Water Supply

Chapter 4 examines Colorado's water supply. Our state's water supply consists of both surface water and groundwater sources, and these supplies are dependent upon complex interactions among geography, weather, and laws and regulations—all of which influence how much water is available for beneficial uses. In Colorado, groundwater accounts for approximately 17 percent of water use, while surface water supplies the remaining 83 percent. Colorado's river and streamflows are highly variable, both seasonally and annually, and provide surface water and replenish alluvial groundwater supplies.

The quality of surface water and groundwater also influences the amount available for different types of uses. As Chapter 2 describes, the use of groundwater and surface water is subject to different management institutions.

Maroon Bells snowpack reflected in Maroon Lake. The Bells are the most photographed mountains in the country.

The Waters of Colorado

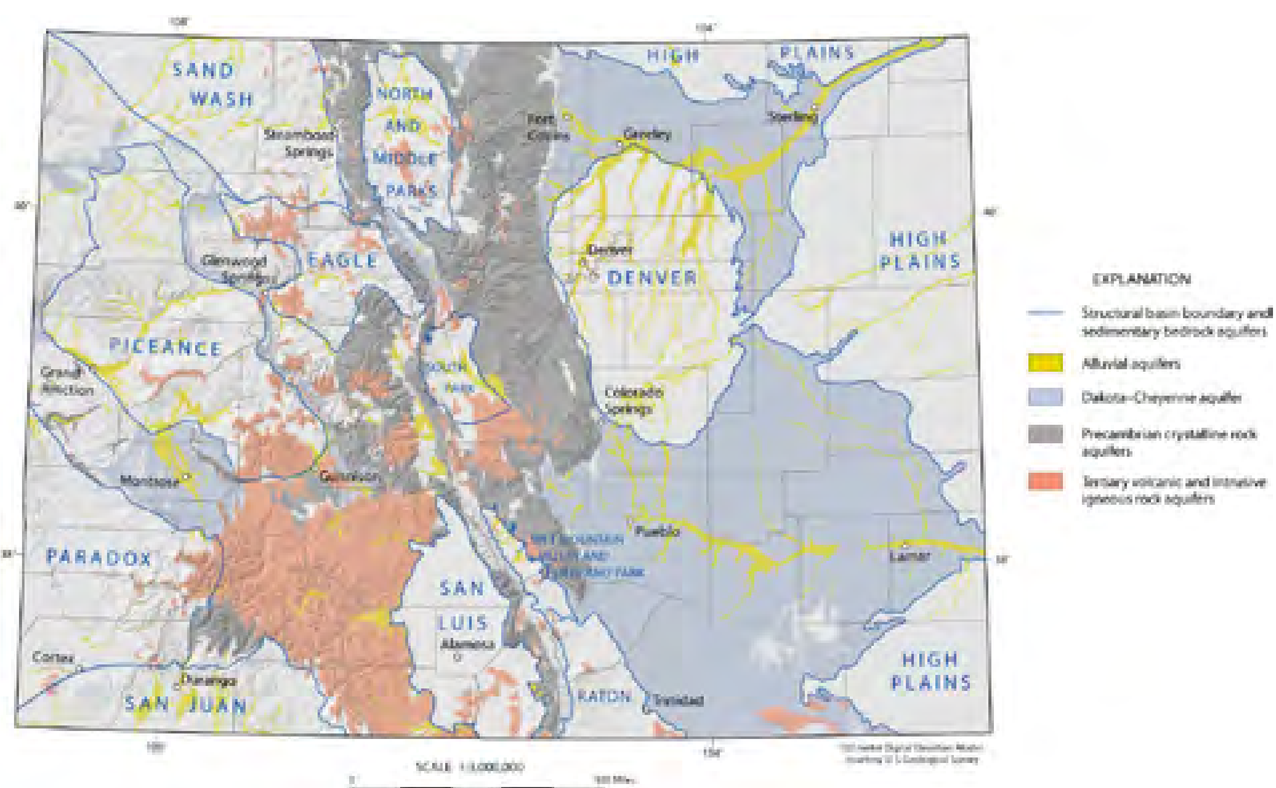
Colorado's geography is diverse, with terrain that ranges from the low-lying plains of Holly at 3,392 feet, to the high peak of Mt. Elbert; at 14,440 feet, Mt. Elbert is the highest peak in the contiguous Rocky Mountain states. The entire state of Colorado resides above 3,300 feet, with a mean elevation of 6,800 feet, the highest of any state.[1] This variability influences precipitation amounts and patterns across the state.

Many major rivers originate in the high Rocky Mountains, and collectively account for 70 percent of Colorado's surface water. These rivers flow east, west, north, and south from Colorado's mountains and plains out of the state, through 18 downstream states and Mexico, and into the Gulf of Mexico or the Pacific Ocean. Four major river systems begin in Colorado: the Arkansas, the Colorado, the Platte, and the Rio Grande.[2]

Colorado has eight primary river basins that span the state: South Platte; North Platte; Arkansas; Rio Grande; Gunnison; Colorado; the Northwest Basin, which includes the Yampa, White, and Green Rivers; and the Southwest Basin, which comprises the Dolores, San Juan, and San Miguel Rivers. The Republican River also begins in Colorado. These basins are dependent on winter snowpack and spring runoff to replenish and sustain their flow which, on average, produce approximately 15 million acre-feet of water annually. Of that, our state consumes roughly 5 million acre-feet, and approximately 10 million acre-feet flows out of Colorado to neighboring states.

The western side of the Continental Divide contains 70 percent of the surface water and 11 percent of the population.[3] The eastern side of the Continental Divide consumes 70 percent of the state's water. [4] As a result, many reservoirs on the western slope serve communities and demands along the Front Range and eastern plains.[a] Water managers rely on networks

FIGURE 4-1 PRINCIPAL AQUIFERS AND STRUCTURAL BASINS OF COLORADO



[a] The western slope includes the Gunnison, Colorado, Yampa/White/Green River basins, and the basin of the Southwest, composed of the Dolores, San Juan, and San Miguel Rivers. The Rio Grande, North and South Platte, Arkansas, and Republican River basins are included in the calculations for the eastern slope. If the Rio Grande Basin is included in the western slope, then western slope water increases closer to 80 percent, which is the figure traditionally used. Nevertheless, since the Rio Grande is not truly west of the Continental Divide, 70 percent is a more accurate figure.

of reservoirs, pumps, tunnels, and ditches to store and move water and to meet demands at peak times. They also must comply with relevant environmental mitigation requirements to maintain ecosystem health. Demand management strategies can help alleviate stress on the system under both normal operating conditions and during shortages, as Chapter 6.3 discusses.

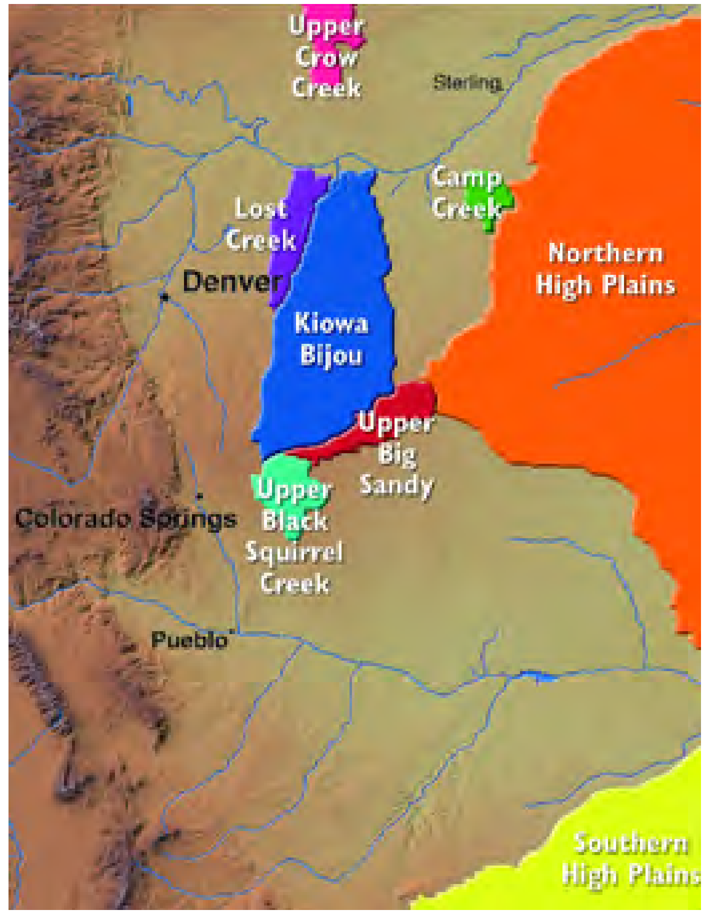
Groundwater plays a major role in the statewide water supply. Nineteen of Colorado's 64 counties and about 20 percent of the state's population rely heavily on groundwater.[5] Most of the groundwater use occurs in the eastern part of the state and in the Rio Grande Basin. The western slope has not developed groundwater to the same extent.

Groundwater resources exist throughout the state in alluvial, sedimentary, and crystalline rock aquifers (Figure 4-1).[6] Alluvial aquifers occur along many of the state's streams and are usually tributary to the stream, in which case the groundwater is administered as part of the stream system. Alluvial aquifers in designated groundwater basins are an exception, and fall under the management and control of the Colorado Ground Water Commission. Designated groundwater basins include eight areas in the eastern part of the state that rely primarily on groundwater, having minimal to no surface water supplies (Figure 4-2). Sedimentary aquifers occur throughout the state, and include multi-aquifer systems such as the Denver Basin and Dakota-Cheyenne aquifers. Crystalline rock aquifers are found in most of the foothills and mountainous areas of the state. Primarily recharged by snowmelt into fractures in the rock, these aquifers have a low storage capability and are usually limited to domestic use.

Groundwater aquifers offer benefits through their natural infrastructure and their protection from evaporation. Nevertheless, relying on groundwater as a primary supply may be challenging due to uncertain and varied natural recharge rates. In some aquifers, such as those in the Denver Basin, the natural recharge rate is very low compared to extraction rates, so groundwater is considered a nonrenewable resource.

Both alluvial and bedrock aquifers offer potentially significant groundwater storage capability. The total, potentially available capacity statewide is approximately 10 million acre-feet of alluvial aquifer storage and more than 150 million acre-feet of bedrock aquifer storage. Many potential storage sites, however, are located far away from significant recharge water sources, and only a few applications of managed groundwater storage exist in Colorado; most are located in the Denver Basin aquifers. Colorado developed rules allowing for recharge and long-term storage in the nontributary Denver Basin aquifers, but there are currently no comparable rules for storage in alluvial aquifers. The State differentiates groundwater recharge for augmentation purposes from groundwater recharge for storage purposes. Recharge in shallower, unconfined alluvial aquifers is physically easier than in the deeper-confined bedrock aquifers. In contrast to recharge for augmentation, storage in alluvial aquifers may be more difficult to manage—and potentially more short-term—because of the transient nature of groundwater flow in tributary alluvial aquifers. While groundwater storage has its advantages, such as lack of evaporation, it also has its challenges, including slow recharge rates and challenges associated with controlling the recharged water, retrieving the water, and delivering the water to the customer.

FIGURE 4-2 DESIGNATED GROUNDWATER[5]



Variability in Water Supplies

Precipitation varies in both amount and distribution across the state, and elevation and the orientation of the mountains and valleys influences it (Figure 4-3). While some regions of the state, such as the San Luis Valley, receive just seven inches of precipitation annually, other regions, such as Wolf Creek Pass, experience an annual average of more than 60 inches of precipitation. Overall, Colorado receives an average of 17 inches of precipitation each year. In general, the mountains receive more precipitation than the eastern plains, and winters are typically wetter than summers. Despite high precipitation during the winter months, demand for water is highest during the summer months and in the growing season.[7]

Our state's variable precipitation patterns have resulted in considerable hydrologic fluctuation, and floods and drought are possible within the same year. In 2011 and 2013, Colorado experienced both extreme flooding and severe droughts during the same periods. These variations from basin to basin may differ by thousands of acre-feet. Furthermore, basin streamflow is not equally distributed across the state, so a low flow in one basin may be greater than a high flow in another, as is the case with the Colorado River and the Southwestern Basins (Figure 4-5).

FIGURE 4-3 **AVERAGE PRECIPITATION IN COLORADO (INCHES) 1981-2010**

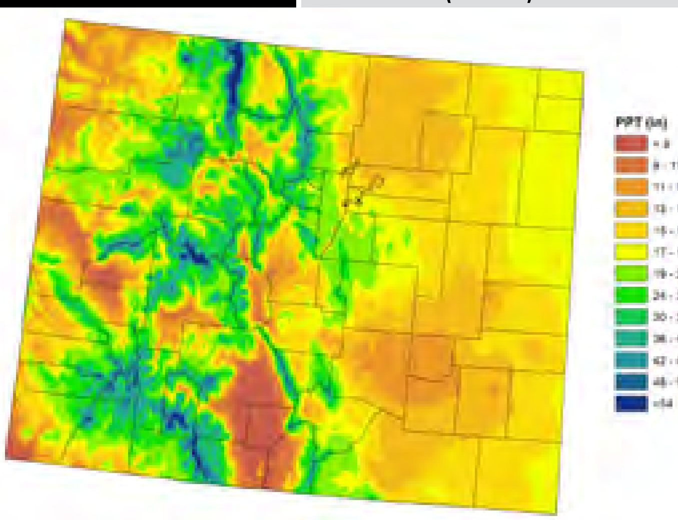


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FIGURE 4-4 **HYDROLOGIC CLASSIFICATION CRITERIA**

Percentile range used to define drought, dry, average, wet, and flood condtions.

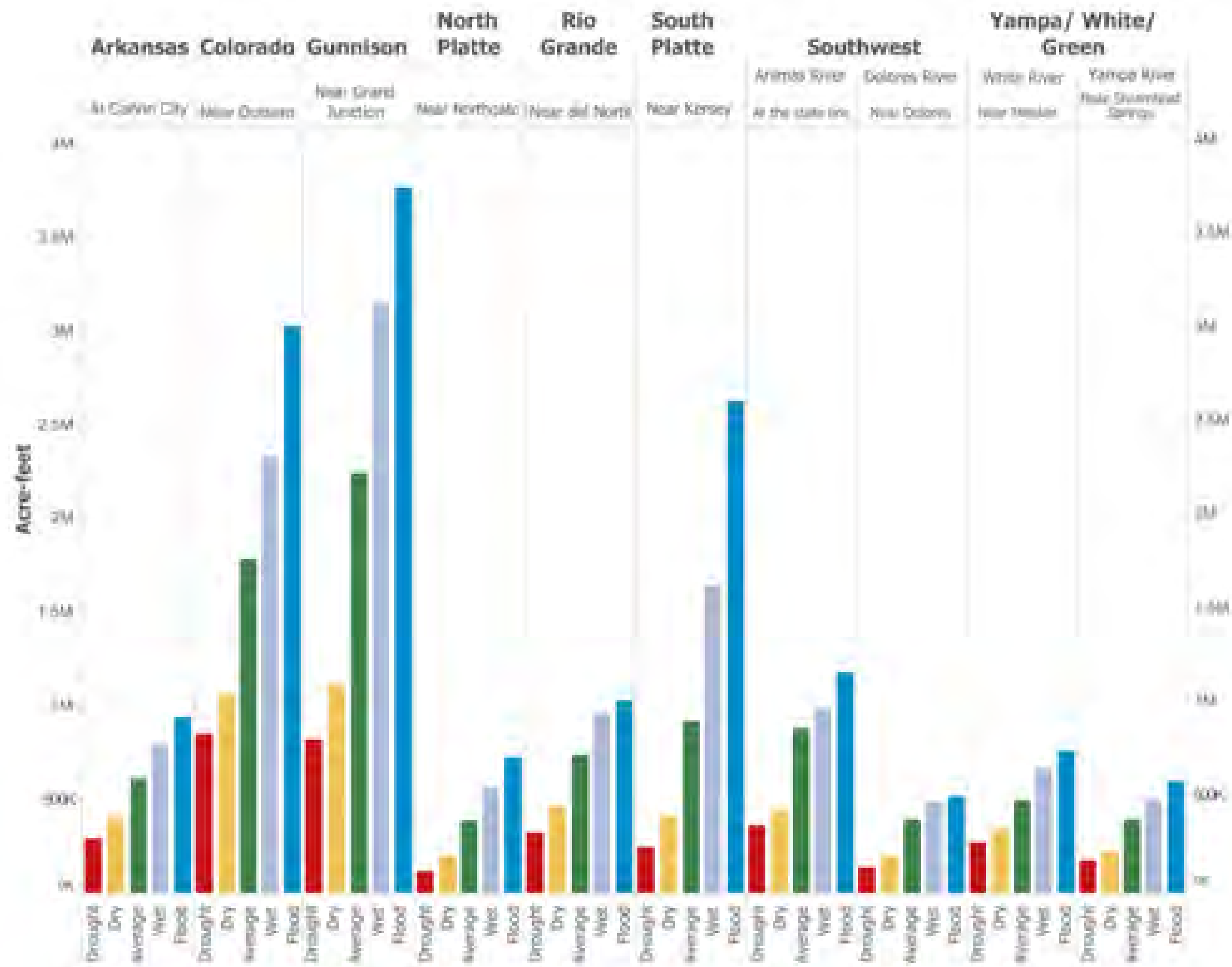
For the purposes of this plan, hydrologic classifications are assigned based on percentile ranking: drought, dry, average, wet, and flood (Figure 4-4). Drought and dry periods have substantial and lasting effects on water supplies and availability for years, while wet years offer relief with as much as six times the amount of annual water supplies compared to dry years (e.g. lower South Platte). Both extremes can affect water supplies and availability throughout the state for years (Figure 4-5). They also have other consequences, such as wildfires and negative economic effects.

For example, in 2002, the driest single year on record, Colorado suffered several severe wildfires. The largest of these fires, the Hayman Fire, raised levels of nitrate and turbidity in the burn area's streams—and those levels remained elevated for five years afterward.[8] Then in 2013, the West Fork Complex Fire damaged watersheds and diminished water quality in the Rio Grande Basin. Substantial hillside and stream erosion resulted from such events. Increased levels of debris in reservoirs affect not only water quality, but also water supply and treatment infrastructure operations.[9]

The CWCB coordinated field data and assisted in the development of reports on the substantial hillside and stream erosion that takes place following medium- and high-intensity wildfires.[10]

Wildfires can affect Colorado's economy and may cost the State millions of dollars in response and recovery efforts alone. They may also affect water providers' budgets. The 1996 Buffalo Creek and 2002 Hayman Fires cost Denver Water $20 million in wildfire-related dredging and maintenance at the Strontia Springs Reservoir, without complete resolution of the problem.[11] In 2012, another year of statewide drought, Colorado Springs Utilities and the City of Fort Collins incurred costs from separate wildfires in the watersheds that supply their municipal water. These naturally occurring events can greatly affect the amount of water supplies that are available for use.

FIGURE 4-5 **ANNUAL FLOW VALUES FOR VARYING CONDITIONS AT SELECT GAGES (ACRE-FEET PER YEAR)**



Annual flow values for drought, dry, average, wet, and flood conditions for 10 locations across the state. This graphic illustrates the variability that exists both within basins and between basins of the state, and shows the uppermost threshold of the percentile range for each of the selected gages. As this was an independent analysis, values may differ slightly from volumes the individual basin implementation plans reported.

Aside from the effects of wildfire, drought and its associated decreased water availability can also have substantial fiscal effects. Colorado State University estimates that in 2012, lost revenues due to the drought in the agricultural sector alone exceeded $409 million statewide.[12] Factoring-in secondary and tertiary economic effects to local communities, the loss increases to $726 million statewide.[13] Drought can also negatively influence air quality, water delivery infrastructure, wildlife, the environment, recreation, and tourism. Drought is unique in that it can last for weeks, months, or years, and the longer a drought persists, the larger its effect. For instance, a municipality may be able to weather a single-year drought by using reservoir storage and drought response measures, but if the storage is not replenished, subsequent years become increasingly more difficult to manage. The same is true in the agricultural sector; ranchers forced to cull herds in response to drought may need decades to recover their stock, or may never recover at all. Both the Rio Grande and Arkansas Basins have been dry most of the past decade, with only three above-average precipitation years since 2000.[14] The Colorado River Basin has experienced the driest 14-year period since 1963, with above-average flows in only three of the last 14 years.[15]

On the other end of the variability spectrum are floods: Too much moisture can result in overflowing

FIGURE 4-6 **AVERAGE MONTHLY FLOWS BY HYDROLOGIC CLASSIFICATION**

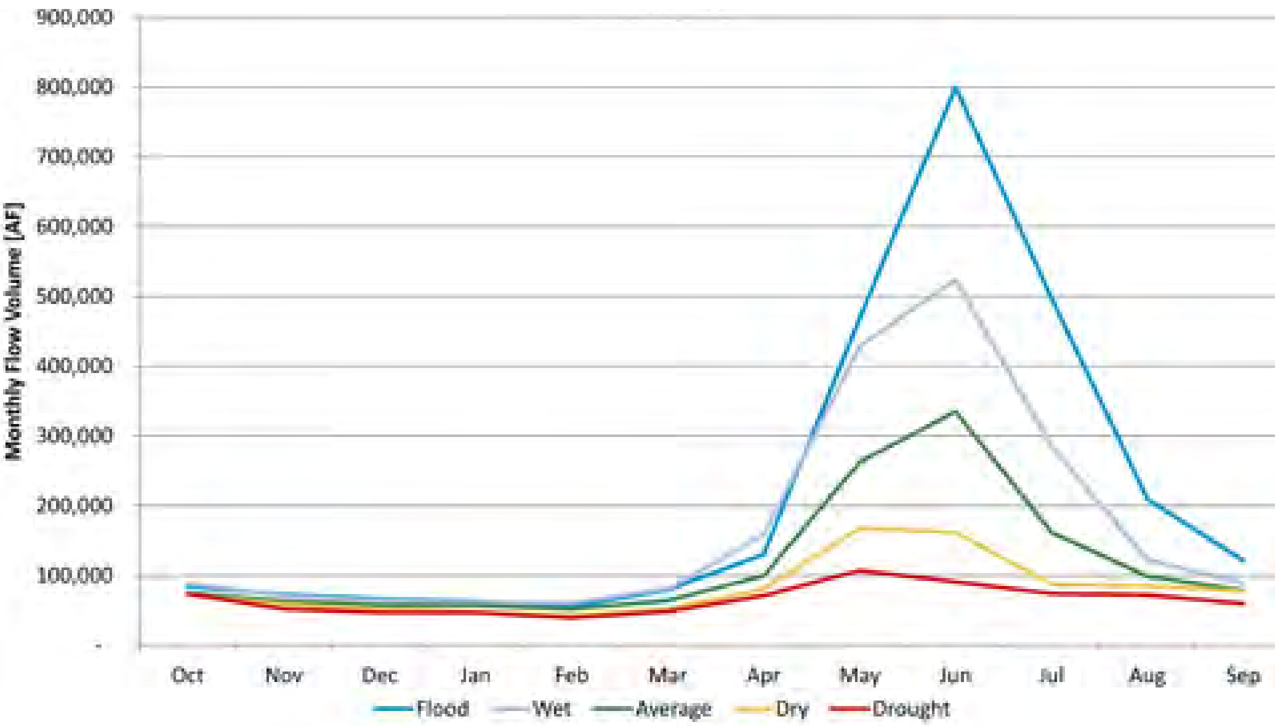


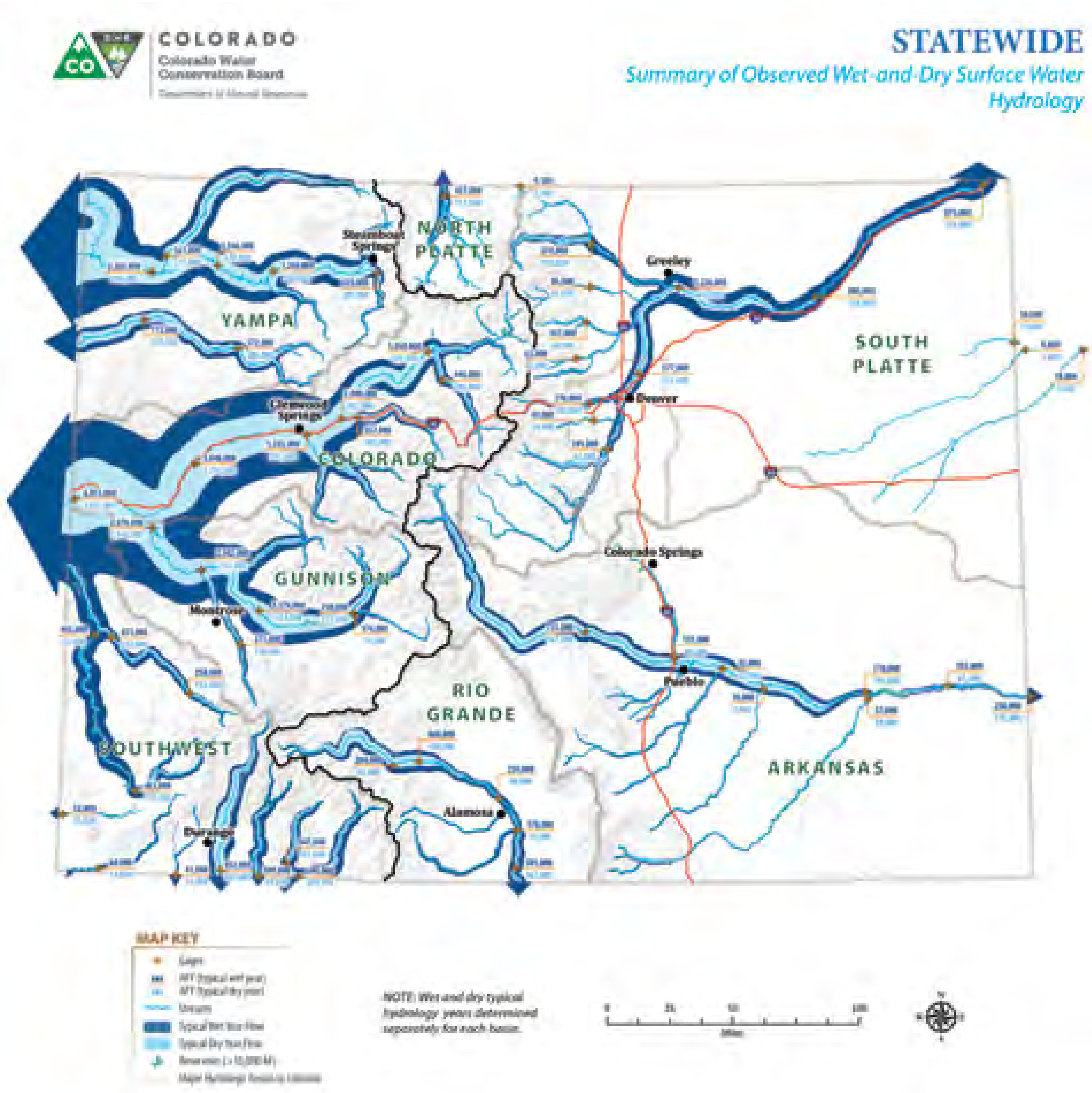
Figure 4-6 uses the same hydrologic classifications as Figure 4-5, but shows average monthly flow volumes on the Colorado River at Dotsero to illustrate the wide variance that can exist among classifications, especially during the runoff season.

reservoirs and extensive damage. In fall 2013, widespread flooding occurred in some regions of the state after as many as 19 inches of rain fell in a few days. For these areas, the events were equivalent to nearly a full year of precipitation. As many as 88 weather stations exceeded 24-hour precipitation records, and the hardest hit areas received more than 600 percent of average precipitation for the month.[16] Water inundated entire communities.

The September 2013 floods resulted in loss of life, power, homes, businesses, and roads. Initial estimates of economic losses have reached $2.9 billion.[17] These events caused Halligan Reservoir to rise 30 feet, capturing nearly 6,000 acre-feet of water in just over 24 hours. Halligan Reservoir transformed from a nearly-empty to a full vessel in a matter of days. Unfortunately, flows were so high that many storage facilities lost the infrastructure necessary to store the excess water.

Floods not only cause community damage; they also affect agricultural operations and water supply because of damaged delivery systems. Flooding events can leave water supply infrastructure, such as diversions and headgates, completely disconnected from their historical source of water. These effects may take weeks, months, or years to fully repair, and some damage may be too great to ever repair economically.

FIGURE 4-7 WET- AND DRY-YEAR FLOWS AT SELECT GAGES



Uncertainties Affecting Supply

In addition to the high hydrologic variability we face as a state, climate change and dust-on-snow events present additional complexities and uncertainties that affect water supply. In recent decades, Colorado has experienced warming and will likely continue to do so in the future. Across the state, average yearly temperature has increased by 2°F in the last 30 years, and by 2.5°F in the last 50 years. This increase affects the timing of snowmelt and peak runoff, which now occur earlier, and there is an increase in heat waves and wildfires. Climate projections show Colorado warming by an additional 2.5°F to 5°F by mid-century, with temperatures in summer increasing more than those in winter. While projections are less clear about whether precipitation will increase or decrease, warming temperatures that drive physical processes, such as evapotranspiration, will result in an earlier

TABLE 4-1 SUMMARY OF PROJECTED CLIMATE CHANGES AND POTENTIAL EFFECTS ON COLORADO'S WATER RESOURCES[18]

ELEMENT	PROJECTED CHANGES AND POTENTIAL EFFECTS	STUDIES THAT HAVE ASSESSED THIS VULNERABILITY FOR COLORADO
Overall Surface-Water Supply	Most projections of future hydrology for Colorado's river basins show decreasing annual runoff and less overall water supply, but some projections show increasing runoff. Warming temperatures could continue the recent trend toward earlier peak runoff and lower late-summer flows.	Colorado Water Conservation Board (CWCB) (2012); Bureau of Reclamation (BOR) (2012); Woodbury et al. (2012)
Water Infrastructure Operations	Changes in the snowpack and in streamflow timing could affect reservoir operations, including flood control and storage. Changes in the timing and magnitude of runoff could affect the functioning of diversion, storage, and conveyance structures.	CWCB (2012); BOR (2012)
Crop Water Demand, Outdoor Urban Watering	Warming temperatures could increase the loss of water from plants and soil, lengthen growing seasons, and increase overall water demand.	CWCB (2012); BOR (2012)
Legal Water Systems	Earlier and/or lower runoff could complicate administration of water rights and interstate water compacts, and could affect which rights-holders receive water.	CWCB (2012)
Water Quality	Warmer water temperatures could cause many indicators of water quality to decline. Lower streamflows could lead to increasing concentrations of pollutants.	Environmental Protection Agency (EPA) (2013)
Groundwater Resources	Groundwater demand for agricultural use could increase with warmer temperatures. Changes in precipitation could affect groundwater recharge rates.	
Energy Demand and Operations Costs	Warmer temperatures could place higher demands on hydropower facilities for peaking power in summer. Warmer lake and stream temperatures, and earlier runoff, could affect water use for cooling-power plants and in other industries.	Mackenick et al. (2012)
Forest Disturbances in Headwaters Region	Warmer temperatures could increase the frequency and severity of wildfire, and make trees more vulnerable to insect infestation. Both have implications for water quality and watershed health.	
Riparian Habitats and Fisheries	Warmer stream temperatures could have direct and indirect effects on aquatic ecosystems, including the spread of non-native species and diseases to higher elevations. Changes in streamflow timing could also affect riparian ecosystems.	Rieman and Isaak (2010)
Water- and Snow-based Recreation	Earlier streamflow timing could affect rafting and fishing. Changes in reservoir storage could affect recreation on-site and downstream. Declining snowpacks could affect winter mountain recreation and tourism.	BOR (2012); Battaglin et al. (2011); Lazar and Williams (2008)

runoff, a longer irrigation season, and a decrease in annual streamflow—especially in the state's southern basins. Even moderate increases in precipitation will not be sufficient to overcome the drying signal. All of these changes are likely to substantially affect water available for beneficial use in Colorado in the coming decades. Table 4-1 illustrates the potential water-related effects of climate change in different areas and sectors, while Table 4-2 highlights projected effects of increased temperatures on a wide array of indicators, as the 2014 Climate Change in Colorado Report describes.

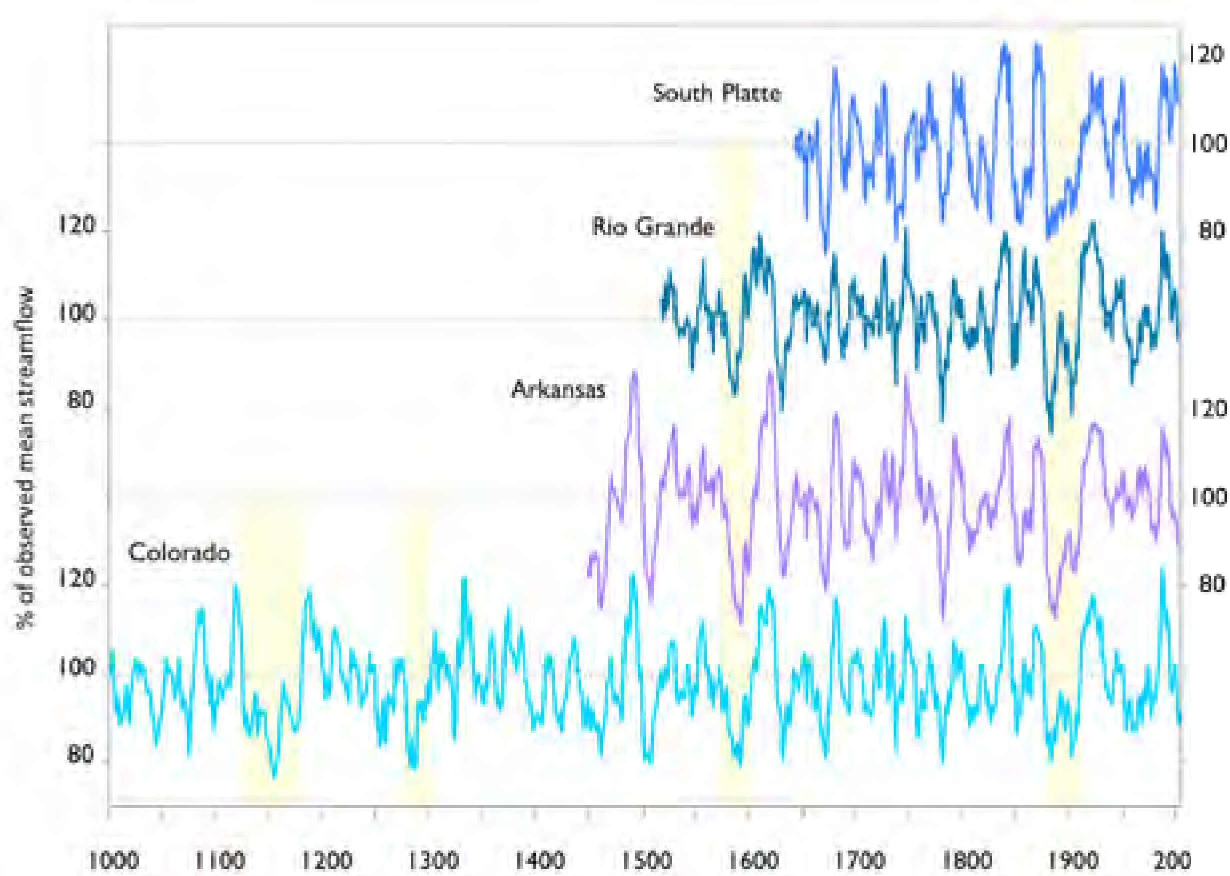
Colorado is accustomed to dealing with variability and drought over the last 150 years, yet tree ring-reconstructed streamflows indicate that the state has endured longer-lasting and more severe droughts than we have seen in our relatively brief, observed record. In fact, the 20th century is unique in that during that time, Colorado experienced two prolonged wet periods and no multi-decadal droughts.[20] Figure 4-8 shows multiple droughts (shaded highlights) that exceed the intensity and duration of the state's observed record.

As Section 6.1 describes, the scenarios the IBCC developed will help the State prepare for whatever may unfold in the future. Three scenarios have a climate different from what was observed during the 20th century, including two scenarios that experience "hot and dry" conditions, and one that features a hydrology and climate described as "between 20th century-observed and hot and dry." Figure 4-9 (page 4-11) illustrates where these scenarios fall in comparison to the current climate, or the 20th century-observed climate.

TABLE 4-2	PROJECTED CLIMATE AND HYDROLOGY CHANGES[19]
INDICATOR	EFFECT OF CLIMATE CHANGE
Annual Streamflow	Decreases in most of the climate projections
Peak Runoff Timing	Earlier in all projections
Crop Water Use	Increases
April 1 Snowpack	Decreases in most projections
Palmer Drought Severity Index	More drought
Heat Waves	More frequent
Cold Waves	Less frequent
Frost-Free Season	Longer

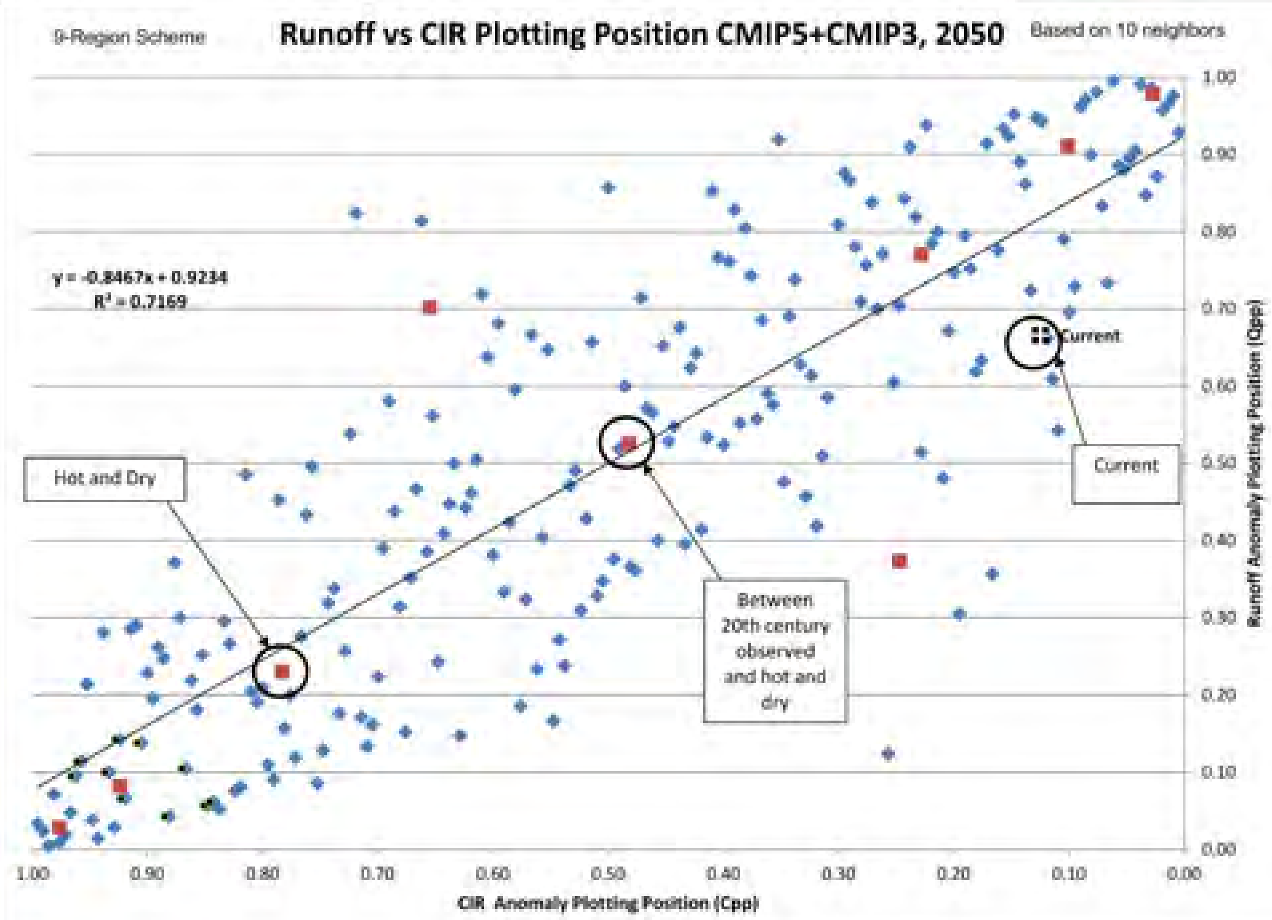
Having quantitatively defined the scenarios, the CWCB's technical team used the data to determine the effects on streamflow. Figure 4-10 (Page 4-13) illustrates projected depleted flows for the year 2050 in acre-feet per year at 11 different sites around the state. In some scenarios, projected flows are less than zero, indicating that some users, both senior and junior, would be unable to obtain their historical supply of water.[22] This analysis projects that both the Arkansas and Rio Grande Rivers will experience these conditions under both climate scenarios, and that the South Platte will experience these conditions under the "hot and dry" climate scenario. While these basins are accustomed to calls dating back well into the 19th century, climate change has the potential to substantially alter the amount of water available to even those with well-established senior water rights. Continued monitoring, research, and planning are critical to determining whether future supplies will fulfill future demands—and continue to fulfill *current* demands. The ability to successfully address these challenges will require collaboration and innovative solutions. In the ongoing efforts of the SWSI, the State will continue to examine the effects climate change may have on our water supplies and demands.

FIGURE 4-8 TREE-RING RECONSTRUCTED WATER-YEAR STREAMFLOWS FOR FOUR MAJOR RIVER BASINS IN COLORADO[21]



Tree-ring reconstructed water-year streamflows as percent of observed mean, showing the 10-year running average, for four gauges representing major Colorado basins: The Colorado River at Lees Ferry, Ariz. (762–2005, shown here from 1000–2005); the South Platte River at South Platte, Colo. (1634–2002); the Rio Grande at Del Norte, Colo. (1508–2002); and the Arkansas River at Salida, Colo. (1440–2002). All four records show the occurrence of droughts before 1900 that were more severe and more sustained than any modern droughts. The yellow shading highlights several notable multi-decadal paleodroughts in the mid-1100s, the late 1200s, the late 1500s, and the late 1800s. The 20th century was unusual in having two persistent wet periods and no droughts longer than 10 years. (Data: TreeFlow web resource; http://treeflow.info.)

FIGURE 4-9 PLOT OF RUNOFF CROP IRRIGATION REQUIREMENTS USING THE BUREAU OF RECLAMATION ARCHIVE



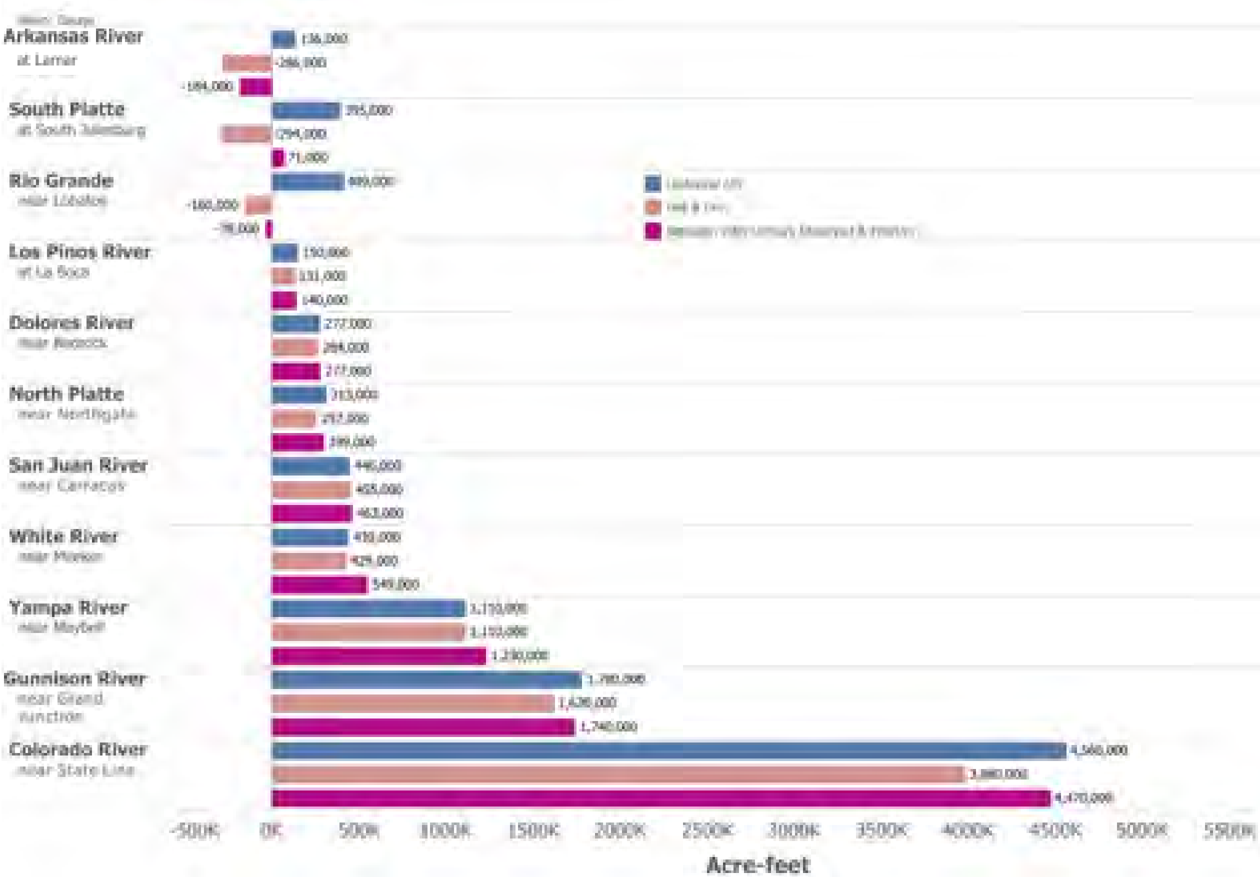
"Hot and dry" is defined as the 75th percentile of climate projections for crop irrigation requirements (water use), and the 25th percentile for natural flows. In other words, only 25 percent of projections have lower natural flows and 25 percent of projections have higher crop irrigation requirements. "Between 20th century-observed and hot and dry" is defined as the 50th percentile for both natural flows and crop irrigation requirements. This scenario represents the middle of the range in terms of severity. Historical or current conditions, which represents no change in runoff or in crop irrigation requirements, fall at roughly the 9th and 67th percentiles; this means that 91 percent of runs show increases in crop irrigation requirements and about two-thirds show reductions in runoff.

Additionally, Colorado's Water Plan will work in concert with the Colorado Climate Plan, which provides state-level policy recommendations and actions that help to improve state agencies' level of preparedness, while simultaneously identifying opportunities for agencies to mitigate greenhouse gas emissions.

In addition to the work the State conducted on climate change, several of the basin roundtables also incorporated uncertainties associated with climate change into their BIPs. Many basins now recognize that, because of climate change, previous assumptions used for planning purposes are no longer sufficient. For example, the Colorado Basin recognizes that while it historically relied on previously firm, dry yields, this is not a reliable source in the future, and therefore encourages water providers to update their master plans accordingly (and to consider implementing interconnected water systems to help mitigate the influences of climate change). The South Platte, Arkansas and Rio Grande Basins all recognize that they must plan for a decrease in water supplies because of the effects of climate change, and Rio Grande Basin expressed that it expects to see its water resources reduce by as much 30 percent in the next 50 to 100 years. In response, the Arkansas Basin is considering conjunctively using tributary and nonrenewable sources to alleviate the effects of reduced yields from climate change, as well as the potential dry-up of nontributary sources.

Colorado's snowpack melts and often feeds rushing streams like this one.

FIGURE 4-10 PROJECTED DEPLETED FLOWS FOR 2050 (ACRE-FEET PER YEAR)



Projected depleted flows for 2050 in acre-feet per year at 11 different sites around the state using the three classifications of historical, hot and dry, and between 20th century-observed and hot and dry.

Almost all BIPs specifically address the need to continue monitoring the effects climate change will have on Colorado's river basins. For example, the Gunnison Basin referenced throughout its plan the need to study the effects of climate change as a means to achieve its primary and complementary basin goals, and to identify actions to protect existing uses. *Research and Public Education on Anticipating, Mitigating and/or Adapting to Climate Changes* describes one approach the Gunnison Basin proposes for meeting this goal. Several other basins identified education and outreach as goals. For instance, as a way to better refine its present and future water planning efforts, the Southwest Basin committed to educating its roundtable members about climate change.

Several basins, including the South Platte/Metro, Yampa/White/Green, Arkansas, and Southwest, incorporated into their own planning processes certain scenarios or projected and potential effects of climate change. As basin and communities continue to examine the effects of climate change on their water supplies, the CWCB will offer technical support as appropriate.

Dust-on-Snow Events

"Dust-on-snow" events also introduce a level of uncertainty into managing water supplies. Dust-on-snow events occur when wind deposits dust from southwestern deserts (and other loose-soil surfaces lacking vegetation) onto mountain snowpack. This increases the effect of solar radiation, which speeds up snowmelt and leads to earlier spring runoff. Studies have shown that dust events can advance snowmelt timing, enhance snowmelt runoff intensity, and decrease snowmelt yields.[23] Dust-on-snow events can result in peak runoff three weeks earlier than normal. This shift is independent of climate change, which may also result in earlier snowmelt patterns.[24] Since 2005, when dust-tracking began, 91 dust-on-snow events have occurred. Ten of these events occurred in 2013, when Colorado observed the heaviest deposition to date.[25]

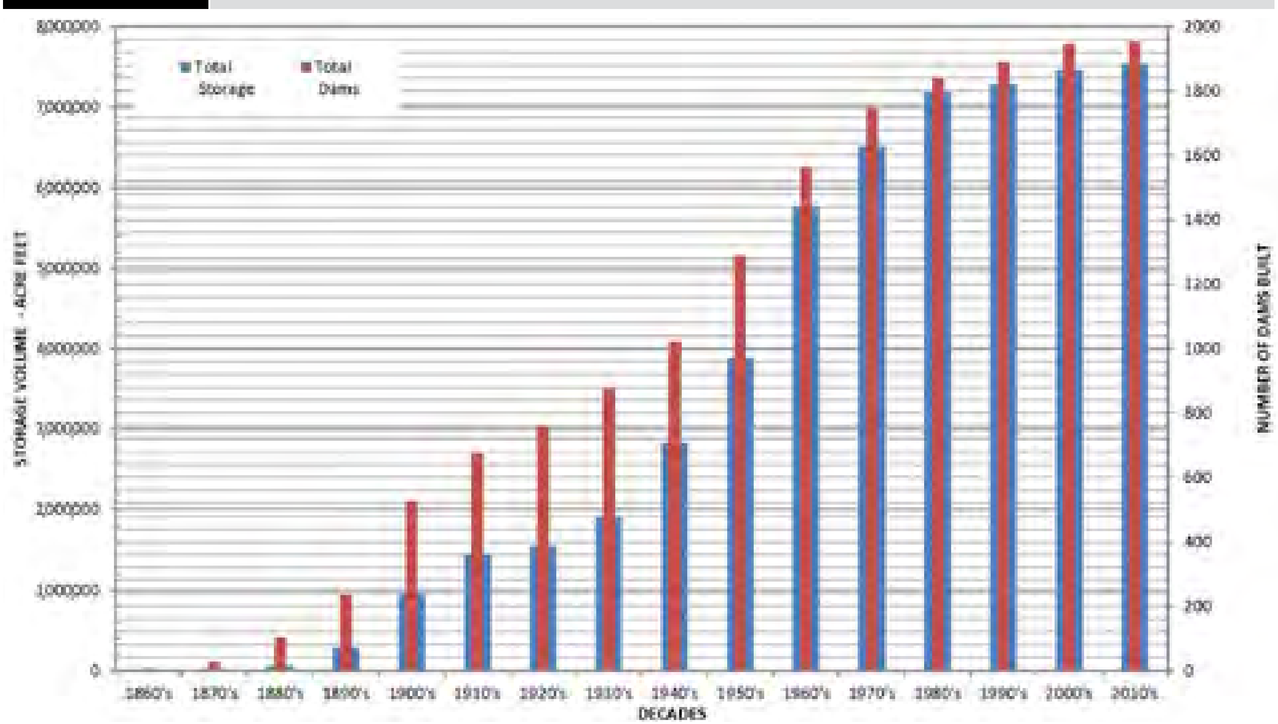
The severity of future dust-on-snow events is uncertain. Nevertheless, if events continue at recently observed rates, they will affect Colorado's present and future water supply by decreasing flows by 5 percent, on average. On the Colorado River, this reduction would result in a decrease of 750,000 acre-feet of water, or twice the amount of water the City of Denver uses annually.[26]

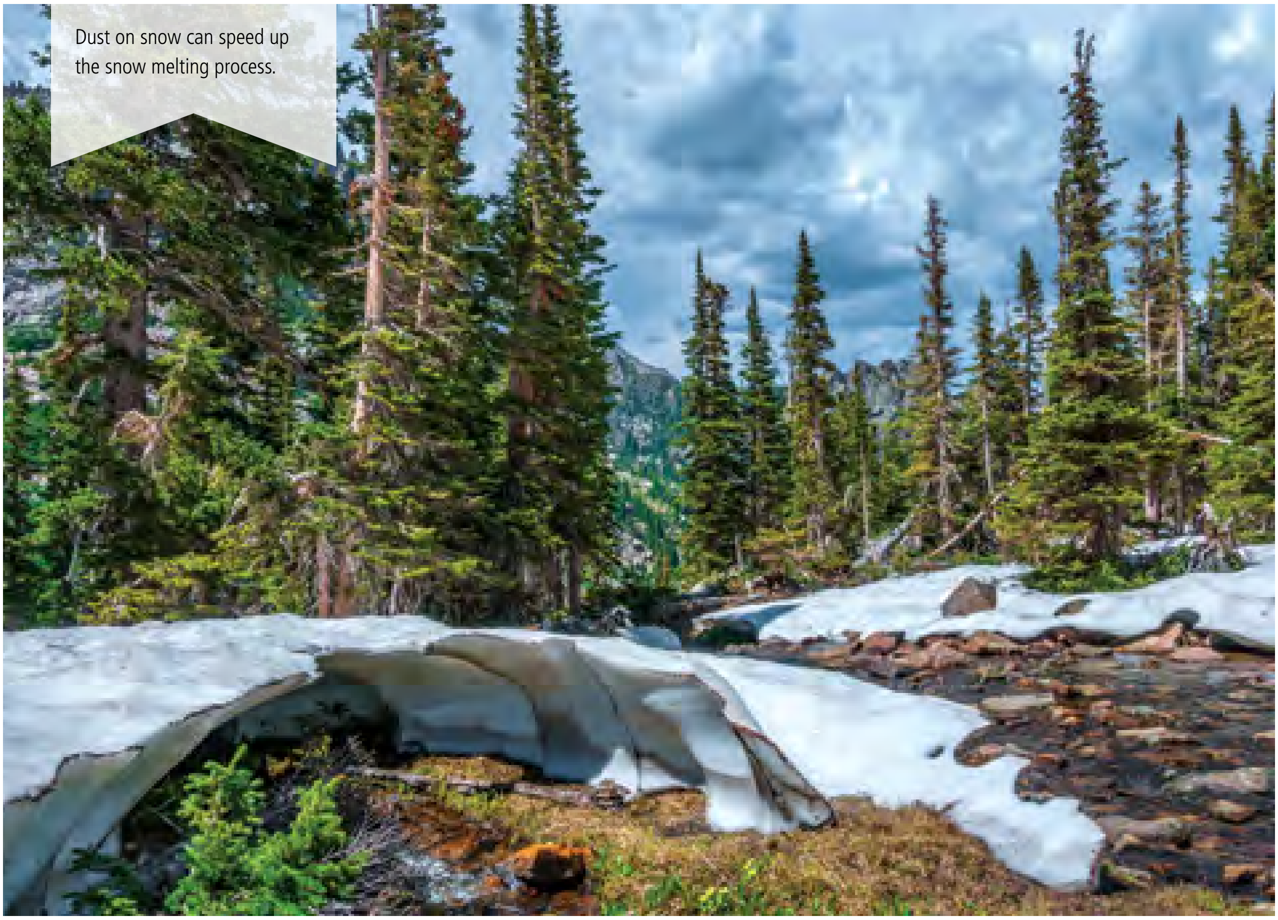
The Role of Storage

While snowpack is Colorado's greatest storage "facility," the State has taken measures to meet the year-round needs of agriculture, municipalities, recreation, and the environment. This includes the construction of numerous reservoirs to hold water during plentiful times and to release water during heightened demand or periods of drought. Nearly half of Colorado's storage capacity is located on the western slope in the Colorado River Basin and its tributaries.[27] Colorado's total storage capacity is approximately 7.5 million acre-feet within 1,953 reservoirs (Figure 4-11), and approximately 4.2 million acre-feet of the state's total storage is located in 113 federally owned reservoirs.

Colorado's water infrastructure, including water storage, is critical to the ability to maintain stable water supplies; water storage infrastructure allows Colorado to use its legal entitlements before water flows out of the state. In addition, water storage infrastructure is essential in assisting with flood control; supporting all types of use—including agricultural, environmental, municipal, and industrial—in periods of drought; complying with interstate compacts; and augmenting stream systems to allow water use by water users that would otherwise not have a right to divert under the prior appropriation system. Most storage

FIGURE 4-11 COLORADO DAM AND RESERVOIR CUMULATIVE CONSTRUCTION AND STORAGE HISTORY




Dust on snow can speed up the snow melting process.

projects, however, were developed in the middle of the last century, and the construction of both new infrastructure and storage has remained relatively static over the last 30 years (Figure 4-12). In fact, construction of storage has declined so much that Colorado's current rate of building storage capacity resembles that of the Great Depression.

While storage is a critical element for managing Colorado's future water supplies, new storage projects may be contentious and face numerous hurdles, including permitting and funding. In many cases, it may be more practical and efficient to reallocate or enlarge an existing dam and reservoir than to build a completely new structure. In determining whether a reservoir is suitable for enlargement, one must consider the legal and physical availability of excess water that can be stored (including the legal and physical availability of water through exchange). The suitability of the structure from a construction and operations standpoint, interstate compacts, and environmental benefits and threats, must also be taken under consideration.

Given these factors, basin roundtables and the IBCC have begun to address the water supply challenges ahead by emphasizing the role of multipurpose projects. These types of projects take into account multiple users and multiple benefits, and diverse interests become involved during the planning process. In planning for Colorado's water supply future, it will be important to enable these types of collaborative approaches to new storage projects, elicit proposals for the enlargement of existing reservoirs and dams, and consider the potential for alluvial and bedrock aquifer storage. Section 6.5 further discusses the future development and implementation of projects and methods with a storage component.

The Colorado DWR's dam database contains information that is useful in examining enlargement potential for existing reservoirs and dams. This includes data about the volume of water a reservoir can hold when filled to the normal high water line, and the volume of water that would be present if the reservoir were filled to its capacity. The "storage delta" is the difference between the volumes of normal storage and maximum storage. For many reservoirs, the storage delta is "flood storage" that is needed for containing floods' flows and, therefore, is not available for storage enlargement. Nevertheless, advances in meteorology, hydrology, and dam engineering make it possible to reassess reservoirs and potentially use existing flood storage for active storage. The portion of the reservoir associated with the storage delta has the largest surface area; therefore, a relatively small increase in the water surface elevation will result in a large increase in water storage capacity. For example, at John Martin Reservoir, an increase of one foot in the normal high water line results in an increased storage capacity of nearly 9,000 acre-feet.[b]

Further, an existing reservoir is understood to have the potential to inundate a known land area that includes the area associated with its maximum capacity. Therefore, a reservoir with a large storage delta can expand its additional storage capacity without increasing the area that is potentially inundated, thereby minimizing the associated environmental effects.

FIGURE 4-12 COLORADO DAM AND RESERVOIR CONSTRUCTION HISTORY AND VOLUME BY DECADE

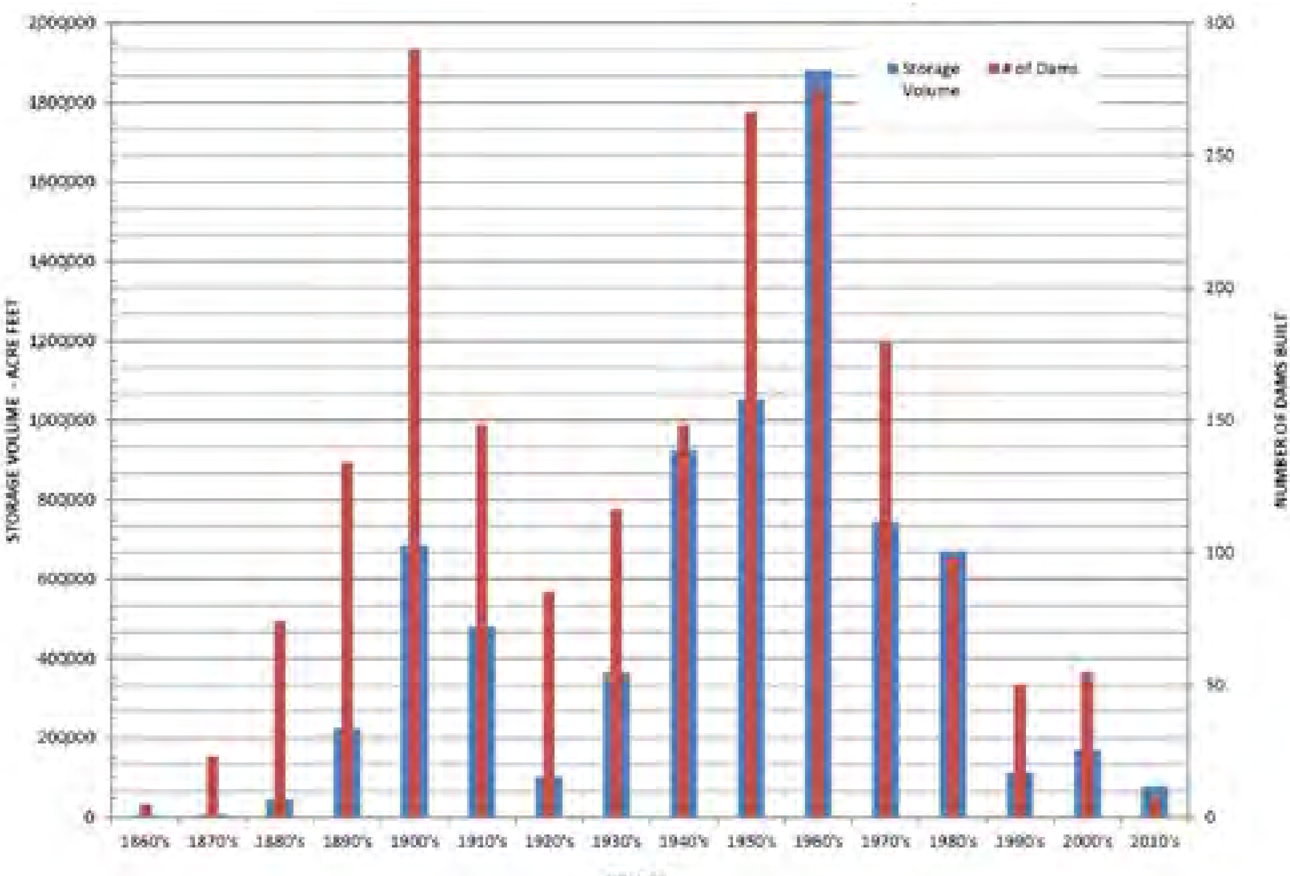
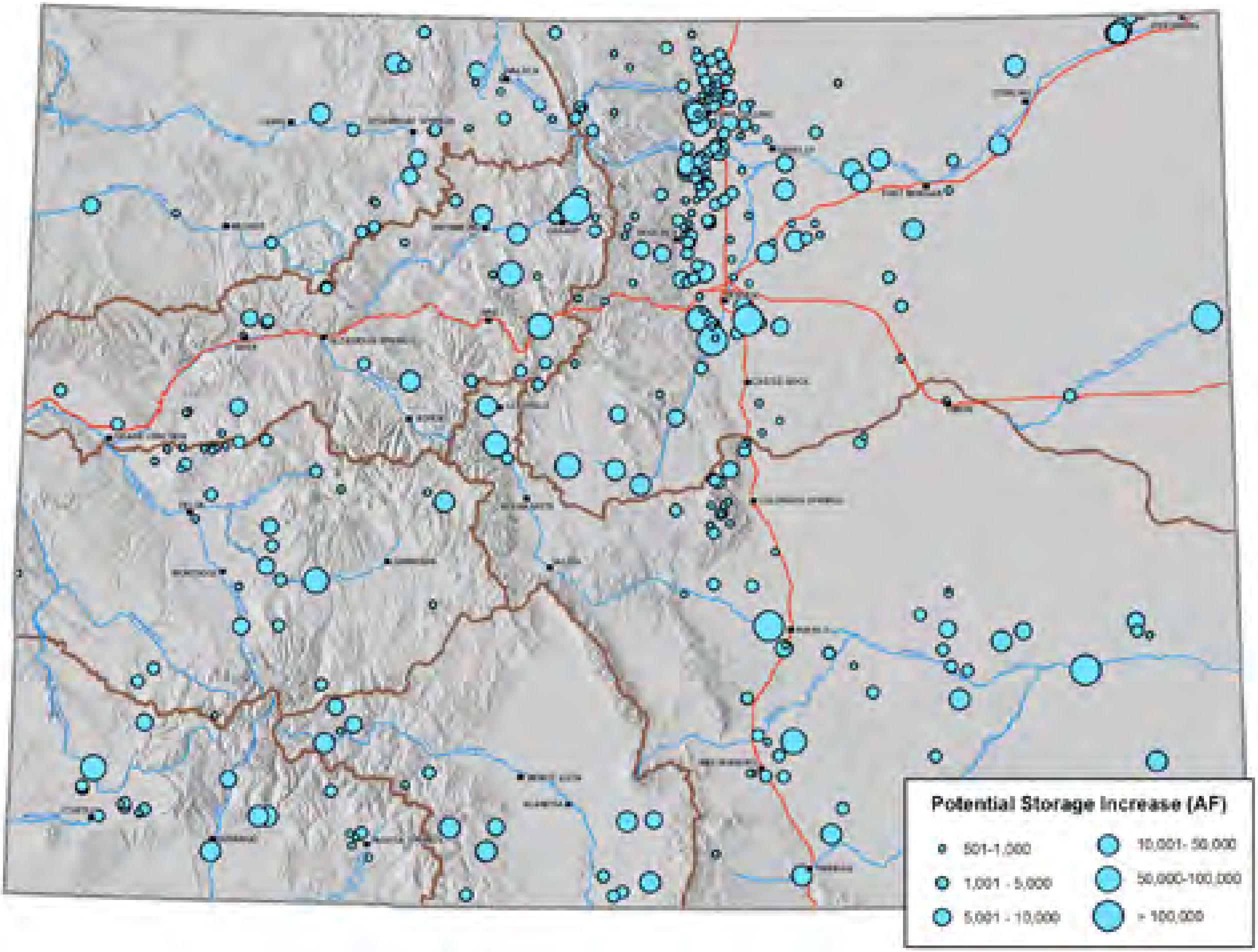


Figure 4.12 does not include storage capacity associated with flood-control reservoirs because storage capacity for flood control can be used on only a limited basis for water supply storage.

[b] This table shows potential reservoir-storage increase. Agreements, interstate compact obligations, and other constraints—notably the unavailability of flood storage and the need to retain freeboard for dam safety purposes—may make the potential increase unusable.

FIGURE 4-13 **POTENTIAL STATEWIDE RESERVOIR STORAGE INCREASE BASED ON STORAGE DELTA FACTOR ONLY**



The dams database contains information about maximum storage, normal storage, and surface area for reservoirs. One can use that information to create a list of reservoirs that have a large storage delta and, therefore, have potential for enlargement. While it is not the only indicator regarding the potential for enlargement, a large storage delta is a threshold criterion. Therefore, one approach for investigating the potential for enlarging storage infrastructure would be to query all 1,900 jurisdictional dams in the database and create the list of reservoirs with a large storage delta—then eliminate reservoirs whose storage delta is associated with necessary flood storage capacity.

In general, the federal BOR and the U.S. Army Corps of Engineers own the reservoirs with the largest storage delta. The BOR reservoirs are primarily for storage of project waters, not for flood storage. Conversely, the U.S. Army Corps of Engineers dams are dual purpose; they have the largest storage deltas because they include dedicated flood storage capacity.[28] After eliminating from the list reservoirs for which the storage delta is associated with necessary flood storage capacity, one would further examine the list according to the factors described above. Figure 4-13 illustrates geographic distribution of the dams by the range of existing potential storage.

Weather Modification

Weather modification, also known as cloud-seeding, increases available water supplies. The World Meteorological Organization has stated that well-designed, well-executed weather modification programs have demonstrable results; furthermore, these programs have no documented, negative environmental effects from the use of silver iodide for cloud-seeding.[29] With seven permitted, ground-based, wintertime cloud-seeding programs, Colorado is a leading state for weather modification activities. The goal of these programs is to increase snowpack and streamflow. In comparison to other sources of new water, cloud-seeding is a relatively low-cost means of increasing system supplies. The recreation sector, especially the ski industry, relies heavily on cloud-seeding. Because of prolonged water supply shortages in the Colorado River Basin, the CWCB in 2006 signed agreements with the New Mexico Interstate Stream Commission, California Six Agency Committee, Southern Nevada Water Authority, and Central Arizona Water Conservation District to collaborate and financially support cloud-seeding in Colorado. Additional information on weather modification efforts within the state is available on the Weather Modification Program pages of the CWCB website.[30]

Water Quality

Water quality and water quantity are inextricably connected, and understanding water supply and demand alone creates an incomplete picture. Enough water with suitable quality for irrigation, drinking, recreational activities, and the protection of aquatic life must be available for use. This section briefly outlines some of the key connections between quality and quantity, while Section 7.3 provides a more detailed discussion.

According to the 2012 Integrated Report, for the reporting period 2010-2011:

- 65 percent of river- and stream-miles and 28 percent of lake and reservoir acreages statewide attain water quality standards.
- For 25 percent of river- and stream-miles and 49 percent of lake and reservoir acreages statewide, data are insufficient for determining whether these bodies meet water quality standards.
- 10 percent of river- and stream-miles and 23 percent of lake and reservoir acreages statewide are not meeting water quality standards for one or more pollutants (i.e., they are impaired water bodies).[31]

Over the past 40 years, Colorado water quality management programs have ensured clean water for uses such as growing crops, providing drinking water, and enjoying water-based recreation. These programs benefit all Coloradans, because clean water is essential to the state's healthy environment, diverse economy, and quality of life. This is why both protecting and restoring water quality are fundamental to supporting Colorado's water values and implementing Colorado's Water Plan.

Water supply decisions must include water quality management considerations in order to enable the State to sustain and improve existing statewide water quality conditions. Section 7.3 provides a more specific discussion about the relationships between water quality and quantity.

Cloud seeding can help to ensure Colorado enjoys a healthier snowpack for recreational activities like skiing.

A LOOK AT HISTORY

Both the Great Depression and the Dust Bowl gripped eastern Colorado in the 1930s, with dust storms often blotting out the sun. This 1937 dust cloud in Prowers County was typical.

SOURCE: University of Oklahoma, Western History Collection.

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