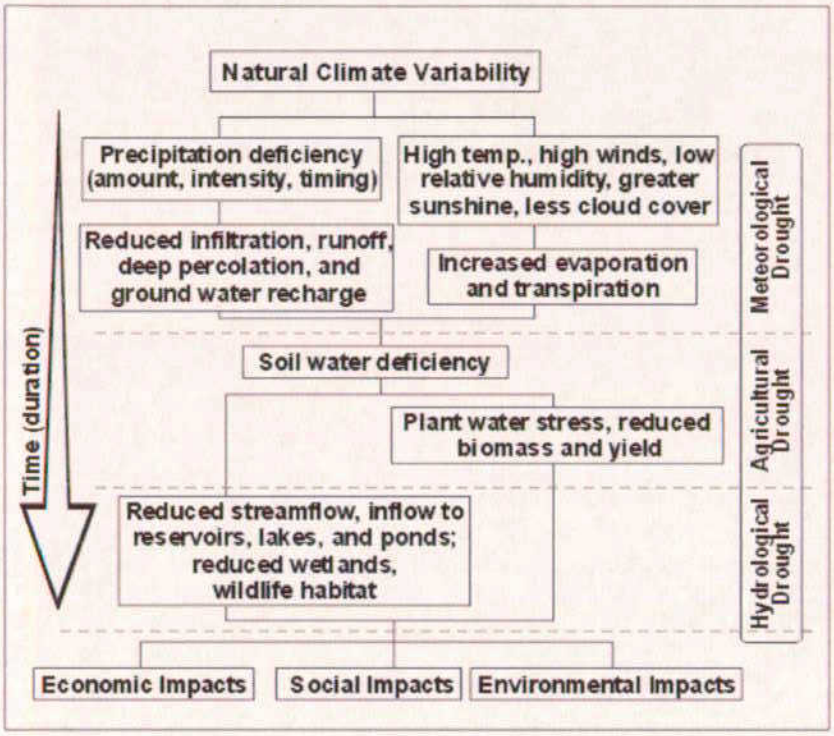


Figure 9 Illustration of operational drought definitions (NDMC 2003)

Further, the lag between different components of the hydrology is shown in comparing streamflow and groundwater responses. (Figure 10)

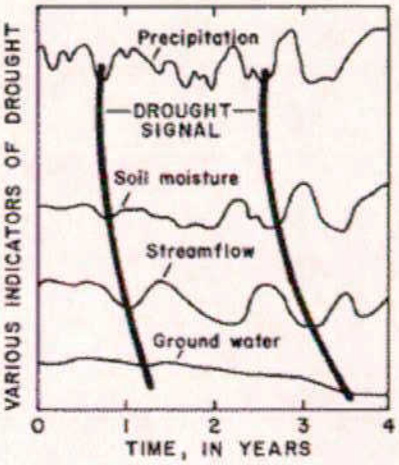


Figure 10 Time lag in hydrologic drought response (USGS 2003)

Each of the definitions provided above has important contextual implications for the state of Colorado. Taken as a collective whole, this account of the meaning of drought will serve as the cornerstone that completes the foundation of our understanding of Colorado's drought history.

Measuring drought's severity: not everyone agrees!

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) enlighten us to their significance, stating, "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 come to 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

Developed by Palmer (1965), the PDSI was the first quantitative tool available for assessing the severity of drought. Although the specific details of these indices are quite complex, the NCMC (2003) provides us with simple explanations of each:

The *Palmer Crop Moisture Index* measures short-term drought on a weekly scale and is used to quantify drought's impacts on agriculture during the growing season.

The *Palmer Drought Severity Index* attempts to measure the duration and intensity of the 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 almost literally overnight from a long-term drought pattern to a long-term wet pattern, the PDSI can respond fairly rapidly.

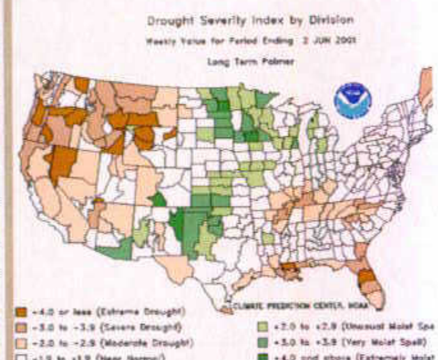
The hydrological impacts of drought (e.g., reservoir levels, groundwater levels, etc.) take longer to develop and it takes longer to recover from them. The *Palmer Hydrological Drought Index*, another long-term drought index was developed to quantify these hydrological effects. The PHDI responds more slowly to changing conditions than the PDSI.

Table 4 Classifications for PDSI

≥ 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

Advantages of the PDSI, as outlined by Alley (1984), 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.



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). As before, we turn to the NCDC (2003) for a straightforward examination of this index.

Table 5 Typical SPI values	
≥ 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

While Palmer's indices are water balance indices that consider water supply (precipitation), demand (evapotranspiration) and loss (runoff), the *Standardized Precipitation Index* is a probability index that considers only precipitation.

The index is negative for drought, and positive for wet conditions. As the dry or wet conditions become more severe, the index becomes more negative or positive. The SPI is computed by NCDC for several time scales, ranging from one month to 24 months, to capture the various scales of both short-term and long-term drought.

The SPI has been used operationally to monitor conditions across Colorado since 1994 (McKee *et al*. 1995). This nationwide SPI map unmistakably illustrates the severity of the 2002 drought across the entire state of Colorado and much of the southwestern United States.

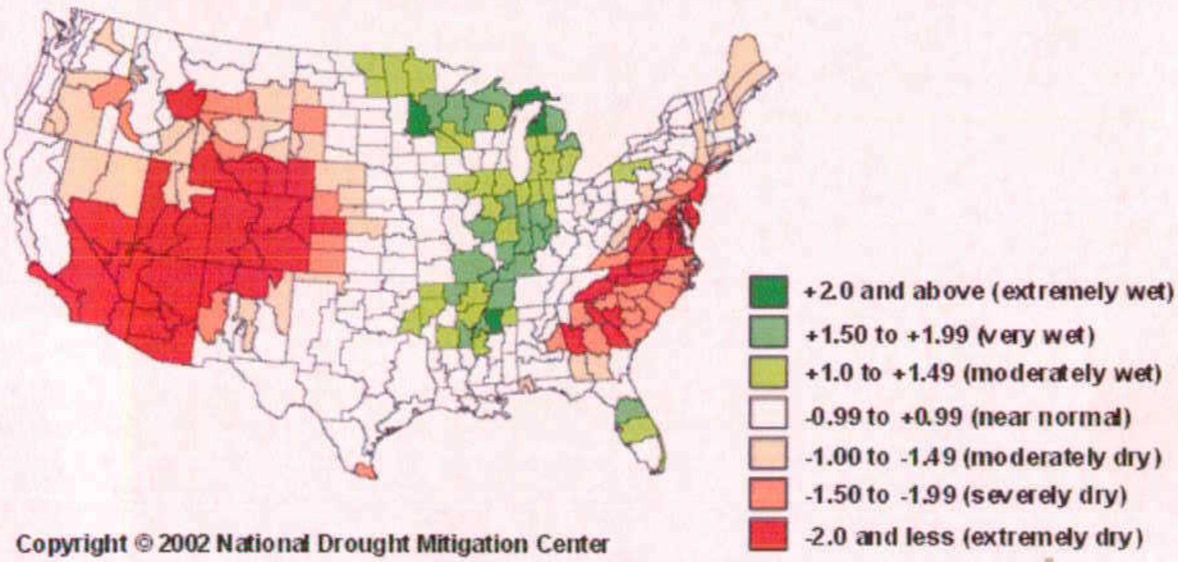


Figure 11 12-month SPI through the end of August 2002 (NDMC 2003)

Water Availability: where does the precipitation come from?

To better appreciate the forces at work during a period of drought, we first must take a brief look at the variability in precipitation across the state from both the perspective of location and time. Figure 12 depicts the annual precipitation found across the state; observe that annual precipitation and elevation are well correlated. By simply examining this figure and Figure 13 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. A

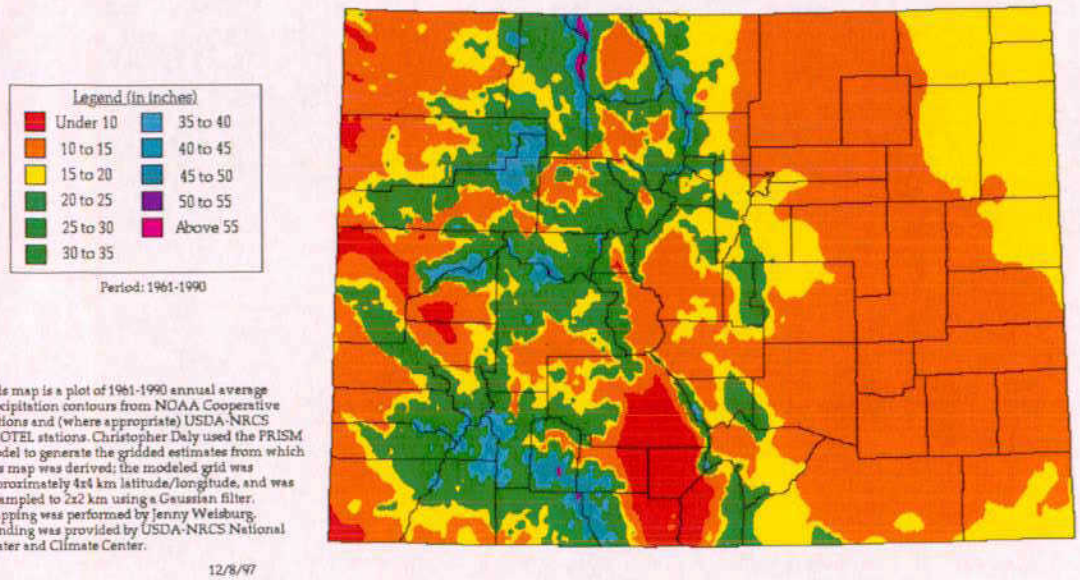


Figure 12 Colorado average annual precipitation (WRCC 2003)

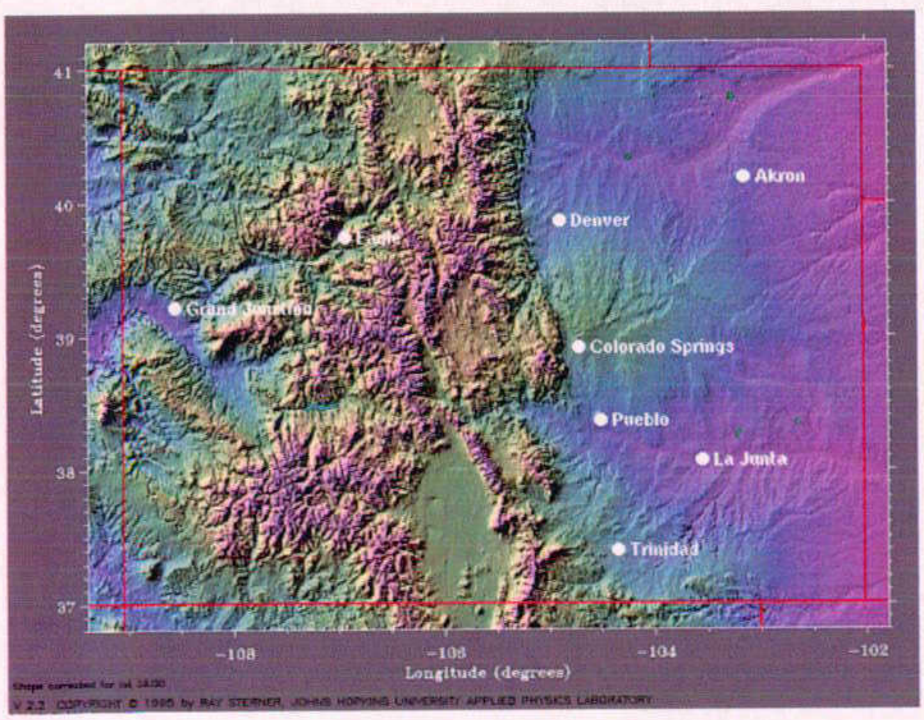


Figure 13 Colorado topography

Wind, topography and precipitation

The sources of atmospheric moisture are depicted in Figure 14. 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.

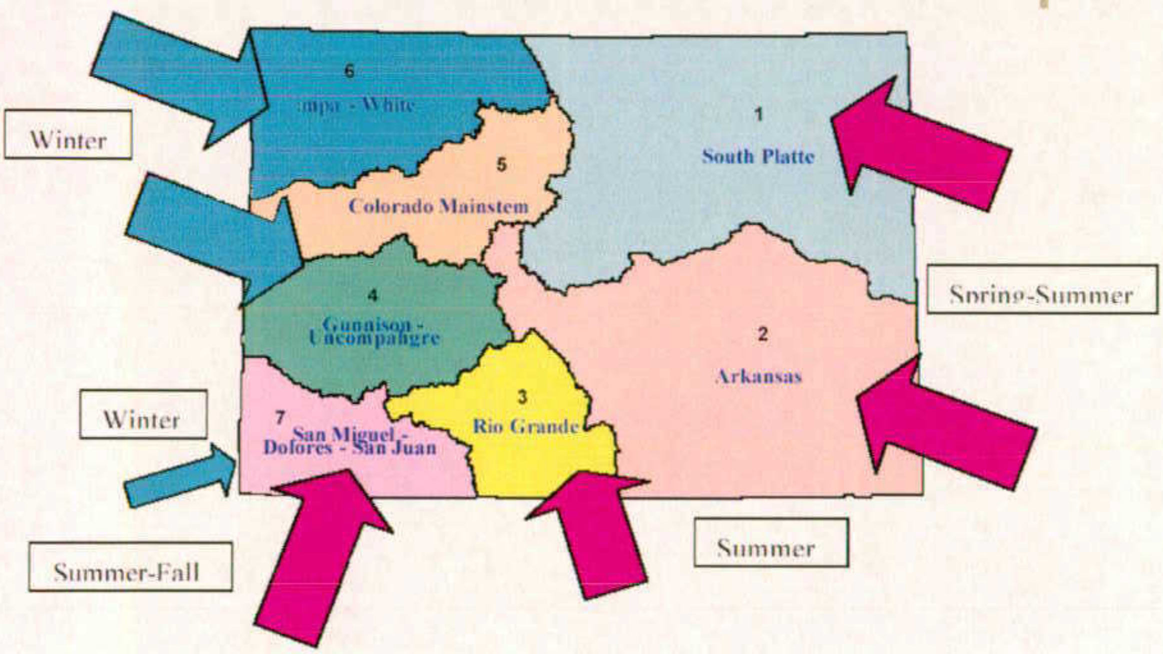


Figure 14. Sources of atmospheric moisture in Colorado (McKee *et al.* 2000)

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 pattern 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 develops over southern New Mexico/western Texas (see Figure 15). The inflow of monsoon moisture is determined by this flow. The clockwise flow of moisture around this area of high

Mountain snow pack provides a significant water source.

pressure introduces moisture into Colorado from both the Gulf of California and the Gulf of Mexico.

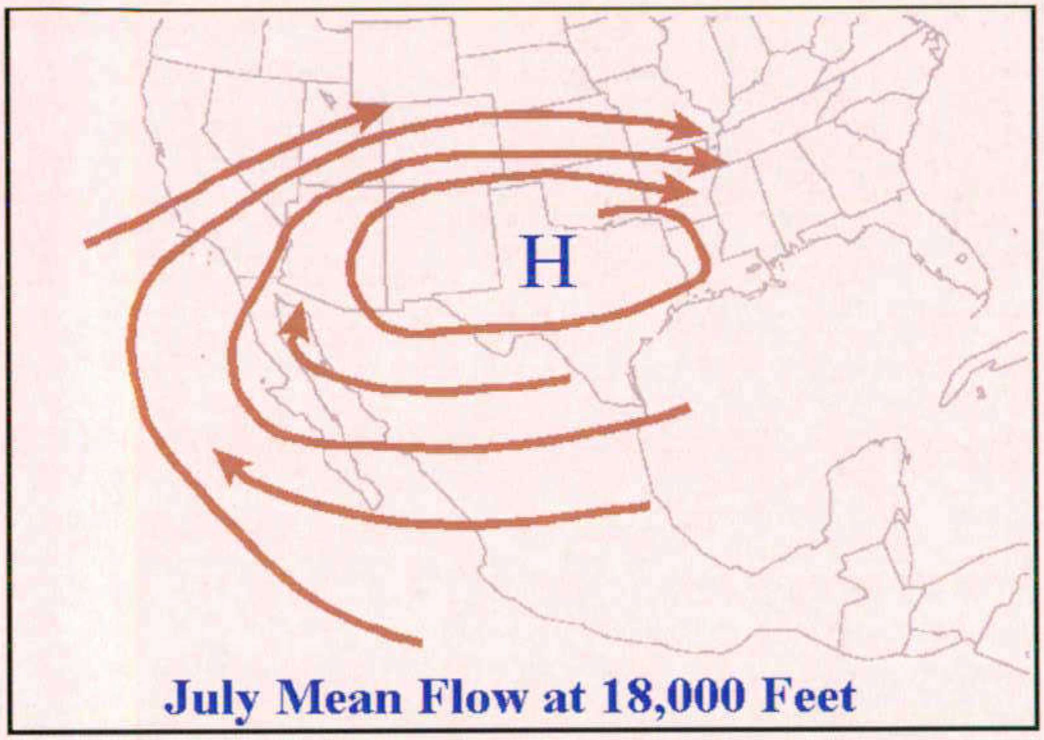


Figure 15 Long-term average of the 500 MB height field for July (from Douglas 1993)

The data in the preceding figure is analogous to an area of high pressure at approximately 18,000 ft 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.

Jet streams, storm tracks, El Nino's and La Nina's

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 manner during winter and spring. A majority of the moisture that falls across the

Monsoon thunderstorms bring summer rains.
Courtesy NOAA

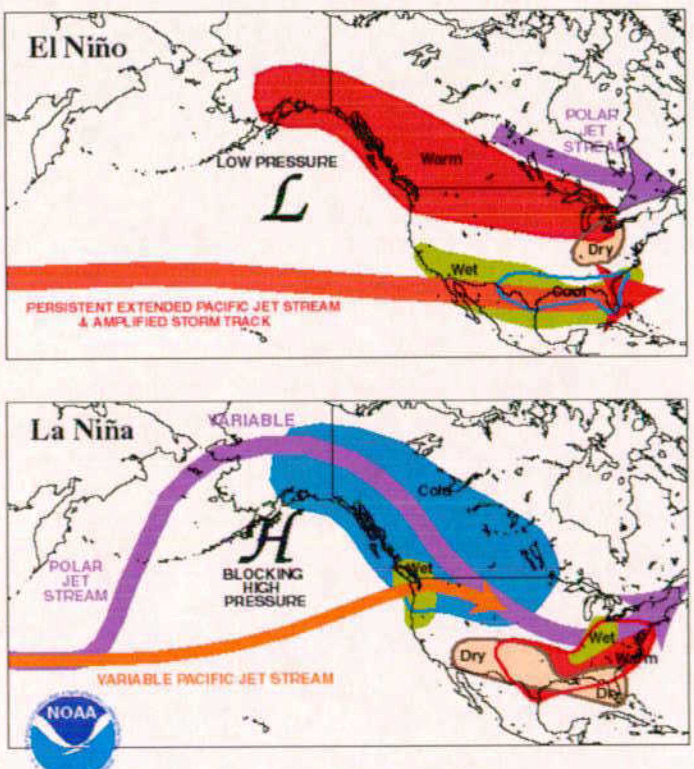
state originates from the Pacific Ocean. This moisture is essentially transformed into precipitation by the following mechanisms, either singularly or in combination:

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 Nino/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 Nino and its counterpart La Nina can be found in Figure 16.



Climate Prediction Center/NCEP/NWS

Figure 16 Typical January-March weather anomalies and atmospheric circulation during moderate to strong El Niño & La Niña (CPC 2001)

In general, El Ninos are typically associated with conditions of higher moisture over Colorado while La Ninas 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 Nino or La Nina 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.

In La Nina 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 Nina years have had a greater tendency to produce drier-than-normal springs across the Front Range. Impacts of El Nino and La Nina on monthly precipitation at Denver and Grand Junction can be seen in Figures 17 and 18.

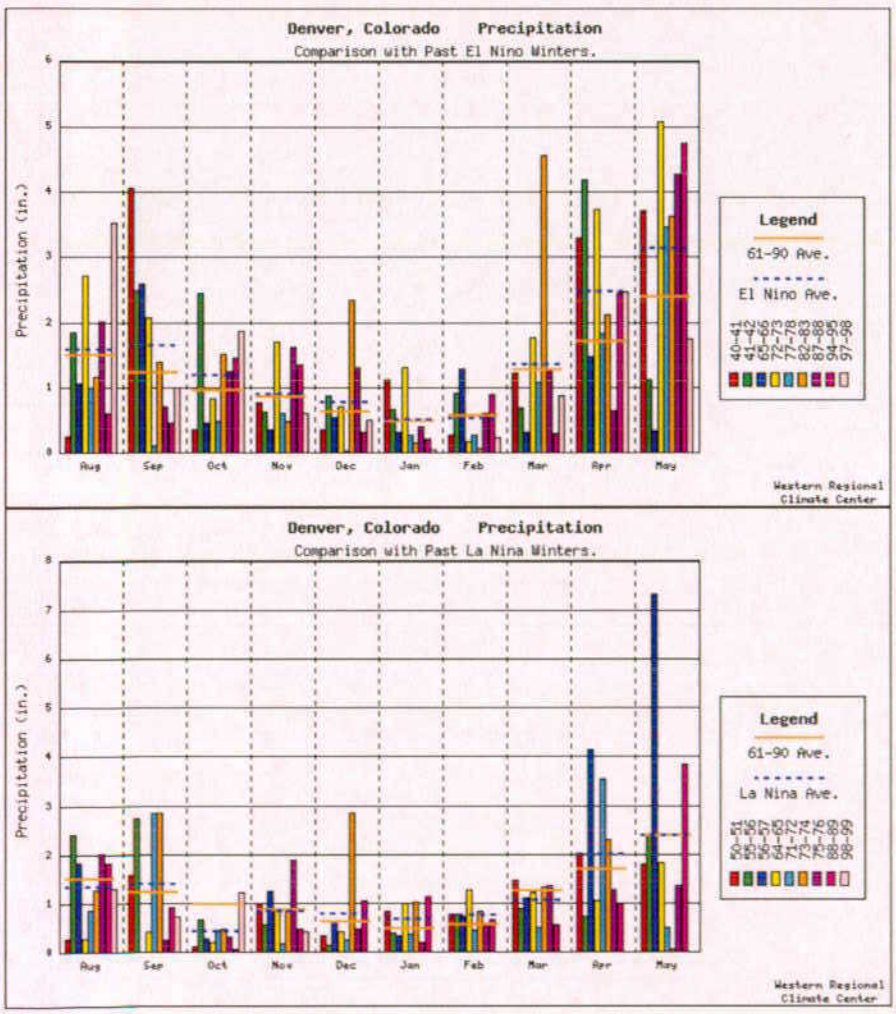


Figure 17 **El Nino and La Nina impacts on monthly Denver precipitation**

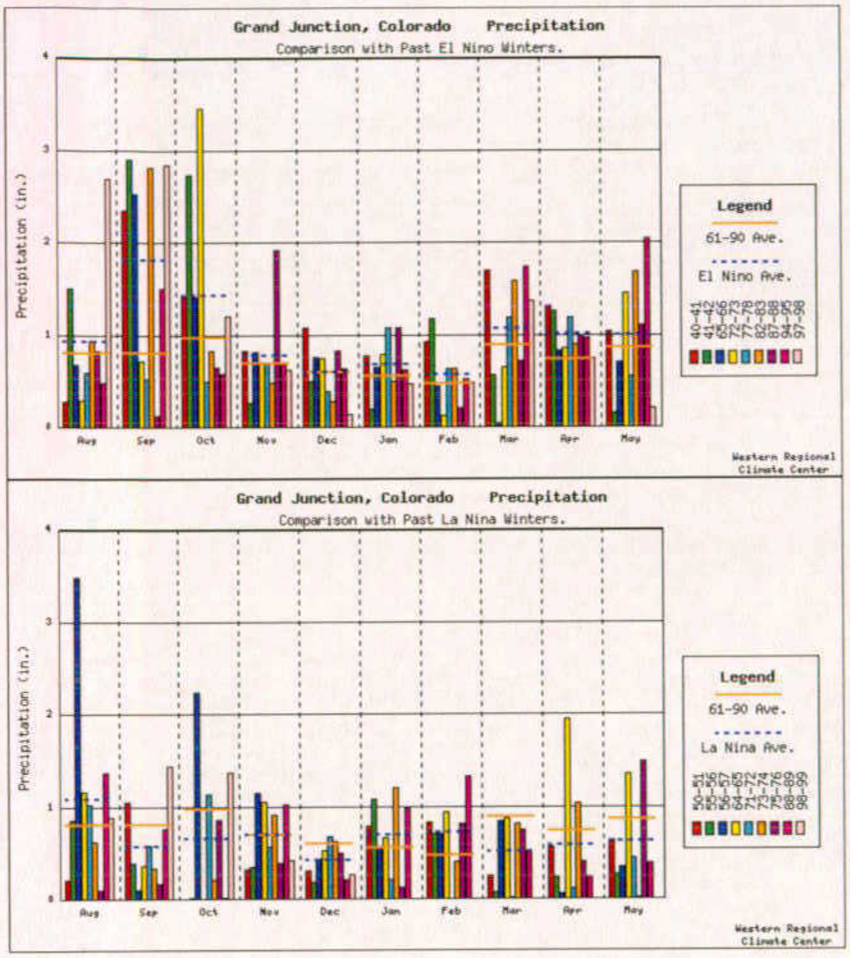


Figure 18 El Nino and La Nina impacts on monthly Grand Junction precipitation

Mother Nature's
Good Guys and Bad Guys

El Ninos tend to create wet years statewide.

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

Note that in Grand Junction and Denver, El Nino years tend to produce more precipitation than in La Nina years. In Grand Junction the impact is more noticeable as a reduction of late summer and fall precipitation during La Nina years with lesser winter and spring impacts noticeable. In Denver both winter and summer precipitation is higher during El Nino periods. The heaviest El Nino precipitation in Denver is evident from late February into early June. The recent Saint Patrick's Day snowstorm of March 17-20 is an excellent example of an El Nino-assisted major precipitation event. From these four figures is quite evident that the El Nino and La Nina patterns influence seasonal precipitation patterns differently east and west of the Continental Divide. These differences are also notable in the state's river basins.

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 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 are provided for each of the seven major Colorado river basins (Figure 19). 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.

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.*

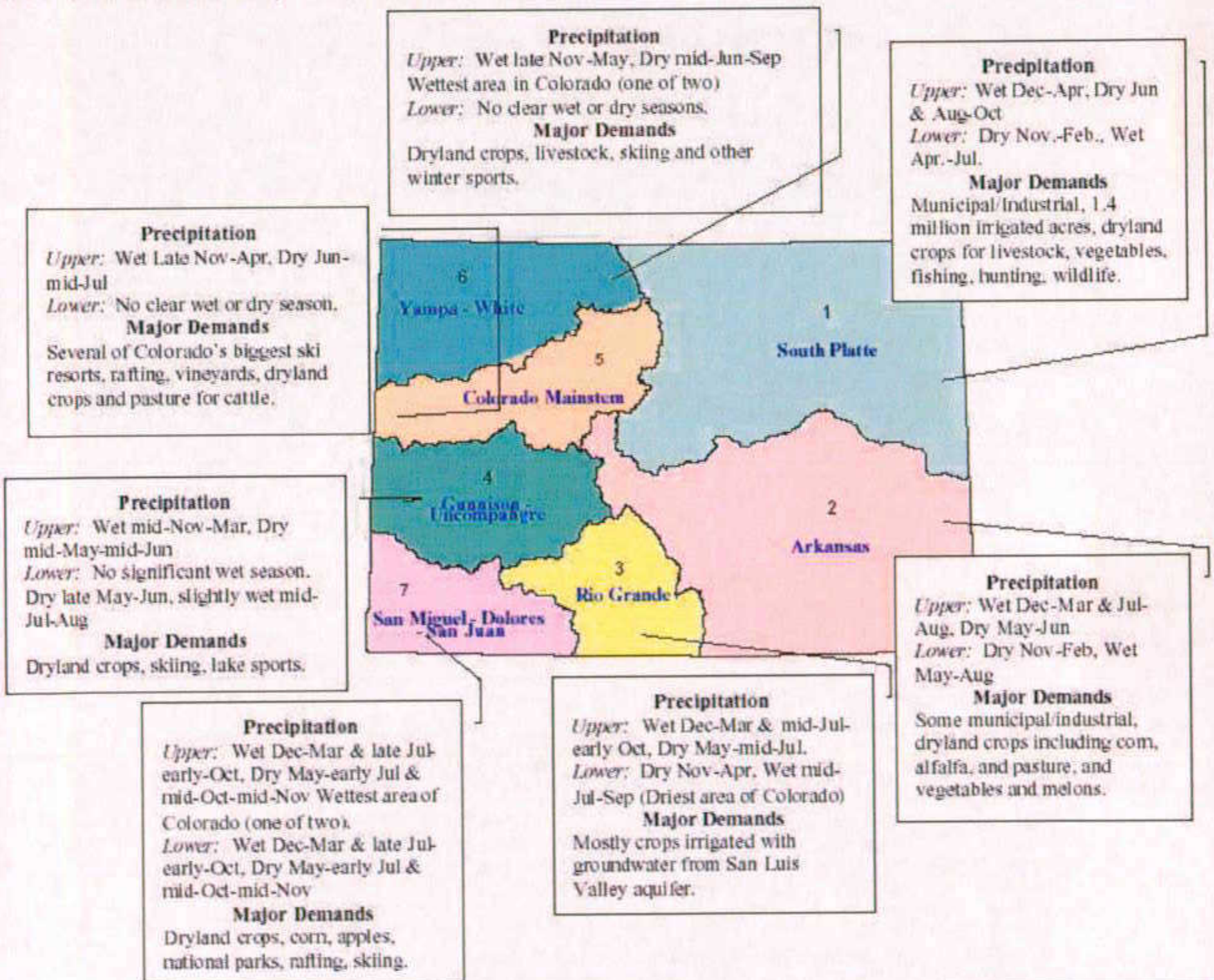


Figure 19 Major water demands in the seven Colorado water divisions (McKee *et al.* 2000)

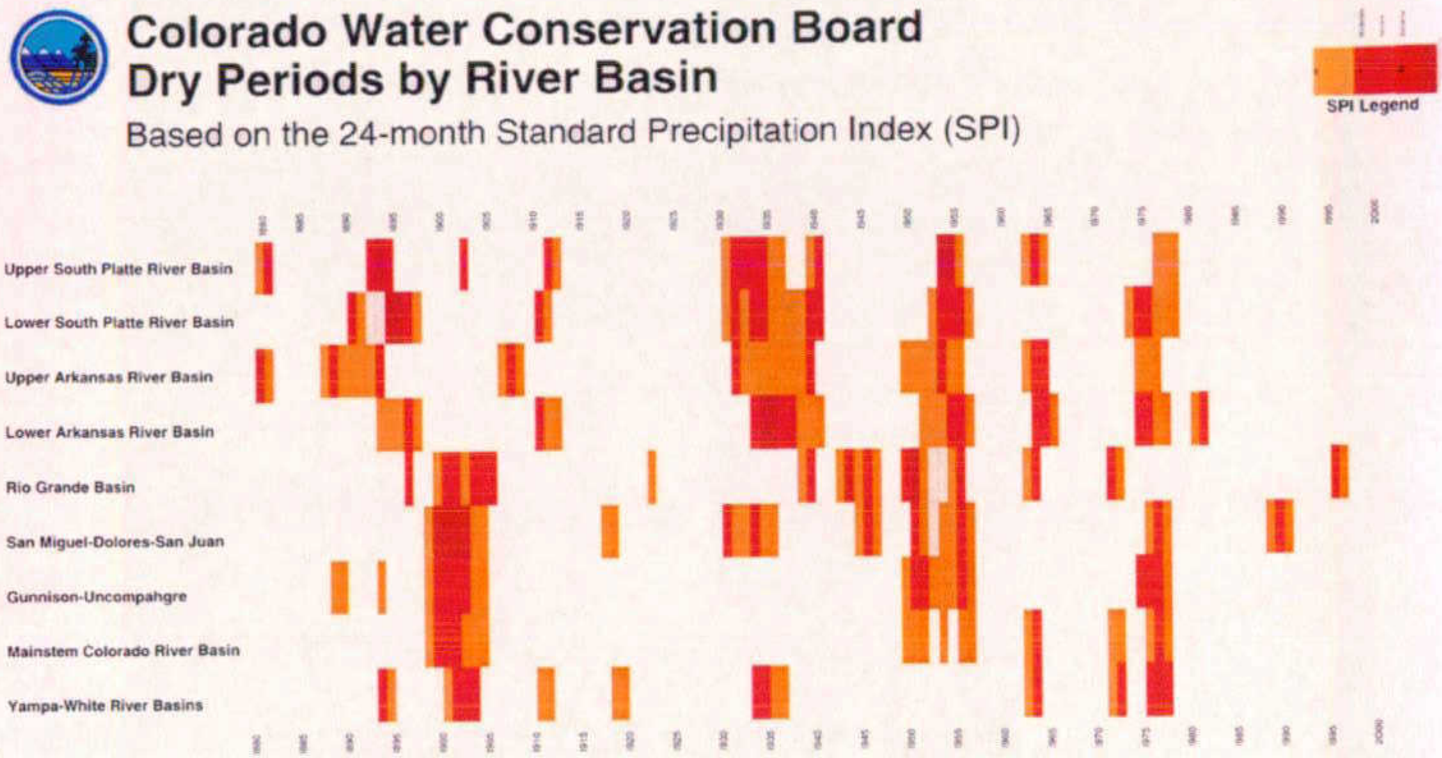


Figure 20 - Plot of drought severity by year for major Colorado River Basins based on 24-month Standard Precipitation Index (created by CWCB, Stanton and Busto, 1997).

Figure 20 was prepared by the Colorado Water Conservation 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 1890s, the 1930s, the 1950s and the 1970s, 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.

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 7-year cycle exists in local or regional drought occurrence. An extensive review by the Colorado Climate Center on drought's cyclicity was inconclusive. So can you believe what you want? An example of how new information can be developed through "database mining" can be seen in Table 6. Table 6 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 Western Regional Climate Center database. Let's look at two fresh approaches to viewing the information.

Table 6: 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		Basin		100 year
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		-12

Table 6 shows some interesting basin-specific information but let's concentrate for the moment on the big picture. The droughts of the 1930's, 1950's and the 1970's show up significant decades of below average precipitation in Colorado's major river basins. Wet periods also show up clearly. Note the drought of the 1950's was not "as sync" from basin to basin as during the other droughts. Of equal importance is the plotting of the decadal changes from basin to basin as shown in Figure 7.

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.

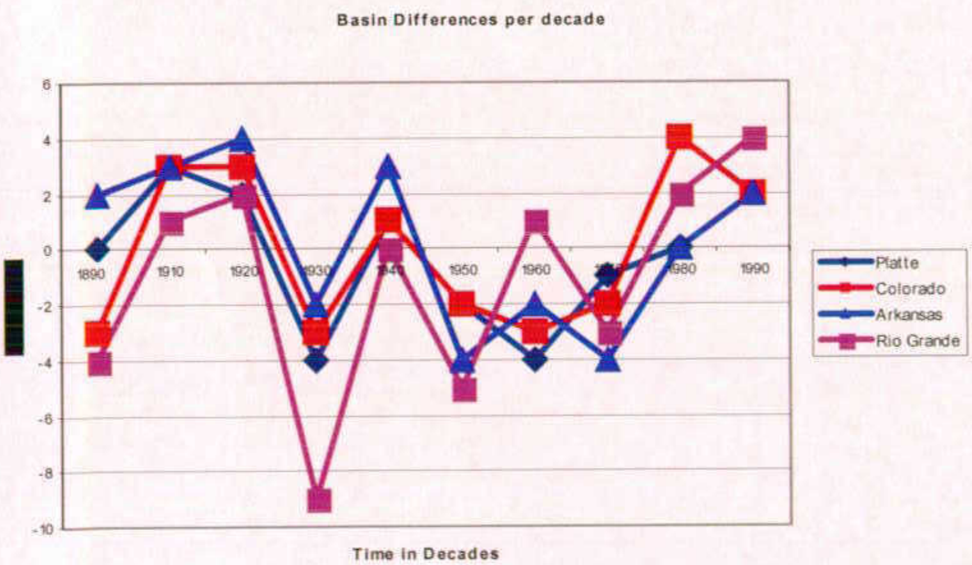


Figure 21 - Comparison of the difference between the numbers of annual basin precipitation years. 2" above and 2" below average summed by decade and by basin.

Figure 21 was prepared by plotting the sum of the basin decadal differences in the number of 2-inch above and below annual precipitation events by decade for the Platte, Colorado, Arkansas, and Rio Grande basins. This analysis portrays the number of "extreme" events and their decadal changes.

The precipitation rich decades of the 1910s and 1920s and the recent wet 1980s and 1990s are easy to pick out. Conversely, the drought or dry periods of the "turn of the century," 1930s, and 1950's to 1970s can be looked at from a relative stance. Note that the two wet periods of the past millennium appear to provide less durational impact than the entire extended dry period of the 1930s through the 1970s.

The extended period of the dry 50s, 60s and 70s offers an amazing difference in duration and intensity compared to the "spike" of the Dust Bowl 1930s. Why? Are there differences from basin to basin or do the basins operate more in tandem then separation? Why? Perhaps, the answer is in the meteorological causes of the dry and wet periods.

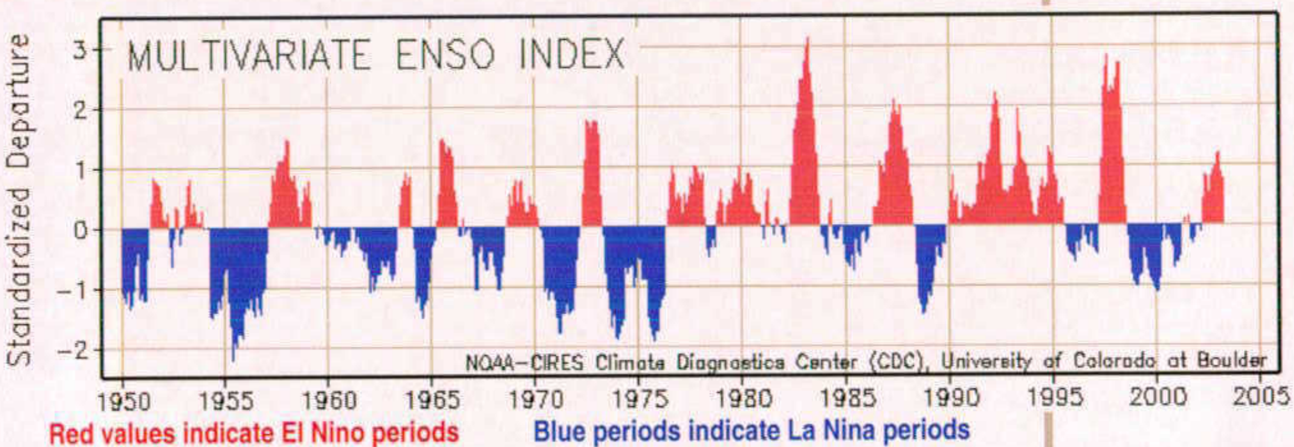


Figure 22 **Annual variation of the MEI from 1950-2003 (Wolter and Timn, 1998)**

El Niño/Southern Oscillation (ENSO) is the most important coupled ocean-atmosphere phenomenon to cause global climate variability on interannual time scales. Wolter and Timn (1998) monitor ENSO by basing the Multivariate ENSO Index (MEI) on the six main observed variables over the tropical Pacific. These six variables are: sea-level pressure (P), zonal (U) and meridional (V) components of the surface wind, sea surface temperature (S), surface air temperature (A), and total cloudiness fraction of the sky (C).

Figure 22 shows the variation of this MEI index from 1950 to 2003. Note that the red values above 0.5 indicate El Nino periods while the blue values of –0.5 or less indicate La Nina periods. Note the regular cycles of the El Nino and La Nina.

A clear way to merge the two data bases in Figures 21 and 22 can be seen in Table 7. Note that the El Nino, or red periods, coincides with periods of above normal precipitation in the Colorado river basins. On the other hand, the La Nina, or blue spikes, coincides with the dry periods or decades in the Colorado River basins. This apparent relationship is reflective of an apparent cause-effect relationship. Additional work will be required to answer the questions posed by this relationship but it may hold a promising means of anticipating above or below water yields in river basins before the start of the Water Year.

Table 7 Comparison of the Number of Annual Basin Precipitation +/- 2" of Average/Decade Compared to decadal El Nino and La Nina Avg. MEI

Basin	1950's		1960's		1970's		1980's		1990's		2000's*		
Above / Below	A	B	A	B	A	B	A	B	A	B	A	B	
Platte	0	2	1	5	0	1	0	0	3	1	1	2	
Colorado	2	4	0	3	0	2	5	1	3	1	2	2	
Arkansas	1	5	2	4	0	4	0	0	2	0	0	2	
Rio Grande	0	5	1	0	1	4	2	0	6	2	1	2	
Total	3	16	4	12	1	11	7	1	14	4	4	8	
Difference	-13		-8		-10		6		10		-4		
MEI Decadal Avg.	-1.3		-0.8		-1.1		+1.4		+ 1.3		?		

* Note that the WY 2002-2003 values are estimated

Impacts of Drought: what might the future hold?

Economic implications

While the implications of drought in Colorado are numerous and have the potential to affect nearly every aspect of life in the state in some manner, the most quantifiable and well-defined consequences are economic in nature. A memorandum, dated April 30, 2002, was sent from the Office of State Planning and Budgeting to Governor Owens (Hart 2002). The purpose of the memo was to "…provide an economic impact estimate for the current drought in Colorado as per the State Drought Mitigation and Response Plan."

At the time, the authors were "…not able to provide a thorough examination of the impacts of the drought on Colorado's economy because there is little statistical data available at [that] point to analyze the impacts. Hence this memorandum provides an overview of the possible impacts." Despite the fact that this memo was clearly written before the effects of the 2002 drought were fully realized, the points summarized within the document, and reproduced below, do provide useful insight into the implications of drought in Colorado.

The list in Table 8 reflects the state's primary economic concerns regarding drought in the spring of 2002. There are, however, other economic sectors and other water uses that are impacted as well.

Table 8 Economic impacts of drought on Colorado tourism and agriculture from the April 30, 2002 Office of State Planning and Budgeting Memorandum

Economic impacts of drought on Colorado tourism
Tourism and agriculture are the two primary sectors in Colorado's economy that will be negatively impacted by the drought
Tourism spending injects approximately $8.5 billion into Colorado's economy and comprises eight percent of the state's work force.
The 1977 drought caused a 40 percent decline in ski lift ticket sales and a 15 percent decline in employment at the ski areas.
State and local government receive approximately $550 million in tax revenue from tourism, a portion of which is at risk from a decline in tourism from the drought.
Economic impacts of drought on Colorado agriculture
Agriculture employs 3.9 percent of the state's work force and comprises 3.5 percent of wages
In the 1977 drought the inventory of livestock actually increased in Colorado while farm income from crops only declined 2.8 percent.

To provide a more general overview of the ways in which drought may impact Colorado, we turn to McKee *et al*. (2000), who elaborate on some of the state's major water demands. First and foremost among water users is irrigated agriculture. Although recent years have seen the arrival of new types of crops, more drought-resistant crops, and advanced irrigation techniques, farmers still face many negative consequences of drought. "Dryland" crops such as winter wheat are particularly susceptible to damage as a result of short droughts during the growing season. Other water demands subject to the possible wrath of drought include:

(1) municipal and industrial water supplies (note that approximately 50% of municipal water is used for watering lawns and landscape during the summer);
(2) recreation, in both the summer (white-water rafting, fishing, boating) and winter (skiing) seasons;
(3) forests and environmental uses; and
(4) (4) hydropower.

Ecological implications

Ecological implications of drought in Colorado are exacerbated by human activity in the region. Woodhouse *et al*. (2002) suggest that the mid-19th century drought (discussed later), which is believed to have been a factor in the decimation of bison populations, "would have had a very limited effect on the bison population if human activities had not been a factor." Even today, the fateful combination of humans and drought continues to threaten the state's natural resources.

The state of Colorado rations its limited water supply through a complex system of appropriative water rights. Human uses, including agricultural, municipal, hydropower, and recreational uses, withdraw every possible drop of water available to them.

As a consequence of the governing water laws and the extensive development of land and water promoted therein, "some rivers have been drawn critically low and some have even dried up completely with little regard for the fish, wildlife, and people who rely upon healthy rivers" (Trout Unlimited 2002).

Such overuse of riverine resources occurs on a regular basis during years with normal precipitation. The adverse effects of drought could create a dire situation for the state's aquatic ecosystems, which may suffer irreversible harm should prolonged drought strike Colorado in the future. Valuable assets at risk include the following:

- Fisheries
- Wildlife
- Biodiversity
- Water quality and temperature
- Aesthetics

A stark example of the ecological threat posed by drought is the increased risk of wildfires. According to information available from the National Climate Data Center (NCDC 2003), the drought of 2002 left the state extremely vulnerable to wildfires, with a total of 915,000 acres being burned statewide.

Sociological implications

From a sociological perspective, "substantial differences in both water resource conditions and the social/economic/political context of potentially impacted areas imply a potentially broad range of variability in the type and extent of impacts that might ensue from a severe sustained drought" (Krannich *et al*. 1995).

In order to assess water scarcity impacts, therefore, attention must be focused on specific water user communities. Water user communities vary significantly within the major river basins. As our Colorado society grows population shifts and increases are very likely. A subsequent chapter will cover this topic further.

What might the future hold?

Drought will be a continuing "un-welcome guest" to 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 9, favors several periods of state-wide drought. 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 9 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 would occur over the next 100 years it would cause major impacts on modern Colorado residents and their way of life. The Drought of 1999-2003 has shown that major impacts on our quality of life and water supplies can be inflicted by short-term drought. **We need to plan for "the inevitable major droughts of the future".**

The remainder of this compendium will present strategies and plans for dealing with the inevitable droughts of the future. As Colorado's population and economic bases grow in the next century careful stewardship of our water supplies will be mandatory.

"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

. Works Cited

Alley, W.M., 1984. The Palmer Drought Severity Index: limitations and assumptions. *Journal of Climate and Applied Meteorology*, 23: 1100-1109.

American Meteorological Society. 2000. *Glossary of Meteorology, 2nd edition.*

Associated Press. 2002, September 23. Tree rings suggest driest year since 1725. Article published in Boulder Daily Camera. Accessed from www.hydrosphere.com on June 27, 2003.

Hart, J. 2002. Economic Impact Task Force Report on the Impact of Drought. Memorandum from State of Colorado, Office of State Planning and Budgeting to Governor Owens.

Henz, J.F. and W.J. Badini 2002: Creative Interpretations of Colorado Drought Risk. Proceedings of the Colorado Drought Conference, December 2002 (in press).

Howe, C.W., L. Bennett, C.M. Brendecke, J.E. Flack, R.M. Hamm, R. Mann, L. Rozaklis, and K. Wunderlich. 1994. The value of water supply reliability in urban water systems. *J.Environ. Econ. Manage.*, 26, 19-30.

Hydrosphere Resource Consultants. 2002. Hydrosphere Featured Project: City of Boulder Tree-Ring Study. Accessed from www.hydrosphere.com on June 27, 2003.

Karl, T.R., and R.W. Knight. 1985. Atlas of Monthly Palmer Hydrological Drought Indices (1931-1983) for the Contiguous United States. Historical Climatology Series 3-7, National Climatic Data Center, Asheville, NC.

Krannich, R.S., S.P. Keenana, M.S. Walker, and D.L. Hardesty. 1995. Social Implications of Severe Sustained Drought: Case Studies in California and Colorado. *Water Resources Bulletin*, 31(5): 851-865.

McKee, T.B., N.J. Doesken, and J. Kleist. 1993. The relationship of drought frequency and duration to time scales. Preprints, *Eighth Conference on Applied Climatology*, Anaheim, CA, Amer. Meteor. Soc., pp. 179-184.

McKee, T.B., N.J. Doesken, and J. Kleist. 1995. Drought monitoring with multiple time scales. Preprints, 9th Conference on Applied Climatology, 15-20 January, Dallas, TX, pp. 233-236.

McKee, T.B., N.J. Doesken, and J. Kleist. 1999. Historical dry and wet periods in Colorado (Part A: Technical Report). Colorado Climate Center: Climatology Report No. 99-1 A.

McKee, T.B., N.J. Doesken, J. Kleist, C.J. Shrier, and W.P. Stanton. 2000. A history of drought in Colorado: lessons learned and what lies ahead. *Water in the Balance*, No.9, 2nd edition.

National Climate Data Center (NCDC). 2003. Website: http://www.ncdc.noaa.gov/. Accessed June 25, 2003.

National Drought Mitigation Center (NDMC). 2003. Website: http://www.drought.unl.edu. Accessed June 24-27, 2003.

Palmer, W.C. 1965. *Meteorological Drought Research Paper 45*, U.S. Weather Bureau, Washington, D.C.

Trout Unlimited. 2002. *A Dry Legacy: The Challenge for Colorado's Rivers*. Colorado Water Project.

Western Regional Climate Center website via the Oregon Climate Service 2003.

Wolter, K., and M.S. Timlin, 1998: Measuring the strength of ENSO - how does 1997/98 rank? *Weather*, **53**, 315-324

Woodhouse, C.A. 2001. Tree-ring reconstruction of mean annual streamflow for Middle Boulder Creek, Colorado, USA. *J. Amer. Water Res. Assoc.*, 37: 561-570.

Woodhouse, C.A. 2003. Using tree rings to reconstruct records of past drought in Colorado. Presentation at Colorado Water Law Drought Protection Strategies seminar, March 27-28, 2003, Denver, Colorado.

Woodhouse, C.A., and P.M. Brown. 2001. Tree-ring evidence for Great Plains drought. *Tree-Ring Res.*, 59: 89-103.

Woodhouse, C.A., and J.T. Overpeck. 1998. 2000 years of drought variability in the central United States. *Bulletin of the American Meteorological Society*, 79(12): 2693-2714.

Woodhouse, C.A., J.J. Lukas, and P.M. Brown. 2002. Drought in the western Great Plains, 1845-56. *Bulletin of the American Meteorological Society*, 83(10): 1485-1493.