Colorado Climate

Fall 2002 Vol. 3, No. 4

Colorado State University

Knowledge to Go Places

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Cover Photo: Pumpkin Patch in October, Photo by © Ronald L. Holle, used with permission.

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Table of Contents

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Central Colorado's Severe Downslope Windstorms

by John F. Weaver, NOAA Research Meteorologist

Those of us who've lived along the Colorado Front Range for any length of time are aware that the late fall through early spring often brings periods of extremely strong, westerly winds. These winds pummel communities along the eastern foothills of the Rocky Mountains with hurricane force – blowing vehicles off roadways, uprooting trees, damaging structures, and pelting unsuspecting residents with a large assortment of flying objects that are collectively known as debris (Figure 1). The events are called severe downslope windstorms, and they can actually strike the downwind side of mountain ranges anywhere on earth. What causes these winds, and how we predict them in Colorado, is the focus of this article.

In the most general sense, winds are driven by pressure gradients – that is, by air attempting to move from regions with higher pressure to those with lower. Thus, if there were a low pressure center over the Nebraska panhandle, and a region of higher pressure near the Four Corners region in southwest Colorado, air would attempt to move northeast to try to fill the low. The speed that the air moves depends on the pressure difference – the greater the difference, the faster the wind.

Unfortunately, nothing in the atmosphere is quite that simple. There are other factors that alter the speed and direction of the air as it tries to equalize pressure differences. The first of these comes about because the earth is constantly turning on its axis. Thus, as the air moves northeastward toward Nebraska, the earth moves out from beneath it, resulting in a ground relative, eastward "turn" to the flow. This ground-relative drift is formally known as the Coriolis effect. In a frictionless environment, the Coriolis effect is generally sufficient to cause the winds to turn just enough that the air simply circles around low pressure in a counter-clockwise fashion in the Northern Hemisphere (and around high pressure centers in the opposite direction).

But there is another complication due to the fact that the earth's surface is rough. This roughness causes the wind speeds within a few thousand feet of the ground to be reduced by frictional turbulence which, in turn, disturbs the otherwise well-balanced pressure/Coriolis circulation. The effect of friction causes the winds to turn a little, toward the low pressure, and the amount of turning depends on the amount of turbulence. It sounds complex, but the combined effect of all of these various factors ends up causing the winds near the earth's surface to generally *spiral* inward toward areas of low pressure, and spiral away from surface highs. So, in our Nebraska panhandle example, the wind would probably end up blowing from the due west, or even the northwest as it moves across the Front Range.

Figure 1. Tree damage during a severe downslope windstorm that occurred on 3 July 1993 in Fort Collins, Colo., with the arrival of an unusually strong, summertime cold front.

The development of the pressure pattern described here – a pattern that can bring strong airflow near the earth's surface – is a necessary ingredient in developing severe downslope winds. Without that fundamental force, severe winds would not occur. But another important ingredient concerns the winds aloft. In order for a respectable surface windstorm to develop, the winds between about 5,000 to 10,000 feet above ground level must also be strong, and they must be blowing in the general direction of the surface winds. This condition occurs most frequently in the winter or early spring, when the jet stream makes its way across Colorado. The strongest winds in the jet stream are generally found at upper levels of the atmosphere – around thirty-thousand feet, or so – but there is a three dimensional structure to the jet that frequently extends a portion of these stronger winds down to mountain top level. The strong, jet-related, westerly flow at mountain top levels are what typically bring strong winds and blowing snow to the mountains. But for those living along the Front Range, it is the phasing of these jet-related winds with the surface flow that represents the second part of the story for developing severe downslope windstorms.

With everything else in place, there are still local-scale, modifying features to consider. Though larger scale atmospheric patterns generally force the air to begin moving in the first place, the specific nature of an individual wind event depends strongly on the topography of the locale where the winds are taking place. If the local terrain along the eastern slope of the foothills is very steep (in cities like Boulder, Colorado Springs, or Westcliffe, to name a few), and if the air mass is relatively stable, then so-called vertically propagating mountain waves can develop (see Figure 2). These massive waves may have horizontal dimensions on the order of several miles, and can extend upward as far as the lower stratosphere. Think of flood waters splashing up against an obstacle, such as a wall or a dam. The water hits the wall, and – if the flow speed is just right – the water will build up a standing "wave" just above the obstacle. The fluid that courses through this standing wave comes crashing down heavily on the other side. If you were in Boulder, then the Flatirons would be the concrete wall, and you would be at the spot where the fluid comes crashing down. In addition to forcing intense winds at the ground, these stationary waves can also present a significant hazard to aviation by producing severe, or even extreme, clear air turbulence. Sometimes, if there is sufficient moisture in the air, we can actually see the "backwash" from such waves in the form of rotor clouds that form just east of the region where the strongest winds are taking place.

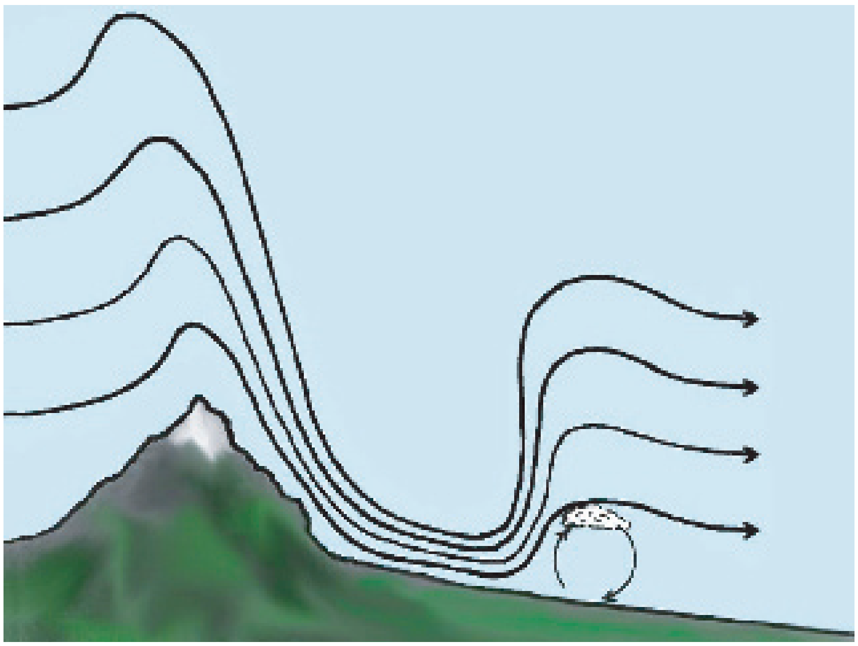


Figure 2. Diagram illustrating some idealized streamlines associated with a vertically propagating wave-type of downslope windstorm that occurs downwind from stark terrain barriers.

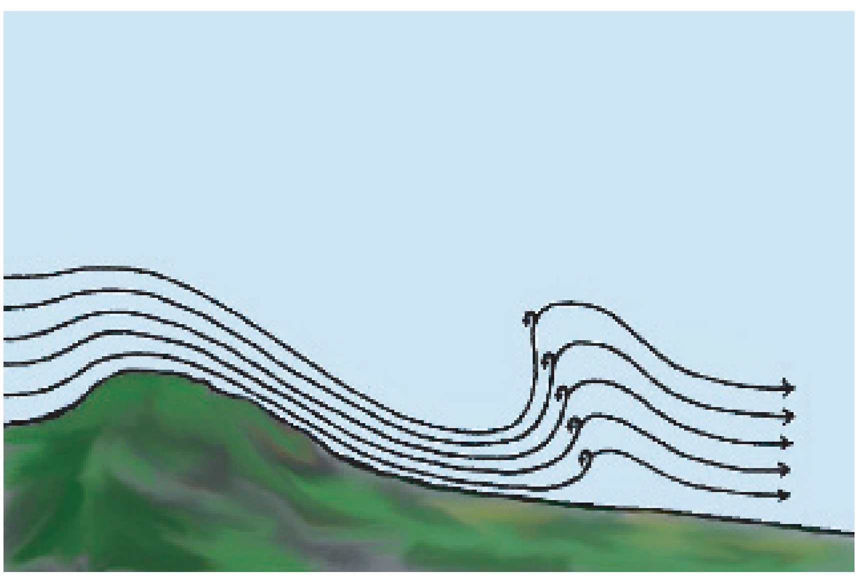


Figure 3. Diagram showing some idealized streamlines associated with a modified hydraulic jump, Bora-driven downslope windstorm that occurs downwind from areas of moderate-profile terrain.

In spots along the Front Range where the terrain to the west is less steep (in cities like Fort Collins or Longmont, for example), severe downslope windstorms can also develop (Figure 3). Such events are most likely to occur if the westerly flow is accompanied by cold air advection – that is, if a cold front tries to move in from the mountains along with the winds. This type of event is known as a "Bora." With shallower terrain, there is no steep "barrier," and vertically-propagating waves cannot set up as easily. Also, the eastward moving air tends to warm by compressional heating (remember the Ideal Gas Law) as it moves down the eastern slopes. This warming causes turbulent vertical motions within the flow, because warm air tends to try to rise. The result is a dampening of the wind speed. The cold air that accompanies a Bora event can offset the compressional heating, allowing the approaching stream of fast moving air to remain shallower – more contained. In fact, since cold air is heavier than warmer air, gravity can often play a role in accelerating the air on its way out of the mountains. Often these severe wind events lead to a so-called "hydraulic jump" just east of the Front Range. The eastward rushing air, out on the flatter terrain to the east of the mountains no longer has as much gravitational acceleration, so it will move slower. At some point (usually out near I-25 in Fort Collins), the current of air will suddenly transition from a shallow, fast moving stream, to a deeper and much slower moving one. The change in wind speed can be dramatic when you cross between the two. Notice that the vertically propagating mountain waves described in the previous paragraph also develop a hydraulic jump out to the east. In the case of Boulder's windstorms, this jump is often found over the western suburbs of Denver. The dramatic backwash, beneath the rotor cloud shown in figure 2, can sometimes result in severe dust devils that form at spots where intense shears between east and west winds develop. A series of very dramatic spin-ups occurred on January 17, 1982. They produced tornado-like damage at the Jefferson County airport – damage which included the upending of several planes that had been tied down with steel cable.

Forecasters have many tools available to identify situations in which severe downslope wind conditions are setting up. But a lot of this information comes from computer models which – though noticeably better in recent years – can easily make an error of twenty or thirty degrees in their predictions of wind direction at both the surface, and aloft. Such small changes in direction can affect the intensity of the surface event, its specific location, and the type of storm that is going to occur. Plus, there are other local-scale complications that can alter the forecast. For example, if a very cold air mass were to be situated over an area where severe winds are trying to develop, it may take a while for the flow to "break through" the colder, more dense dome of air, and reach the surface. Sometimes the air can be so cold and so deep that the predicted wind event never comes to pass. Nevertheless, forecasting success for severe downslope windstorms has been improving routinely as newer and more complex computer products come on line. Highway officials and emergency responders concerned with high profile vehicles on the Colorado roadways, building contractors who find themselves at wind-sensitive stages in their construction, light and power companies worried about power poles blowing over or trees falling onto wires, can all plan for, or plan around, these uniquely localized windstorms with an increasing degree of confidence.

About the author: John Weaver is a NOAA research meteorologist working at the Cooperative Institute for Research in the Atmosphere (CIRA) at Colorado State University. He specializes in severe weather research and satellite meteorology.

Colorado Climate in Review

by Nolan Doesken

July 2002

Climate in Perspective

July was a month of heat, drought, smoke and fire. Wildfires that had ignited in June continued to burn into early July. New fires were ignited over western Colorado, many caused by lightning. Overall, thousands and thousands of acres burned as Colorado suffered through the worst drought period in recent memory. Crop conditions also continued to deteriorate as a combination of heat, low humidity, lack of precipitation and inadequate irrigation water plagued Colorado farmers. Water levels on rivers, streams and reservoirs usually drop quickly during July, but this year there was little to start with, and many rivers were at record low levels. July was not bone dry, however. Several stormy periods brought heavy rains to some areas. Higher humidity along the Front Range helped slow the spread of the huge Hayman fire southwest of Denver, and it was eventually controlled. Tropical moisture associated with the North American Monsoon did fuel numerous afternoon showers over the mountains and temporarily quieted the wildfire outbreak later in July. However, local flash floods occurred over several of the recently burned areas.

Precipitation

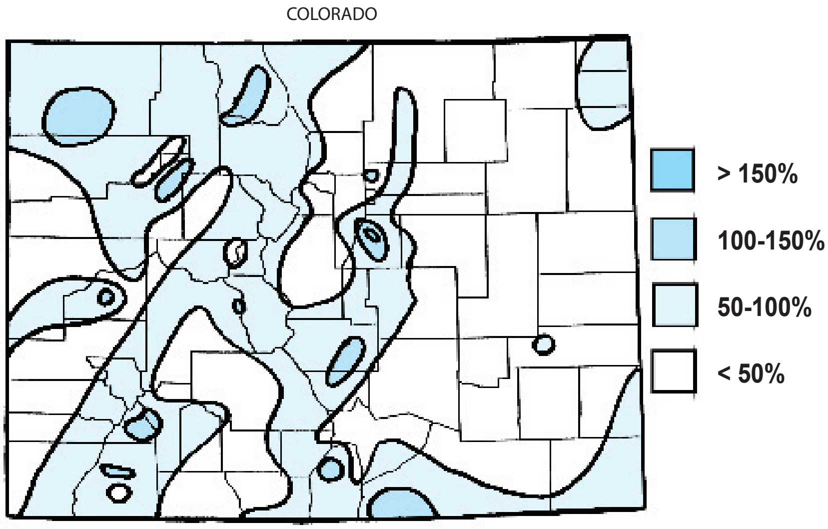
July was another dry month for most of Colorado. Precipitation was scant and widely scattered across the eastern plains and Front Range. Most areas east of the mountains ended up with less than half the July average. A few areas missed out on nearly all the storms. For example, Fort Collins only received 0.07" for the month and Boulder was right behind with only 0.09". Idalia, north of Burlington, reported only a trace of precipitation all month. Akron totaled just 0.10", 4% of average. Rocky Ford received only 0.06" of moisture while temperatures soared to 100 degrees or higher on 13 days. Western Colorado fared a bit better, although some areas received less than half of average. Afternoon thundershowers were generally light but fairly numerous over the mountains, and most of the mountains got 50 to 80% of their long-term average. There were several heavy storms, however, that helped lift localized areas above average for the month. Two storms late in July dropped heavy rains near Trinidad. Trinidad Lake ended up with 4.08" or rain for the month, 154% of average. Heavy rains also fell near the Hayman fire in Douglas County. The Sedalia weather station totaled 3.96" in July.

Temperature

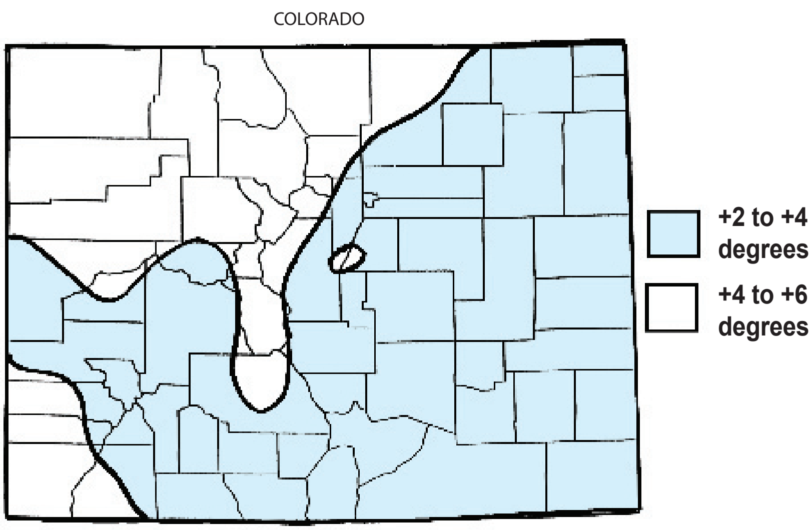
Hot weather was again the rule over Colorado in July. Temperatures climbed into the 90s and low 100s most days at lower elevations, while 80s were common in the mountain valleys. Crested Butte, known for pleasant summer temperatures, saw the mercury climb into the 80s on 17 days during July. For the month as a whole, July temperatures were one to three degrees Fahrenheit warmer than historic averages while across north central, northwest and extreme southwestern Colorado, temperatures were four to as much as six degrees above average.

July Daily Highlights

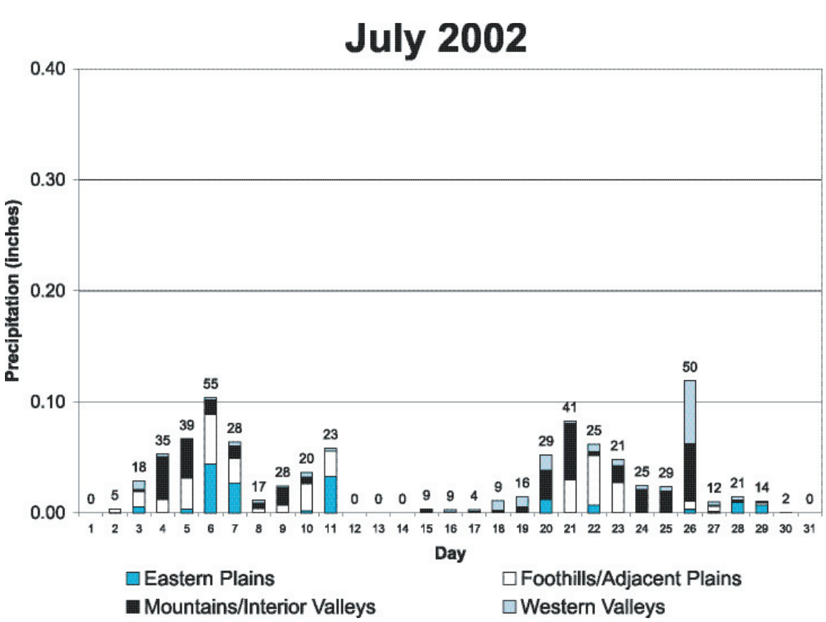
1-3 Forest fires burned, smoke filled the skies, and temperatures set new records. Larkspur in Douglas County, not far from the huge Hayman fire, hit 101°F on July 1, the hottest temperature ever recorded there. The downtown Denver cooperative weather station at the Denver Water Department hit 105°F. Temperatures remained very hot 2-3rd , but humidity increased and some isolated severe thunderstorms with high winds and hail developed. Parts of Weld County were pelted by storms on the 3rd with hail and heavy



July 2002 precipitation as a percent of the 1961-1990 average.



July 2002 temperature departure from the 1961-1990 average.



rains near Keensburg and east of Greeley. Some spotty rains fell in the mountains as well.

4-6 A little cooler and more humid statewide, but still hotter than average for this time of year. Wildfire spread slowed a bit as moister air moved in. Some lively thunderstorms developed each day but only affected small areas. On the 4th, heavy rains hit areas of southern Colorado near Canon City and Rye. Heavy rains fell on the 5th in portions of the Denver metro area and in Weld County. Castle Rock reported 1.57" while more than 2" of rain fell north and east of Greeley. Several inches of rain were reported to have caused flooding in southern Prowers and northern Baca counties in southeastern Colorado. As much as 3" of rain fell in eastern Phillips county on the 6th, and flash flooding was also reported near Walsenburg.

7-17 Persistent hot, dry weather with little or no precipitation across western Colorado. The official Grand Junction weather station reached 100 degrees or higher for 10 days in a row including back to back 105°F highs on the 13th and 14th. The nearby Fruita weather station reported 111°F on the afternoon of the 13th. Temperatures east of the mountains were not quite as hot. An upper level disturbance and some low-level moisture combined to produce a round of localized but extreme storms on the 10th. Hail was reported over several counties from Denver and Colorado Springs eastward. A storm near Parker deposited hail stones up to 2½" in diameter and more than 2.5" of rain. Haswell in Kiowa County received 1.95" and small hail from a brief but intense late evening storm. The remainder of the period was dry statewide until scattered afternoon showers began developing over western Colorado later in the period.

18-26 Modest amounts of subtropical moisture associated with the North American Monsoon circulation reached northward into western Colorado and fueled a period of almost daily showers and thunderstorms. Some storms rumbled across the Front Range but most dissipated before heading across the parched Eastern Plains. Rainfall was not exceptionally heavy with few daily totals exceeding 1.00", but it was sufficient to subdue many of the wildfires. Some of the greater rainfall reports during the period included 1.20" at Spicer, southwest of Walden on the 20th, 1.90" at Trinidad Lake measured on the morning of the

Statewide average daily precipitation graph(s) (left and throughout this article) shows relative amounts of precipitation for each region. Label on each column indicates percent of stations with measurable precipitation for each day.

22nd, and 0.94" at Lemon Dam measured on the 24th. Rainfall was particularly widespread across western Colorado on the 25th ending on the 26th with many stations reporting 0.50" or more of much-appreciated rainfall. In addition, some very localized flash floods were reported during this period including a damaging flood near Rifle on the 18th and a late day flashflood in Cottonwood Creek southwest of Buena Vista. It seemed that it took less rain this summer to produce flooding, possible due to the sparse and very dry vegetation and hard soils.

27-31 July ended with a return to dry weather over most of the state with hot days and warm nights. Many locations experienced high temperatures above 100 degrees such as the 107°F reading at Yuma, on the 30th and south of Sedgwick on the 31st. A few thundershowers developed 27-28th, but precipitation totals were light. By the 31st, the severity of drought again seemed extreme, and crops – what were left of them – were stressed and withering.

July 2002 Monthly Extremes

Description	Station	Extreme	Date
Precipitation (day)	Haswell	1.95"	Jul 11
Precipitation (total)	Trinidad Lake	4.08"	
High Temperature	Fruita	111°F	Jul 14
Low Temperature	Fraser	30°F	Jul 29

August 2002

Climate in Perspective

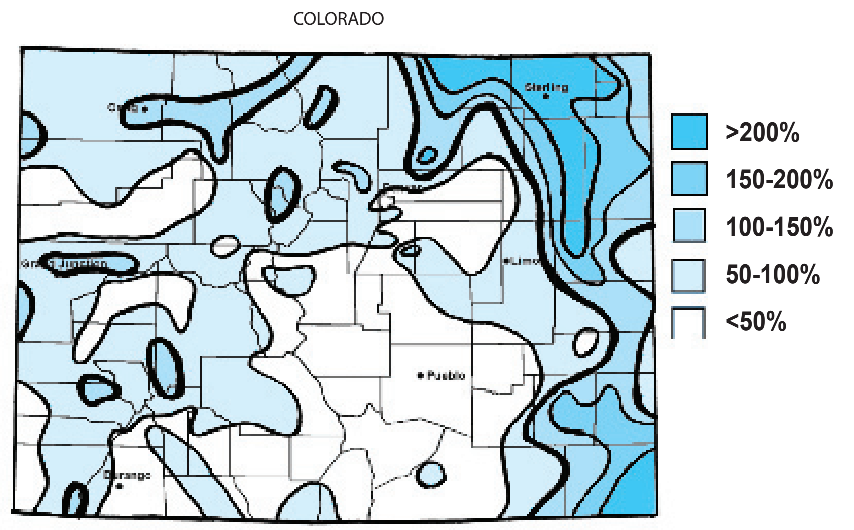
Huge forest fires continued to burn in portions of the Colorado mountains as drought conditions continued. Crop and rangeland conditions were also in tough shape, and many communities enforced water use restrictions as the entire state suffered along with portions of several other western states. Low streamflows and warm water temperatures also presented survival challenges for fish populations on some rivers. Tabulations of precipitation for September 2001 – August 2002 showed this to be the driest consecutive 12-month period for many of Colorado's long-term weather stations. But on the bright side, temperatures were closer to average than they had been in several months. Episodes of severe thunderstorms that behaved more like early summer than late August began to bring drought relief to a few areas. For example, three severe hail storms in one evening pelted the Akron area late on the 24th. Crop damage would have been severe in most years, but crop conditions were so poor that the hail had little additional impact.

Precipitation

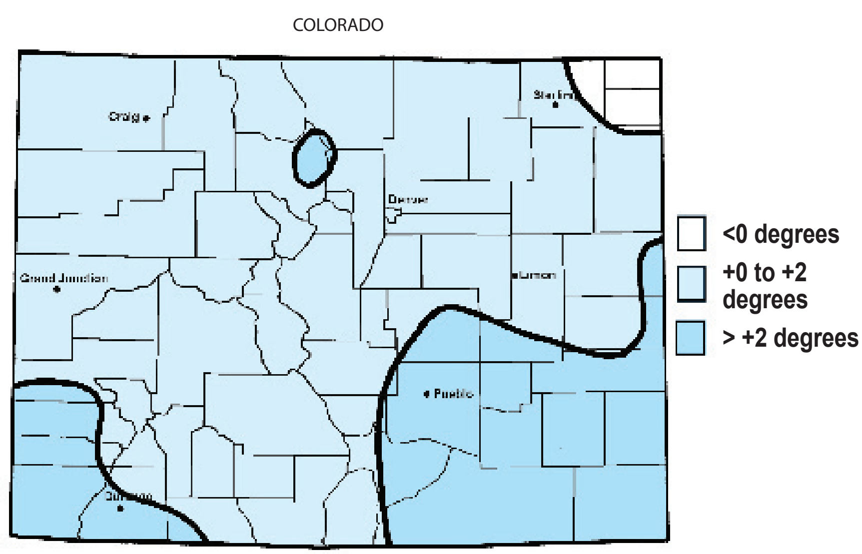
August was another very dry month with broad areas of southern and central Colorado totaling less than half the long-term average for August. Buena Vista, which often receives generous rainfall in August, totaled just 0.13" (6% of average) and Westcliffe added 0.18" (7%). The Front Range urban corridor was also very dry with most cities areas reporting less than 50% of average. Boulder was a localized exception thanks to nearly one inch of rain from a severe thunderstorm on the 5th. On the bright side, one area of Colorado was considerably wetter than average. From Logan and eastern Weld County southward to extreme southeast Colorado, several locations totaled over 4" of rain for the month. Flagler, for example, reported 4.40", 223% of average. A few areas west of the Continental Divide such as Steamboat Springs, Green Mountain Reservoir, and Palisade, also ended the month with above average August rainfall

Temperature

August was hotter than average for the 5th consecutive month. Periods of cloud cover and some weak cold fronts



August 2002 precipitation as a percent of the 1961-1990 average.



August 2002 temperature departure from the 1961-1990 average.

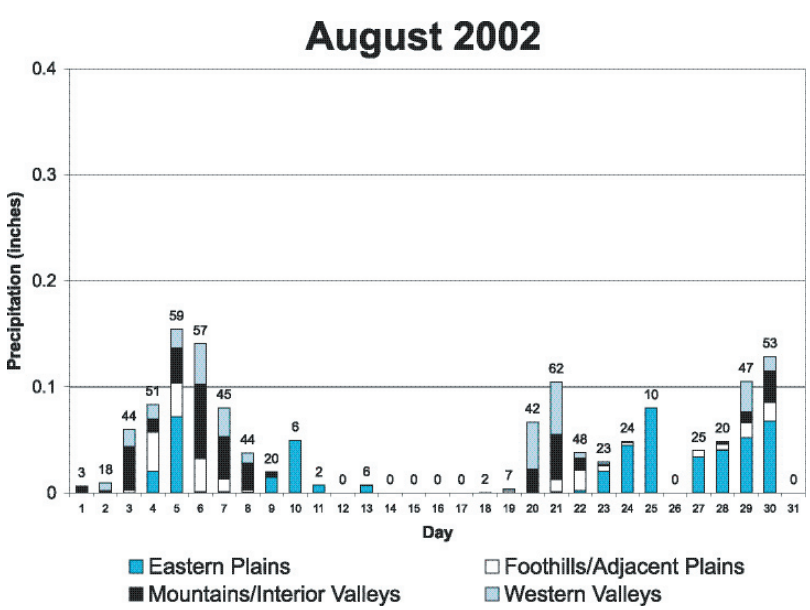
from the north brought welcomed relief. Also, low humidity meant that temperatures dropped quickly when the sun dipped below the horizon, especially up in the mountains. At Fraser, for example, morning low temperatures were below freezing on 16 days in August. For the month as a whole, most weather stations ended up one to two degrees Fahrenheit above average

August Daily Highlights

1 Dry statewide, but windy and cooler, especially over northeastern Colorado. Highs only in the 70s at places like Brush, Greeley and Denver, nearly 25 degrees cooler than the day before.

2-8 Subtropical moisture pulsed northward into Colorado for a few days in early August resulting in several days of higher humidity, moderate temperatures, and frequent mountain showers. This weather helped firefighters control several large fires, but it also caused localized flash flooding when mud and debris rushed down burned mountainsides. One such flash flood occurred on the 3rd near Vallecito Reservoir and another was reported near Glenwood Springs on the 5th. Rainfall was not extreme, but some significant amounts were reported. Examples include 0.94" at Vail on the 4th, 1.03" at Green Mountain Dam, and 0.91" at Walden on the 5th. A complex of storms rumbled across northeast Colorado late on the 4th with widespread heavy rains and some local flooding. Fleming and Crook, east of Sterling, each totaled over 2" in a few hours

9 A clump of thunderstorms developed over east central Colorado and dumped hail and local heavy rains. Damaging hail was reported in Lincoln and Kiowa counties. Precipitation totaled 1.24" at Haswell and 1.69" in Lamar.



10-19 Mostly sunny and dry statewide with very low humidity and smoky skies from several large wildfire flare-ups. Temperatures at lower elevations flirted with the 100-degree mark each day in western Colorado. East of the mountains, temperatures oscillated between very hot and downright pleasant as dry Canadian air pushed in 12-13th, 15th and 17th. Many new record highs were set on the 16th including 103ºF in Greeley and 98ºF at Castle Rock. Humidity increased on the 19th over western Colorado, and some thundershowers developed.

20-21 A widespread showery period as moisture moved up into the region. The mountains and western valleys received much needed rains. Norwood reported 0.53" on the 20th and Hayden got 0.80" of rain and some hail on the 21st. Storms nipped extreme southeast Colorado late on the 20th. The cooperative station at Campo 7S received 3.20".

22-30 The sense of extreme drought began to soften a bit over eastern Colorado as weather patterns changed and more moisture moved in accompanied by an unstable air mass with occasional outbreaks of spring-like severe weather. Localized hail was reported in parts of eastern Colorado on the 22nd and 23rd. Then a major hail outbreak occurred on the 24th as storms moved southward across Logan, Washington, Yuma and Kit Carson counties. One area near Akron was pelted by three separate storms. More than 1" of rain fell in some areas. Briefly hot on the 26th, and then more severe storms on the 27th. Large damaging hail occurred near Golden with stones up to 2" in diameter. Storms on the plains on the 28th caused some localized flooding in several areas, including parts of Lamar. Las Animas recorded 1.82" of rain. Western Colorado had some downpours too, especially on the 29th; 0.84" fell at Telluride. Walsh in extreme southeast Colorado was hit hard twice with 2.11" and 2.51" reported the morning of the 29th and 30th, respectively. Even so, the ground remained brown and barren after months of drought.

31 August ended hot and dry. A few large late-day thunderstorms developed out near the Kansas border. A few of the forest fires, particularly those near Steamboat Springs, continued to burn.

August 2002 Monthly Extremes

Description	Station	Extreme	Date
Precipitation (day)	Campo 7S	3.20"	Aug 21
Precipitation (total)	Walsh	5.59"	
High Temperature	Crook	108°F	Aug 1
	Wray 2E	108°F	Aug 1
Low Temperature	Sugarloaf Resvr	25°F	Aug 25

September 2002

Climate in Perspective

September started hot, dry and irritating. Then, a welcome weather pattern shift occurred. Moisture surged into the state, and for the first time in a long time nearly all of Colorado enjoyed long periods of damp showery weather. Lawns in many parts of the state turned green, and even some green up of open rangelands was noted. All forest fires that were still burning were eventually controlled, and the air was finally fresh and clean after a long, hot and smoky summer. The drought of 2002, while far from over, at least was interrupted, and there was a certain sense of relief statewide. Harvest began, and the results showed that many crops had suffered. Ranchers took a particularly hard hit and good hay at a good price was hard to find. But with rains falling almost daily for the last three weeks of the water year, it seemed that the worst was over.

Precipitation

Rains were frequent, widespread and sometimes heavy – exactly what Colorado needed after such a terribly dry year. In western Colorado, most locations had rainfall on nearly half the days during the month. Rains were less widespread and less frequent east of the mountains, but a few areas were doused by very heavy storms. For the month as a whole, precipitation totals were above to much above average over all of the mountains and western valleys of Colorado. A number of weather stations reported over double their September average. Gateway, near the Utah border, totaled nearly 3" of rain for the month. East of the mountains the moisture patterns were more spotty. Parts of southeastern Colorado were quite wet while areas north of the Arkansas River continued very dry as did much of the lower South Platte River basin. A band from near Colorado Springs northeastward to Limon and Wray was wet with a few areas reporting more than 200% of average.

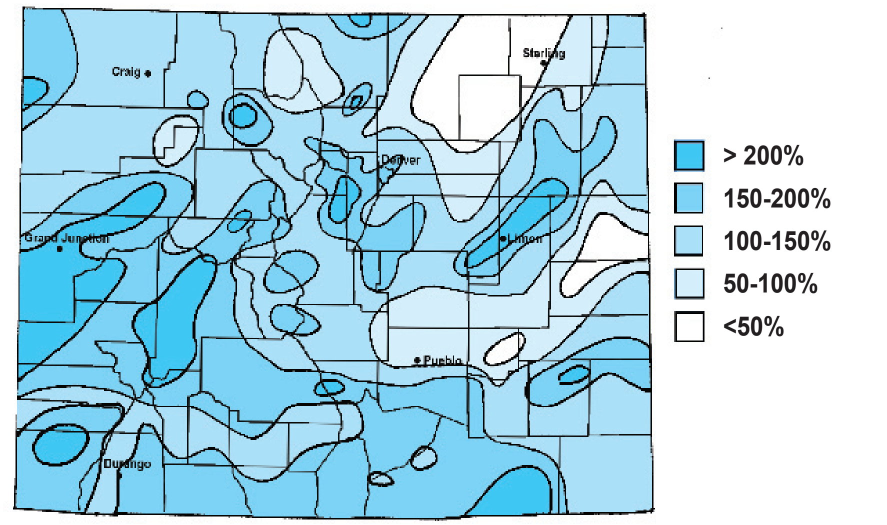
Temperatures

Several cool days in mid and late September were not enough to offset the much above average temperatures early in the month. As a result, most of Colorado ended up one to three degrees warmer than average, making this the sixth consecutive month with above average temperatures. In western Colorado, which experienced many cloudy, damp days, September monthly temperatures were very near the long-term average. There were no early frosts or freezing temperatures except in the typical mountain valleys.

September Daily Highlights

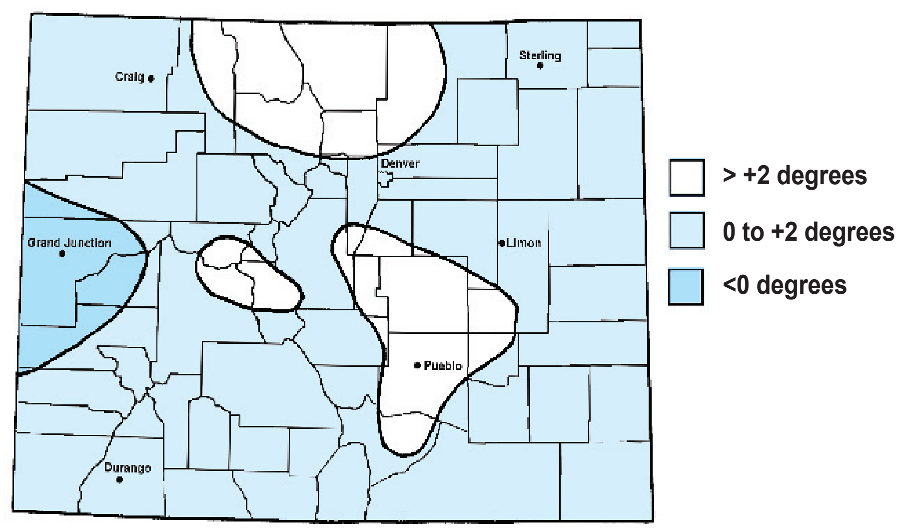
1-6 Colorado experienced another week of hot temperatures with little or no precipitation as high pressure dominated the area. High temperatures

COLORADO

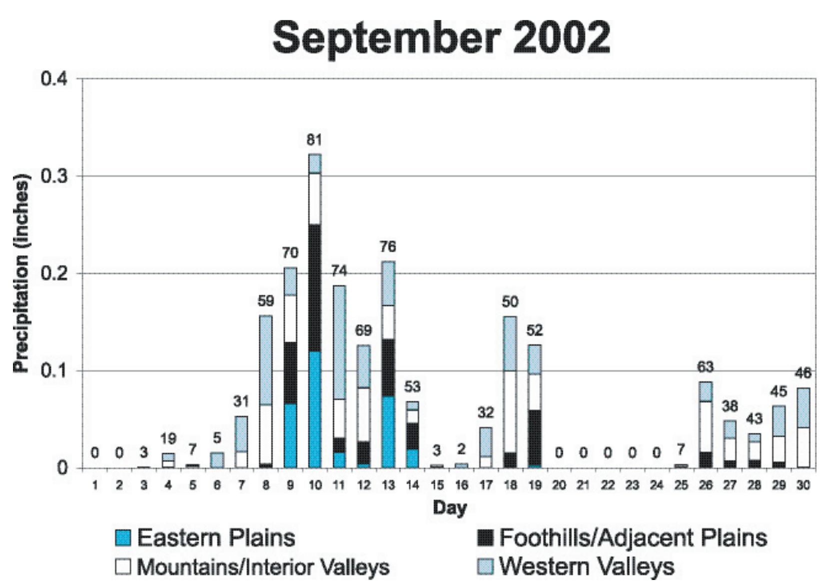


September 2002 precipitation as a percent of the 1961-1990 average.

COLORADO



September 2002 temperature departure from the 1961-1990 average.



in the 90s were common at lower elevations. Clouds and a few showers extended into far western Colorado in advance of an approaching low pressure trough.

7-13 Very moist subtropical air combined with a mid-latitude upper level low pressure trough to bring Colorado its wettest week of weather in a long time. Hot temperatures continued east of the mountains 7-8th, but with increasing humidity. Many areas of far western Colorado received rain on the 7th. Cedaredge picked up 0.72" from a good shower. Thundershowers continued across western Colorado on the 8th, but some locally heavy storms also developed over portions of northeast Colorado and expanded into widespread rain overnight. Several areas from Loveland east to Nebraska received close to an inch of rain. More than 1.50" fell near Haxtun. Genoa, east of Limon, reported a whopping 3.45" and flooding occurred in and near Limon where over 5" of rain may have fallen. Rains were widespread over central Colorado on the 9th. Many locations reported well over an inch of rain at their morning observation time on the 10th. Buena Vista, for example, reported 1.12", and Guffey got 1.90". The Front Range foothills were particularly favored. Then, later on the 10th, heavy rains began falling over southwestern Colorado. Durango picked up 1.75" and Vallecito Reservoir, where forest fires had bared large areas earlier in the summer, totaled 2.72". Extensive flooding with mud and debris occurred. Widespread light to moderate rain and thunderstorms continued over western Colorado on the 11th and 12th pushing into eastern Colorado on the 12th as low pressure moved directly over Colorado. Local areas of Denver were doused with over 2" of rain in a brief deluge, and large hail fell on portions of Elbert, Douglas and Lincoln counties. Rains finally let up in western Colorado on the 13th, but a few isolated large storms developed across eastern areas as the storm finally headed east. I-25 in south Denver was blocked briefly by floodwaters. For the week as a whole, precipitation averaged over the entire state exceeded 1.25".

Photo courtesy of the Colorado State Forest Service.

14-16 Mostly sunny and pleasant, but clouds began pushing into western Colorado on the 16th associated with a Pacific disturbance.

17-19 A vigorous low pressure trough moved across the Rockies bringing widespread moisture from Utah eastward to the Front Range along with chilly temperatures. Many areas of western Colorado received 0.50 to 1.00". A few areas got even more. For example 1.33" accumulated in Aspen, including their first inch of new snow for the season, and Rye totaled 1.49" for the storm.

20-24 Mostly sunny, mild and dry across Colorado. A Canadian cold front brought dry cool air into eastern Colorado 21-22nd with high temperatures only in the 60s and low 70s across the plains. Frost formed at night in the typical cold pockets indicating that autumn had indeed arrived. Temperature warmed sharply on the 24th.

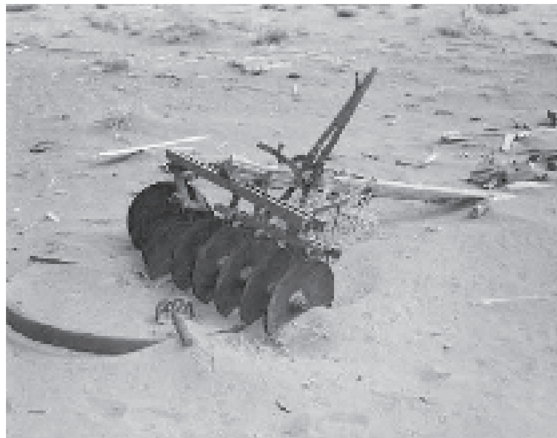
25-30 Unsettled weather marked the end of September as a low pressure trough in the upper atmosphere stayed in place over the western U.S. Temperatures remained fairly close to average for this time of year, and showers and local thunderstorms developed each day over the mountains and western Valleys. Most showers were light, but Green Mountain Reservoir reported 0.71" on the 25th, Crested Butte got 0.62" on the 26th, Blanca added 0.52" on the 28th, and the Gateway gauge showed 0.60" on the 29th. Fruita and Palisade both reported moderate hail on the 29th, causing some damage to late fruit crops. Only a few showers crossed over to the eastern plains. Eastern Colorado had a cold day on the 26th as a Canadian cold front dropped in and then quickly retreated again.

September 2002 Monthly Extremes

Description	Station	Extreme	Date
Precipitation (day)	Genoa	3.45"	Sep 9
Precipitation (total)	Vallecito Dam	5.91"	
High Temperature	La Junta	102°F	Sep 1
Low Temperature	Sugarloaf Resvr	15°F	Sep 27

What Exactly Is a 100-Year Drought?

by Nolan J. Doesken

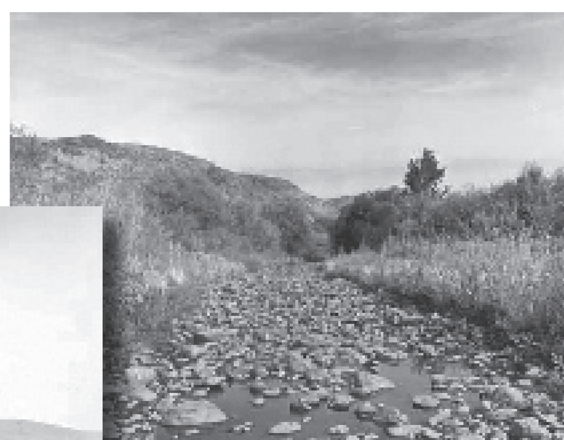


A 100-year event refers to any event that has a one-percent chance of occurrence in any year at a given point. Probabilities like this are normally determined based on past historic data. The term "100-year" event is most often used to describe heavy rains or a peak or annual stream flow volumes at a particular point along a river or stream. Flood plains are often designated based on estimated 100-year flood flow volumes. The values of a 100-year event are area and duration dependent and cannot easily be generalized.

Based on statistical studies, you would like to have 200-400 years of data in order to make a reasonable stab at estimating the magnitude of a 100-year event. In other words, there is quite a bit of uncertainty in many estimates of 100-year events. We only have about 100 years of historic observations of precipitation and streamflow, so we can estimate 25-year events well, but our estimates of 100-year events are much less certain. For example, for Loveland the 100-year rain storm for a duration of 24 hours is currently estimated to be about 5.0 inches and for a 6-hour duration about 3.6 inches, but we don't know this value for certain.

Is there such a thing as a 100-year drought? Yes, it is fairly easy to calculate based on annual streamflow values on rivers where flow rates have been measured for many years. For precipitation it's a bit more difficult as there are infinite possibilities on how to define drought based on quantities, durations and areas. But once you arrive at an acceptable definition, you go through the historic data and determine what the probability of occurrence of any precipitation shortage over a prescribed period of time and a defined area might be. There would be a whole myriad of "100-year drought" numbers you could come up with based on your assumptions.

The Colorado Water Conservation Board has examined Colorado streamflow records and can assign probabilities to annual and peak streamflow volumes. From this, you could estimate a 100-year drought based on single-year streamflow statistics. Likewise, the paleoclimatologists studying tree rings could do the same. We have not tried to do the same with precipitation at this time simply because of the large number of potential combinations and the fact that no definition satisfies all users.



Recap of the Drought of 2002 in Colorado

by Nolan J. Doesken and Roger A. Pielke, Sr.

Historical analysis of precipitation shows that drought is a frequent visitor to Colorado (McKee and Doesken, 1999). Short duration drought as defined by the three-month Standardized Precipitation Index (SPI) occur somewhere in Colorado in nearly nine out of every ten years. However, severe, widespread long-lasting droughts are much less common. As of 2000, McKee et al. showed that Colorado had experienced five episodes of long-duration widespread drought since 1890 based on the 48-month SPI (Figure 1) with the most recent drought period ending in the late 1970s.

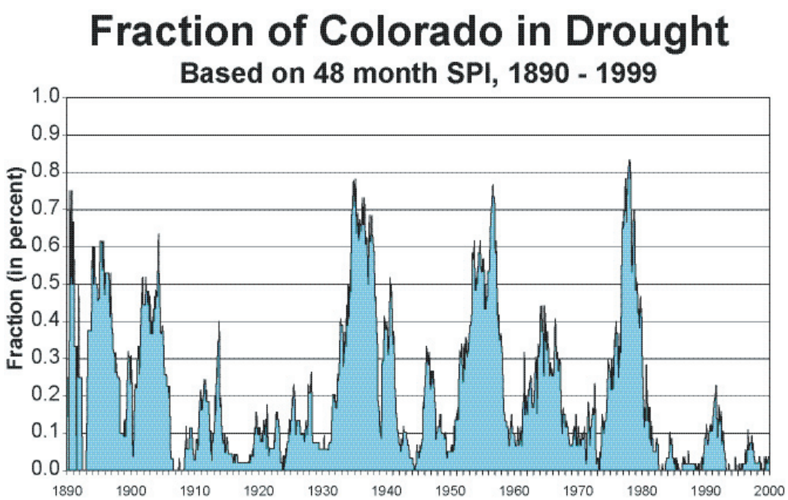


Figure 1. Time series through 1999 of percent of Colorado experiencing drought based on the 48-month SPI at or below the drought threshold value of – 1.

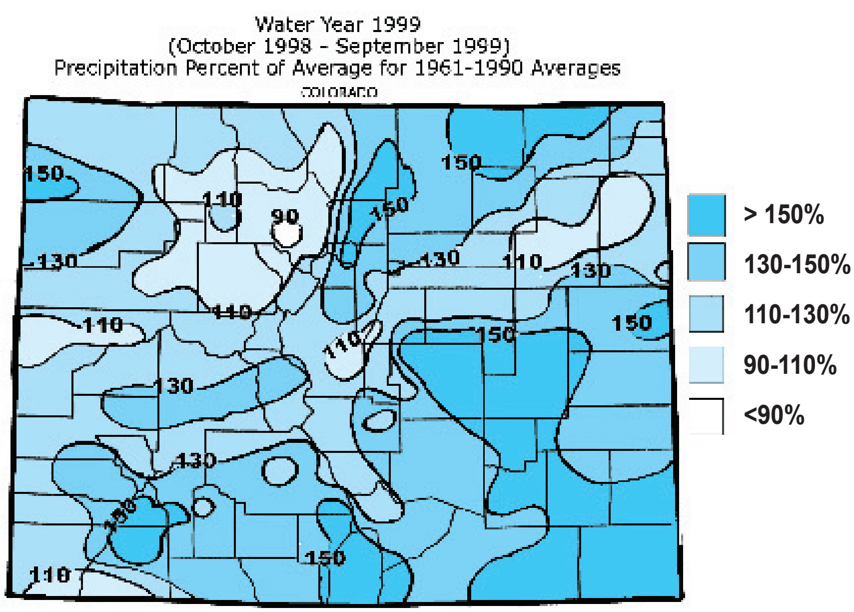


Figure 2. Precipitation for the 1999 water year (October 1, 1998 through September 30, 1999) as a percent of average.

Precipitation data for Colorado showed that the 1980s and 1990s were two of the wettest decades in Colorado since 1930 and helped raise the annual precipitation average for the 1971-2000 to the highest level experienced since such data have been compiled for several portions of the state, especially southeastern Colorado.

As a result, people in Colorado were not thinking drought. In fact, 1999 was one of the wettest years on record (Figure 2). Data from the previous 110 years, however, showed that prolonged periods free from widespread multi-year drought were uncommon with the longest period lasting approximately 25 years just prior to the onset of the dustbowl drought of the 1930s. (Figure 1). So while the public was very comfortable with abundant water supplies for this semiarid portion of the country, climatologists were uneasy. As it turned out, they had good reason.

An Evolution of the 2002 Drought In Colorado

The drought of 2002 had its beginnings in the autumn of 1999. After a very wet spring in 1999 and a soggy August, precipitation patterns reversed, and the fall of 1999 was very dry across most of Colorado. The winter of 1999-2000 followed with below average snow accumulation and much above average temperatures. The mountains of southwestern Colorado were particularly hard hit by a shortage of snow for winter recreation and summer water supply. With a very dry spring and early summer in 2000 over northeast Colorado and the South Platte watershed, drought conditions emerged quickly. In fact, the whole western U.S. was soon engulfed in a severe drought that resulted in the most severe wildfire season on record. A persistently hot summer did not help matters as transpiration rates were much higher than average over irrigated areas. Precipitation for the 2000 water year is shown in Figure 3.

The 2001 water year was less extreme but still tended on the dry side. Colorado's northern and central mountains were the driest with respect to average and this was very significant since that area is the source of most of the water for municipal, industrial and agricultural uses in the state (Figure 4). While spring and summer precipitation was relatively normal, hotter than average temperatures for the second summer in a row again resulted in high evaporation rates and continued depletion of soil moisture and surface water supplies. This set the stage for "The drought of 2002."

Beginning in September 2001, storm systems were few and precipitation was sparse across the Central Rockies. Much of western and southern Colorado received less than half the average September precipitation and temperatures were several degrees above average across the entire state. Beneficial moisture fell from two storm systems that primarily affected northeastern and east central counties of Colorado.

October weather patterns appeared more favorable as a variety of storm systems crossed the region. However, precipitation from passing storms was very light, and when the month was over, precipitation totaled again less than half the average over the majority of the state. Some areas east of the mountains received no moisture at all. Temperatures were also mild ranging from about average near the Kansas border to as much as four degrees Fahrenheit above average over southwest Colorado.

Early November was unseasonably warm and dry. Most mountain slopes and peaks remained bare. Only in late November did significant snow fall. Dry powdery snow was widespread and quite deep in the mountains by the end of the month, although snow water content remained below average. In hindsight, the late November snow siege was really the only prolonged stormy period for the year. It was very helpful in getting the Colorado winter recreation season off to a good start.

December brought many more opportunities for mountain snows, but most resulted in only a few inches here and there. The higher peaks and mountain ranges, particularly in northern Colorado, added some good snow, but the surrounding valleys stayed very dry. Temperatures, fortunately, were cold in the mountains and valleys, so there was little melting. Many areas of the state picked up less than half the December average, and east of the mountains only a few hundredths of an inch of moisture was measured. Southeast Colorado fared a bit better due to a few storms coming up across Texas.

January 2002 brought seasonally cold temperatures to the state and above average snowfall for the Front Range urban corridor and the southeastern plains of Colorado. Unfortunately, January precipitation east of the mountains contributes very little to overall water supplies. In the mountains, January snows usually contribute significantly to the accumulating mountain snowpack. But in 2002, January precipitation in the mountains was much below average. Southwestern Colorado was the driest portion of the state with many stations in the San Juan, Animas and Dolores watersheds receiving less than 10% of the 30-year average.

February was also a disappointment. Despite cold temperatures and several storm opportunities, very little snow materialized. North central counties did best with a few stations reporting near average snowfall and water content. But for most of Colorado, February was extremely dry with many stations reporting less than 25% of the long-term average. Because of the cold temperatures and frequent small snows, Colorado's huge winter recreation industry was able to limp along with surprisingly good snow conditions, but the snowpack water content by the end of February was only 80% of average

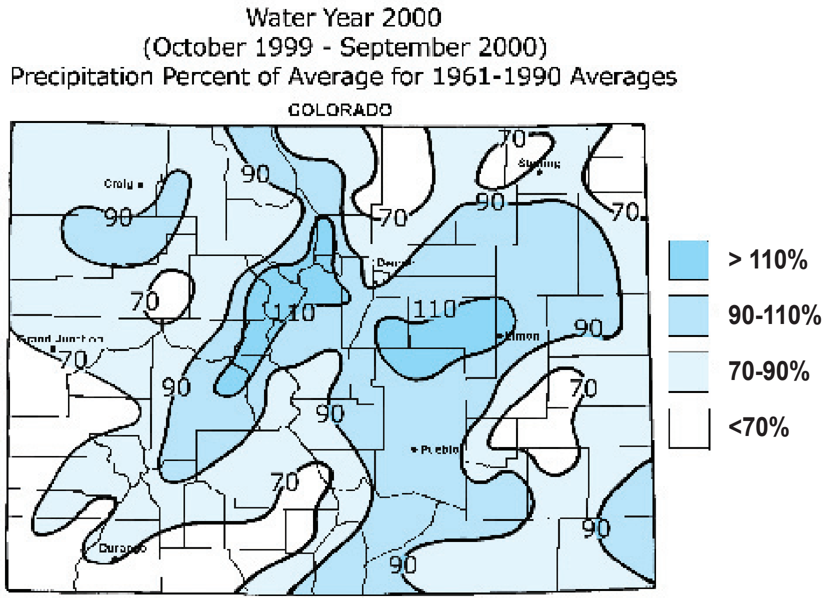


Figure 3. Precipitation for the 2000 water year (October 1, 1999 through September 30, 2000) as a percent of average.

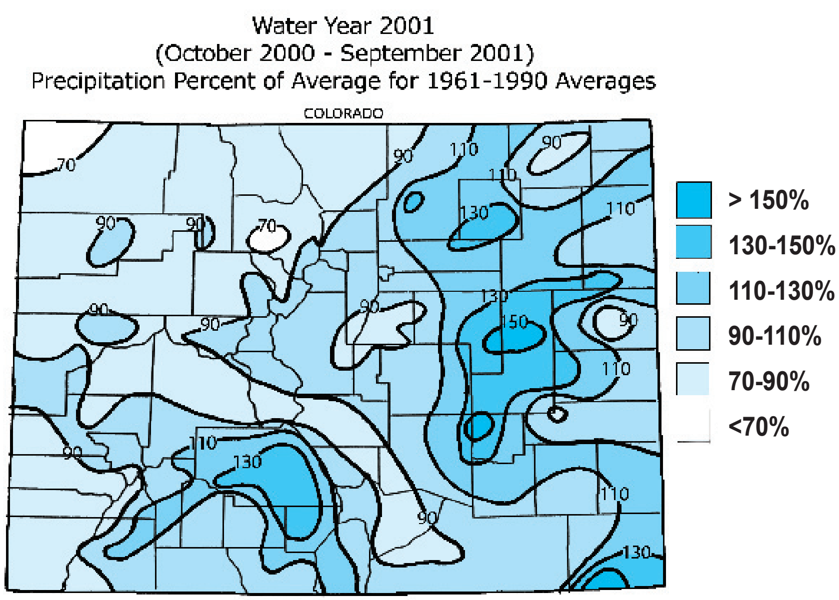


Figure 4. Precipitation for the 2001 water year (October 1, 2000 through September 30, 2001) as a percent of average.

at best in portions of northern Colorado, while in southern Colorado the snow water content was only about 40-50% of average.

March did not give many hints of the severe drought ahead. Widespread storms crossed the region at least every week, and temperatures were reluctant to begin the normal spring thaw. Unfortunately, none of the storms contributed the copious wet snows that Colorado spring snowstorms typically produce. Furthermore, the storms nearly skipped southeastern Colorado completely. Only northwestern Colorado ended up wetter than average for the month of March. Some parts of northern and central Colorado were

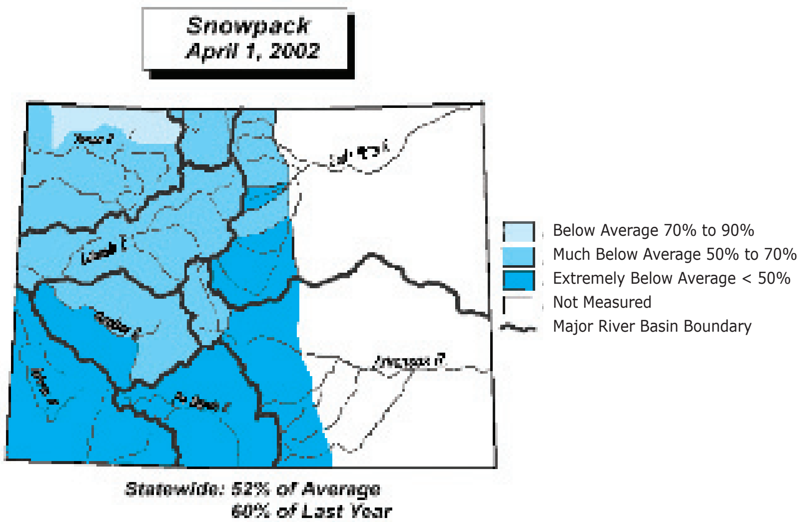


Figure 5. April 1, 2002 snowpack for state of Colorado (from the National Resources Conservation Service, http://www.co.nrcs.usda.gov/snow/data/snmap402.html).

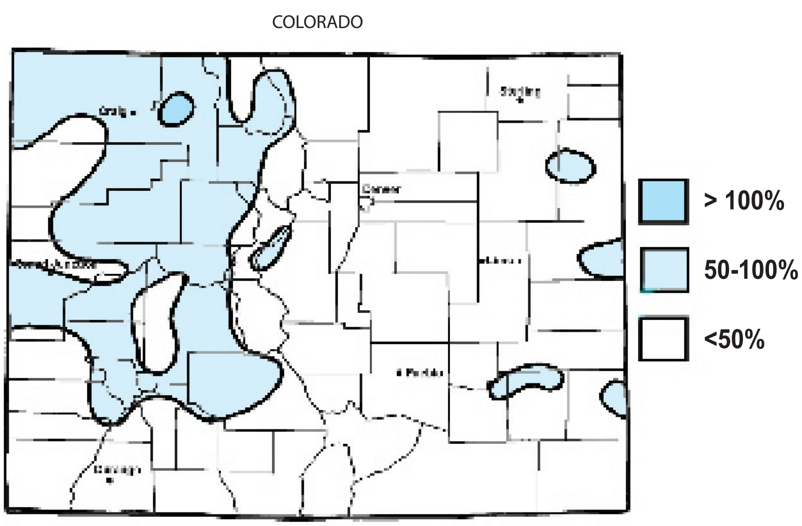


Figure 6. April 2002 precipitation as a percent of the 1961-1990 average for Colorado.

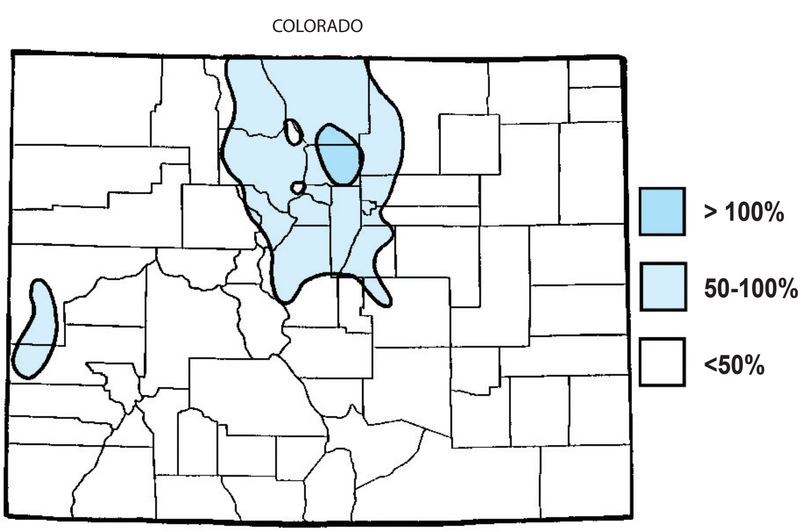


Figure 7. May 2002 precipitation as a percent of the 1961-1990 average for Colorado.

near average. Most of Colorado however was very dry with nearly half the state less than 50% of the average.

By the end of March, the statewide snow water equivalent, as a percent of average, was a mere 52% and all portions of Colorado's mountains were far below average, Figure 5. While not as bad as the winter of 1976-77, these were still very extreme conditions for a state that derives most of its surface water from melting snow. Despite these poor figures, there was little public and government perception of severe drought. This was possibly a result of the heavy snows in late November, and the seasonally cold temperatures during the winter (one of the colder winters in recent years) and the favorable winter skiing and snow boarding conditions that had been consistently portrayed by the media. Also, several of the very wet years in the 1990s had low snowpack conditions in early April only to be followed by excessive spring and summer precipitation. So folks just weren't too worried.

But then came April and the reality of drought quickly hit home. The spring storms that sometimes dump heavy and widespread precipitation were non-existent in April. Almost no precipitation fell in eastern Colorado, and mountain precipitation was also meager. To make matters worse, April temperatures soared to record highs, especially in the mountains, and mountain snow melted or evaporated at an alarming rate. Relative humidity on several afternoons fell to below 10%. Fire danger, which typically stays low to moderate through early June, was already high by mid April, and the first severe forest fire of the season ignited near Bailey on April 23rd (Snaking Fire). For the month as a whole, precipitation was less than half the average over ¾ of the state (Figure 6) and less than 25% of average over broad areas. Temperatures ranged from about average near the Nebraska border to over 10 degrees Fahrenheit above average in the high valleys of the central mountains making this the warmest April on record for several mountain locations. Strong winds also occurred. Farmers trying to get crops planted had to apply early irrigation water resulting in premature depletion of the already limited water supplies.

May, while not quite as much warmer than average as April, was even drier. Only the northern Front Range area received significant moisture (Figure 7). At a time of year when Colorado's rivers and streams are normally churning with snowmelt runoff, there were only brief hints of a spring snowmelt runoff. Irrigation water demand was high, but it was soon obvious that supplies would not last through the growing season. Municipalities began to face the possibility that available water supplies might not provide for the typical summertime demand. Many areas began implementing strict water conservation regulations. More forest fires erupted and each new fire seemed to spread faster than the one before.

June arrived accompanied by relentless summer heat. Vegetation that normally grows lush and tall during the spring barely greened up. By June, relative humidity often dropped to less than 10%, and bans on outside burning were enforced statewide. Temperatures routinely climbed in the 90s and low 100s degrees F at lower elevations east and west of the mountains. Dry air allowed nighttime temperatures to dip to comfortable levels most every night. Little or no precipitation fell for the entire month over western Colorado (Figure 8). East of the mountains, a few thunderstorms occurred and some local areas enjoyed respectable rainfall amounts. Parts of far eastern Colorado, for example, reported more than 4 inches of rain in June. But with persistent high temperatures, frequent strong winds, and low humidity, the rain scarcely greened the native vegetation. Winter wheat crop conditions continued their rapid deterioration, and ranchers began selling or moving all or parts of their herds in response to the poor range conditions and high cost of feed. The most severe fires of the season erupted in June including the Hayman fire southwest of Denver which quickly grew to be the largest documented forest fire in Colorado (137,760 acres) since records have been kept.

July brought a few changes. While precipitation was again below average statewide, and temperatures were above average for the fourth consecutive month, some increase in humidity was observed later in the month. Initially, wildfire smoke could be seen almost every day, but eventually, as humidity rose, fires spread more slowly, and some were successfully extinguished. July is normally the most lightning prolific month of the year, but in 2002 thunderstorms were few. This helped the fire situation by reducing the number of natural ignitions. There were some focused locations with showers and thunderstorms during July. A few small, localized areas, mostly in or near the mountains, ended up with near average rainfall for the month. But most areas remained dry. The eastern plains were parched with most areas reporting less than 30% of their average July precipitation. Even where irrigation water held out, crops withered under the stress of heat and low humidity. Many area water supplies came to an end, irrigation was curtailed, and crop failure ensued. By late July, almost all of Colorado was in a serious drought.

Photo courtesy of the Colorado State Forest Service.

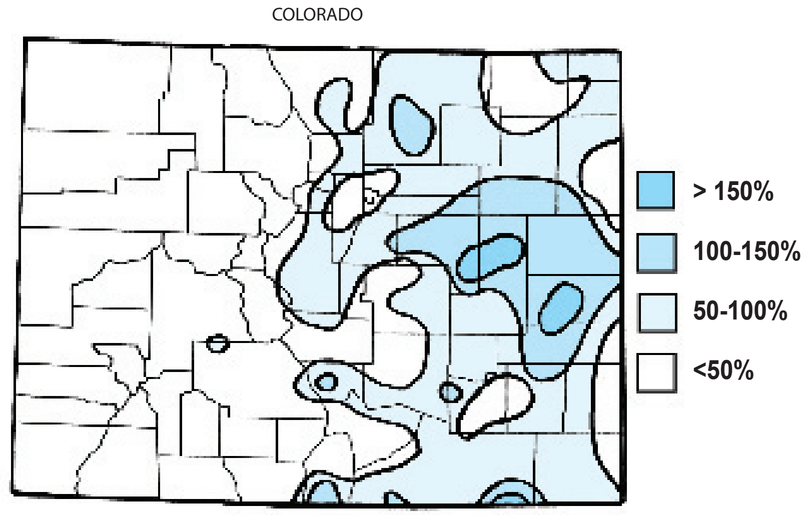


Figure 8. June 2002 precipitation as a percent of the 1961-1990 average for Colorado.

Furthermore, drought conditions were not limited just to Colorado but extended over much of the Great Plains and Rocky Mountain States (Figure 9).

August arrived with some optimism. The first several days of the month were not quite as hot and subtropical moisture helped to fuel more afternoon showers and thunderstorms. But the monsoon moisture surge was brief and soon ended. By the 10th of August heat and low humidity returned accompanied by another round of fast-spreading fire activity. Crop and range conditions continued to deteriorate as did streamflows and water levels in the state's largest reservoirs. By mid-August, media reports likened this to the great Dust Bowl of the 1930s in response to unusually late occurring 100°F+ temperatures in Front Range cities. As the month neared its end,

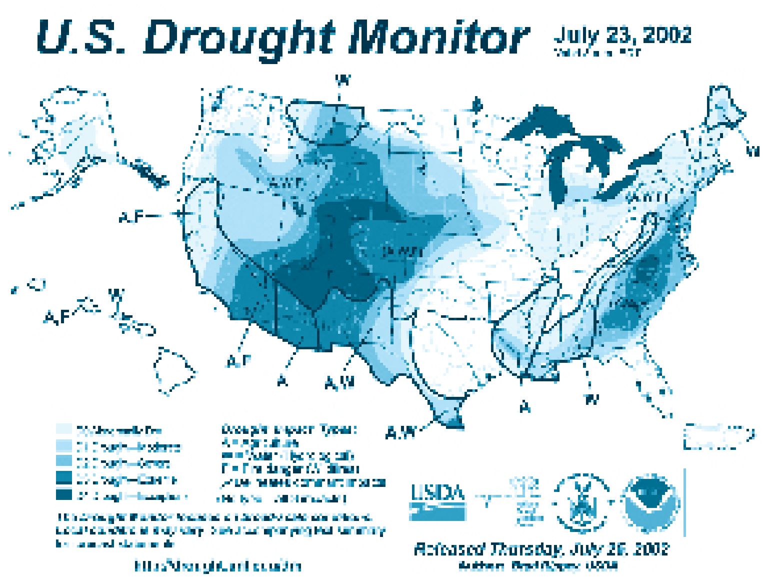
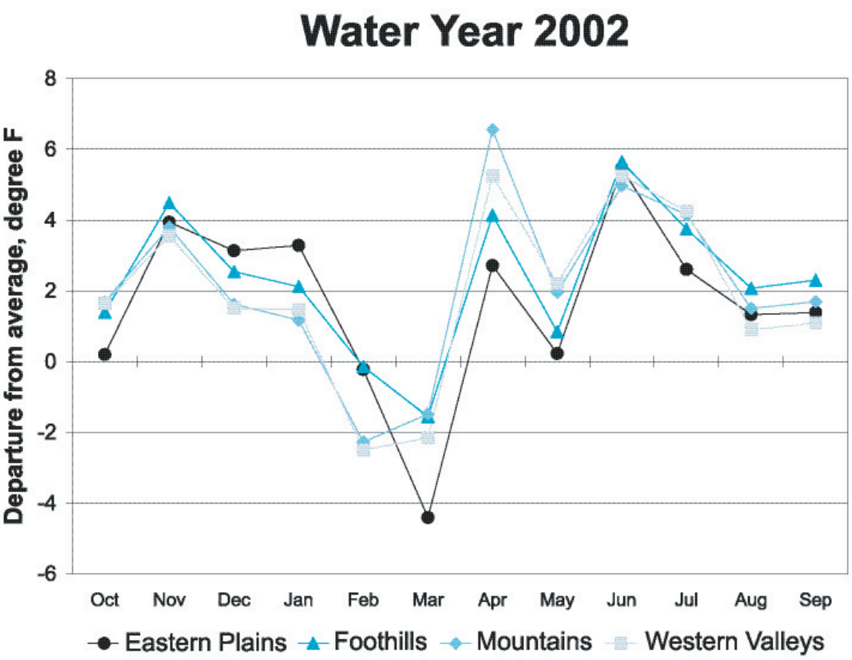
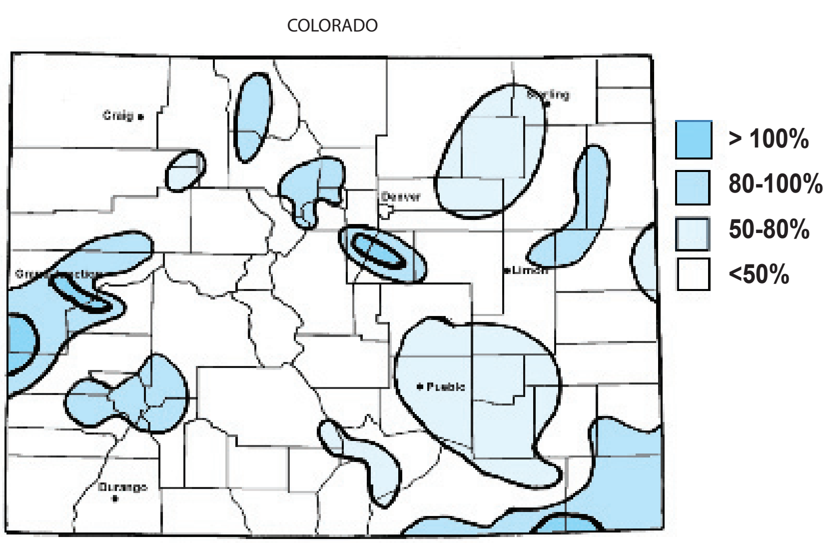


Figure 9. U.S. Drought Monitor for July 23, 2002 shows much of Colorado in "exceptional" D4 drought (from National Drought Monitor, University of Nebraska – Lincoln, http://drought.unl.edu/dm).

a subtle change in weather patterns brought a round of spring-like thunderstorms loaded with hail and high winds to portions of eastern Colorado. The hail did little damage, however, since so few crops were still growing in late August. For the state as a whole, August precipitation was still below average, but unlike previous months there were some large areas of eastern Colorado that received heavy rains. More than double the August average was observed from eastern Weld County down to northwest Kit Carson County.



Regionally averaged monthly temperature departures from the 1961-1990 averages, October 2001 through September 2002, for Colorado's Eastern Plains, the Front Range foothills and adjacent plains corridor, the Colorado mountainous region, and the western valleys and plateau region (Western Slope).



May though September 2002 growing season precipitation totals as a percent of the 1961-1990 average.

Humid and stormy weather continued into September. For the first time since August 2001, the majority of Colorado received above average rainfall. Temperatures were still warmer than average, but with the cooler air of fall, frequent showers and a few soaking rains, grass actually began to green up a bit. Parts of Colorado accumulated at least double the average monthly rainfall. Even the bone-dry areas of southwest Colorado received some much appreciated moisture with some areas reporting over 4 inches of moisture for the month. With cooler weather imminent, and the growing season drawing to a close, the worst of the 2002 drought was at last behind us.

2002 In Historical Perspective–How Bad Was It?

•Snowpack: April 1 is the date most often used to compare snowpack regions in Colorado as this is close to the time where the accumulation of water in the mountain snowpack reaches its maximum. Figure 10. Shows how April 1, 2002 snowpack water content compares to previous years for the state of Colorado as a whole. 1977 was actually drier than 2002. However, snow melted more quickly in April and May with less additions to snowpack so by May mountain snowpack was at its lowest level for the 1968-present record.

•Accumulated Precipitation: Figure 11 shows 2002 water year precipitation as a percent of average. The driest consecutive 12–month period was the September 2001 though August 2002 period. Based on 16 of Colorado's best long-term climatic stations representing all regions of the state, nine experienced their driest year on record. The number of sites that were driest on record was somewhat less for the October 2001 – September 2002 period (see Table 1 on page 16).

There have been individual years in Colorado that have been drier at individual points or portions of the state – 1894, 1934, 1939, 1954 and 1966 are some examples. However, what made 2002 so unusual was that all of the state was dry at the same time. All seasons were dry and all regions were dry. In a state that straddles the Continental Divide and where seasonal patterns and wet and dry seasons vary greatly across the state, it is very hard for all areas of the state to experience severe drought at the same time. In fact, much of the western US, both east and west of the Rocky Mountains shared in this drought experience (Figure 9).

•Soil Moisture: By all accounts, soil moisture was nearly depleted in the upper 36 inches of the soil profile over broad areas of Colorado by late August 2002. No historic data exists to better quantify this. Late August and September rains helped to moisten near-surface soil moisture but did little to improve deep soil moisture.

•Streamflow: The combination of low winter snowpack, a dry and warm spring and a very hot summer, all following on already dry conditions prior to 2002 in the mountains, resulted in a year with extremely low runoff

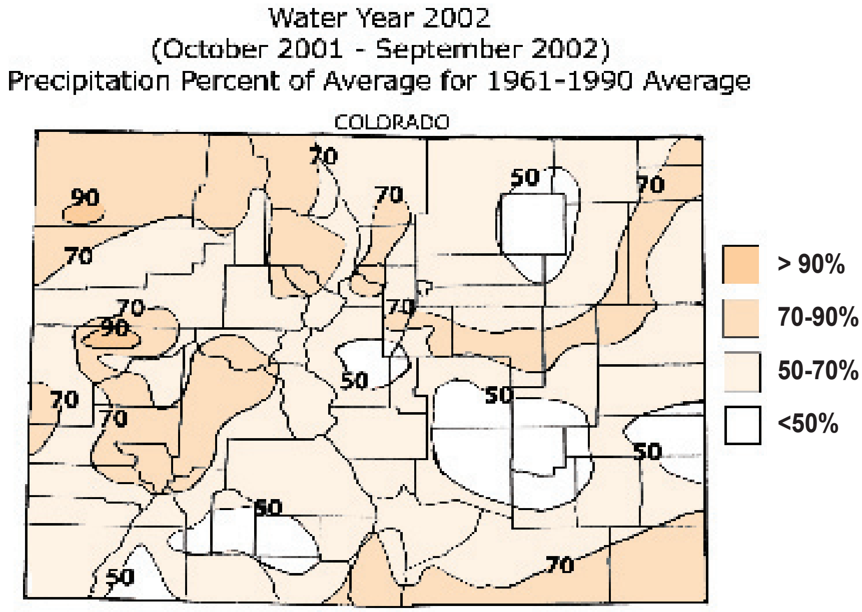


Figure 11. Precipitation for the 2002 water year (October 2001 through September 2002) as a percent of the 1961-1990 average.

and streamflow. Figure 12 shows a historic time series of streamflow from one river along the Front Range of Colorado. 2002 was clearly the driest year in over 100 years of record based on streamflow. Similar conditions were experienced in watersheds all over the state, and these low streamflows explain clearly why irrigation water was insufficient to raise crops in many areas and why municipalities relying on surface water had to enforce strict water conservation measures. From a longer-term perspective there have been longer "streamflow droughts" such as the conditions that occurred along the Colorado Front Range in the mid 1950s. However, as an individual drought year, 2002 appears to have been unsurpassed during the period of instrumental record.

•Reservoir levels: Reservoirs are an effective means of storing water from times of abundance for use during times of scarcity. 2002 was one of those time. Figure 13 shows Colorado statewide reservoir storage as of October 1 of each year. The excess of the late 1990s helped Colorado survive the drought of 2002, but very little useable water remained even with strictly enforced water restrictions.

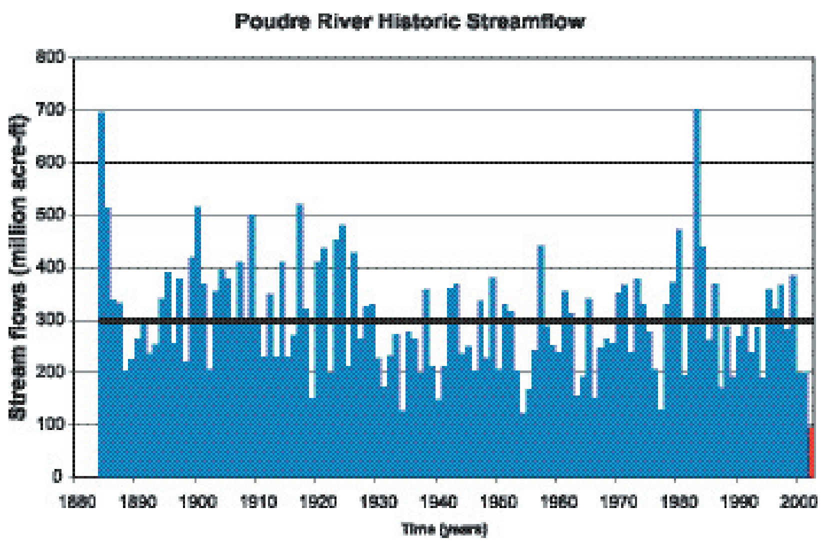


Figure 12. Annual flow records for the Poudre River along the northern Front Range in Colorado for the period 1884-2002. The figure shows some extreme drought events such as those in the 1930s, 1950s, and the drought of the 2000s. Note that the 2002 flow is the smallest value in the entire record. (From J.D. Salas et al., 2003.)

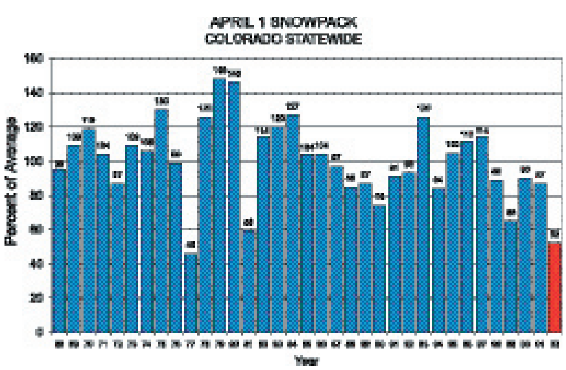


Figure 10. April 1 Snowpack percent of average for Colorado by year from 1968 through 2002 (from NRCS, Snow Survey Division).

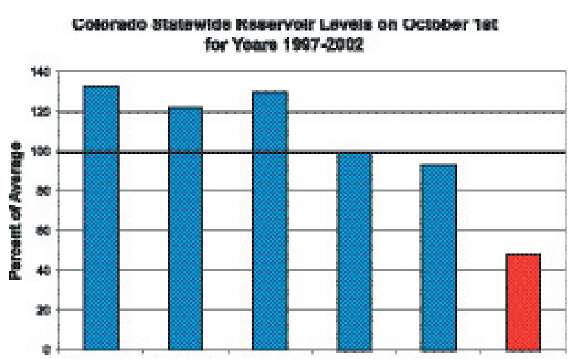


Figure 13. Time series of Colorado composite reservoir storage as a percent of average on October 1st for years 1997 through 2002 (complied from NRCS data at http://www.wcc.nrcs.usda.gov/cgibin/resv_rpt.pl?state= colorado).

2003 – A Shaky Road To Recovery

In semiarid regions like Colorado far removed from maritime air masses, drought is never truly over. Colorado citizens wanted nothing more than to return to the years of water abundance like the 1980s and 1990s. The winter of 2002-2003 did little to end the drought. Rather deficits continued to accumulate. A wet spring in 2003 and one remarkable snowstorm, in particular, did make a difference. In just over 48 hours, three to as much as eight inches of water was deposited in the form of extremely heavy snow along the Colorado Front Range March 17-19, 2003. This storm took a very important bite out of the drought since it watered the area of Colorado that most heavily utilizes surface water supplies. Timely moisture in April, May and June helped fuel an excellent spring runoff from Colorado's northern and central mountains, and helped a quicker than expected recovery in reservoir storage. Nevertheless, in late 2003, drought conditions continue across much of the western U.S. going into the winter of 2003-2004 (Figure 14).

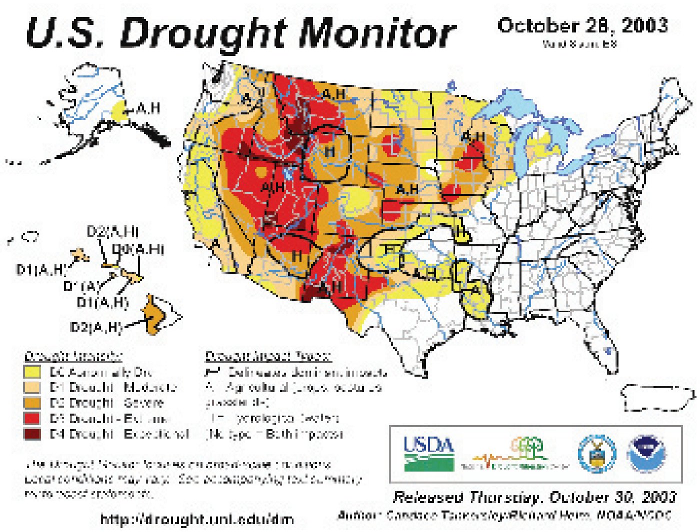


Figure 14. U.S. Drought Monitor for October 28, 2003 shows the current condition of Colorado (from National Drought Monitor, University of Nebraska – Lincoln, http://drought.unl.edu/dm).

Is the drought over? Not yet. Conditions can and do change, but as of fall 2003 Colorado remains very vulnerable to more drought impacts. Coloradans, and those who rely on water flowing out of this state should be prepared for more drought.

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Table 1. Precipitation Accumulation Analysis for 12-month (Sep. 2001-Aug. 2002), 13 month (Sep. 2001-Sep. 2002) and 2002 Water Year (Oct. 2001-Sep. 2002) Compared to Period-of-Record (POR) and 1941-2002 Period. In parentheses are the magnitudes of the standard deviations below the average for the time period, based on the available data for each station.

Climatic Station	Period of Record (POR)	Sep 2001 – Aug 2002 (12 months)			Sep 2001 – Sep 2002 (13 months)			2002 Water Year (Oct 2001 – Sep 2002)		
		POR Rank	1941-2002 Rank (SD)	inches	POR Rank	1941-2002 Rank (SD)	inches	POR Rank	1941-2002 Rank (SD)	inches
Grand Lake 1NW	1940-2002	1	1 (1.87)	12.57	2	2 (1.42)	16.03	1	1 (1.71)	12.87
Taylor Park	1941-2002	1	1 (2.02)	10.42	2	2 (1.65)	12.74	3	3 (1.51)	11.94
Grand Junction WSO	1892-2002	8	5 (1.39)	5.54	31	20 (0.63)	8.08	43	27 (0.34)	7.93
Meeker	1891-2002	7	5 (1.78)	10.37	8	6 (1.64)	11.95	7	7 (1.58)	10.87
Montrose No. 2	1896-2002	3	3 (1.54)	5.83	15	8 (1.02)	8.01	29	1 (0.80)	7.59
Mesa Verde NP	1923-2002	1	1 (2.30)	7.43	1	1 (1.97)	9.83	3	3 (1.79)	9.68
Del Norte 2E	1920-2002	1	1 (2.55)	3.19	3	3 (1.96)	5.18	3	3 (1.80)	4.69
Center 4 SSW	1891-2002	1	1 (2.69)	2.44	1	1 (2.20)	3.82	4	4 (1.92)	3.69
Colorado Springs WSO	1892-2002	1	1 (2.13)	6.50	1	1 (2.01)	7.81	2	1 (1.97)	6.79
Pueblo WSO	1891-2002	1	1 (2.65)	3.80	1	1 (2.64)	4.45	1	1 (2.56)	3.96
Rocky Ford 2SE	1892-2002	1	1 (2.33)	3.62	1	1 (2.36)	4.26	1	1 (2.31)	9.36
Cheyenne Wells	1897-2002	4	2 (1.67)	9.20	10	5 (1.39)	11.45	9	5 (1.48)	9.91
Akron 4E	1905-2002	1	1 (2.02)	9.40	1	1 (1.83)	10.90	1	1 (1.88)	3.73
Leroy 7WSW	1891-2002	4	2 (1.91)	10.58	4	2 (1.82)	11.58	4	2 (2.05)	9.57
Kassler	1899-2002	8	4 (1.49)	12.56	9	5 (1.44)	13.83	6	4 (1.48)	12.17
Fort Collins	1890-2002	3	2 (1.96)	7.87	3	2 (1.84)	9.32	5	4 (1.66)	8.44
Stations Ranked Driest		9	9		6	6		4	6	

National Weather Service Length of Service Awards for Western Colorado

30-Years Length-of-Service at Paonia

Robert Lund (left), receives a 30-year Length of Service award for volunteer weather observing as his home just outside of Paonia, Colorado. Presenting the award is Data Acquisition Program Manager (DAPM) John Kyle from the NWS office in Grand Junction. Also present was senior forecaster Jeff Colton.

20-Years Length-of-Service at Ridgway

Richard Crabb of Ridgway, Colorado, receives a 20-year Length of Service award from the National Weather Service in Grand Junction. John Kyle, DAPM, from Grand Junction National Weather Service Office presented the award. Photo by John Kyle.

15-Years for Maybell

Tom and Joyce LeFevre (left) of Maybell, Colorado, receive a 15-year Length of Service award from the NWS in Grand Junction. Presenting the award is John Kyle.

15-Years for Glenwood Springs

Gabe Chenoweth (left), KMTS Glenwood Springs, accepts his 15-year Length of Service award at the radio station in Glenwood Springs, Colorado. John Kyle of the Grand Junction NWS presented the award.

10-Years for Gunnison

Sherry Fenske and Mark Daily, Gunnison County Electric Association, received a 10-year Length of Service Institution award from the NWS in Grand Junction.

Congratulations to all on this very important service to the state and our country!

National Weather Service Cooperative Observers Length of Service (LOS) Awards are presented after 10 years of service. Institutions that provide cooperative observations are awarded LOS Awards at 25, 50, 75 and 100 year intervals. Individual cooperative observers receive such awards after 10, 15, 20, 25, 30, 35, 40, and 45 years of service.

Cirrus Clouds over Eagle, Colorado. Photo by ©Ronald L. Holle, used with permission.

Duststorm near Cheyenne Wells, photo by © John Haynes.

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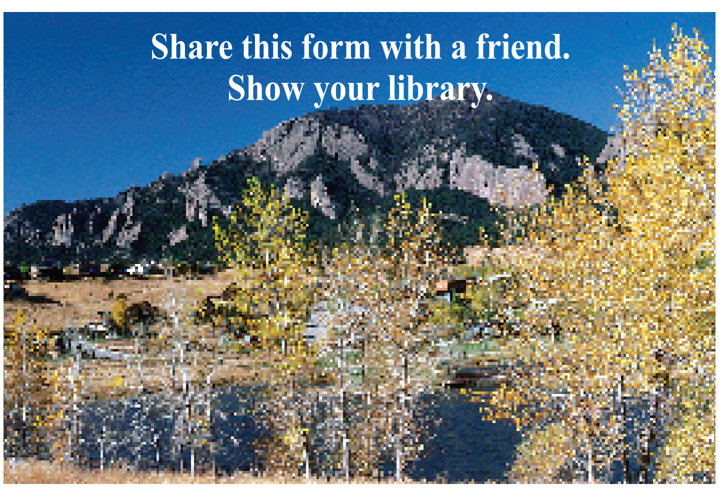

Flatirons in October, photo by © Ronald L. Holle.

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