Pure appl. geophys. 162 (2005) 1455–1479
0033 – 4553/05/091455–25
DOI 10.1007/s00024-005-2679-6

Pure and Applied Geophysics

Drought 2002 in Colorado: An Unprecedented Drought or a Routine Drought?

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Abstract — The 2002 drought in Colorado was reported by the media and by public figures, and even by a national drought-monitoring agency, as an exceptionally severe drought. In this paper we examine evidence for this claim. Our study shows that, while the impacts of water shortages were exceptional everywhere, the observed precipitation deficit was less than extreme over a good fraction of the state. A likely explanation of this discrepancy is the imbalance between water supply and water demand over time. For a given level of water supply, water shortages become intensified as water demands increase over time. The sobering conclusion is that Colorado is more vulnerable to drought today than under similar precipitation deficits in the past.

Key words: Drought, precipitation, Colorado, streamflow, snowpack, paleoclimatology.

1. Introduction

In reference to the 2002 drought, the Governor of Colorado stated in his 2003 State of the State address,

"…. scientists tell us that this is perhaps the worst drought in 350 years."
(http://www.thedenverchannel.com/print/1913350/detail.html?use = print)

Clearly, such an assessment of drought severity depends on how drought is defined. Drought is characterized in a number of different ways, each with associated definitions of onset and recovery, duration, and related impacts. For example,

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meteorological drought could be measured by numbers of days below a specified precipitation threshold, or departure from a baseline average; an agricultural drought could be measured by soil moisture deficit and impacts on crops; and a hydrological drought could be measured by a period of precipitation deficit and impacts on water supply such as streamflow and surface and subsurface water storages. Spatial and temporal scales must also be considered in defining drought. The variety of ways to define drought makes a simple assessment of drought severity a difficult task.

In this paper, we explore the severity of the 2002 drought, defined by a variety of moisture-related variables including precipitation, snowpack, streamflow, reservoir storage, and tree growth. Although the 2002 drought is considered by some to be the third of a three-year drought, here we focus on 2002 as a single year event. The definition of the year varies somewhat according to variable measured, but in general, we consider it from fall 2001 though summer 2002. Its impact is gauged on the regional to statewide level.

Figure 1 shows the magnitude of the drought as determined by the U.S. Drought Monitor (http://drought.unl.edu/dm/), where the western third of the state is in the highest (‘‘exceptional’’) category. In this display, drought has been defined based on the interpretation of available water deficit information by researchers at the National Drought Mitigation Center at the University of Nebraska at Lincoln, as well as input from a variety of experts in the field, including some of the co-authors of this paper. ‘‘Exceptional drought’’ refers to conditions found between once every fifty years or never before on record. This is one assessment of drought that our paper examines using a variety of analysis techniques.

2. An Evolution of the 2002 Drought in Colorado

The drought of 2002, with all of its devastating wildfires, profound water shortages and widespread crop losses, 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 entire western U.S. was by then engulfed in a severe drought that resulted in the largest severe wildfire season in the last century for the western U.S. (http://www.nifc.gov/stats/wildlandfire-stats.html). A persistently hot summer made the situation worse, as transpiration rates were considerably higher than average over irrigated areas.

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. While spring

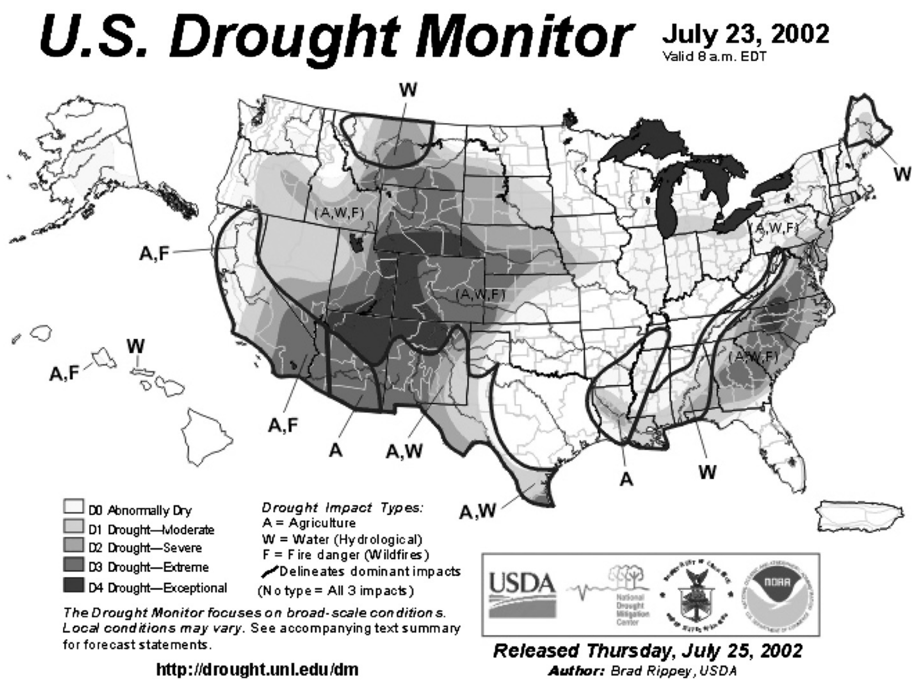


Figure 1
U.S. Drought Monitor for July 23, 2002 shows much of the state of Colorado in ''exceptional'' D4 drought (from National Drought Monitor, University of Nebraska – Lincoln, http://drought.unl.edu/dm).

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 C above average across the entire state. Beneficial moisture fell from two storm systems that primarily affected the 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 over 2 degrees C above average over southwest Colorado.

Early November was unseasonably warm and dry. Most mountain slopes and peaks remained bare. Then, just in time for the Thanksgiving weekend, the snow began to fly. 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, however, it was very helpful in starting the Colorado winter recreation season.

December brought many more opportunities for mountain snows, but most resulted in only a few centimeters 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 quite 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 millimeters 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 add 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 precipitation fell. 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 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 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, had dropped to 52% (Figs. 2 and 3). While not as bad as the winter of 1976–1977, these were still some very disappointing figures. Because of the heavy snows in late November, the seasonally cold temperatures and a relatively small precipitation deficit in the Front Range, and favorable publicity about good snow conditions for winter recreation, there was no strong public and government perception of a severe drought.

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 (Fig. 4), 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 30 miles southwest of Denver on April 23rd (Snaking Fire). For the month as a whole, precipitation was less than 50% the average over three quarters of the state (Fig. 5). Temperatures ranged from about average near the Nebraska border to over 4 degrees C 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 which enhanced evaporation losses beyond the seasonal average. 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 (Fig. 6). At a time of year when Colorado's rivers and streams are normally churning with snowmelt runoff, streamflow remained eerily placid. Irrigation water demand ramped up fast,

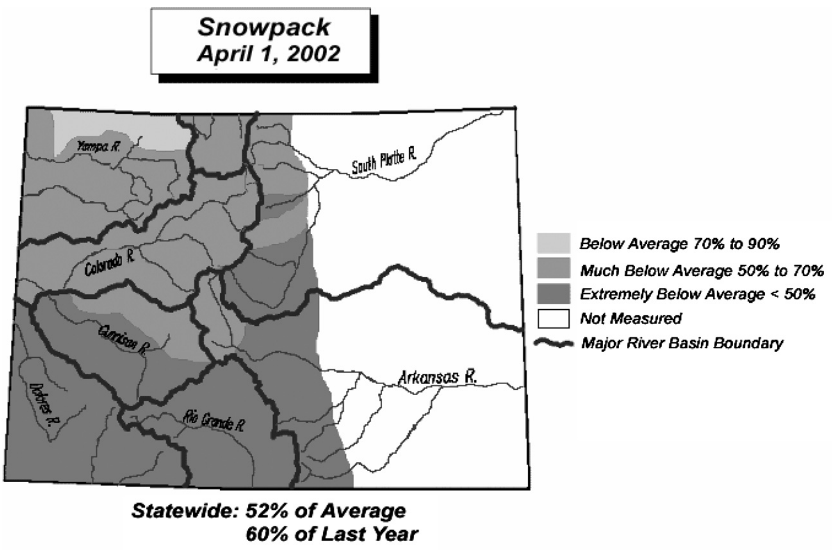


Figure 2
April 1, 2002 snowpack for state of Colorado (from the National Resources Conservation Service, NRCS, http://www.co.nrcs.usda.gov/snow/data/snmap402.html).

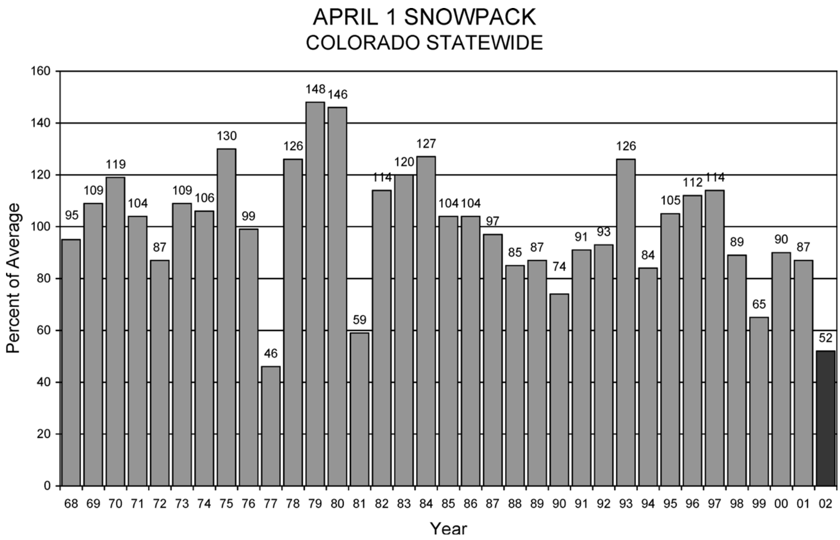


Figure 3
April 1 Snowpack percent of average for Colorado by year from 1968 through 2002 (from NRCS, Snow Survey Division).

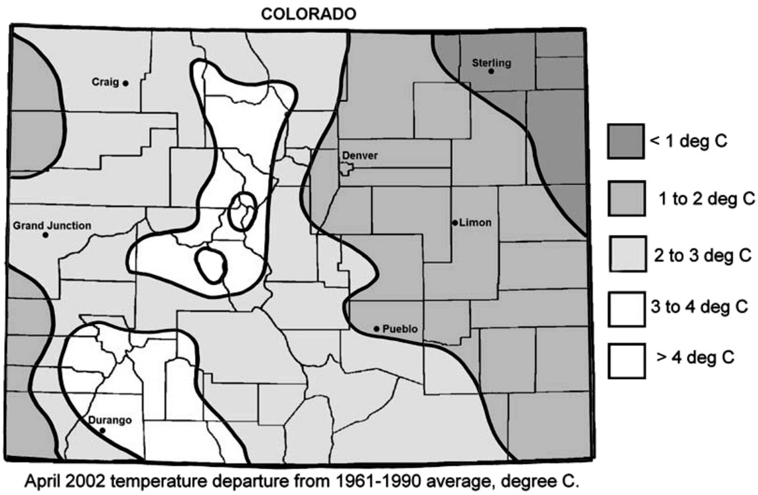


Figure 4
April 2002 temperature departures from the 1961–1990 average for the state of Colorado, USA (degrees C).

but it soon became obvious that supplies would not last through the growing season. Municipalities began to face the dire prospect that available water supplies might not provide for the typical summertime demand, so many areas began implementing

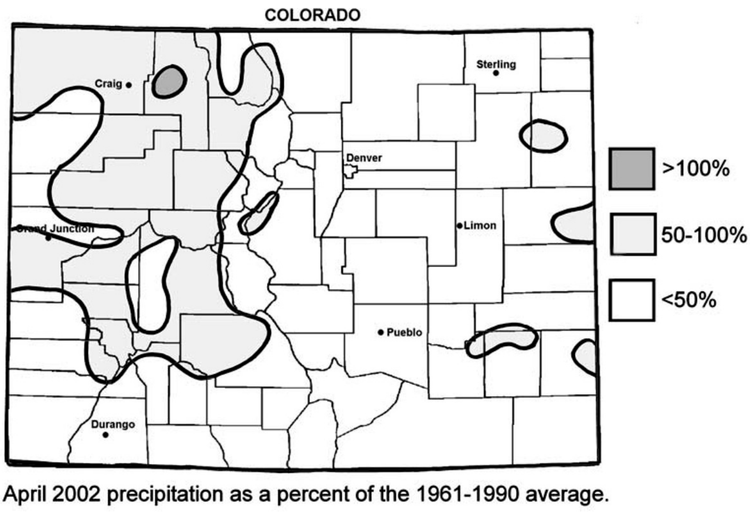


Figure 5
April 2002 precipitation as a percent of the 1961–1990 average for the state of Colorado, USA.

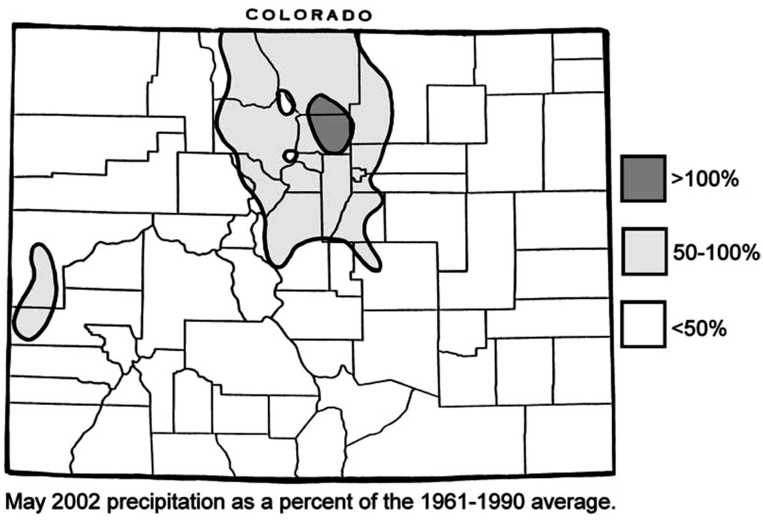


Figure 6
May 2002 precipitation as a percent of the 1961–1990 average for the state of Colorado, USA.

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 over much of the state. Temperatures routinely climbed to the 30–40° C range 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 of June over western Colorado (Fig. 7). East of the mountains, a few thunderstorms occurred and some locales enjoyed respectable rainfall amounts. Parts of Cheyenne County, for example, reported more than 100 mm 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 quickly sold or moved 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 (557 km^2) 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

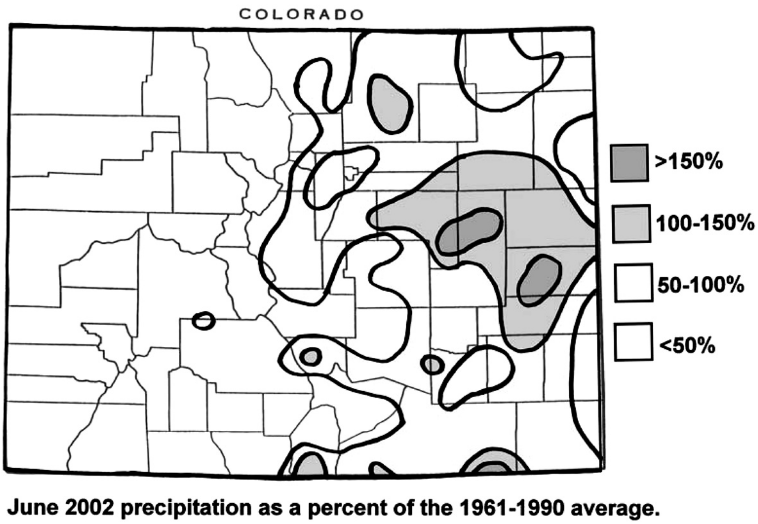


Figure 7
June 2002 precipitation as a percent of the 1961–1990 average for the state of Colorado, USA.

average rainfall for the month. But most areas remained dry. The eastern plains were parched with most stations 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 irrigation water supplies came to an end, and crop failure ensued. By late July, Colorado was in a very serious drought. Furthermore, drought conditions were not limited just to Colorado but extended over much of the Great Plains and Rocky Mountain States (Fig. 1). In hindsight, the drought pattern that evolved though July 2002 started 3–4 years earlier but intensified in the year 2002.

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. Temperatures during the day occasionally reached over 38° C temperatures in Front Range cities. As the month neared its end, 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.

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, grasses actually began to green up a bit. Quite a few stations accumulated at least double the average monthly rainfall. Even the bone-dry areas of southwest Colorado got some much appreciated moisture with some areas reporting over 100 mm 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.

Fig. 8 shows precipitation for the entire 2002 Water Year as a percent of the 1961–1990 average. For the first time since such records have been kept, the entire state was below average and the majority of the state was less than 70% of average. The driest areas of the state below 50% were Weld County, an area surrounding Colorado Springs, Pueblo and Rocky Ford, a section near Durango, and portion of the San Juan Mountains and east to Del Norte and Center. These areas generally covered the sites in Table 1 where 2002 Water Year was the driest year on record.

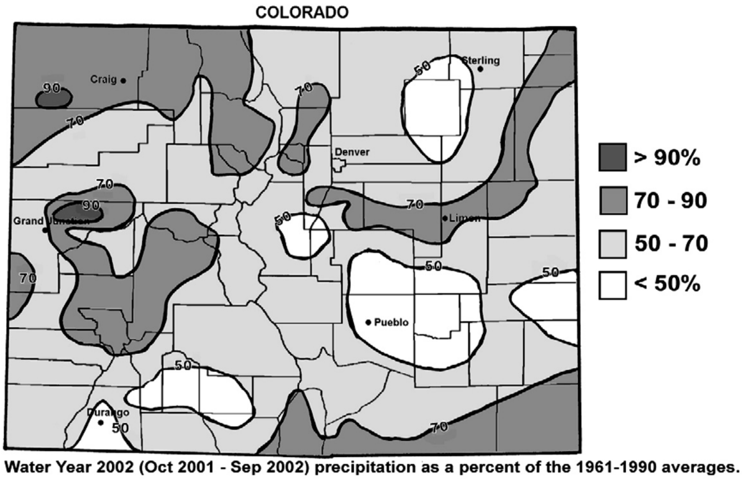


Figure 8
Water Year 2002 (October 1, 2001 – September 30, 2002) precipitation as a percent of the 1961–1990 average for Colorado, USA.

3. *Quantitative Analysis*

There is no question that the state of Colorado suffered a serious drought in 2002. The impacts to municipal water supplies, agriculture, recreation and streamflows were exceptionally severe. This section of the paper investigates the question as to whether or not the severity of water deficits were out of proportion to the actual precipitation deficit.

A. September 1, 2001 to August 31, 2002 Precipitation

The first evaluation concerns the observed precipitation in eight experimental Colorado climate divisions (Fig. 9) for the core period of the Colorado drought. These climate divisions are based on the similarity of historical precipitation anomaly patterns, and allow for a more representative assessment of Colorado climate anomalies than conventional NCDC climate divisions (WOLTER, 2003). Table 1 presents accumulated precipitation data for 12-month (Sep. 2001 – Aug. 2002), 13-month (Sep. 2001 – Sep. 2002) and 12-month 2002 Water Year periods (Oct. 2001 – Sep. 2002). The magnitude of the standard deviations below the average for each station for each time period are also shown. Two observing sites in each of the 8 regions were analyzed. Stations were ranked for the period-of-record and 1941–2002 time period (the longest period of record in common for all stations). While the time period available varies (the higher altitudes have shorter records), the data can place the 2002 drought in perspective.

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 Stations	Region	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)	mm	POR Rank	1941–2002 Rank (SD)	mm	POR Rank	1941–2002 Rank (SD)	mm
Grand Lake 1NW	1	1940–2002	1	1 (1.87)	319	2	2 (1.42)	407	1	1 (1.71)	327
Taylor Park	1	1941–2002	1	1 (2.02)	265	2	2 (1.65)	324	3	3 (1.51)	303
Grand Junction WSO	2	1892–2002	8	5 (1.39)	141	31	20 (0.63)	205	43	27 (0.34)	201
Meeker	2	1891–2002	7	5 (1.78)	263	8	6 (1.64)	303	7	7 (1.58)	276
Montrose No. 2	3	1896–2002	3	3 (1.54)	148	15	8 (1.02)	203	29	1 (0.80)	193
Mesa Verde NP	3	1923–2002	1	1 (2.30)	189	1	1 (1.97)	250	3	3 (1.79)	246
Del Norte 2E	4	1920–2002	1	1 (2.55)	81	3	3 (1.96)	132	3	3 (1.80)	119
Center 4 SSW	4	1891–2002	1	1 (2.69)	62	1	1 (2.20)	97	4	4 (1.92)	94
Colorado Springs WSO	5	1892–2002	1	1 (2.13)	165	1	1 (2.01)	198	2	1 (1.97)	172
Pueblo WSO	5	1891–2002	1	1 (2.65)	96	1	1 (2.64)	113	1	1 (2.56)	101
Rocky Ford 2SE	6	1892–2002	1	1 (2.33)	92	1	1 (2.36)	108	1	1 (2.31)	238
Cheyenne Wells	6	1897–2002	4	2 (1.67)	235	10	5 (1.39)	291	9	5 (1.48)	252
Akron 4E	7	1905–2002	1	1 (2.02)	239	1	1 (1.83)	277	1	1 (1.88)	95
Leroy 7WSW	7	1891–2002	4	2 (1.91)	269	4	2 (1.82)	294	4	2 (2.05)	243
Kassler	8	1899–2002	8	4 (1.49)	319	9	5 (1.44)	351	6	4 (1.48)	309
Fort Collins	8	1890–2002	3	2 (1.96)	200	3	2 (1.84)	237	5	4 (1.66)	214
Stations Ranked Driest			**9**	9		6	6		4	6	

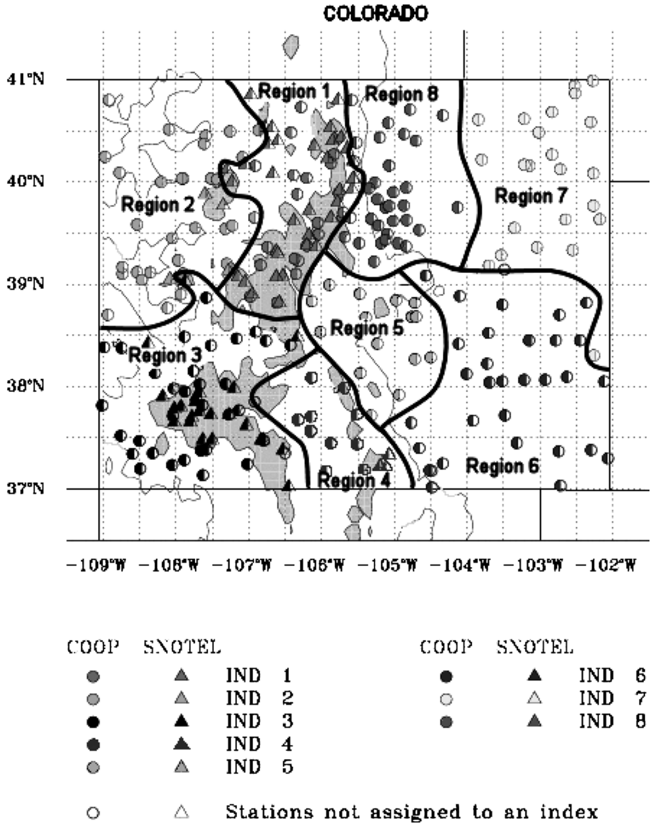


Figure 9
Climate divisions for the state of Colorado (from Klaus Wolter, NOAA-CIRES Climate Diagnostic Center).

For 9 of the 16 sites, the 12-month time period of September 1, 2001 to August 31, 2002 was the driest for the period-of-record and the 1941–2002 record. Table 1 also presents the 13-month time period with September 2002 added. This month was obviously relatively wet, as only 6 sites were the driest during the period-of-record and the 1941–2002 period. Using the 2002 Water Year (October 1, 2001 to September 30, 2002), 4 of the 16 sites were the driest of record (or 5 of the 16 sites for the 1941–2002 ranking). Clearly, the time period examined (even shifted by one month or adding a month) provides a different perspective on the severity of the precipitation deficit in Colorado. Grand Junction, for example, was 1.39 standard deviations below the mean for the September 2001 to August 2002 time period, but this was reduced to 0.34 standard deviations below the mean for the Water Year and 0.63 for the September 2001 to September 2002 time period.

If we assume the precipitation for 12-month and 13-month time periods follows a normal probability distribution and adopt a probability of 1% or less as being exceptional, for the period September 2001 to August 2002, 5 of the 16 stations were in this category (Del Norte, Center, Mesa Verde, Pueblo, and Rocky Ford). The assumption of a statistical normal distribution is appropriate for time scales longer than 12 months (McKee et al., 1993). We apply this assumption for our 12-month and 13-month data sets since the data should be at least close to this distribution. For the Water Year and the period September 2001 to September 2002, 2 sites (Pueblo and Rocky Ford) were in this class out of the 16 sites. Using a 5% or less probability, for the period September 2001 to August 2002, 13 sites were in this category. For the Water Year, 10 were in this class, while for the 13-month time period, 11 were in this class. To place these probabilities in context, a 5% probability means that there is a 1 in 20 chance of precipitation being below the observed value for that time period, while a 1% probability indicates a 1 in 100 chance. This analysis suggests that most of these precipitation observing sites had a serious drought but the deficit, even in the core period of the drought, was not exceptional. Of course, in making this conclusion, we are accepting these station as being representative of their respective climate divisions.

In all three time periods evaluated, over the common interval of record and using the actual observed data rather than the standard deviations to determine whether the drought was exceptional, four stations consistently ranked the driest (Colorado Springs, Pueblo, Rocky Ford, and Akron), suggesting that this drought, as a single year ranks as the most severe precipitation deficit on record for some of south central and southeastern Colorado and a small portion of the South Platte Basin in northeastern Colorado. For these four locations, the deviations from the mean for the September 2001 to August 2002 time period in terms of the standard deviation were 2.13, 2.65, 2.33 and 2.02 below the average, respectively. To place these values in context, assuming a normal probability distribution, a value of 2.65 would have a probability of occurrence of 0.4% in any one year. Even for the Water Year and for the September 2001 to September 2002 time period, the precipitation was more than two standard deviations below average except for Colorado Springs (-1.97 for the Water Year) and Akron (-1.88 for the Water Year and -1.83 for the 13 months).

In the historical perspective, the Dust Bowl years of the 1930s were more severe over parts of the Eastern Plains of Colorado, while the northern Front Range of Colorado was drier in the mid-1950s. Based on the instrumental record, however, observed statewide precipitation anomalies in 2001–2002 were among the most severe of the last century. Ironically, the most populated region of the state, the northern Front Range (region 8 in Fig. 9) had the least severe precipitation deficit, but was affected by harsher drought conditions over the upstream mountains (region 1). The use of a statewide average, of course, masks the actual variations with Colorado which is why we choose to use climate divisions within the state.

B. Cumulative Precipitation Plots

The 2002 Water Year data presented in Table 1 can be presented on a month-by-month basis, along with cumulative series of the 30-year average, the driest year, and the wettest year (Fig. 10). These plots show the absence of wet months for the period October 1, 2001 to September 30, 2002. The cumulative precipitation values for the 2003 Water Year illustrate the recovery for much of the state, while the southwestern part of the state, in particular, remained in a precipitation deficit, albeit not as severe as the previous year.

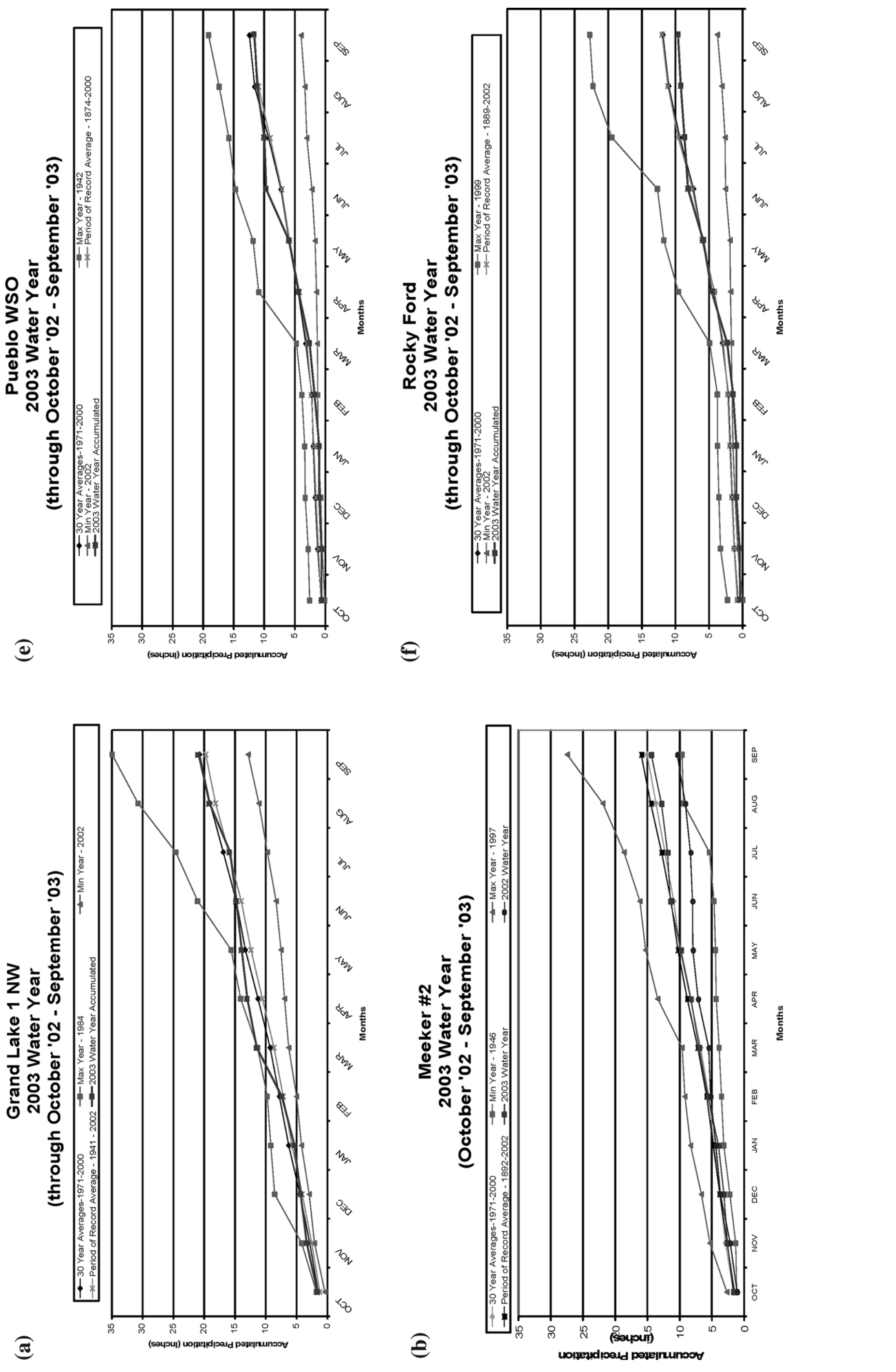
C. Snowpack

Figure 11 presents the snowpack for the major water basins in Colorado during the first half of 2002, while Figure 12 presents the cumulative plot for the years 1999–2000, 2000–2001, 2001–2002, 2002–2003, as well as the average. The deficit for 2001–2002 is clearly evident, including the early melt of the snowpack. Thus, the 1 April 2002 statewide average that was the second lowest after 1977 (Fig. 3), fell to the lowest level on record (since 1968) by 1 May 2002. By comparison, the 1977 snow drought was embedded in a string of near-average to above-average years (Fig. 3), thus minimizing its impact on the state in terms of reservoir management. It is noteworthy that the last four snow seasons depicted here share an early melt-out date along with below-normal snowpack for most of the season. This increases the length of time that snowmelt water is exposed to evaporative losses in open reservoirs. Thus not only was the snow accumulation particularly below average in 2002, the early loss of snow prevented it from being used later in the spring season. Moreover, the wet years that occurred before this drought promoted vegetation growth, which increased the transpiration demand for water. Such an increase of transpiration would reduce the amount of water available for river runoff.

Figure 13 illustrates the regional temperature departures for the 2002 Water Year. For the month of April 2002, these warmer than average temperatures explain the early snow melt in the mountains, as well as a more rapid than usual physical evaporation and transpiration of what little soil moisture existed in the soil throughout the state.

▶

Figure 10
Cumulative precipitation totals for 2002 Water Year, 2003 Water Year, 30-year average, and maximum and minimum years for regions (a) Grand Lake, (b) Meeker, (c) Mesa Verde National Park, (d) Center, (e) Pueblo, (f) Rocky Ford, (g) Akron and (h) Fort Collins, Colorado. One inch = 25.4 mm.


(e)
Pueblo WSO
2003 Water Year
(through October '02 - September '03)
30 Year Averages-1971-2000
Min Year - 2002
2003 Water Year Accumulated
Max Year - 1942
Period of Record Average - 1874-2000
(f)
Rocky Ford
2003 Water Year
(through October '02 - September '03)
30 Year Averages-1971-2000
Min Year - 2002
2003 Water Year Accumulated
Max Year - 1999
Period of Record Average - 1889-2002
(a)
Grand Lake 1 NW
2003 Water Year
(through October '02 - September '03)
30 Year Averages-1971-2000
Period of Record Average - 1941 - 2002
Max Year - 1984
2003 Water Year Accumulated
Min Year - 2002
(b)
Meeker #2
2003 Water Year
(October '02 - September '03)
30 Year Averages-1971-2000
Period of Record Average - 1892-2002
Min Year - 1946
2003 Water Year
Max Year - 1997
2002 Water Year
Accumulated Precipitation (inches)
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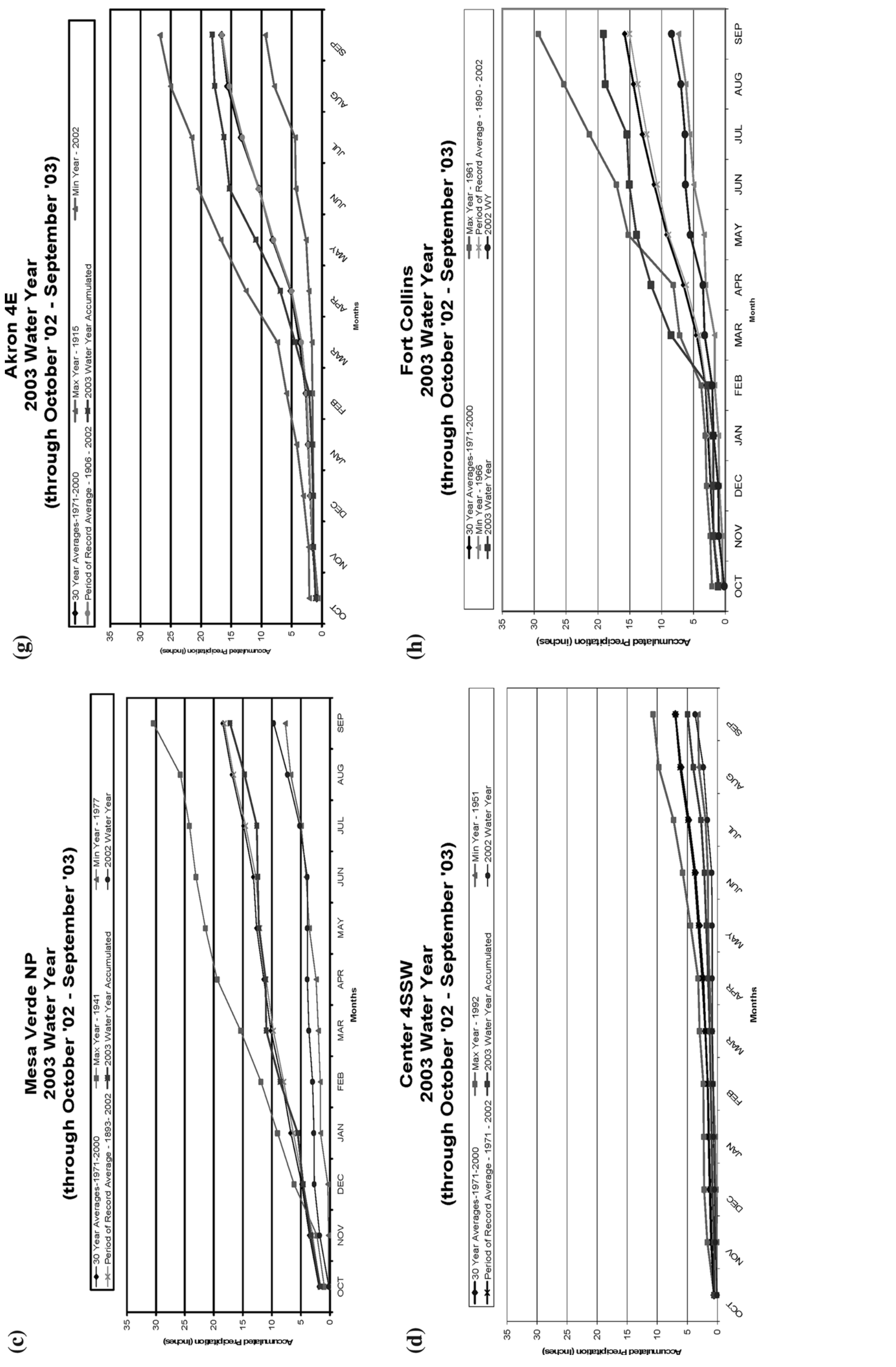

(c)
Mesa Verde NP
2003 Water Year
(through October '02 - September '03)
30 Year Averages-1971-2000
Period of Record Average - 1893 - 2002
Max Year - 1941
2003 Water Year Accumulated
Min Year - 1977
2002 Water Year
Accumulated Precipitation (inches)
Months
(d)
Center 4SSW
2003 Water Year
(through October '02 - September '03)
30 Year Averages-1971-2000
Period of Record Average - 1971 - 2002
Max Year - 1992
2003 Water Year Accumulated
Min Year - 1951
2002 Water Year
Accumulated Precipitation (inches)
Months
(g)
Akron 4E
2003 Water Year
(through October '02 - September '03)
30 Year Averages-1971-2000
Period of Record Average - 1906 - 2002
Max Year - 1915
2003 Water Year Accumulated
Min Year - 2002
Accumulated Precipitation (inches)
Months
(h)
Fort Collins
2003 Water Year
(through October '02 - September '03)
30 Year Averages-1971-2000
Min Year - 1966
2003 Water Year
Max Year - 1961
Period of Record Average - 1890 - 2002
2002 WY
Accumulated Precipitation (inches)
Month

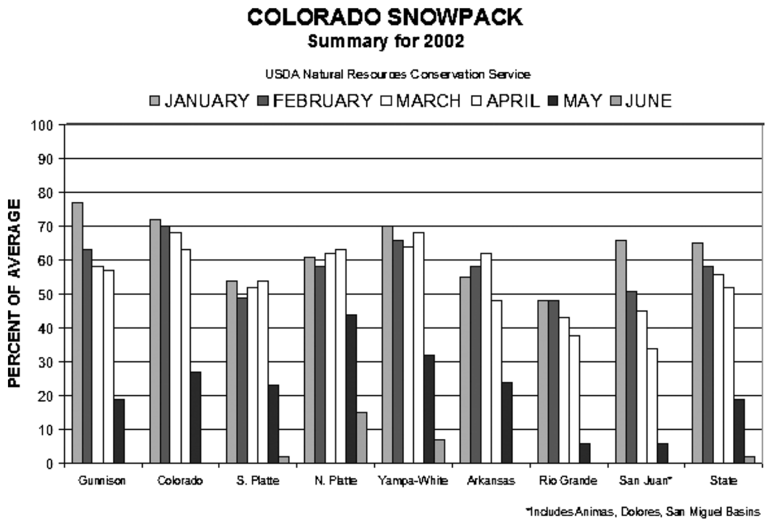

Figure 11
Colorado basin snowpack as a percent of average for months January to June 2002 (from USDA, NRCS).

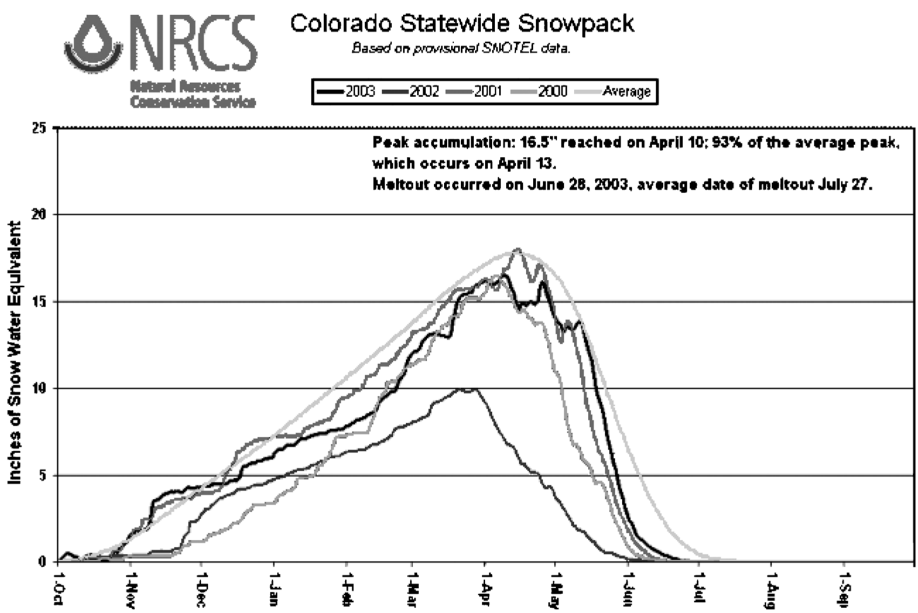

Figure 12
Cumulative statewide snowpack for Colorado for years 1999–2000, 2000–2001, 2001–2002, 2002–2003, and average (from USDA, NRCS). One inch = 25.4 mm.

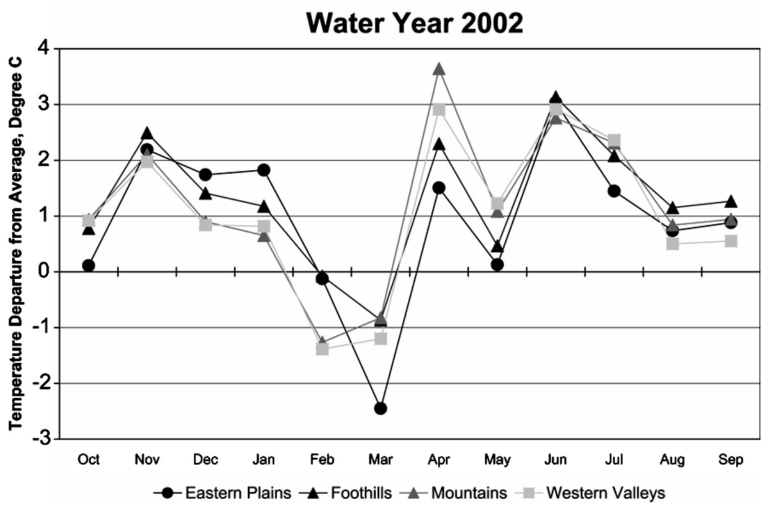

Figure 13
Temperature departures from average for the 2002 Water Year for the Eastern Plains, Foothills, Mountains and Western Valleys. Notice the warm temperatures for April 2002 in the Mountain region, greater than 3°C above average.

D. Streamflow

From the water resources perspective, streamflow is a key hydrological process that summarizes various atmospheric, land surface, and subsurface components of the hydrologic cycle. It is particularly useful for water resources managers because it reflects the water that may be available at a given diversion point of a stream or may be entering lakes and reservoirs. Because water supply hydraulic structures are generally designed to meet projected water demands, drought analysis typically involves the relationship of both water supply and water demand. Thus, when streamflow in a given time period becomes smaller than the demand, a deficit occurs and a sequence of continuous deficits may become a hydrological drought. To illustrate this issue for Colorado, this section presents a detailed example of the severity of the deficit in the Water Year 2001–2002 taking as example the streamflow data of the Poudre River.

The time series of naturalized annual flows of the 2002 Water Year (Oct. 2001 - Sept. 2002) for the Poudre River in northeastern Colorado at the Mouth of the Canyon station for the period 1884–2002 is shown in Figure 14. It indicates that the Water Year 2002 had the lowest flow in the historical record. Streamflow records for the major river basins in the state showed similar decreasing flows throughout the period 1999–2002 with the Water Year 2002 being the smallest or near the smallest on record. Considering that the average annual flow for the entire record is about 299,011 acre-ft., the time series in Figure 14 shows a wet period of about 40 years in

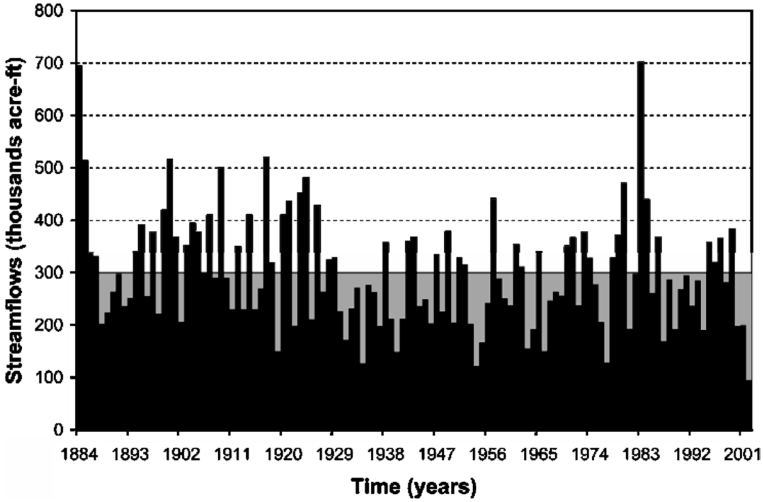

Figure 14
Annual flow records of the Poudre River for the period 1884–2002. The figure shows some extreme drought events such as those in the 1930s, 1950s, and the drought of the 2000s. Note that the 2002 flow is the smallest value in the entire record (after SALAS *et al.*, 2005). One acre-ft = 1233.5 cubic meters.

the first part of the record and a drier period in the rest of the record. In addition, the time series indicates that various drought episodes have occurred in the Poudre River throughout the historical record, such as those of the 1930s, the 1950s, as well as the 3-year drought in the period 2000–2002. Because the standard deviation of the annual flows is 106,512 acre-ft, the 2002 streamflow (95,000 acre-ft) is 1.9 standard deviations below the mean. However, the annual streamflows are somewhat skewed (0.98), so perhaps a better picture of the drought severity in that year may be obtained from the transformed annual flow data. In such cases, the 2002 transformed annual flow is 40.2, which is 2.8 standard deviations below the mean (of the transformed flows). Either case illustrates the severity of the drought in that year. Also Figures 15 (a) and (b) show respectively in the original and transformed flow domains, the plots of the monthly streamflows during the Water Year 2002 compared to the long-term mean monthly flows, the mean monthly flows minus one monthly standard deviation, and the mean monthly flows minus two monthly standard deviations. Clearly, both Figures 15 (a) and (b) show that the monthly flows for the year 2002 especially for the months of May, June, and July are significantly low.

To characterize further the severity of the 2002 drought, we use the concept of return period (mean recurrence interval). For our study the 119 years of historical annual streamflow data were statistically analyzed and the first-order autoregressive (AR-1) model fitted to the transformed flows. The model was tested based on various fitting techniques and comparing certain statistics obtained from the historical and

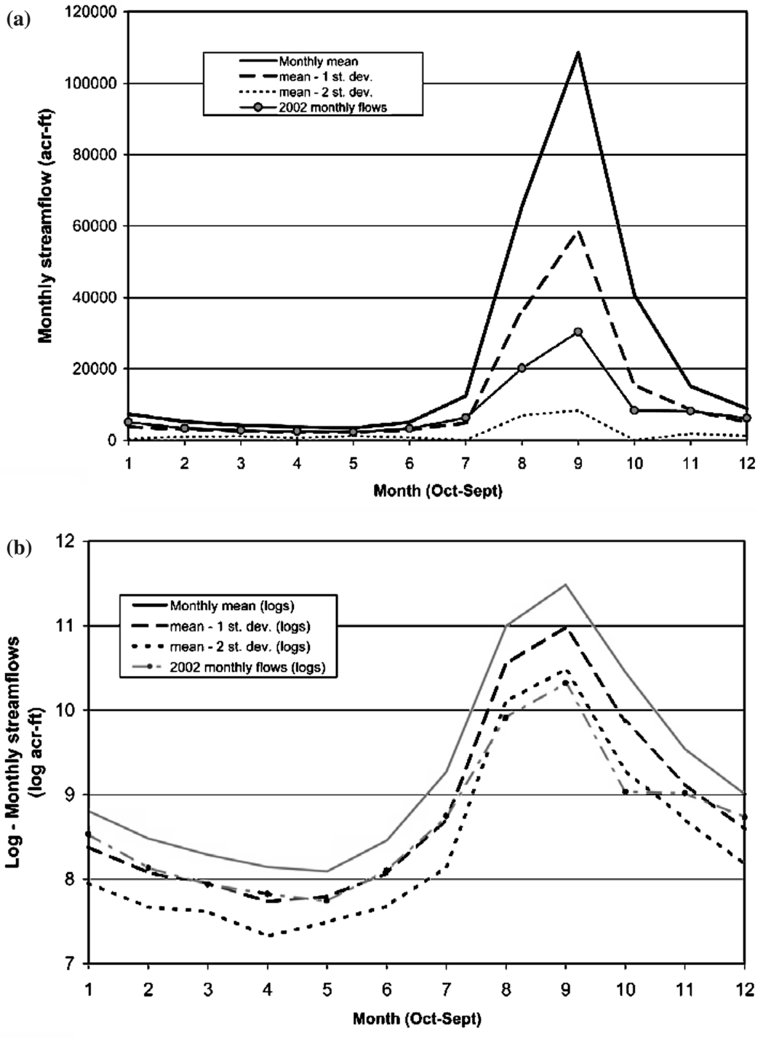

Figure 15
Comparison of the 2002 monthly flows of the Poudre River versus the monthly mean, monthly mean minus one standard deviation, and monthly mean minus two standard deviations in the (a) original flow domain and (b) the log-transformed flow domain. Note the significant low flow conditions especially for the 3-month period May, June, and July. One acre-ft = 1233.5 cubic meters.

generated samples (e.g., SALAS, 1993). The AR(1) model was then used for simulating a 200,000-year sample from which drought severity was determined. For ease of reference, we use the following notation. The deficit threshold D_0 is defined as a fraction of the threshold water demand x_0, i.e. $D_0 = \lambda x_0$, so that for a single year drought $0 \leq \lambda \leq 1$, and λ is called the deficit coefficient. The water demand threshold used for the drought analysis of the Poudre River is the long-term mean, i.e.,

$x_0 = 299,011$ acre-ft and the deficit threshold D_0 is the drought in the year 2002 that reached a deficit of 204,011 acre-ft, i.e., $\lambda = 0.682$.

Given that we are concerned with characterizing the severity of a single year drought event, it may be tempting to estimate the return period of the 2002 Water Year deficit (204,011 acre-ft) by the usual frequency analysis of the historical deficits. This analysis will give an estimate of about 120 years of return period. However, because the data are autocorrelated such an approach would not provide an accurate estimate of the return period. Thus, we estimated the return period of 1-year droughts exceeding a specified level of deficit based on the concept of mean interarrival time. The estimated return periods for various levels of deficit are shown in Figure 16 for both the generated and the historical data. Only a few points are shown for the historical data because of the lack of enough drought events from which to calculate the return periods. Nevertheless Figure 16 shows a close agreement between the generated and historical results. Thus, from Figure 16 the estimated return period of the 2002 drought with deficit of 204,011 acre-ft is *436 years*! In conclusion the analysis of this river (and other rivers in the state appear to have such extreme deficiencies of flow), shows that the impact of this drought was exceptional with respect to water supplies.

E. Reservoir Storage

The snowpack deficit, and resultant reduced river flow, of course, would be expected to result in less reservoir storage. As discussed in Section C above, the

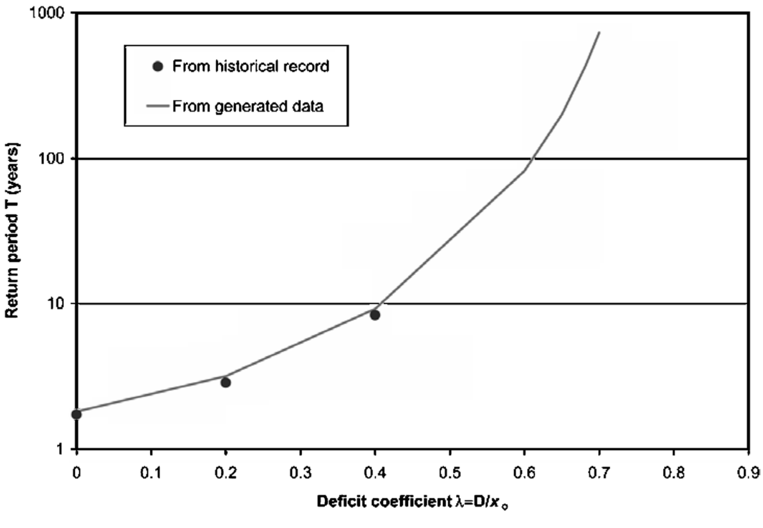

Figure 16

Comparison of the return period (T) of single-year deficit obtained from the generated flow record versus the T obtained from the historical record for various values of the deficit coefficient λ.

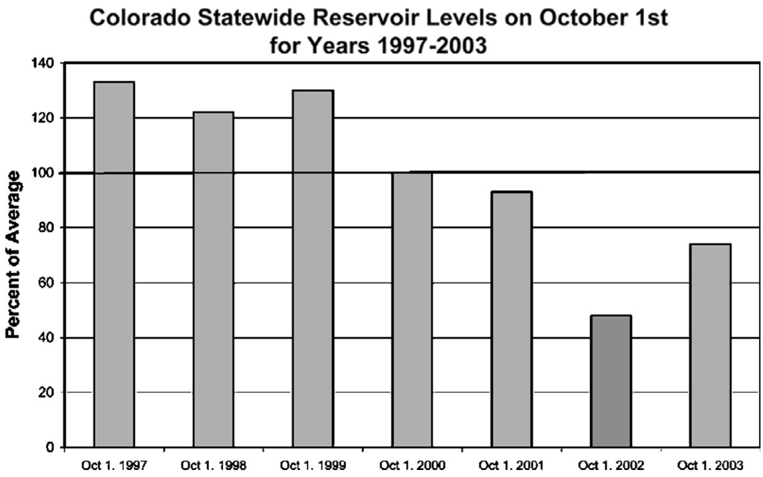

Figure 17
Colorado statewide reservoir storage levels as a percent of average for the end of the growing season (from the NRCS).

warmer than average maximum temperatures shortened the melt season, as well as resulted in greater evaporation losses. The reservoir storage percentage at the end of the growing season in 2002, shown in Figure 17, shows the lower than average volume for the state. As the warm, dry growing season continued in 2002, the large depletion of water storage as a result of above average irrigation and municipal water demand resulted in the implementation of water restrictions, as discussed in Section 2.

F. Paleo-historical Perspective

Instrumental records of precipitation, snowpack, and reservoir storage provide a temporal context for assessing the 2002 drought that ranges from several decades to slightly more than a century, depending on the record. This time frame can be extended with paleoclimatic proxy data, which document a potentially broader range of natural climate variability. In much of the western U.S., lower elevation coniferous trees have proved to be excellent proxies for hydroclimatic variability, as tree growth at lower elevation generally responds to variations in available moisture. In Colorado, variations in tree-ring widths of these conifers are closely correlated to seasonal precipitation (spring in particular) as well as metrics that integrate climate conditions prior to and/or concurrent with the growing season, such as total water year flow and winter snowpack. Thus, variations in tree-ring widths are a proxy for past moisture variability and can be used to reconstruct past climate. In western Colorado, tree-ring data have been useful for high-quality reconstructions of Water Year streamflow, April 1 snow water equivalent (WOODHOUSE, 2003), the Standard

Precipitation Index (SPI), and seasonal precipitation, indicating tree sensitivity to drought measured in a number of ways.

Twelve tree-ring chronologies from sites in the basins of Gunnison River and the main stem of the Colorado River were resampled in June, 2003 to update them to 2002. Each chronology is comprised of dated and measured series from about 20–30 trees (two samples per tree) which have had growth trends and high order autocorrelation, both related primarily to biological factors, removed (FRITTS, 1976; COOK and KAIRIUKSTIS, 1990). The start dates of the tree-ring chronologies range from A.D. 1135 to A.D. 1440, allowing an assessment of the 2002 ring width within the time frame of last five to eight centuries. When evaluated for the 20th century (1900–2002), 2002 is the narrowest ring in just three of 12 chronologies, but when the 12 chronologies are averaged together, 2002 is the narrowest ring, followed by 1902, 1977, and 1954. When the 12 chronologies are averaged for the full common chronology period, 1440–2002, 2002 is the third narrowest out of 563 years. In individual chronologies, 2002 ranks in the narrowest 6th percentile to the narrowest half a percentile, so it is clearly a very low growth year even in the context of 500–800 years. The two narrowest rings in the 12-chronology average are 1685 and 1851. Thus, 2002 is the narrowest tree-ring width in the Gunnison/Upper Colorado region of western Colorado in 150 years, reflecting drought severity as defined by tree growth. Preliminary results suggest 2002 tree growth was at least as suppressed in most areas of the Front Range as well.

4. *Conclusion*

The evaluation of the severity of the 2001–2002 drought varies according to variable measured and spatial scale considered. Although this paper presents only a subset of the data that recorded this drought in Colorado, some conclusions can be drawn.

From a precipitation perspective, the 2001–2002 drought in Colorado was almost certainly not a statewide record; however, it was the driest for the available period September 1, 2001 to August 30, 2002 record for 9 of 16 representative sites. However, shifting this period by just one month, or adding one month, eliminated the majority of the observing sites from the driest on record. Nonetheless, for some parts of the state (the southern Front Range in particular), it was the most severe single drought year in the instrumental record (back to the late 19th century).

For statewide snowpack, low seasonal snowpack and warm April temperatures resulted in early snowmelt and losses due to evaporation in 2002, but 1977 was a year of comparable severity in the 35-year record available (as defined by the April 1 snowpack), followed by 2002. By May 1, however, the 2002 snowpack was reduced to below that of 1977. These dry and warm conditions are reflected in streamflows and reservoir storage, which integrates conditions from previous years. Streamflow records for the major river basins in the state showed similar decreasing flows throughout the period 1999–2002 with the Water Year 2001–2002 being the smallest or near the smallest on record. As an example, the analysis of the 119 years of streamflow records for the Poudre River showed that the severity of the water deficit in the Poudre in the Water Year 2002 was of the order of 400+ years return period which confirms the severity of this aspect of the drought. 2002 shows to be a year where a particularly severe water shortage had developed.

The tree-ring record, providing a longer-term context for evaluating 2002, shows tree growth for a large portion of western Colorado to be the lowest in 150 years. This small growth increment, as with snowpack, streamflow, and reservoir storage, reflects the cumulative effect of both moisture deficits and warm temperatures.

Although precipitation deficits were not exceptional in all areas of the state, evaporation losses, hot temperatures, and higher than average municipal and irrigation demand, resulted in a drought event that severely impacted many economic sectors in Colorado, and provided a "wake-up call" for many Colorado water management agencies.

The magnification of the impacts, therefore, with respect to the actual precipitation deficit indicates Colorado society is now more vulnerable to short-term drought than in the past. This sobering message is the one the policy makers need to digest and react to.

Acknowledgements

This work was supported by the Colorado Climate Center under the Colorado Agricultural Experiment Station, the Drought Analysis and Management Laboratory of Colorado State University, as well as the Western Water Assessment (WWA) project, funded through NOAA-Office of Global Programs, and the Denver Water Board.

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(Received November 12, 2003, accepted March 5, 2004)