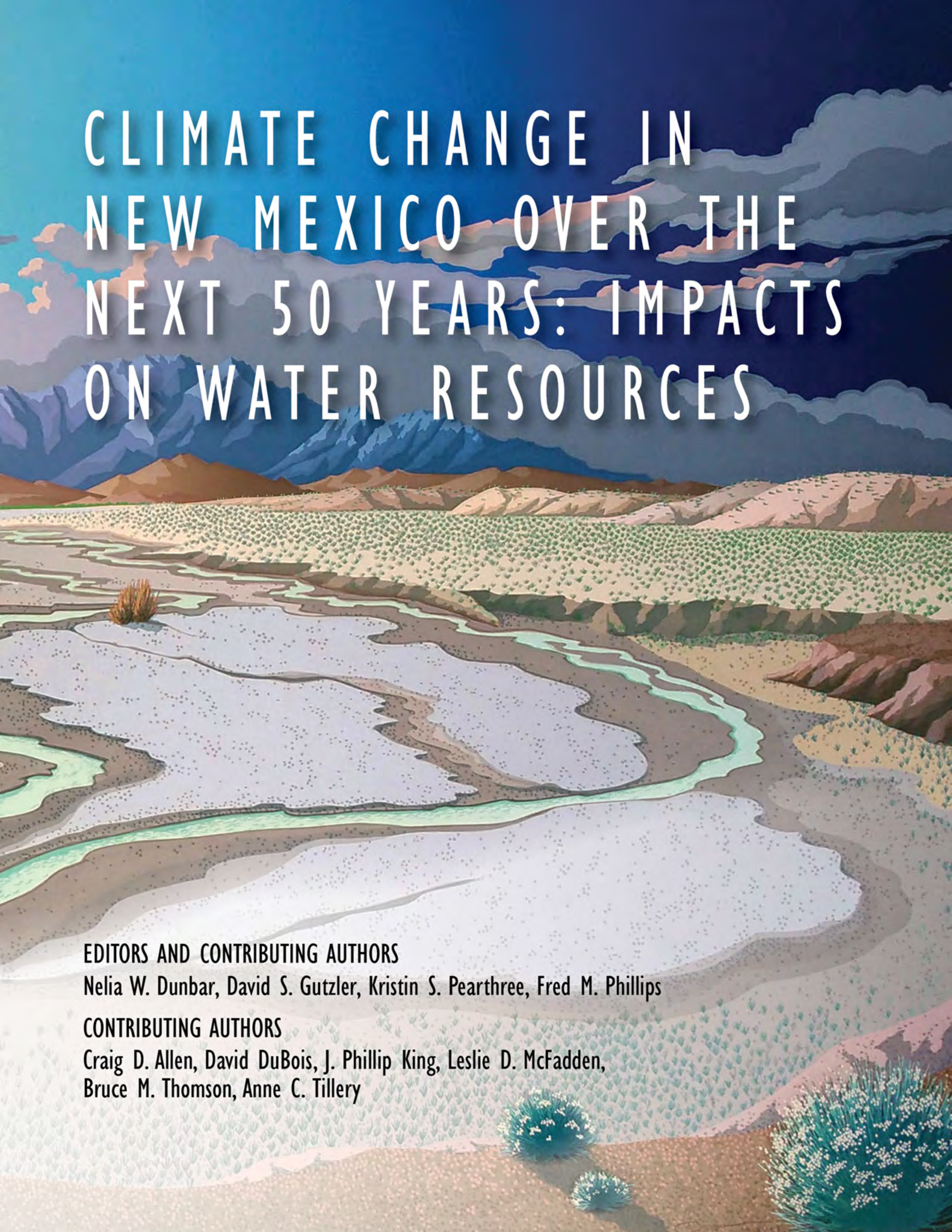

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New Mexico Bureau of Geology and Mineral Resources

Established by legislation in 1927, the **New Mexico Bureau of Geology and Mineral Resources** is a research and service division of the New Mexico Institute of Mining and Technology (New Mexico Tech). The Bureau of Geology is a non-regulatory agency that serves as the geological survey for the State of New Mexico. Through our offices, website, and publications, our staff serves the diverse population of our state by conducting research; distributing accurate information; creating accurate, up-to-date maps; providing timely information on potential geologic hazards; acting as a repository for cores, well cuttings and a wide variety of geologic data; providing public education and outreach through teaching and advising, our world-class Mineral Museum, and teacher/student training programs; and serving on geoscience-focused boards and commissions within the state. There is something at the Bureau for everyone who has ever wondered about the exceptional geology of New Mexico.

The **New Mexico Interstate Stream Commission** (NMISC) is a sister agency to, and administratively attached to, the New Mexico Office of the State Engineer. NMISC activities are overseen by eight appointed Commissioners in addition to the State Engineer, who serves as the Commission's Secretary. The NMISC oversees New Mexico's obligations and entitlements under eight interstate stream compacts to which New Mexico is a party. To ensure compact compliance, NMISC staff analyze, review, and implement projects in New Mexico and analyze streamflow, reservoir, and other data on stream systems. The NMISC is authorized by statute to investigate, develop, conserve and protect the water supplies of the state. In addition, the NMISC supports and conducts regional and state water planning efforts, implements Indian Water Rights Settlements, manages the State's Strategic Water Reserve and supports compliance with federal environmental regulations such as the Endangered Species Act. Further, Governor Michelle Lujan Grisham directed the NMISC to develop the New Mexico 50-Year Water Plan.

This report represents a collaboration between two state agencies: the New Mexico Bureau of Geology and Mineral Resources and the New Mexico Interstate Stream Commission. The work was carried out by the Bureau at the request of the New Mexico Interstate Stream Commission in support of development of New Mexico's 50-Year Water Plan. The purpose of the report was to provide a solid and scientifically based foundation about climate change in New Mexico over the next five decades upon which to build the 50-Year Water Plan.

The Bureau appreciates the New Mexico Interstate Stream Commission's vision in supporting the development of this project. The Bureau also deeply appreciates the expertise and commitment of the eight experienced scientists who developed the core chapters of this consensus study. We hope this report will be used by many in and around New Mexico for many years to come.

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This report underwent review in draft form by individuals chosen for their technical expertise in the topics addressed, as well as their relevant research focus on the southwestern United States. Some reviewers provided an evaluation of the entire report and others reviewed only specific sections. The purpose of this independent review was to provide candid and critical comments to ensure that the report is scientifically sound and responsive to the study charge.

We thank the following individuals for their review of this report:

Kevin Hobbs, New Mexico Bureau of Geology and Mineral Resources, New Mexico Tech, Socorro, New Mexico

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Dana Price, United States Army Corps of Engineers, Albuquerque, New Mexico

Connie Woodhouse, University of Arizona, Tucson, Arizona

Anonymous Reviewer

This article has been peer reviewed and approved for publication consistent with U.S. Geological Survey Fundamental Science Practices (https://pubs.usgs.gov/circ/1367/).

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations of this report nor did they re-review the final draft before its release. The review of this report was overseen by Nelia Dunbar, David Gutzler, Kristin Pearthree, and Fred Phillips. They were responsible for making certain that the independent examination of this report was carried out thoroughly and fairly, and that all review comments were carefully considered. Responsibility for the final content rests entirely with the authoring committee, the New Mexico Bureau of Geology and Mineral Resources, and the New Mexico Interstate Stream Commission.

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OVERVIEW

Introduction: Climate Change in New Mexico

The Earth is warming in response to increasing atmospheric carbon dioxide, and this warming will result in greater aridity in many parts of the world, including New Mexico. The primary observed and projected impacts include warmer temperatures, decreased water supply (partly driven by thinner snowpacks and earlier spring melting), lower soil moisture levels, increased frequency and intensity of wildfires, and increased competition and demand for scarce water resources. These effects may be accentuated by positive feedback cycles, tipping points, or compounding events. This report compiles, assesses, and integrates existing peer-reviewed published research, technical reports, and datasets relevant to the broad topic of changes to New Mexico's climate over the next 50 years and resultant impacts on water resources, and represents the scientific foundation upon which New Mexico's 50-Year Water Plan will be developed. New Mexico is a geographically, geologically, and climatically diverse state. Projected climate changes, and related impacts on water resources in different geographic areas of New Mexico over the next 50 years, will vary not only by region but also as a function of local elevation, and even by hillslope orientation. The currently observed trends of increasing temperature and constant, but more variable, precipitation will continue over the next 50 years.

Future Climate Projections

Global climate models driven by increasing greenhouse gases project an average temperature increase across the state of New Mexico of between 5° and 7°F over the next 50 years. This regional temperature increase follows the trend observed over the past half-century, at a somewhat amplified rate, with the northwest corner projected to experience a slightly higher rise during the same period. Although all models indicate significant increases in temperature, these models do not consistently project a significant change in average annual precipitation across the state, mirroring the absence of a clear trend in recent historical observations. However, some consistent differences in seasonality of precipitation emerge. During the winter, the northern mountains may receive somewhat more precipitation, whereas the southern parts of the state may be drier. Spring precipitation, critical for snowmelt runoff and ecosystems, may decline. Also in the southern part of the state, a trend towards somewhat stronger monsoonal activity may result in more summer precipitation, perhaps shifting toward somewhat later in the year.

The coupled trends of increasing temperature with no clear increasing trend in precipitation leads to a confident projection of increasingly arid conditions, including decreased soil moisture, stressed vegetation, and more severe droughts. Snowpack and associated runoff are projected to decline substantially by 2070, generating diminished headwater streamflow. Warmer temperatures will also cause lower river flows due to increased evaporation as rivers flow downstream. The impact of climate change on New Mexico's resources are, unfortunately, overwhelmingly negative.

Impacts on the Land-Surface Water Budget

All water that we use in New Mexico originates as rain or snow falling onto the landscape, which either goes to groundwater, surface water, or returns to the atmosphere. Of the precipitation that falls on the state, 1.6% runs off into streams and rivers and 1.8% infiltrates into the ground, recharging subsurface aquifers. Much larger proportions are transpired by plants (78.9%), or evaporated (17.7%). The impact of climate change on all of these pathways will affect our state's water budget. Notably, because of the larger percentages of water lost to evaporation or transpiration, even very small changes in these factors will result in large changes to runoff and recharge. As mentioned in Chapter 2, the climate will continue to warm over the next 50 years without a likely increase in precipitation, leading to greater statewide aridity. Hydrological modeling indicates declines in both runoff and recharge going forward, amounting to 3 to 5% per decade for both quantities. Historical trends in runoff indicate significant year-to-year variability, as do trends in soil moisture and recharge. But all are generally decreasing, consistent with the results of climate models that project a drying climate. Combining the historical trends with modeling of future changes, significant decreases in runoff and recharge seem very likely.

Terrestrial Ecosystems and Feedbacks to Water Resources

Climate is a fundamental driver of ongoing and future vegetation changes in New Mexico. Future changes in vegetation will affect the distribution and abundance of water resources in New Mexico. Major shifts in climate and vegetation across New Mexico's landscapes have occurred in the past, but the scale and rate of recent and projected climate change is probably unprecedented during the past 11,000 years. Recent warming, along with frequent and persistent droughts, have amplified the severity of vegetation disturbance processes (fire, physiological drought stress, insect outbreaks), driving substantial changes in New Mexico vegetation since the year 2000. Ongoing and projected vegetation changes include growth declines, reduced canopy and ground cover, massive tree mortality episodes, and species changes in dominant vegetation—foreshadowing more severe changes to come if current warming trends continue as projected. Such major alterations of New Mexico vegetation likely will also have substantial ecohydrological feedbacks with New Mexico water resources. Since water-related environmental stresses occur in parallel with water supply shortages for people, such climate-change driven water stress could lead to increasing conflict between management of declining water availability for human use (e.g., irrigation) versus "wild" water retained for the maintenance of historical ecosystems.

Impacts on Soils

Soils play a strong role in determining how New Mexico's diverse landscapes will respond to climate change. Soil cover acts like a sponge, holding in water that falls as rain or snow. The presence of soil supports vegetation, and substantially reduces runoff and erosion. Soil enhances other processes such as infiltration of water and aquifer recharge. Soils can be damaged by a warming climate. Loss of vegetation in the northwest high desert and eastern plains, where soils are not well developed and easily damaged, will lead to dustier conditions in much of the state. On mountain hillslopes, the loss of vegetation cover in response to ongoing climate change will increase soil erosion, which then increases hillslope runoff. This, in turn, causes additional increases in soil erosion and bedrock exposure, which can largely prevent widespread recolonization by most plants, including trees. Soils on mountain hillslopes that face south, which are typically hotter and drier, will be damaged sooner by a warming climate than those on generally north-facing hillslopes that are slightly cooler and moister. Soils take many thousands of years to form, so these hillslopes will increasingly support sparse forests, or, in some circumstances, be entirely deforested. These changes are already well underway in some mountains in New Mexico.

Landscape Change, Fire, and Erosion

New Mexico has a dynamic landscape; climate change and increasing fire frequency over the next 50 years will amplify recently observed instability. As the climate changes to warmer conditions, less rainfall will infiltrate into aquifers, leading to increased overland runoff. Landform processes can be complex but, in general, the predicted changes in climate and precipitation will lead to increased upland erosion caused by runoff and increased downstream sediment deposition. Canyons, mesas, and small basins or valleys filled with sediment will be particularly affected. Rapid rearrangement of sediments by water is disruptive and potentially hazardous to ecosystems and societies. Dramatic examples of accelerated erosion following the Whitewater–Baldy, Las Conchas, and other wildfires here in New Mexico illustrate the types of hazards created when forested landscapes are severely burned. Post-wildfire erosion is typically initiated by intense rainfall events. Given that both the number of wildfires and rainfall intensities are likely to increase as the climate warms, New Mexico can expect to see increases in widespread erosion and sedimentation across and downstream from upland forested areas in the state. The large volume of sediment predicted to be on the move will be of concern for many reasons, including filling reservoirs, choking channels, and blocking or destroying infrastructure. Positive feedback loops lead to further reductions in slope stability.

Surface and Groundwater Supplies and Impacts on Users

Surface-water supply shortages induced by climate change will drive both agricultural and municipal/industrial water users to rely more heavily on groundwater. Less surface water will lead to lower recharge to some groundwater aquifers. The Lower Rio Grande is an in-progress example of this effect, with prolonged surface-water shortage leading to plunging groundwater levels. All water users in the state will experience decreased water availability as the climate warms and aridification occurs. This decrease in water availability will likely trigger changes of use from lower-value uses to higher-value uses, and this generally means a migration from agricultural water use to municipal/industrial uses. New Mexico has a rich and diverse history of water use that is central to its collective identity. This permanent shift towards a more arid climate will upset the hydrologic balance that has weathered cyclical drought. The declining mean and increasing variability in the surface-water supply is not cyclical, and recovery periods will be fewer and farther between. This will require difficult and divisive policy and management decisions, undoubtedly accompanied by an increase in disputes and litigation. New Mexico is by no means alone in facing these daunting challenges.

Extreme Precipitation and Stormwater Management

A warming climate could increase the magnitude of future storms, leading to extreme precipitation events and increased flooding in New Mexico. Warmer air can hold more water vapor, approximately 7% more moisture for each 1°C (1.8°F) increase in temperature. Global climate models (GCMs) used to predict future conditions are not detailed enough to simulate individual storms. Three major types of storms occur in New Mexico: short duration, high intensity local storms in summer (usually monsoonal); long duration general storms (caused by winter weather fronts); and occasionally the remnants of tropical storms. The principal risk from extreme precipitation events will be flooding in small watersheds from high-intensity local storms, precisely the storms that are hardest to simulate in climate models. Large-scale regional studies have corroborated the hypothesized increase in extreme precipitation with warming temperature, but few such studies exist on the impact on local storms in the four-corner states. A study of extreme precipitation events in Colorado and New Mexico was recently completed and has updated estimates of the magnitude of severe storms possible in our state. Data and modeling studies suggest that while the risk of the most severe storms might not increase beyond current estimated values, less severe (but still high intensity) storms may occur more frequently than at present, which could impact existing stormwater management infrastructure.

Impacts on Water Quality

A warming climate may affect the quality of both surface and groundwater resources in New Mexico; the most likely effects may include increased temperature along with concentrations of nutrients, dissolved oxygen, and pathogenic organisms. Although the quality of groundwater may be affected, it is likely to be limited to locations with shallow groundwater depth and where surface water recharges the aquifer. The New Mexico Environment Department publishes an assessment of the quality of the state's surface waters every two years. This recent assessment finds that the major causes of impairment of streams and rivers are temperature, nutrients (nitrogen and phosphorous compounds), *E. coli* bacteria, turbidity, and dissolved aluminum. The parameters most likely to be affected by a warming climate are temperature, nutrients, and *E. coli* concentrations. Studies suggest that loss of riparian vegetation is the biggest factor affecting water temperature. Modeling studies of the effects of climate warming on nutrient concentrations are somewhat inconclusive. Recent investigations suggest that *E. coli* concentrations may increase as a result of microbial regrowth in warming stream sediments in slow moving stream reaches. A future threat to water quality is runoff following wildfire events. Postfire runoff can cause depletion of dissolved oxygen far downstream from the burned watershed.

Statewide and Regional Impacts

All regions of New Mexico will be affected by climate change, but the topographic complexity of the state will generate distinct impacts by location. The average temperature will warm across the state, probably between 5° and 7°F, whereas average precipitation is likely to remain constant, even if more variable from year to year, with the possibility of more extreme precipitation events. Snowpack, runoff, and recharge will decline, stressing both surface and groundwater resources. Surface-water quality will decline. Plant communities will be stressed by higher temperatures and greater aridity, leading to more extreme wildfires and increased erosion. Damage to soils, related to a number of factors, will create greater atmospheric dustiness and lower water infiltration to aquifers.

Although latitude plays a role in the effects of climate change, the bigger impact in New Mexico is related to local topography and elevation. For the purposes of this report, we are dividing New Mexico into four physiographic regions, based on projected climate change impacts and associated effects on hydrology. These four regions, which are defined by a combination of latitude and topography, are: the High Mountains (northern mountains, Gila/Mogollon–Datil, and Sacramento Mountains); the Northwestern High Desert (Colorado Plateau, San Juan Basin, and Zuni Mountain region); the Rio Grande Valley and Southwestern Basins; and the Eastern Plains.

Recommendations: Data Gaps and Challenges

The process of evaluating and projecting climate change in New Mexico over the next 50 years, and examining the impacts on water resources, illuminated a number of research topics that should receive attention from the state's science community. A high-priority research target is to better understand a number of facets of precipitation that New Mexico might experience over the next half century. These would include seasonality of precipitation, snowpack dynamics, and extreme precipitation. Better understanding of the latter would allow New Mexico planners to be able to consider how to put localized, heavy precipitation to good use, and to mitigate damage associated with flooding. Climate, hydrology, and ecology numerical models, which allow projection of conditions and behaviors of these natural systems in New Mexico over the next half century, are also needed. Finally, a number of observational data gaps have been identified, most notably a thorough and geographically distributed assessment of the water levels in New Mexico aquifers. Other topics include impact of climate change on soil moisture and groundwater quality, as well as landscape and ecological responses to climate change, both in terms of magnitude and timescales of response. This can be carried out, in part, by long-term ecological monitoring.

I. INTRODUCTION

Nelia W. Dunbar and David S. Gutzler

The Earth is warming in response to increasing atmospheric carbon dioxide, and this warming will result in greater aridity in many parts of the world, including New Mexico. The primary observed and projected impacts include warmer temperatures, decreased water supply (partly driven by thinner snowpacks and earlier spring melting), lower soil moisture levels, increased frequency and intensity of wildfires, and increased competition and demand for scarce water resources. These effects may be accentuated by positive feedback cycles, tipping points, or compounding events. This report compiles, assesses, and integrates existing peer-reviewed published research, technical reports, and datasets relevant to the broad topic of changes to New Mexico's climate over the next 50 years and resultant impacts on water resources, and represents the scientific foundation upon which New Mexico's 50-Year Water Plan will be developed. New Mexico is a geographically, geologically, and climatically diverse state. Projected climate changes, and related impacts on water resources in different geographic areas of New Mexico over the next 50 years, will vary not only by region but also as a function of local elevation, and even by hillslope orientation. The currently observed trends of increasing temperature and constant, but more variable, precipitation will continue over the next 50 years.

Abundant scientific research demonstrates that the Earth's atmosphere, oceans, and surface are warming, and that this warming is largely driven by human-induced activity, principally through a sustained increase in carbon dioxide (CO_2) accumulating in the atmosphere since the beginning of the industrial revolution. Carbon dioxide and certain other gases, such as methane, trap heat in the troposphere, causing the planet's surface to warm (as discussed in IPCC, 2014 and USGCRP, 2017). This natural warming process, which is being enhanced by human activity, is called the greenhouse effect. Other extreme weather events, including droughts, prolonged heat waves, intense precipitation events and associated flooding, are occurring with greater frequency as the troposphere warms. And, increasing ocean and atmospheric temperatures are promoting rapid melting of Arctic and Antarctic land-based ice, leading to sea-level rise. Global climate is expected to continue to change in response to ever-increasing levels of atmospheric greenhouse gases, primarily CO_2.

The most significant negative impacts of climate change are distinct in different parts of the world, depending on the sensitivity of local systems to various climate perturbations (USGCRP, 2018). In the southwestern United States, the primary observed and projected impacts include warmer temperatures, decreased water supply (partly driven by thinner snowpacks and earlier spring melting), lower soil moisture levels, increased frequency and intensity of wildfires, and increased competition and demand for scarce water resources (Gonzales et al., 2018). Water quality may also suffer, and will affect people world-wide, but will be particularly detrimental to indigenous communities (Jantarasami et al., 2018).

In addition to those reasonably well-understood climate-related hazards, there is a real possibility for three types of less obvious changes in the climate and hydrological systems due to climate disruption (USGCRP, 2017):

1. "Positive Feedback" (or "self-reinforcing") cycles—Where a small change in one, or several systems can lead to accelerated change. For example, during times of higher temperatures and associated greater demand for surface water, water users will pump additional groundwater. Additionally, as water levels in aquifers drop, the rate of water loss from rivers to underlying aquifers may increase, reducing availability of surface water. The higher temperature will lead to more evaporation, and therefore less recharge of aquifers. Associated longer growing seasons and higher temperatures increase stress on the aquifers by further increasing the water demand of vegetation. All of these interrelated factors will lead to lower water availability.
2. "Critical Threshold" (or "tipping point") events—A threshold is crossed in a natural system that triggers an irreversible reaction. Reversing the trigger does not restore the natural system to its original condition. For example, when water is pumped from certain aquifers, the pore space in the aquifer will collapse, resulting in a permanently reduced capacity of the aquifer. This change is irreversible.
3. "Compounding events"—Perturbation in one element of a natural system triggers a change in another system. For example, loss of vegetation and modification of the land surface by intense wildfires can increase the speed at which precipitation flows off the land, and in turn, lead to increased flood intensity.

Examples of the three effects listed above have already happened in New Mexico, as will be noted in the following chapters of this report. As climate disruption accelerates, we should be prepared for other examples of positive feedback, critical threshold and compounding events to occur.

In 2006, the New Mexico Office of the State Engineer convened a group of scientists who produced a report entitled *The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources* (Watkins et al., 2006). The report was generated in response to Governor Bill Richardson's recognition that the most significant impact of climate change on New Mexico was going to be the negative impact on the state's water resources. Watkins et al. (2006) focused on a set of challenges listed below:

- Increasing temperature
- Changes in snowpack elevations and water equivalency
- Changes in available water volumes and timing of water availability
- Increasing precipitation in the form of rain rather than snow due to increasing temperatures
- Smaller spring runoff volumes and/or earlier runoff that will impact water availability for irrigation and for ecological and species needs
- Milder winters and hotter summers, resulting in longer growing seasons and increased plant and human water use
- Increased evaporative losses from reservoirs, streams, and soils due to hotter, drier conditions
- Increased evapotranspiration by agricultural and riparian plants
- An increase in extreme events, including both droughts and floods

New Mexico still faces all of these challenges today, but in the elapsed 15 years, additional research has led to a greater depth of knowledge about both climate change in general and specific consequences to New Mexico. Two Intergovernmental Panel on Climate Change (IPCC) reports (AR4 in 2007–08 and AR5 in 2013–14) have been published since 2006, and AR6 was released in late 2021. Two volumes of the 4th National Climate Assessment for the United States were published in 2017 and 2018, containing a wealth of regionally specific information. And new scientific research on broad impacts of climate change in the Desert Southwest region, including New Mexico, has continued to move forward. With the proposed development of a 50-Year Water Plan for New Mexico by the Interstate Stream Commission, a renewed assessment of climate change and its impact on water resources is timely, in order to provide a foundational assessment for the 50-Year Water Plan.

The primary goal of this report, informally referred to as the "Leap Ahead" analysis, is to compile, assess, and integrate existing peer-reviewed, published research, technical reports, and datasets relevant to the broad topic of changes to New Mexico's climate over the next 50 years, and resultant impacts on water resources. The motivation for preparing this report was to have a solid, science-based foundation in support of New Mexico's 50-Year Water Plan published in 2022. The authors of this report are expert New Mexican scientists whose research specialties span a broad and complementary range of research areas. The chapters of the report to follow this introduction are as follows:

2. Future Projections of Climate in New Mexico
3. Effects of Climate Change on the Land-Surface Water Budget
4. Climate Change: Terrestrial Ecosystem Responses and Feedbacks to Water Resources in New Mexico
5. Impacts on Soils
6. Landscape Change, Fire, and Erosion
7. Changes in Surface-Water and Groundwater Supplies and Impacts on Agricultural, Municipal, and Industrial Users
8. Effects of Climate Change on Extreme Precipitation Events and Stormwater Management in New Mexico
9. Impacts of a Warming Climate on Water Quality in New Mexico
10. Summary of Statewide and Regional Impacts of Climate Change on Water Resources
11. Recommendations: Data Gaps and Challenges

In many of the chapters in this report, authors will refer to "uncertainty" associated with a given natural process that may occur as a result of climate change. Uncertainty is inherent to scientific investigations, or any field that relies upon experiments and models, and results from the difficulty of being able to obtain complete information about a natural process, or from a lack of agreement about how to interpret results. In many cases, including examples in this report, uncertainty can be expressed in terms of a numerical range in results. In other cases, uncertainty can be expressed as a degree of confidence, as has been done in past IPCC reports, with likelihoods such as "very likely" or "very unlikely" being used. This level of uncertainty analysis is beyond the scope of this report, but readers who want to learn more about how this process was handled by the IPCC may refer to Mastrandrea et al. (2010).

New Mexico is a geographically, geologically, and climatically diverse state. Projected climate changes, and resultant impacts on water resources in different geographic areas of New Mexico over the next 50 years will vary not only by region, but also as a function of local elevation, and even by hillslope orientation. Chapter 10 of the report will summarize climate change impacts on water resources that will affect the entire state, but will also then focus on particularly important impacts on different regions of the state. For each region, the key climate-related factors that may impact diminishing (or increasing) water resources will be highlighted.

Finally, in addition to synthesizing the state of knowledge on climate change and impacts on water resources in New Mexico over the next 50 years, an important aspect of this report has been to identify significant data and modeling gaps, uncertainties, and to suggest research directions to strengthen our understanding of these important topics. This is addressed in the final chapter of the report, serving as a blueprint for valuable research directions that will help us better understand and adapt to the impacts of the looming challenges ahead.

The historical climate baseline for New Mexico is key to understanding the changes that are described in this report. A concise, illustrated introduction to the climate of New Mexico, and its past and future variability is presented below.

New Mexico has a temperate, semiarid climate, as described by Gutzler (2004). It is located in the subtropical latitude belt where descending air from the Hadley Circulation maintains a generally dry climate compared to latitudes near the equator or farther north, with a very pronounced seasonal cycle. Its interior position within the North American continent means that moisture evaporating off the ocean must propagate a long distance to reach New Mexico, enhancing the tendency for rain out before water vapor reaches the state. Its high elevation, with the continental divide and Rio Grande rift mountains defining high and complicated topography, keep average annual temperatures cooler than surrounding states to the west and east (Fig. 1.1a). The mountains promote cloud formation and precipitation when moist airflows are forced upslope, so the map of averaged annual precipitation (Fig. 1.1b) mimics a map of topography. These moist airflows are associated with frontal systems propagating off the Pacific Ocean in winter, and monsoonal moisture from the south in summer. Hydrologic variability from year-to-year, or on longer time scales, can arise when these moist air flows follow different paths (such as winter storm tracks shifting north or south due to Pacific Ocean variability), or when temperature change affects the water balance at the surface (such as, by changing how much snow accumulates, or by changing surface evaporation rates).

Specific information, with supporting illustrations, on selected aspects of New Mexico's past and future climate is summarized below:

- The average temperature across New Mexico has risen by more than 2°F from 1970 to 2020 (Fig. 1.2), in parallel with global temperatures.
- Annual precipitation shows no obvious long-term trend in the instrumental record, but interannual and decadal-scale swings are large (Fig. 1.2). Decadal averages of precipitation values peaked in the 1980s and have since declined for the three subsequent decades. The decadal average of statewide precipitation for 2011–2020 was very close to the average for the drought decade of the 1950s. Four of the five lowest annual statewide precipitation values since 1931 have occurred since the turn of the twenty-first century.
- Based on projections of the climatic response to global emissions of greenhouse gases, New Mexico temperatures are likely to increase significantly in coming decades (Fig. 1.3). The projected increase in temperature is described in more detail in Chapter 2.
- The record of past drought in New Mexico reflects the pronounced natural variability of precipitation, a considerable fraction of which can be explained by natural fluctuations of Pacific Ocean temperatures (such as the El Niño cycle). New Mexico has experienced extended periods of wetter or drier conditions for many centuries (Fig. 1.4), and these fluctuations are expected to continue in future decades. Intermittent profound drought periods, the dry half of natural variability such as we are experiencing today, are endemic to the Southwest. The first few years of the ongoing drought epoch are shown as declining values at the end of the time series in Fig. 1.4. The approximate frequency of swings between drought and pluvial (wetter) conditions in this figure (approximately twice/century) suggests that New Mexico's climate might transition back toward an epoch of wetter conditions sometime in the next few years, but we currently have no reliable way to predict when such a swing might take place.
- Snowpack has been declining over the past several decades in association with warming temperatures and increases in dust blowing onto snow (Livneh et al., 2015), promoting earlier snowmelt. When snowpack becomes dust-covered, the snow's ability to reflect solar radiation decreases, causing more solar radiation to be absorbed, and therefore more rapid melting. Observed snowpack in the headwaters of the Rio Grande has declined >20% spanning an epoch of both drought and pluvial conditions (Fig. 1.5, top curve). Snowmelt runoff (not shown in this graph) has been occurring earlier as average spring temperatures rise. Streamflow in major rivers (Rio Grande headwaters shown as an example in bottom curve of Fig. 1.5) so far has not exhibited long-term trends as clearly as the trends in snowpack or temperature. However, flow deficits during recent drought years have been lower than flows in earlier severe drought episodes, suggesting that the effects of declining snow and rising temperature are starting to become evident as a worsening of low-flow conditions during severe droughts.

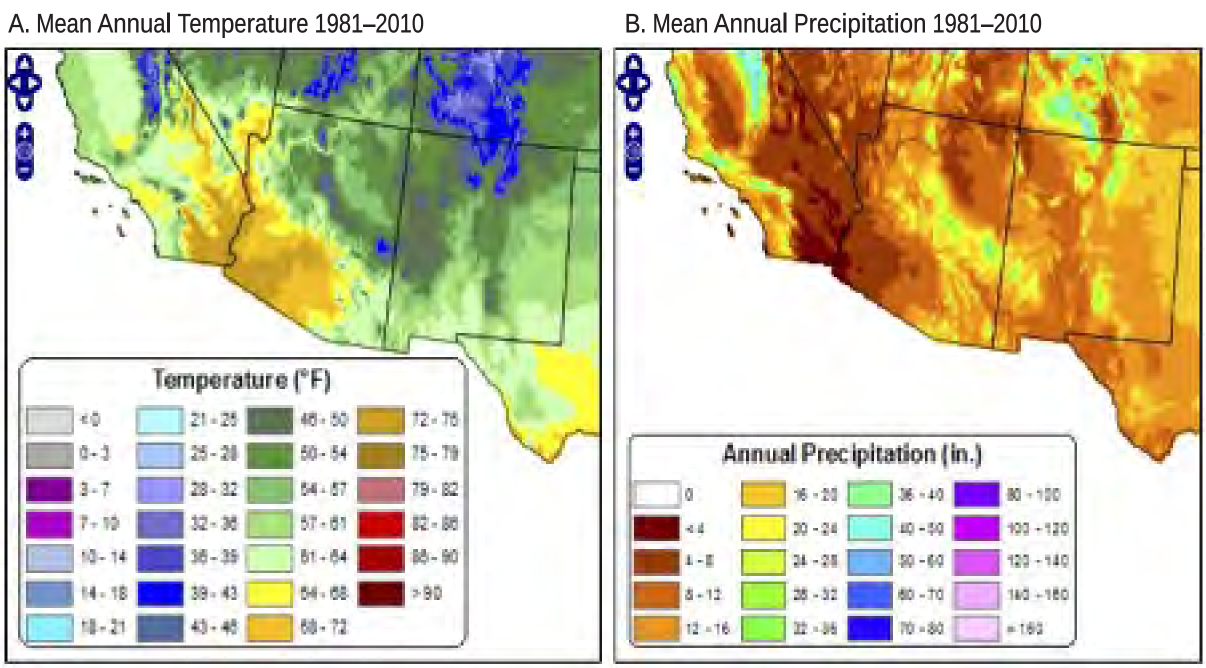

Figure 1.1. 30-year average "normal" values of observed annual temperature and precipitation, 1981–2010 (from PRISM group at Oregon State University).

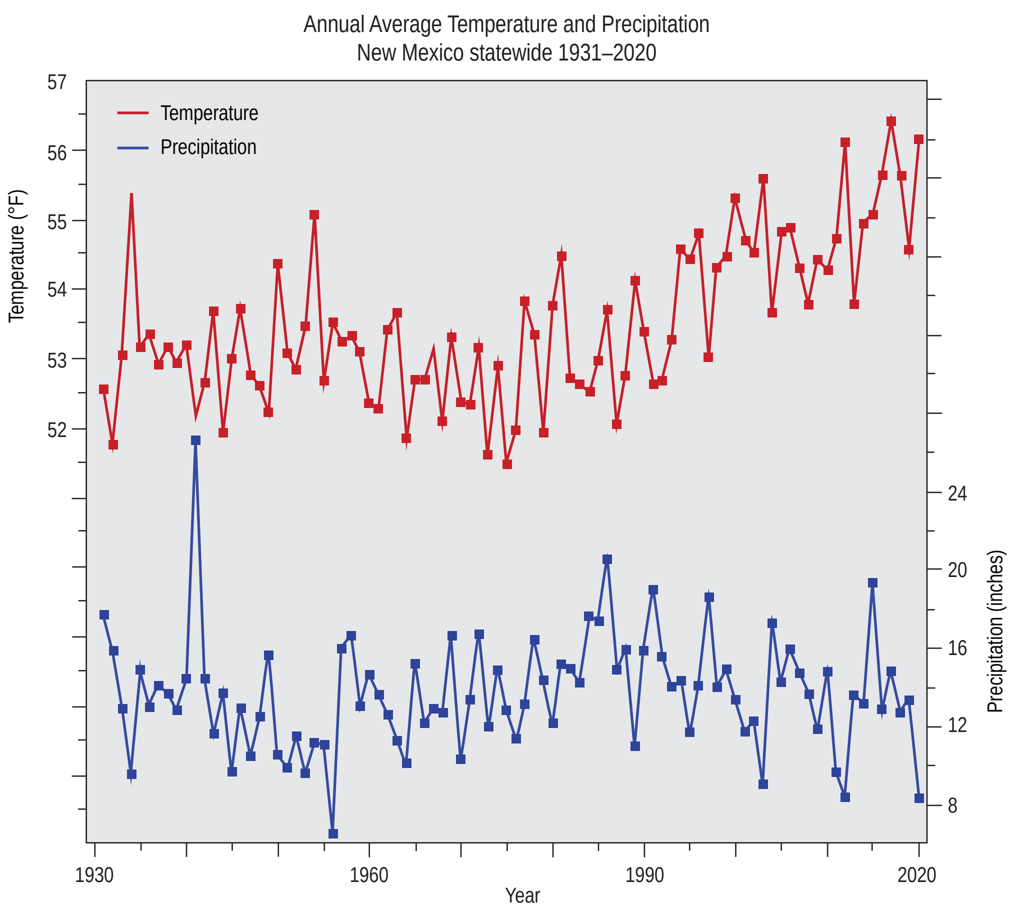

Figure 1.2. Observed annual temperature (red) and precipitation (blue) averaged over the state of New Mexico, 1931–2020. Source: updated from New Mexico Universities Working Group (2015) and Gutzler (2020).

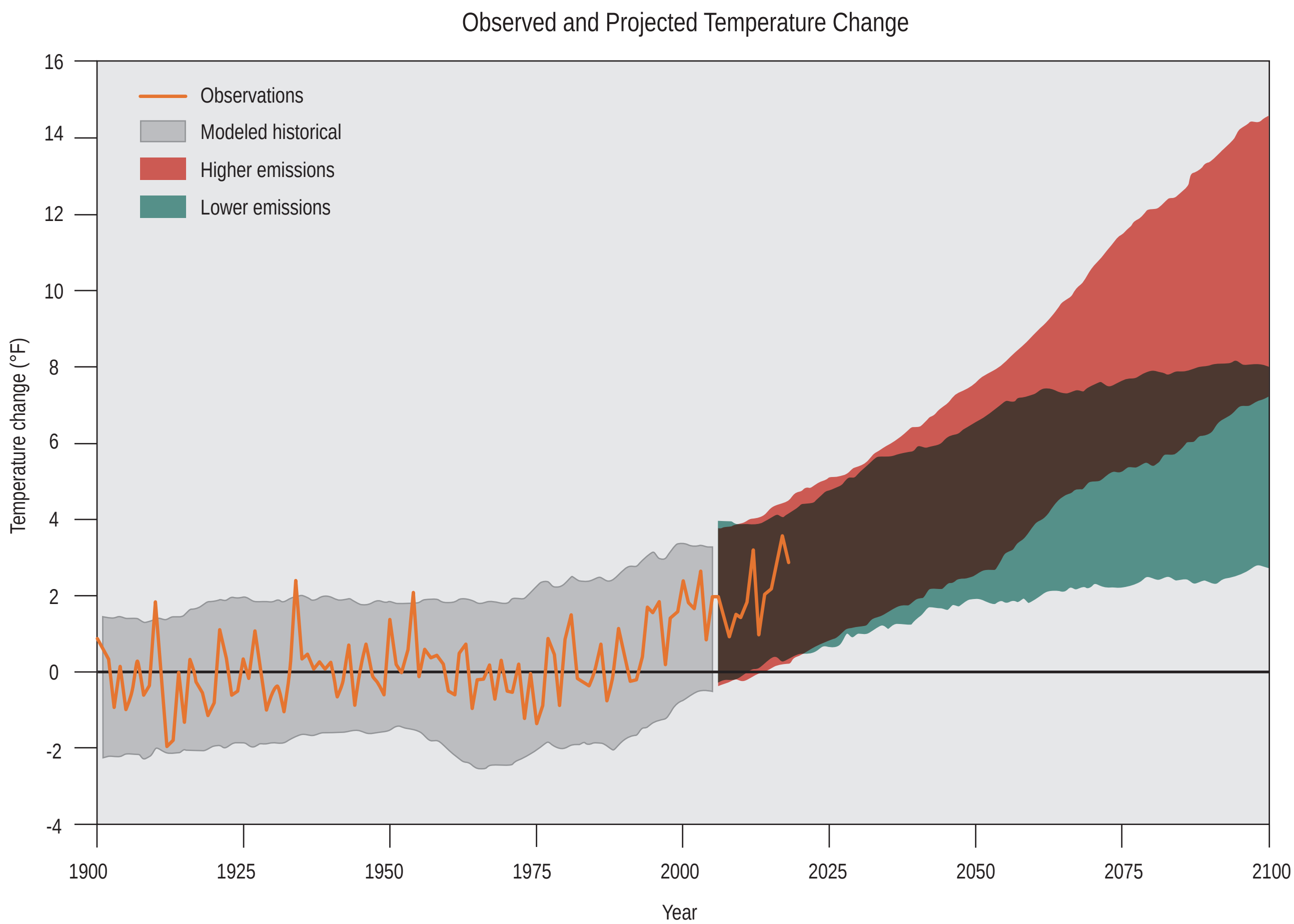

Figure 1.3. Observed and projected changes (compared to the 1901–1960 average) in near-surface air temperature for New Mexico (USGCRP, 2017). Observed data are for 1900–2018. Projected changes for 2006–2100 are from global climate model simulations of possible futures, one in which greenhouse gas emissions increase at an accelerated rate (higher emissions) and another in which greenhouse gas emissions increase at a rate similar to that observed today (lower emissions). Shading indicates the range of annual temperatures from a large set of CMIP5 global climate models. Observed temperatures are generally within the envelope of model simulations of the historical period (gray shading), serving to validate the model simulations. Historically unprecedented warming is projected during the twenty-first century, as discussed in more detail in Chapter 2.

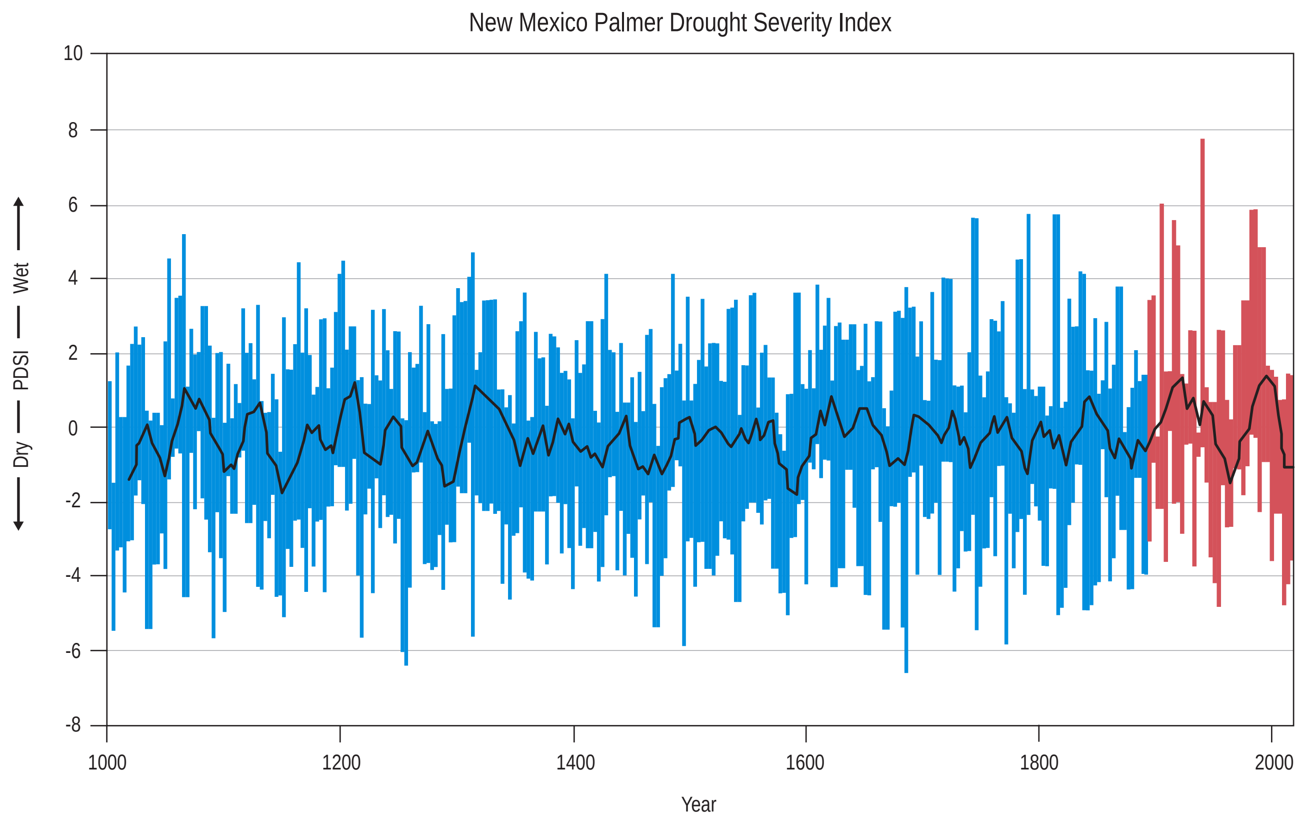

Figure 1.4. Time series of the Palmer Drought Severity Index (PDSI) from the year 1000 to 2018 (USGCRP, 2017). This index uses temperature and precipitation data to estimate relative dryness. Values for 1895–2018 (red) are based on measured temperature and precipitation. Values prior to 1895 (blue) are estimated from indirect measures such as tree rings. The thick black line is a running 20-year average. In the modern era, the wet (pluvial) periods of the early 1900s and the 1980s–1990s and the drought period of the 1950s are evident. The extended historical record (in red) indicates episodic occurrences of similar extended pluvial and drought periods.

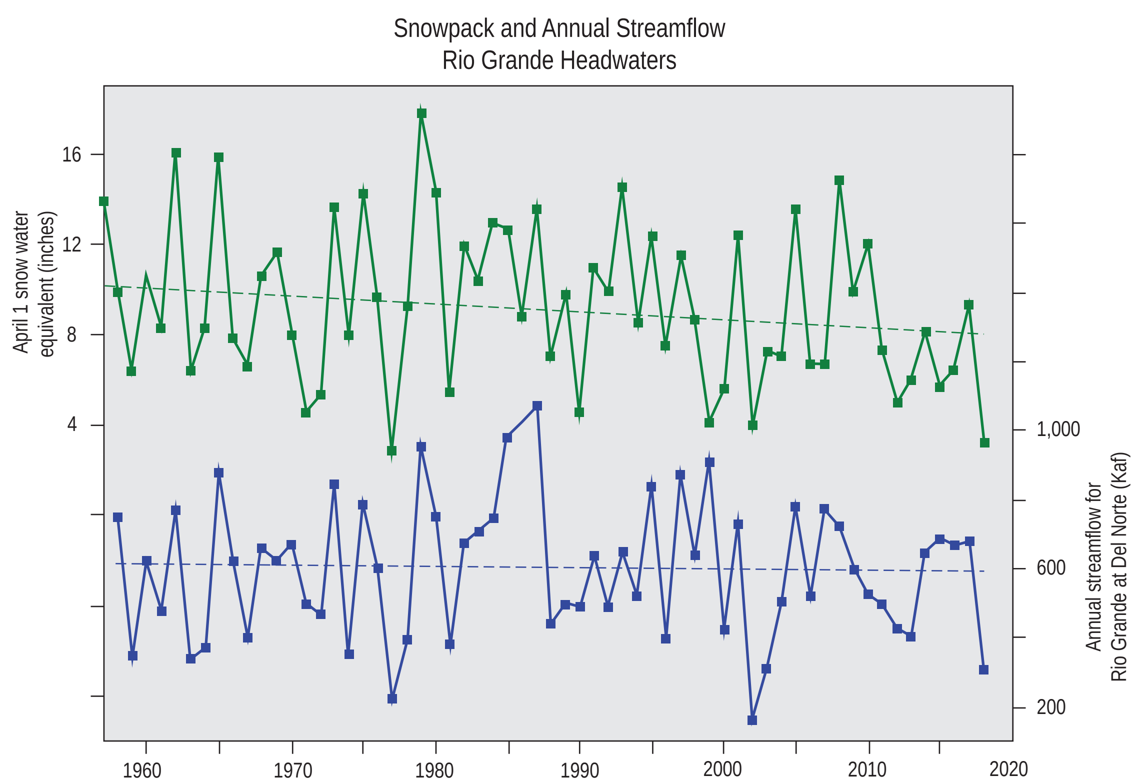

Figure 1.5. Observed April 1 snowpack (green) and annual streamflow (blue) in the Rio Grande headwaters. Kaf = thousand acre-feet. From Gutzler (2020).

II. FUTURE PROJECTIONS OF CLIMATE IN NEW MEXICO

David S. Gutzler and David DuBois

Global climate models driven by increasing greenhouse gases project an average temperature increase across the state of New Mexico of between 5° and 7°F over the next 50 years. This regional temperature increase follows the trend observed over the past half-century, at a somewhat amplified rate, with the northwest corner projected to experience a slightly higher rise during the same period. Although all models indicate significant increases in temperature, these models do not consistently project a significant change in average annual precipitation across the state, mirroring the absence of a clear trend in recent historical observations. However, some consistent differences in seasonality of precipitation emerge. During the winter, the northern mountains may receive somewhat more precipitation, whereas the southern parts of the state may be drier. Spring precipitation, critical for snowmelt runoff and ecosystems, may decline. Also in the southern part of the state, a trend towards somewhat stronger monsoonal activity may result in more summer precipitation, perhaps shifting toward somewhat later in the year.

The coupled trends of increasing temperature with no clear increasing trend in precipitation leads to a confident projection of increasingly arid conditions, including decreased soil moisture, stressed vegetation, and more severe droughts. Snowpack and associated runoff are projected to decline substantially by 2070, generating diminished headwater streamflow. Warmer temperatures will also cause lower river flows due to increased evaporation as rivers flow downstream. The impact of climate change on New Mexico's resources are, unfortunately, overwhelmingly negative.

Introduction

As discussed in the previous chapter, New Mexico is characterized by a semiarid climate with enormous natural variability of precipitation and streamflow. Observations from the past half century show a clear and pronounced warming trend, together with exceptionally wet conditions in the late twentieth century followed by decades of historic drought continuing to the present day. In this chapter we summarize projections of future climate for the next half century, out to 2070. Evidence derived from model projections suggests a high likelihood of continuing temperature increases coupled with pronounced precipitation variability. Projections of precipitation change are made with much lower confidence, with diminished precipitation in Spring representing the most likely seasonal trend. Large interannual and decadal variability of precipitation should continue and extremes in precipitation are projected to intensify regardless of any trend in the total annual precipitation. Effects of projected temperature and precipitation changes on surface-water supplies are most pronounced for temperature-related variables, including diminished snowpack and snow-fed streamflow (with continuing high interannual and decadal variability), increased evaporation rates from open-water surfaces, diminished groundwater recharge, drier soils, increased frequency of wildfire-conducive weather and a general trend toward more arid conditions. Episodic droughts, when they occur, will become much more severe as temperatures increase.

Previous Assessments of Twenty-first Century Climate Projections for New Mexico

New Mexico is projected to become hotter and more arid over the next 50 years, as the result of human-caused climate change. This expectation results from multiple generations of Global Climate Model (henceforth denoted "GCM") projections made over the past 15 years (Watkins et al., 2006; Seager et al., 2007; Gutzler and Robbins, 2011; Llewellyn and Vaddey, 2013; Reclamation, 2011, 2016, 2021; USGCRP, 2014, 2018; IPCC 2013, 2021). The validity of these projections has been reinforced by continuing observations of persistent hot, dry environmental conditions in the first two decades of the twenty-first century (Chapter 1). A strong, long-standing scientific consensus from these reports indicates that New Mexico should plan for a hotter, more arid climate, with a rate of change dependent on global policy to mitigate greenhouse gas emissions.

This section reviews the evidence derived from GCM projections, to support the more specific projections outlined in the sections to follow. As discussed in Chapter 1, New Mexico has a semiarid climate with diverse spatial variability and sharp gradients in temperature, precipitation and vegetation in mountainous regions.

Several previous water resource assessments carried out for the state of New Mexico have highlighted the likelihood of more arid conditions in future decades as climate changes. Watkins et al. (2006) used tree-ring analyses and high-resolution climate models to highlight both the past severe droughts and likely future trends toward warmer, drier conditions across the state. A decade later, a team of researchers from three New Mexico universities assessed risks to water security in the southern Rio Grande Valley in New Mexico, a region of intensive irrigated agriculture (Chermak et al., 2015). Each of these studies warned that projected decreases in water supply associated with a warmer, more arid regional climate pose substantial risks to the public welfare and the economy of the state.

The climate change findings in these statewide studies relied on, and reached conclusions consistent with, national climate assessments that also examined historical and projected future climate change across the Southwest (USGCRP, 2014, 2017, 2018). A consistent theme derived from all of these studies is the near-certainty of warmer temperatures, and the high likelihood of drier overall conditions and deeper droughts, for the state of New Mexico and all of the southwestern U.S. over the next 50 years.

In this chapter, we update the assessments cited above to provide climate projection information in support of the topical sections to follow. In the years since the Chermak et al. (2015) and 4th National Climate Assessment (USGCRP, 2017, 2018) reports, new products have been derived from GCM projections by coupling projected climate change to surface hydrologic models, to simulate regional changes in streamflow and soil moisture (variables that will also be discussed in following sections). In addition, new analyses of historical observations have confirmed that many of the hydrologic changes expected to accompany warming temperatures, such as declining snowpack, are already apparent in recent observations (Fig. 1.5).

We first present GCM-based projections for temperature and precipitation. For this report we use output from the widely-used "CMIP5" (Coupled Model Intercomparison Project, Phase 5) archive[1] used for international (IPCC, 2013) and national (USGCRP, 2017) assessments. CMIP5 models simulate historical climate using observed, time-varying greenhouse gas concentrations, and continue into the future using several future scenarios that differ by the assumed increase in greenhouse gas concentrations used to drive the model. The

1. Output from the next generation of global climate simulations, CMIP6, is newly available for analysis and is the centerpiece of the recently released IPCC (AR6) assessment (IPCC, 2021). However we base this chapter on the CMIP5-based results that have been thoroughly vetted, downscaled, and used for hydrologic modeling over the past eight years. Preliminary results from CMIP6 suggest that the newest generation of GCMs projects warming that may occur at a somewhat faster rate compared to CMIP5.

"RCP4.5" scenario is considered to be a "mid-range" assumption, and "RCP8.5" is a higher-emissions scenario that generally leads to higher temperatures and greater overall large-scale climate change. Each GCM also simulates "natural variability" that influences regional climate associated with oceanic phenomena such as El Niño, fluctuations of the monsoon circulation and other climatic processes.

Global climate models are run at a horizontal resolution of 50–100 miles (depending on the model), which is appropriate for large-scale climate but much too coarse to properly resolve individual thunderstorms, narrow mountain ranges, and other important features of local climate and topography. Here we use results from an ensemble of 20 CMIP5 simulations that have been downscaled and bias-corrected by the MACA project ("Multivariate Adaptive Constructed Analogs," Abatzoglou and Brown [2012]). In the MACA dataset, the global model output is downscaled to 1/24 degree (roughly 2.5 miles) using a statistical procedure based on historical observations and actual topographic features to introduce realistic high-resolution spatial variability to the coarse-resolution model output. We emphasize that these are "off-the-shelf" modeling results, not developed specifically for this report. Detailed regional climate modeling customized to the needs of New Mexico water resources assessment is beyond the remit of our working group.

Downscaled CMIP5 Temperature Projections

The MACA-downscaled simulations, spatially averaged statewide, consistently simulate significant increases in temperature in decades to come. Figure 2.1a shows annual temperature, averaged over 20 simulations driven by the high-emissions (RCP 8.5) scenario, from 1950 to 2070. The red portion of the time series indicates that the average increase in annual statewide temperature projected by these models is approximately 5°F by mid-century and 7°F from 2000 to 2070, with relatively modest model uncertainty represented by the dark pink shading about the average. These projections represent with high likelihood, a staggering increase in temperature that would have profound consequences for life (and water resources) in New Mexico. This projected trend continues the observed warming trend from the past half century at a somewhat amplified rate. The corresponding set of projections generated by the lower emissions scenario (RCP 4.5) continues warming at about the same rate that has been observed over the past half century.

Temperatures are projected to rise all across New Mexico as shown in Fig. 2.1b, with the largest increases in the northwestern part of the state. All of southwestern North America is expected to experience a significant increase in temperature during the twenty-first century, extending the observed warming trend at a rate depending on future atmospheric greenhouse gas concentration increases (USGCRP, 2017; IPCC, 2021).

Downscaled CMIP5 Precipitation Projections

Unlike temperature, there is no clear trend in projected statewide total annual precipitation toward either wetter or drier conditions. The multi-model ensemble precipitation change for the high-emissions scenario (Fig. 2.2) exhibits an insignificant (nearly flat) average trend, with an envelope of variability among the different models of nearly 50%. The map of ensemble-average precipitation change associated with Fig. 2.3 (not shown) is nearly featureless across New Mexico. Furthermore, inspection of the 20 individual simulations included in the ensemble average (not shown) reveals that some simulations project increases in precipitation across the state, whereas other simulations project decreases. We conclude that, at least on an annual statewide basis, the suite of CMIP5 models included in the MACA archive do not exhibit a clear and significant trend in future precipitation—a continuation of the absence of a clear trend in recent historical observations (Fig. 1.2).

Projected trends in precipitation stand out somewhat more clearly when separated by seasons. In winter (Fig. 2.3a), frontal systems propagating eastward off the Pacific Ocean tend to track farther north on average, so the southern part of the state exhibits a tendency toward less precipitation while the northern mountains tend to receive somewhat more, averaged over all 20 simulations in the MACA model archive. The spring season (Fig. 2.3b) exhibits a general statewide drying trend. For much of the state, spring is already the driest season of the year, so the trend toward less spring precipitation (combined with hotter temperatures) represents a clear trend toward aridity.

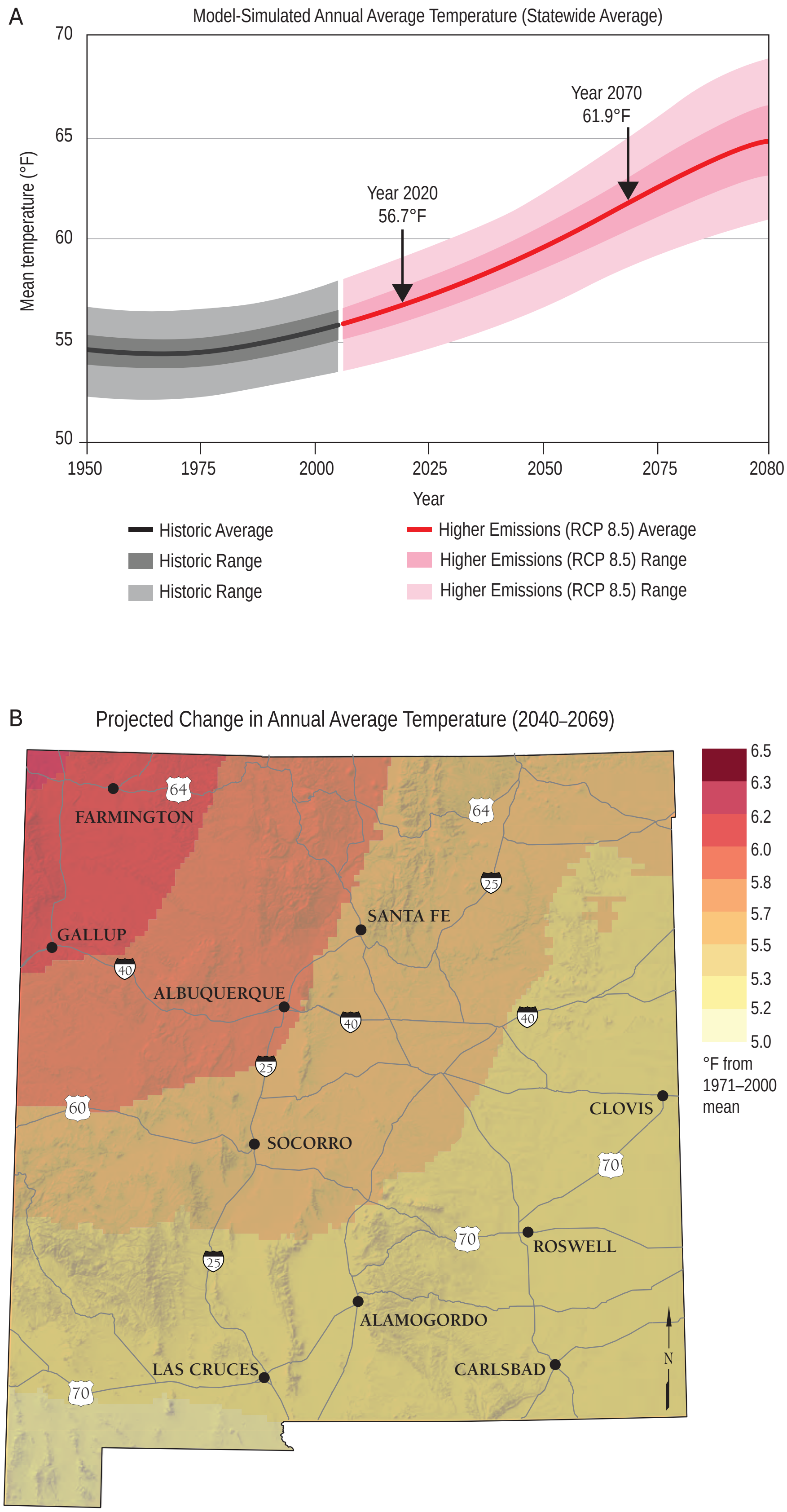

Figure 2.1. (a) Annual average temperature simulated by 20 CMIP5 climate simulations by different models, spatially averaged over the state of New Mexico. The black portion of the time series represents model output that has been bias-corrected, so that the statistics of temperature match observations over the historical period, when models were forced by observed atmospheric greenhouse gas concentrations. The red portion of the curve represents future conditions, with the models all forced by the same high-emissions (RCP 8.5) greenhouse gas scenario. The thick central line is the 20-model average; the envelope of annual model variability is denoted by the gray and pink shading. The inner, darker gray and pink shading includes half of the simulations (the "interquartile range). (b) Annual average temperature change simulated by the same ensemble of simulations used for Fig. 2.1a. Temperature change is defined as the difference between two thirty-year averages: (2040–2069) minus (1971–2000); the central years of these averaging periods are 70 years apart, so this plot represents 70-year temperature changes across the state.

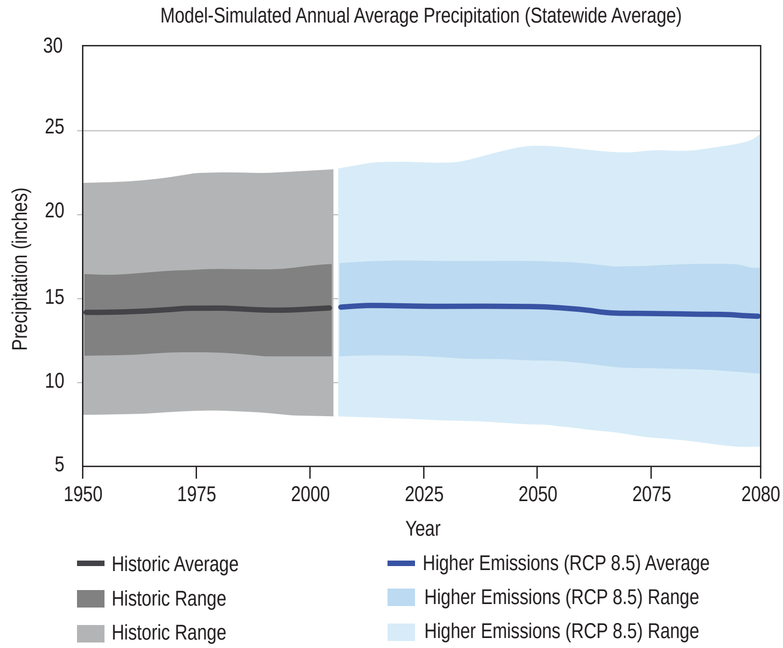

Figure 2.2. Annual average precipitation simulated by 20 CMIP5 GCMs, spatially averaged over the state of New Mexico, corresponding to the temperature time series in Fig. 2.1a.

Summer precipitation (Fig. 2.3c) includes a modest trend toward stronger monsoon precipitation in the southwestern corner of the state, combined with a trend toward less precipitation in the northeast. The latter feature is part of a more general geographical trend toward drier summers in central North America. The trend in autumn precipitation averaged over 20 simulations is generally small, with some tendency for increasing precipitation in southwestern New Mexico, where the trend toward spring dryness and autumn wetness is associated with a projected tendency for the monsoon season to shift toward later dates, both in terms of its onset and its end (Cook and Seager, 2013).

However, the 70-year changes shown in Fig. 2.2, averaged over 20 simulations, typically represent rather small average trends among different individual simulations, each of which includes large natural variability. With this in mind, we emphasize that the maps shown in Figs. 2.1 and 2.3 suggest broad guidance regarding future climate change, and should not be interpreted as providing specific local guidance (such as would be indicated by a daily weather forecast map).

To illustrate how modest the projected trends are compared to interannual variability, Fig. 2.4 shows precipitation time series derived from four different simulations, which were selected to show a wide range of projected changes. Fig. 2.4a shows results for winter and summer precipitation for a single 1/24 degree grid cell in the Sangre de Cristo Mountains northeast of Taos, at a surface elevation of approximately 10,000 ft (location denoted by the blue x in Fig. 2.3a). Fig. 2.4b depicts the same information for a grid cell southwest of Deming in the southwestern part of the state (denoted by a red x in Fig. 2.3a).

In the Sangre de Cristo Mountains (left, panel **a**), the 20-model average in Fig. 2.3 shows a modest upward change in winter and a downward change in summer. But these trends can be difficult to pick out in individual simulations (Fig. 2.4b) within the "noise" associated with simulated natural variability. Careful statistical analysis picks out these trends, however, leading to the smooth large-scale features on the maps in Fig. 2.3.

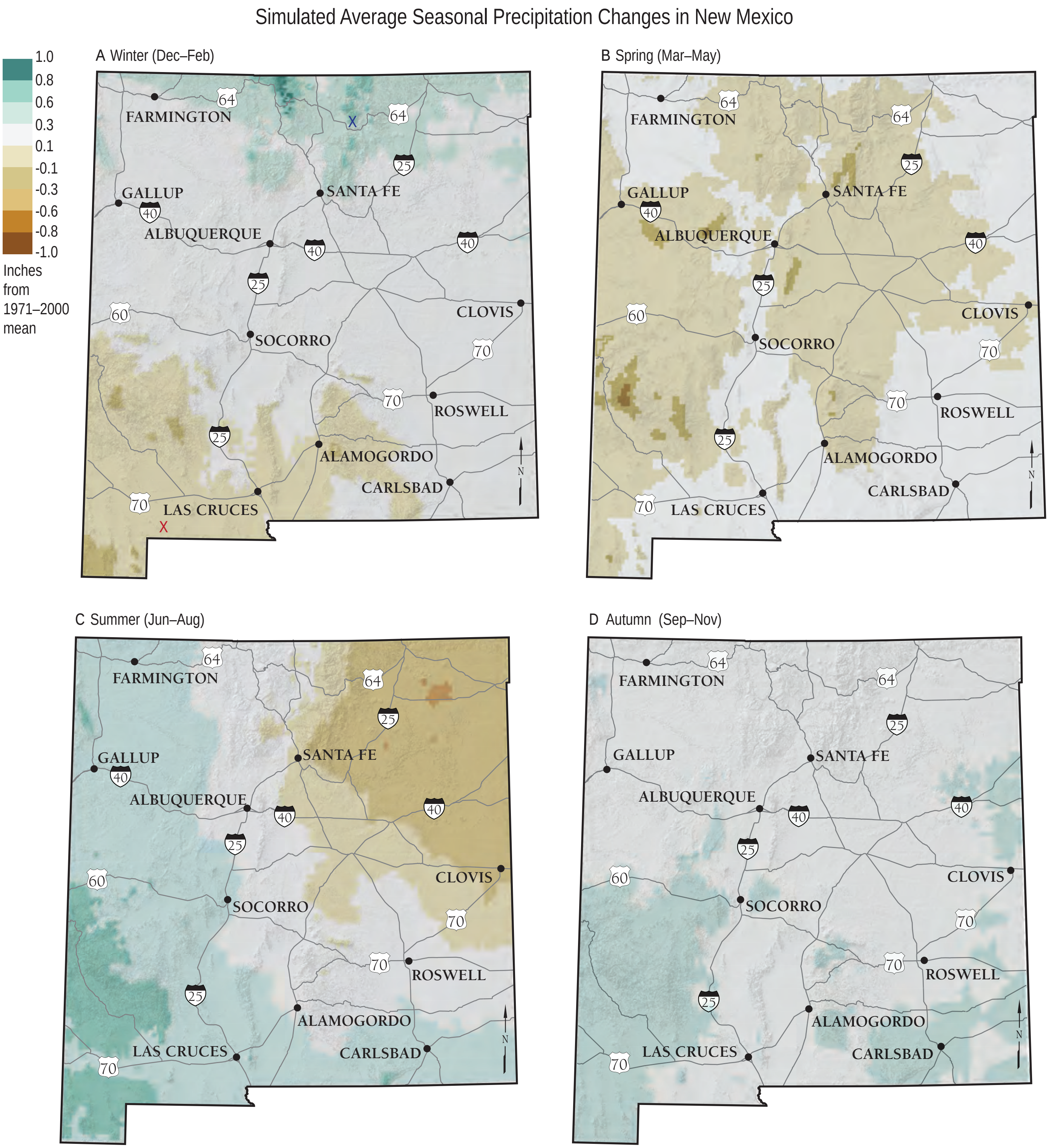

Figure 2.3. Seasonal average precipitation changes simulated by the same ensemble of climate simulations used for Fig. 2.1. (a) winter (b) spring (c) summer (d) autumn. As in Fig. 2.1a, each map shows differences between two thirty-year averaging periods 70 years apart: (2040–2069) minus (1971–2000). The color scheme is the same for each plot, with green colors indicating increasing precipitation and brown colors indicating decreasing precipitation. In panel (a), the blue and red x symbols denote the locations associated with time series shown in Fig. 2.4.

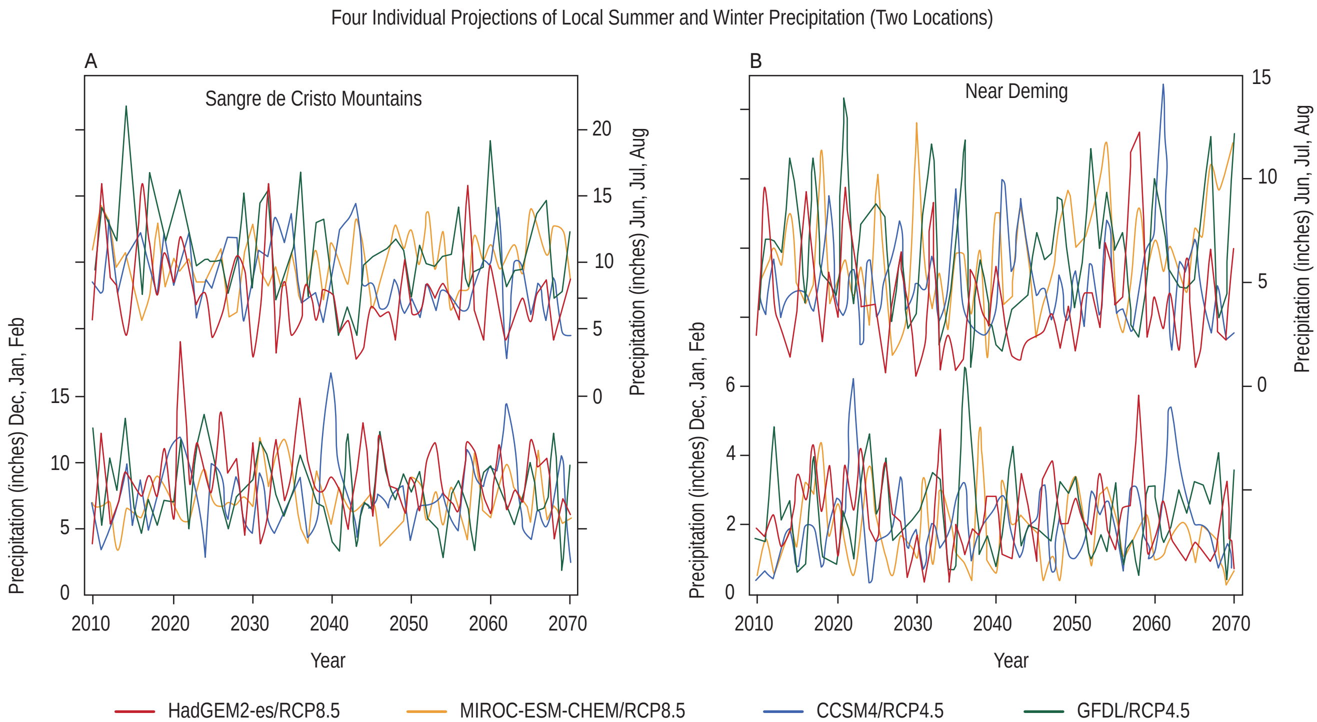

Figure 2.4. Time series of seasonal average precipitation changes simulated by four GCM simulations, for two individual model grid cell locations. (a) Grid cell located at 36.6N, 105.4W, in the Sangre de Cristo Mountains in north-central New Mexico (marked by a blue x in Fig. 2.3a). (b) Grid cell located at 32N, 108W, near Deming in southwestern New Mexico (marked by a red x in Fig. 2.3a). Each panel contains two sets of four curves. The upper set of curves in each panel shows annual values of summer (Jun–Aug) precipitation, and the lower set of curves shows annual values of winter (Dec–Feb) precipitation. Individual simulation results are color coded: red = HadGEM2-es/RCP8.5, orange = MIROC-ESM-CHEM/RCP8.5, blue = CCSM4/ RCP4.5, green = GFDL/RCP4.5.

The same general character is true of the individual time series for the grid cell near Deming (right, panel **b**). In particular, the relatively weak overall increase in summer monsoon precipitation shown in Fig. 2.3c, which represents a possible welcome respite from the general story of increasing aridity across most of the state, is seen to be a small average trend among disparate, highly, variable projected time series (upper set of curves in Fig. 2.4b).

Extreme precipitation values derived from CMIP5 model projections show a significant tendency for heavier extreme daily precipitation (Fig. 2.5, adapted from the most recent National Climate Assessment, USGCRP, 2017). As we will discuss in more detail in Chapter 8, trends in extreme precipitation are difficult to estimate from observations, and challenging to simulate in GCMs. Nevertheless, there are strong physics-based reasons to expect that the risk of extreme precipitation should increase in a warming climate. The assessment of projected trends in one-day extreme precipitation amounts shown in Fig. 2.5, averaged over large regions of the U.S. to improve statistical significance, indicates that CMIP5 simulations project such an increase nationwide.

Projections of Other Hydrologic Variables

The chapters to follow in this report consider many climate-related variables that affect water resources in the state. In this subsection we present a brief introductory overview of several of these variables, focusing on those that can be simulated directly from the same GCM simulations that have been used in this chapter to assess temperature and precipitation changes.

Evapotranspiration and Soil Moisture—As temperature rises, the capacity of the near-surface atmosphere to accommodate water vapor increases strongly. Hence moist surfaces or open water tend to generate higher evaporative surface-water losses in

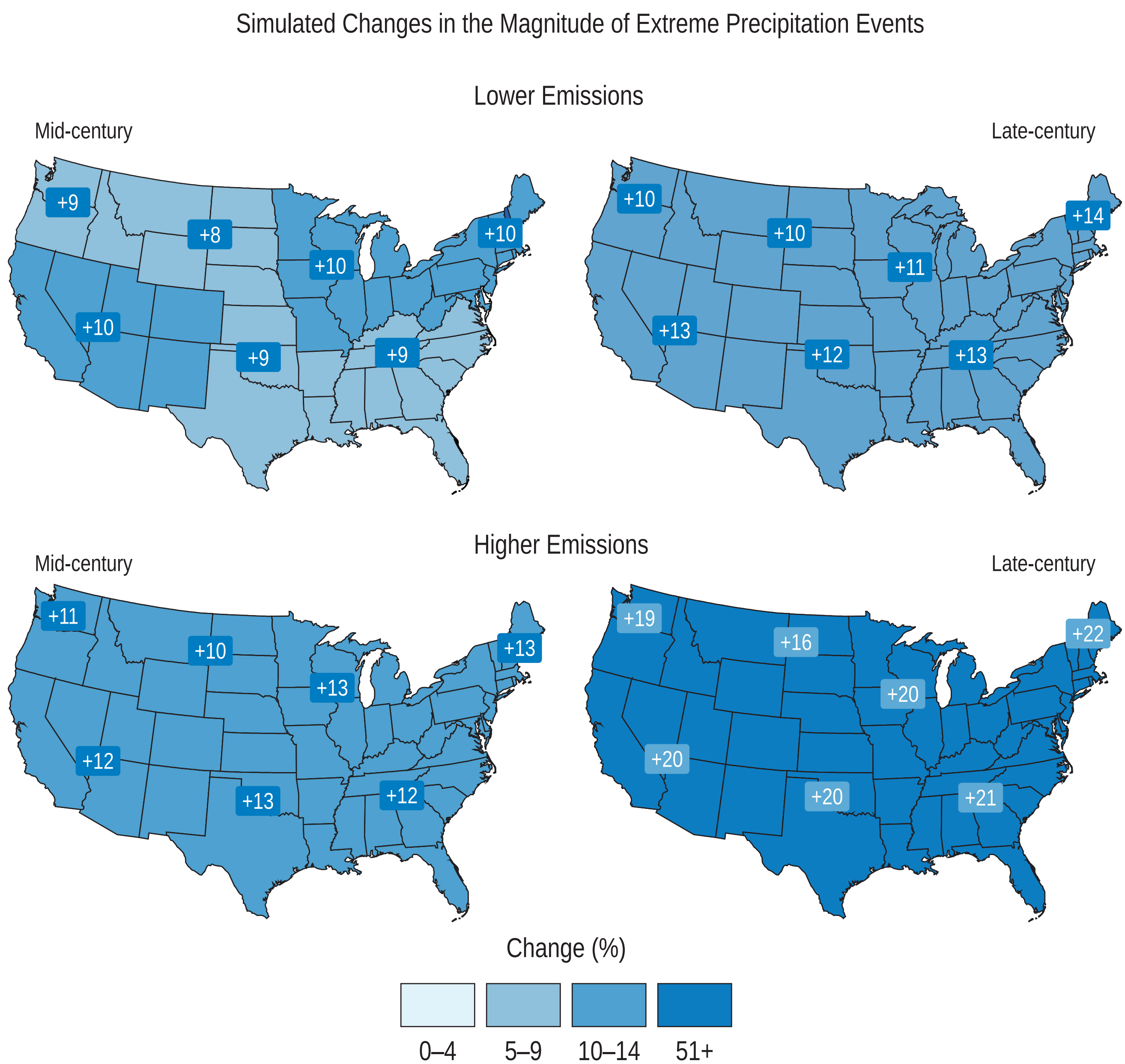

Figure 2.5. Projected change from a historical baseline period (1901–2005) in the magnitude of extreme precipitation events, here defined as the one-day precipitation maximum expected once every 20 years, derived from statistically downscaled CMIP5 GCM simulations (using an average of CMIP5 models, but a different statistical downscaling technique than the MACA post-processing used for Figs. 2.1–2.4; USGCRP, 2017, Fig. 7.7). Results from a lower emissions scenario (RCP 4.5) are on the top; higher scenario results (RCP8.5) are on the bottom. The left-side maps show changes as a percentage of present-day 20-year return values expected by mid-century; late-twenty-first century changes are shown on the right. All changes projected nationwide are positive, indicative of higher 20-year return values of maximum daily precipitation.

a warmer climate. This tendency can be quantified by the potential evapotranspiration (PET), which is a measure of how much water would evaporate over a large area covered with uniform vegetation if there is unlimited water available at the surface. Potential evapotranspiration can be interpreted as the demand for water by surface vegetation. Potential evapotranspiration is also a function of the humidity and air pressure of the overlying atmosphere so it is not just a measure of temperature. The estimate of changes in PET driven by the temperature and precipitation changes already discussed, suggests that the average annual value of PET will be 3 to 9 inches higher by mid-century, relative to its late twentieth century value (Fig. 2.6a).

The projected increases in PET are associated with projected declines in soil moisture. The increase in PET depletes the moisture available to withdraw from the surface, leading to drier soils. Based on nearly the same set of high-emissions simulations used for the temperature and precipitation projections shown here, the U.S. National Climate Assessment (USGCRP, 2017) projected significant declines in soil moisture centered on New Mexico (Fig. 2.6b), especially in the winter and spring seasons. The pattern of spring soil moisture decline is very similar to the spatial pattern of temperature increase in Fig. 2.1b, with greatest changes in the northwestern quadrant of the state. Chapter 3 of this report assesses soil moisture changes in New Mexico in more detail, and subsequent chapters on ecosystem changes will highlight the importance of the projected decrease in soil moisture across the state.

Evaporation of surface water from reservoirs is increasing as temperatures rise, similar to PET but without any limiting factors associated with dry soils and sparse vegetation. Open-water evaporation increases with temperature more strongly than evaporation from surrounding land surfaces. Reclamation (2015) projected that evaporation from Elephant Butte Reservoir will increase at a rate of about 8 inches/year for every degree (Celsius) increase in annual average daily maximum temperature (Tmax). Therefore, if Tmax increases by 5°F (approximately 3°C), this estimate would imply an additional 2 feet of annual evaporative loss. This would constitute a 30% increase in evaporative water loss over the present-day rate, and the lake would then evaporate more than one-third of its average annual inflow. Such an increase in evaporation would provide a strong incentive to minimize storage (hence reservoir surface area) at Elephant Butte to prevent additional evaporative loss.

The trend toward aridity illustrated in Fig. 2.6 has crucially important implications for assessing episodic droughts in the warmer climate of the twenty-first century. Drought, by definition, is an anomalously dry period. Droughts are often associated with lack of precipitation or streamflow (less water reaching the surface) but are also affected by evapotranspiration (more water leaving the surface). Tree-ring studies across southwestern North America have shown that profound droughts lasting multiple decades have occurred once or twice per century for at least a thousand years (as discussed by Gutzler, 2004; Watkins et al., 2006; and many others; see Fig. 1.4). In terms of precipitation, the current multi-year drought in New Mexico fits into this picture of recurring precipitation deficits, but increases in temperature have increased the severity of this drought (Weiss et al., 2009).

In the nearer-term past, observations of Navajo elders also provide a picture of increasing aridity in the twentieth century (Redsteer et al., 2018). Small increases in temperature and changes in precipitation type (rain versus snow) can have large impacts on the arid to semiarid environments of the Navajo Nation (Redsteer et al., 2018). These authors suggest that climate change, and resulting water scarcity, may result in younger generations of Navajo people moving away from reservation lands.

Water shortages associated with past severe droughts have caused large-scale landscape change, vegetation mortality, and social disruption, as discussed in more detail in subsequent chapters of this report. The trend toward aridity will tremendously amplify the impacts of future droughts by changing the underlying longer-term climatic conditions upon which temporary drought conditions are superimposed. Various measures of drought, such as the Palmer Drought Index shown in Fig. 1.4, are projected within the next few decades to reach, and then surpass, levels of dryness associated with the worst southwestern droughts in the historical record (Gutzler and Robbins, 2011; Williams et al., 2013).

A

B

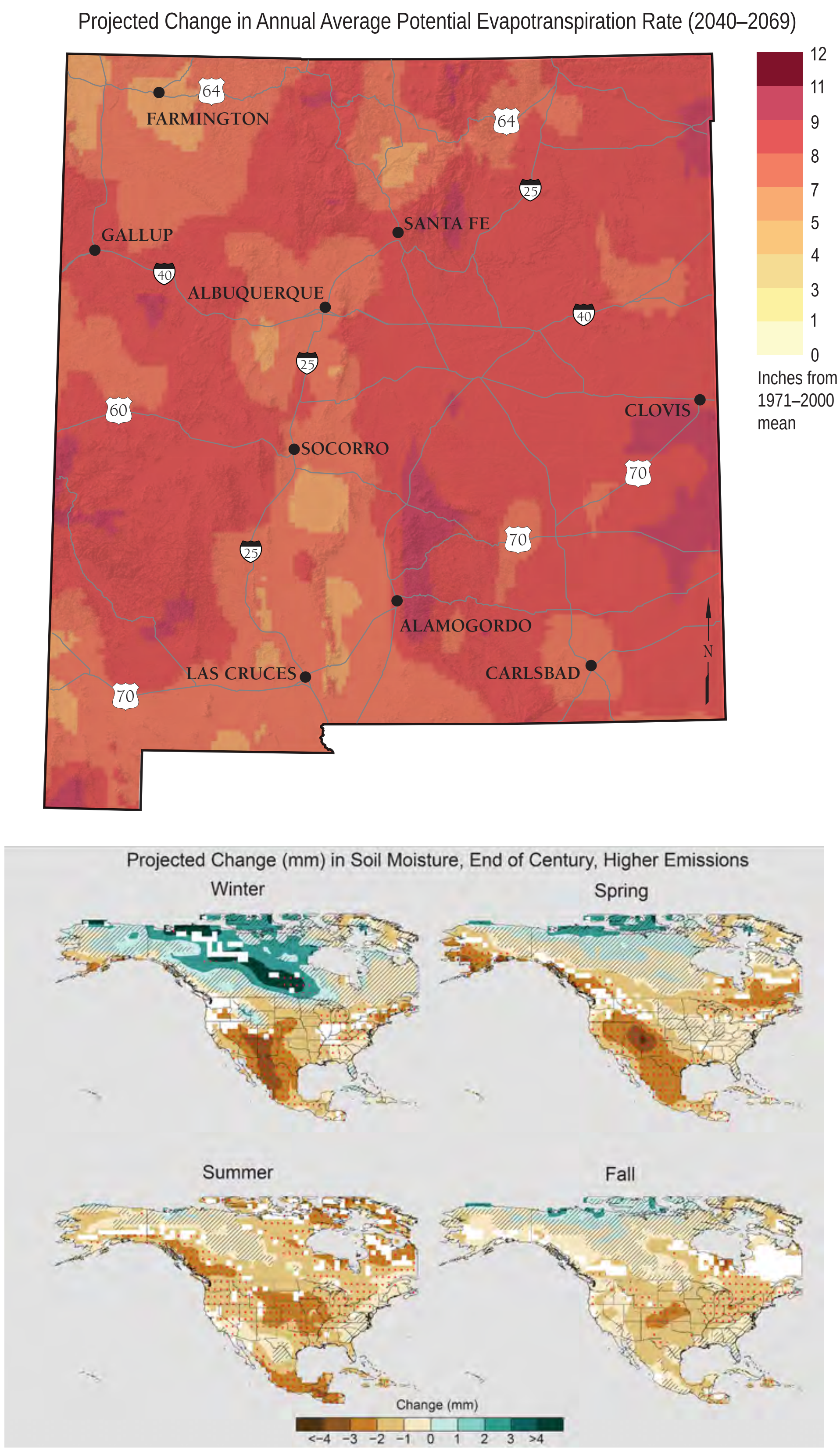

Figure 2.6. (a) Projected change in annual rate of Potential Evapotranspiration (PET) (inches from 1971–2000 mean), derived from the same projections used for Figs. 2.1b and 2.3. (b) Projected changes in seasonal soil moisture by the end of the twenty-first century across North America, adapted from USGCRP (2017).

Snow and Snowmelt Runoff—Snowpack at high elevations is projected to decline very substantially by 2070 across the southwestern U.S. (USGCRP, 2017; Mote et al., 2018), continuing a long-term decrease in snowpack that has been observed (including in the Rio Grande headwaters by Chavarria and Gutzler, [2018]) over the past half century. The projected decrease in snowpack occurs as the result of warmer temperature, despite possible increases in total winter precipitation (Fig. 2.2), as shown in Fig. 2.7 for the Rio Grande headwaters, as an example.

Surface-water supplies from major rivers are projected to decrease over the next half century, based on GCM projections coupled to surface hydrologic models. Reclamation (2011, 2014, 2021) has generated streamflow simulations from downscaled GCM projections using successive generations of CMIP simulations. Gutzler (2013) used an early generation of these simulations (CMIP3) to estimate future near-term trends in flow in the upper Gila River. Snowmelt runoff in the Gila headwaters was projected to decline by about 8% averaged over the 30-year period centered in 2035, a trend that would be expected to continue farther into the future.

More recently, Bjarke (2019) assessed newer CMIP5-based snowmelt runoff in the Rio Grande headwaters in southern Colorado, using Reclamation's projections (Reclamation, 2014), which, in turn, used many of the same simulations assessed in the MACA archive and shown earlier in this section (the Reclamation projections were downscaled and bias-corrected using a different statistical method). A sample of these projections (Fig. 2.7) illustrates how snowpack and snowmelt runoff are projected to evolve. The four colored lines represent downscaled projections derived from the same four GCM simulations used to illustrate precipitation change near Deming and in the Sangre de Cristo Mountains in Fig. 2.4. In Fig. 2.7, temperature and precipitation (in panel a) and 1 April snowpack (in panel b) are averaged over downscaled grid cells corresponding to the headwaters of the Rio Grande. Streamflow during the snowmelt runoff season is shown (panel b) for a simulated point on the mainstem of the Rio Grande corresponding to the Del Norte gage in southern Colorado. Eleven-year running averages have been implemented to emphasize variability on the scale of a decade or more.

As before, temperature projections for all four simulations (the lower set of curves in Fig. 2.7a) indicate warming, with simulations driven by the higher-emissions scenario (red and orange lines) warming the most. Precipitation projections (upper set of curves in Fig. 2.7a) generally show slight decreases, especially in the higher-emissions scenarios, but not all projections show such a decrease, as would be expected given the average increase in winter precipitation seen in southern Colorado in Fig. 2.3a. Snowpack on 1 April (lower set of curves in Fig. 2.7b), near the historical average peak snow date in the Rio Grande headwaters, shows a clear decrease in three of the four simulations. Snowpack declines more than precipitation in general, due to the increase in temperature that is consistent across the simulations.

Finally, streamflow in the snowmelt runoff season (upper set of curves in Fig. 2.7b), which results from both melting snowpack and late spring precipitation, exhibits substantial decadal variability (as do observed flows in the historical record), and a wide range of projected long-term trends. The red and green curves show substantial long-term declines consistent with both decreasing snowpack and diminished precipitation. Streamflow projected by the blue and orange curves, in which snowpack declines but total precipitation does not, exhibits smaller long-term change.

Reclamation (2014) and Bjarke (2019) showed that the overall average of nearly 100 simulations is a very slight decrease in Rio Grande headwaters streamflow volume, but with a huge range in the twenty-first century projections. Peak snowmelt runoff occurs earlier in nearly all simulations.

Can we narrow the range of uncertainty in projected runoff by selecting the simulations in which we should have the most confidence? Assessing similar projections for the upper Colorado River basin, Udall and Overpeck (2017) estimated that the temperature effect on diminished snowpack was likely to be so large, and projected with so much more confidence than precipitation change, that policymakers should place more weight on projections of declining snowmelt runoff regardless of precipitation uncertainties. Bjarke (2019) also argued that sharply diminished streamflow was more likely, because the Reclamation simulations

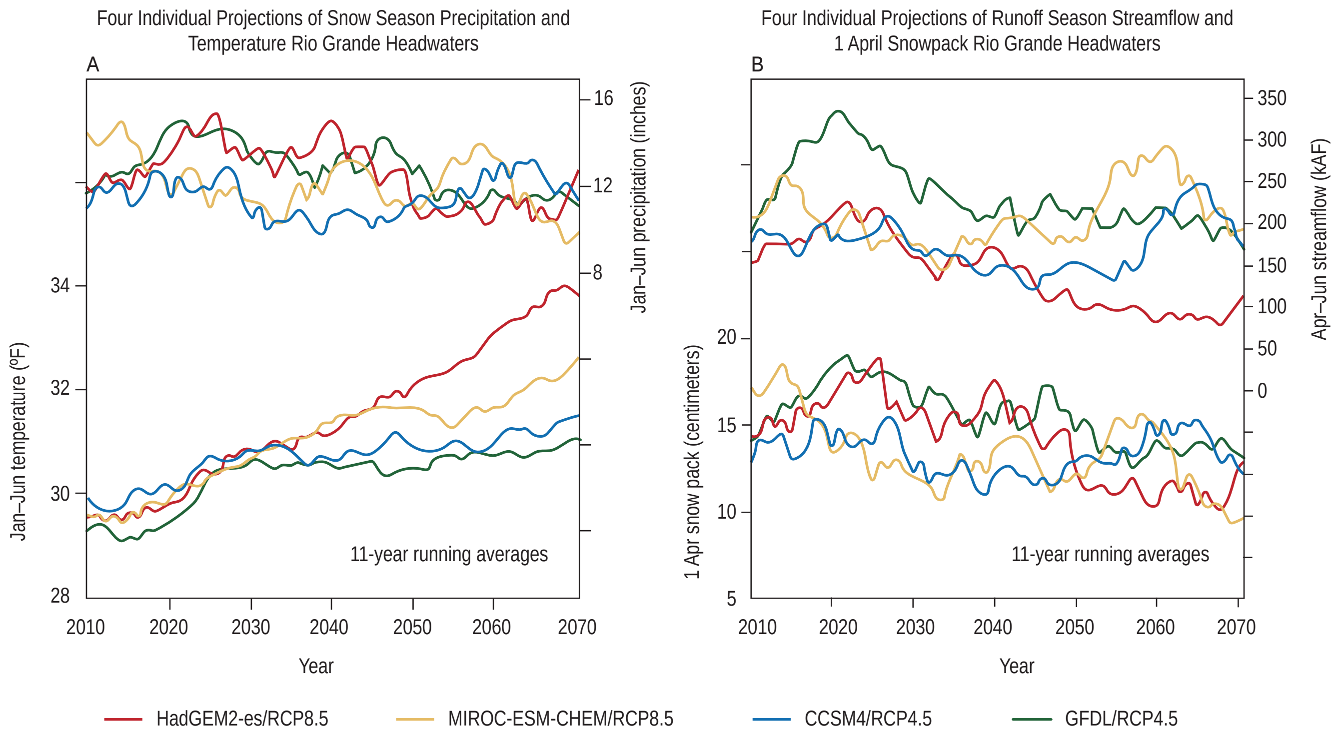

Figure 2.7. (a) Projected Jan–Jun temperature (bottom set of curves) and precipitation (top set of curves) in the Rio Grande headwaters basin in southern Colorado, derived from the same four downscaled projections used for Fig. 2.4 with the same color coding. (b) Projected 1 April snowpack (bottom set of curves) and Apr–Jun streamflow, in thousand-acre-feet (KAF), at a point on the river corresponding to the Del Norte stream gage (top set of curves), corresponding to the precipitation and temperature projections shown in (a). An 11-year running average, centered on each year, has been applied to all time series to emphasize variability on decadal and longer time scales.

that project increasing runoff uniformly failed to simulate the decline in snowpack and the changes in snowpack-runoff relationships observed during the half century of the simulations that reproduced the late twentieth century historical period. Chavarria and Gutzler (2018) and Bjarke (2019) highlighted spring precipitation as an increasingly important component of headwaters flow as snowpack diminishes, so the relatively confident projection of decreasing spring precipitation (Fig. 2.3b) portends diminished river flow as temperature increases and snowpack declines. Musselman et al. (2021) make a similar point, showing that earlier snowmelt (driven by warming temperature) correlates with diminished snowmelt runoff.

In summary, recent research suggests that the projection of just a small decrease in headwaters streamflow, derived from averaging together a large ensemble of widely varying CMIP5 simulations with different precipitation projections, may represent an overly optimistic vision of future Rio Grande flow. And notwithstanding the uncertainty in headwaters flow, increased PET in a warmer climate makes projections of lower river flows downstream much more likely, because flows will diminish as the river flows south (Townsend and Gutzler, 2020).

Key Gaps and Research Needs

The projections assessed in this chapter are mostly derived from GCMs run globally, so the well-documented general limitations of current models apply to the region-specific results emphasized here. The simulation of clouds and cloud-related processes represent the single biggest uncertainty in global climate modeling. Uncertainties in cloud simulation leads directly to the precipitation uncertainties discussed below. But, in addition, the effect of clouds in modulating temperature (so-called "cloud feedbacks") is also a key uncertainty in model projections. Although surface temperature changes are simulated and projected with much more confidence than precipitation changes, uncertainties associated with clouds have been shown to represent the primary reason that models differ with regard to how much global warming to expect in future decades as greenhouse gas concentrations continue to increase.

Projecting precipitation across the Southwest United States remains a key uncertainty in model projections. New Mexico is located on the southern periphery of the winter storm track, the average band of latitude where winter frontal systems move eastward from the Pacific Ocean across the North American continent. The winter storm track is projected to shift northward as global temperatures rise, leading to the pattern of projected winter precipitation change shown in Fig. 2.3 (decreasing precipitation to the south, increasing precipitation to the north). However, the average shift of the winter storm track varies from one model simulation to another, leading to uncertainty in how much (or even whether) we can expect winter precipitation to decline across New Mexico.

With regard to winter precipitation, we note that the results assessed in this chapter are derived from CMIP5 global models, which were generated about a decade ago. During the time that this report was generated in early 2021, the next generation of global models (CMIP6) has been assessed by the IPCC as part of its 6th Assessment report. CMIP6 models are somewhat more consistent than CMIP5 models were in projected lower winter precipitation across southwest North America, including New Mexico (Gutierrez et al., 2021). More detailed assessment of CMIP6 results will be helpful to address the question of reduced winter precipitation in New Mexico and the headwaters of the San Juan River and Rio Grande in southern Colorado.

In summer, precipitation across central and western New Mexico is supplied by the North American monsoon circulation. GCMs, with their coarse spatial resolution (using model grid cells typically about 50 miles on a side) have difficulty resolving the mountainous topography and small-scale thunderstorm clouds that are integral to the monsoon. Hence model projections of the future monsoon circulation have been variable and uncertain across generations of models, with different models projecting quite different future conditions and little consensus over even the sign of projected precipitation change. Uncertainties regarding summer monsoon projections remain in the current (CMIP6) generation of GCMs.

The uncertainties in projecting summer precipitation extend to understanding extreme precipitation values (which typically occur in summer) as well as projecting average or total precipitation. Chapter 8 of this document assesses extreme precipitation in more detail, including key research needs and gaps.

Additional snowpack and snowmelt runoff research will be critical for improving estimates of future flows in major snow-fed rivers across New Mexico. Our state features several of the southernmost snow-dominated rivers in North America. Rivers such as the Gila, Pecos, and Rio Grande are among the most sensitive rivers in the world to the effects of diminishing snowpack as winter and spring temperatures increase. Current research efforts are aimed at quantifying the total water content of snowpack in high-elevation mountains, and improving our understanding of the processes that determine how much snow water on hillslopes reaches the valley bottoms to become river flow, and how these processes will change as temperatures increase and the overall quantity and seasonal duration of snow diminishes.

Each of the uncertainties described above could, to some extent, be addressed in projects that refine the results of global models by customized application of higher-resolution regional models. Such New Mexico-specific modeling efforts were not possible for this report given our time and budget constraints. However, it is certainly possible to formulate projects that address specific New Mexico hydrologic projections using existing modeling and expertise.

III. EFFECTS OF CLIMATE CHANGE ON THE LAND-SURFACE WATER BUDGET

Fred M. Phillips and Bruce M. Thomson

All water that we use in New Mexico originates as rain or snow falling onto the landscape, which either goes to groundwater, surface water, or returns to the atmosphere. Of the precipitation that falls on the state, 1.6% runs off into streams and rivers and 1.8% infiltrates into the ground, recharging subsurface aquifers. Much larger proportions are transpired by plants (78.9%), or evaporated (17.7%). The impact of climate change on all of these pathways will affect our state's water budget. Notably, because of the larger percentages of water lost to evaporation or transpiration, even very small changes in these factors will result in large changes to runoff and recharge. As mentioned in Chapter 2, the climate will continue to warm over the next 50 years without a likely increase in precipitation, leading to greater statewide aridity. Hydrological modeling indicates declines in both runoff and recharge going forward, amounting to 3 to 5% per decade for both quantities. Historical trends in runoff indicate significant year-to-year variability, as do trends in soil moisture and recharge. But all are generally decreasing, consistent with the results of climate models as would be expected in a drying climate. Combining the historical trends with modeling of future changes, significant decreases in runoff and recharge seem very likely.

Introduction

Over the coming 50 years, the climate of New Mexico will almost certainly become warmer and likely drier than at any previous time in human history (see Chapter 2). How will this change affect the availability of water for human needs? To answer this question, we must recognize that ultimately all water that we use originates as rain or snow falling over the landscape. This precipitation on the landscape is divided ("partitioned") to end up in different flows: some as streams or rivers that are easily accessed by people for various uses, some as groundwater that supports flow in streams and springs and can be pumped directly, and some that returns to the atmosphere as water vapor. In order to understand how human-caused climate change will affect the availability of water, we have to understand how this partitioning works, which is a way of stating that we have to understand the water budget.

The Land-Surface Water Budget in a Semiarid Climate

The hydrological budget consists of flows of water (in all phases: gas, liquid, solid) through different parts of the environment, such as through streams or within aquifers. It is the division of the water into these different flows that determines how much is available for human or ecosystem use. At the center of this division is the land surface, which is principally the surface of the soil, but is actually best thought of as extending down from the tops of the highest vegetation to the base of the root zone (Fig. 3.1). The input of water comes from the atmosphere as either rain or snow. This water may wet the leaves of the plant, never reaching the ground, or may reach the ground and either soak into the soil or else run off from the surface into a stream or arroyo. The water that wets the leaves returns to the

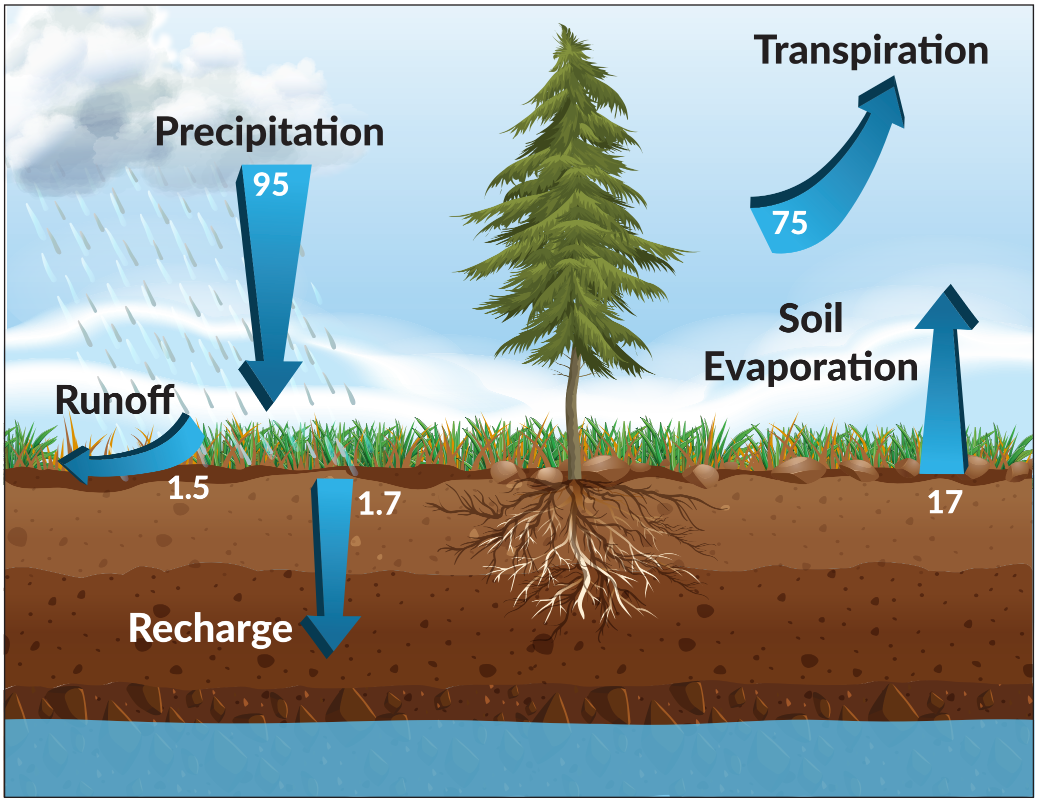

Figure 3.1. Average water budget of New Mexico, based on analysis of Peterson et al. (2019). Values are in millions of acre-feet per year. Evapotranspiration has been separated into evaporation and transpiration based on the analysis of Jasechko et al. (2013).

atmosphere by evaporation and does not enter the local hydrological system. The water that soaks in becomes part of the soil-moisture reservoir. Over time, the soil moisture may do one of three things: (1) be evaporated from the soil surface, (2) be absorbed by roots, move upward as plant sap, and be vaporized back into the atmosphere through stomata on the plant leaves (called "transpiration), or (3) trickle downward through the soil until it escapes past the base of the root zone and becomes groundwater recharge. It is usually difficult to distinguish between water lost to the atmosphere through evaporation and that lost by transpiration, hence the combination of evaporation and transpiration is often referred to as "evapotranspiration."

The division of the hydrological flows depends more than anything else on the aridity of the locality, which is commonly quantified by the "aridity index." The aridity index is defined as the ratio of the average potential evapotranspiration to the average precipitation, over the entire year. Potential evapotranspiration is the amount of water, per unit area, that could be lost to the atmosphere over a large area covered with dense, uniform vegetation if there is unlimited water available at the surface. As Figure 3.2 illustrates, over the large majority of New Mexico, the aridity index varies from a high of about 8 to a low of about 0.5, meaning that the atmosphere could potentially evaporate up to 8 times as much water as the soil actually has to offer (Seager et al., 2017). The relatively cool and moist tops of the highest mountains in the state may have aridity indexes as low as 0.5 (i.e., 2 times as much precipitation falls as can be evapotranspired). These areas of low aridity index are a very small fraction of the area of the state, but they generate a large majority of the runoff and recharge.

Under a climate as arid as New Mexico's, two flows strongly dominate the water budget: precipitation and evapotranspiration (in other words, actual evapotranspiration, not the amount that could potentially evapotranspire given an unlimited

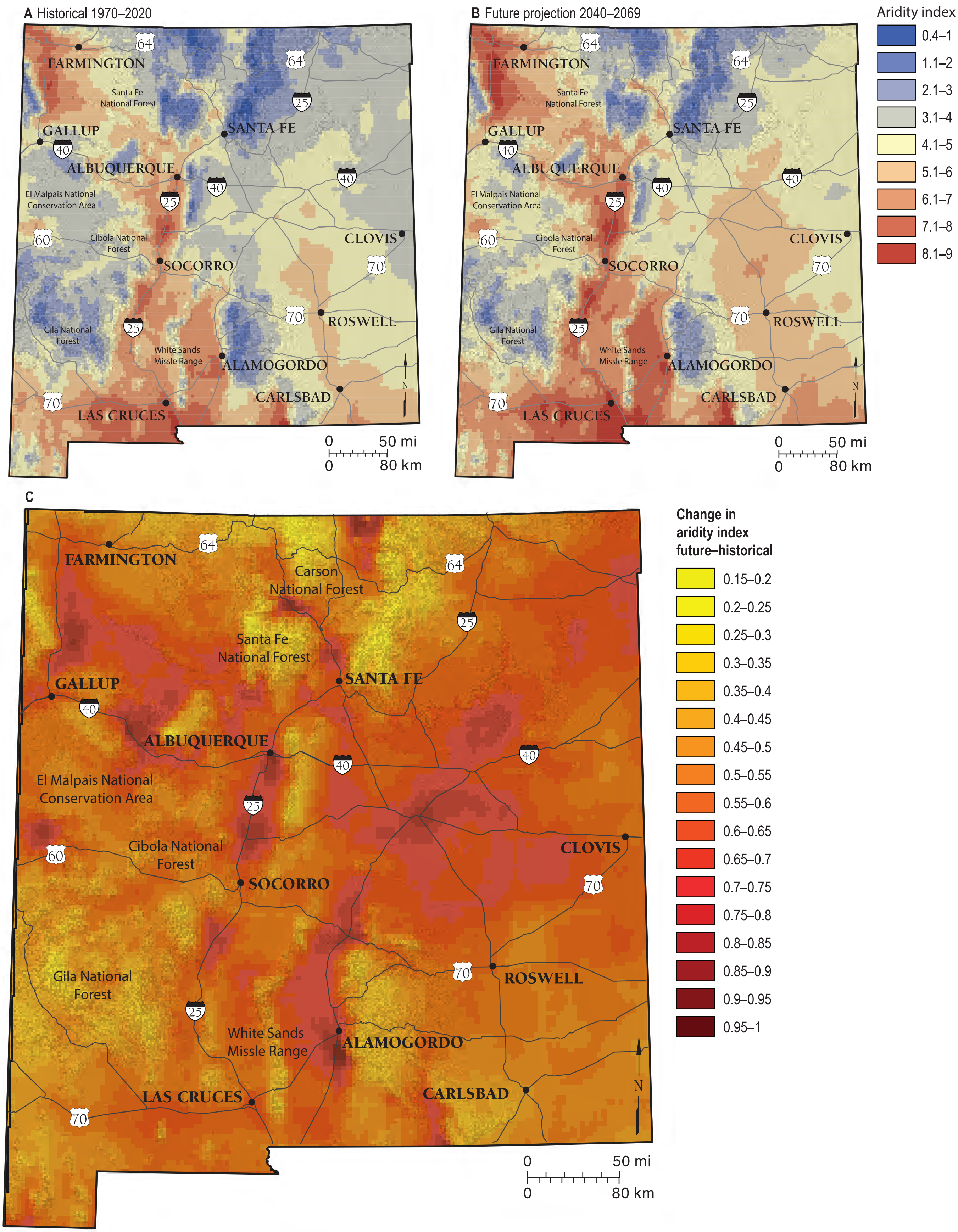

Figure 3.2. Projected change in the aridity index over New Mexico. (a) Average aridity index from 1970–2000 data, (b) Average aridity index from 2040–2069 projections, generated from 20-model ensemble RCP8.5. (c) Difference between 2040–2069 and 1970–2000 aridity indexes. Aridity index is defined as the ratio of average potential evapotranspiration to the average precipitation.

water supply). Precipitation onto the land surface of New Mexico amounts to about 95 million acre-feet per year (Fig. 3.1). Of this, about 91.8 million acre-feet per year, or 96.6%, returns to the atmosphere as evapotranspiration (Peterson et al., 2019). The remaining 3.4% (3.2 million acre feet) is about equally divided between runoff and recharge. When considering the effects of climate change on the water budget, this carries two implications. The first is that evapotranspiration is highly predictable. Even if precipitation changes, evapotranspiration will nearly always equal, but be slightly less than, precipitation over most of the state. This is because water evaporates and transpires so readily when the climate is so arid. The second is that the terms in which we are most interested for water resources, runoff (supplying streamflow) and recharge (supplying groundwater), will be very sensitive to even small changes in the relative magnitudes of precipitation and evapotranspiration. For example, if a climate change, such as lower temperature and increased precipitation, caused 1.7% less precipitation to be evapotranspired and to become runoff instead, the total state runoff would double! Small changes in the land-surface water budget can thus have a major impact on human society.

The utility to humans of the different divisions of the hydrological cycle differ greatly. Water that evaporates from leaves and soil, comprising about 20% of the precipitation that falls on the land surface in the Southwest (Jasechko et al., 2013), provides few direct benefits to humans. The main one is a cooling effect—a significant part of the reason that the monsoon season in New Mexico is cooler than the earlier part of the summer. The water that is transpired through plant leaves (currently about 79% of precipitation) is essential for plant growth because it carries nutrients to the leaves and is necessary for photosynthesis. Rain falling on agricultural fields, along with irrigation water, is necessary for crop production. On natural lands, the transpiration component of the water budget supports all plant life and, based on the plants, animal life. Benefits to humanity are obvious, ranging from grass for livestock grazing to the aesthetic appreciation of a beautiful vegetated landscape. The tiny fraction that runs off from the soil (1.6%) or recharges groundwater (1.8%) yields the largest relative benefit to society. Essentially all water that we use for human consumption, for industry, and for irrigation comes from these two components. The main purpose of this chapter is to explore how future climate change will affect the partitioning of precipitation into these two flows.

Effects of Climate Change on the Land-Surface Water Budget

Global climate change, as projected in the chapters above, will reduce both runoff and groundwater recharge in New Mexico. Change in precipitation cannot be projected with confidence, but most models project that it will decrease rather than increase across most of New Mexico (see Chapter 2), while variation from year to year will remain high. Temperature, however, will certainly continue to rise. As temperature increases, the ability of the air to hold water vapor also increases (in other words, for a constant mass of water vapor in the air, the relative humidity goes down as the temperature goes up). This will cause liquid water to be lost more rapidly from leaves and soil, and thus dry out the landscape, even if precipitation does not decline. Dry soil "sucks in" precipitation faster than wet soil, causing less runoff. Recharge cannot occur until the whole thickness of the upper soil layer is quite wet and if the soil becomes drier, recharge will happen less frequently.

However, phenomena related to the timing and frequency of precipitation events complicate the simple scenario presented above. First, seasonality of precipitation plays a strong role. In warm, semiarid climates, recharge is much more likely if most of the precipitation falls in the winter when temperature is cold and plants are not active, so evapotranspirative demand is low (Small, 2005). But in lowland settings where winter snow does not persist, runoff may be favored by a shift toward intense summer convective storms that dump precipitation so rapidly that the water flows away before it has a chance to sink into the soil. Second, groundwater recharge and runoff are favored by relatively large precipitation events that are clumped together in time and they are reduced when precipitation falls in a large number of small events that are evenly spaced in time (Small, 2005). We will refer to this as the "clumping effect." When precipitation events are small and evenly spaced, they tend to be absorbed by the soil and largely evapotranspired back to the atmosphere. The soil dries out. It rarely becomes wet enough to produce recharge. When rain does fall, it tends to be absorbed by the dry soil rather than running off. In contrast, when precipitation falls in fewer events and they are clumped together, by the end of those stormy periods the soil becomes wet and the later storms are likely to produce both runoff and recharge.

The implication of these findings is that more information beyond projections of evapotranspirative demand and precipitation are needed to estimate future trends in runoff and recharge. Changes in the seasonality of precipitation, the frequency and clumpiness of precipitation events, and the size of storms are also important. The forcing exerted by all of these factors on the land-surface water budget must then be used to drive hydrological models that realistically incorporate snowmelt, runoff, infiltration, soil-water storage, and interaction with plant roots that draw out the soil water to be transpired. The uncertainties associated with quantifying and modeling all these processes make the task of projecting runoff and recharge a difficult one.

Dynamical models of the atmosphere and ocean that are used to assess future climate (such as the projections of temperature and precipitation described in Chapter 2) do not simulate in any detail the surface-water processes described above. Global climate models are designed to simulate atmospheric weather on very large spatial scales, for which the fine details of recharge and runoff at the surface—which are so important for local water resources—are just a secondary influence. In order to assess changes in local and regional water resources that result from large-scale climate change, a different class of surface hydrologic models must be developed and implemented. Such models include more detailed hydrologic processes (as conceptualized in Fig. 3.1) at much finer horizontal resolution, using downscaled output from a global climate model as the driver for hydrologic simulations (see the first part of Chapter 2 for a more complete discussion of this topic). These are the types of models that are required for state water-resource planning at the 50-year time scale.

We divide the models that are commonly used for detailed, local water-budget projections into three categories, in order of increasing complexity: mass-balance accounting models, one-dimensional surface-process models, and three-dimensional hydrologic systems models. Detailed information on the characteristics of these types of models is unnecessary for the typical reader of this report, but we have included an appendix (Appendix A) containing such a description for the use of state water-planning specialists, who will ultimately have to choose the most suitable type of model for their planning objectives.

Information Available for Projecting Changes in Runoff and Recharge

We have two principal methods for projecting changes in the land-surface water balance over the next 50 years. The first is implementation of the various numerical models discussed in Appendix A, which require input (principally temperature and precipitation) from downscaled global climate model (GCM) simulations. The advantage of these is that many of them can give detailed projections of changes over the varied landscapes of New Mexico. One disadvantage is that they depend on GCM simulations of future conditions, which can vary widely due to different scenarios of change in the greenhouse gases and different model structures. The alternative is to attempt to discern trends from recent records of hydrological responses (for example, runoff from stream gages or water levels in wells) over the past 50 years. These cannot supply detailed spatial projections, but, if reliable trends can be detected, they have the advantage of being grounded in actual observed climate-hydrology variations. If a certain amount of global warming has produced some specific change in the water balance, for example less runoff, then it does not seem likely that additional warming will reverse that trend. More speculatively, the rate of change can be extrapolated into the future to estimate future hydrological flows and water resources.

Figure 3.2 shows the projected change in the aridity index over New Mexico for the RCP 8.5 scenario. The index everywhere increases, with the increase ranging from ~0.25 to ~1.0. The increases are numerically largest in the most arid parts of the state and are smaller in the mountainous areas where the value currently is lower. However, in a relative sense, the increases are often proportionally larger in the less arid areas. The relative change in the northeastern part of the state (eastern plains) is particularly large. This pervasive increase in the ratio of potential evapotranspiration to precipitation implies that precipitation will be increasingly partitioned more into evaporation and transpiration and less into runoff and recharge.

Modeled Changes in Runoff—Numerous studies have attempted to simulate changes in streamflow in the southwestern United States. Of these, the most important for our purposes is the Reclamation report "West-Wide Climate Risk Assessment: Upper Rio Grande Impact Assessment" (Llewellyn and Vaddey, 2013). This study employed the VIC model (described in Appendix A), driven by downscaled and bias-corrected GCM scenarios as discussed in Chapter 2, to simulate water supply and demand on the Rio Grande through 2100. The median precipitation projection from the GCMs decreased by about 10% between the mid-twentieth century and 2100, but projected Rio Grande discharge at the Colorado border decreased by 30% over the same period (Fig. 3.3 [Llewellyn and Vaddey, 2013, Fig. 31C]). This difference is largely due to an increasing proportion of precipitation and snowpack being partitioned into evapotranspiration as the watershed warms. Results for tributaries to the Rio Grande in New Mexico were virtually the same as for the Colorado portion. The study did not attempt to simulate changes in groundwater recharge throughout the drainage basin, but did indicate that groundwater levels along the Rio Grande Valley would decrease due to reduced input from the river and associated flood irrigation.

Other studies have arrived at similar conclusions. Udall and Overpeck (2017) also used VIC combined with the Bureau of Reclamation GCM projection datasets to estimate median reductions in Colorado River discharge of 25 to 35% by century's end (Fig. 3.4, indicated by the green probability density curves). Although the Upper Colorado River impinges on only a small portion of New Mexico (the San Juan River drainage), it directly adjoins the headwaters of the Rio Grande in Colorado, and projections for it thus provide useful information for assessing changes in the Rio Grande. Garfin et al. (2013) used a similar methodology to arrive at similar reductions of discharge, but over a much wider area of the

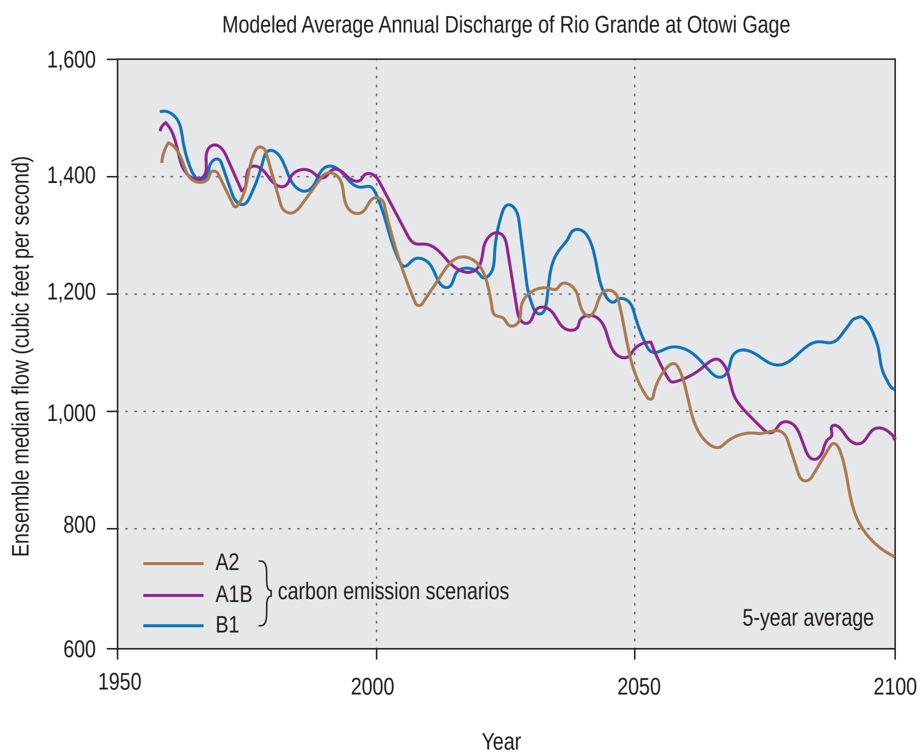

Figure 3.3. Modeled 5-year average discharge of the Rio Grande at the Otowi gage, in cubic feet per second, from 1950 to 2100 (Llewellyn and Vaddey, 2013). A2 represents high, A1B represents moderate, and B1 represents low carbon emission scenarios.

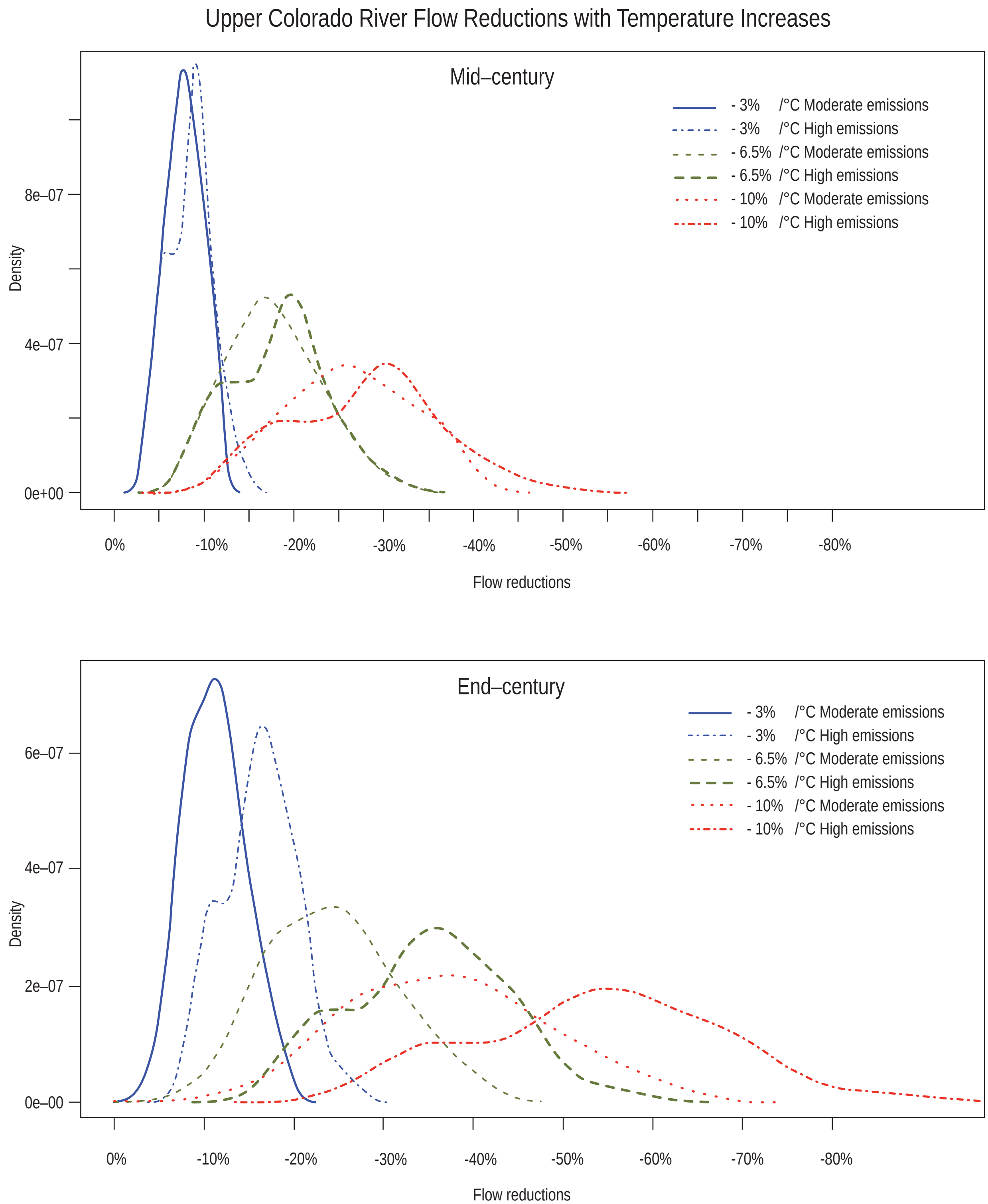

Figure 3.4. Probability of change in the flow in the Upper Colorado River as a function of greenhouse gas emissions and the sensitivity of runoff to temperature, from Udall and Overpeck (2017). The percentages in the legend are percent reduction in runoff per degree Celsius of warming and range from a reasonable lower limit to a reasonable upper limit, with the most likely value (-6.5% per degree) in the middle. The 'moderate emissions' scenario corresponds to SRES A1B/RCP4.5 and the 'high emissions' to SRES A2/RCP8.5.

Southwest. Jiménez-Cisneros et al. (2014) presented a global synthesis of the projections from 16 global models (5 General Circulation Models [GCMs] and 11 Global Hydrological Models [GHMs]) that indicates widespread reductions in streamflow (10 to 30%) over the Southwest. Elias et al. (2015), on the other hand, used a highly specialized snowmelt model (Snowmelt-Runoff Model or SRM) to project changes in the discharge of the Rio Grande. They attempted to bracket the entire range of possible future climates, in some cases using projections of future precipitation as high as 40% above the twentieth century. These yielded limiting maximum estimates of runoff as much as 25% greater than historical, but for more reasonable precipitation changes (12 to 23% reductions in precipitation), runoff decreased by 0 to 24% in most of the basins comprising the Upper Rio Grande. Projected reductions of flow in the Upper Colorado River basin are attributed to increased evaporation of snowpack (Milly and Dunne, 2020).

***Modeled Changes in Recharge*—**Fewer studies have attempted to project changes in recharge than changes in runoff. Most studies that do, calibrate their models against historical records of base flow (flow during periods when there is little or no precipitation) in rivers and streams. This is not appropriate for much of New Mexico, because there are no perennial streams over much of the state. Models must then be calibrated against long-term, water-level records from wells, which is much more difficult.

The difficulties of projecting recharge in arid/semiarid environments are illustrated by the global study of Döll (2009), which used the WaterGap Global Hydrology Model (WGHM) to project recharge increases in the Southwest of approximately 100% by the 2050s for most of the GCM climate projections. As discussed in Appendix A, this model was not constructed with arid climates in mind. The authors had to perform arbitrary modifications of the input data to achieve even remotely reasonable recharge values, thus the confidence in this projection is low.

Meixner et al. (2016) compiled the results of four previous studies for southwestern aquifers that used the WAVES model. They also heuristically estimated recharge changes for four other aquifers. Their best estimate of the future changes was a decrease of 10 to 20% in recharge, but with a quite wide range of uncertainty. One of the studies they included was in the High Plains of eastern New Mexico, by Crosbie et al. (2013). They projected a median decrease in recharge on the High Plains of 12% by 2050, but the changes ranged from -50% to +24% depending on the amount of precipitation predicted by the GCM climate models.

The Meixner et al. (2016) study was extended by Niraula et al. (2017), who performed quantitative recharge projections over the entire U.S. West using standard GCM climate projections linked to the VIC model. For the Southwest, the average recharge change from 10 GCM scenarios through 2050 was a decrease of 4.0 ± 6.7%. For New Mexico, the model averages showed small decreases in recharge over most of the state, but small increases in some of the northern mountains. This large uncertainty in the projected recharge change results from the underlying variability in the GCM simulations. The magnitude of the recharge change is also surprisingly small and may reflect inherent limitations in the VIC hydrological model used (see below).

Condon et al. (2020) employed a relatively detailed and realistic hydrological systems model, ParFlow-CLM, to examine the effect of increased atmospheric demand on groundwater resources over a substantial portion of the U.S. They did not consider the effects of withdrawals from wells. Although they did not explicitly present their simulations in terms of changes in the recharge rate, they did present modeled changes in the water-table elevation by the end of the present century. In New Mexico, water-table depth under natural conditions is most closely tied to recharge. The eastern parts of the state showed negligible changes in water-table depth, but most of the state showed declines ranging from 0.5 to 2 m, depending on location and the severity of the warming scenario. These changes in the water table are of similar magnitude to other climate-sensitive areas of the United States. Most importantly, they are consistent with a significant reduction of recharge in all scenarios, rather than the increase in recharge indicated by a minority of studies.

***Modeled Changes in Runoff and Recharge*—**Very few New Mexico-specific studies have investigated future changes in both runoff and recharge from the same model. One of these is Bennett et al. (2020), which applied the INFIL model to the Pajarito

Plateau (location of Los Alamos National Laboratory) in north-central New Mexico to project climate-driven changes between 2040–2069 and the historical data. The INFIL model is similar to the PyRANA model described in Appendix A. As with other studies described above, they used a range of GCM simulations, from small temperature increase to large, and from drier to wetter conditions (precipitation), to drive the hydrological model. The change in runoff varied from -11 to +21 mm/yr and recharge from -9 to +6 mm/yr. In general, both modeled runoff and recharge had a tendency to increase at higher elevation and to decrease at lower elevation. They concluded: "Our major findings indicate that the amount of available water for processes such as infiltration and runoff is sensitive to changes in the seasonal distribution of precipitation that may not be reflected in the aridity index. We also find that the delivery in terms of the form and rate of precipitation is as important, if not more important, than the overall amount of precipitation…" As discussed in the introduction to this chapter, although a significant increase in the aridity index (PET/P) over the next 50 years is strongly indicated, secondary changes, such as small increases in precipitation amount, seasonality, and clumpiness, can strongly influence runoff and infiltration in ways different than the aridity index changes alone would suggest. This study confirms that inference.

Analyses of Historical Runoff Trends—Most of the modeling studies cited above have attempted to bracket possible changes in hydrological flows by using the full range from the GCM outputs in terms of temperature and precipitation. Others have used medians of many outputs bracketed by standard deviations or other statistical measures of the variability. As noted, either method tends to produce projections of runoff or recharge with very large uncertainties (often larger than the projected change). One approach to additionally constraining projections is to examine historical data.

The influence of anthropogenic global warming on global temperature began to rise above natural background fluctuations in the 1970s (Chapter 2). However, it is only in the past 20 years that the signal has become unequivocal. Nearly all hydrologists now accept the principle that the hydrological system no longer fluctuates around a stable mean value, but rather that many parts of the system are now varying around a mean that is veering in one direction or the other (Milly et al., 2008). If the effects of warming on processes such as runoff and recharge are large, they might produce observable anomalies over this period. By analyzing data collected over the past 50 or 20 years we can hope to find trends that might support better selection of GCM outputs to drive hydrological models. This is important because unnecessarily wide bounds on hydrological projections renders the projections less valuable for planning purposes.

As discussed in Chapter 2, the mean annual temperature of New Mexico is very clearly increasing at a relatively linear rate of about 0.7°F per decade. This has resulted in an increase of about 2.7°F since the 1980s. Any changes in precipitation are much more difficult to detect (Fig. 1.1). According to the USGCRP (2017) and Garfin et al. (2013), annual precipitation has increased slightly (0 to 5%) over most of New Mexico when comparing averages from 1986–2015 with 1901–1960. However, it has decreased by about the same amount in the area of the Rio Grande headwaters in Colorado, and recall that the precipitation across New Mexico was particularly high in the 1980s and 1990s. Most of the increase has been in the fall, but spring precipitation, important for snowpack and runoff, has decreased markedly statewide. In contrast, Slater and Villarini (2016) detected a signal of decreasing precipitation over New Mexico. Udall and Overpeck (2017) found a slight decrease in annual precipitation over the Upper Colorado River basin since the 1980s, although the trend was small in comparison to the year-to-year fluctuations. In general, any long-term changes in precipitation are small enough that, over the interval of detectable global warming, they are difficult to separate from normal fluctuations.

Reanalysis of weather data from 1979–2014 has indicated a fairly strong trend of decreasing atmospheric relative humidity of about 1.5% per decade over New Mexico (Douville and Plazzotta, 2017). This can plausibly be posited to drive increased evapotranspiration, shifting the land-surface water balance away from runoff and recharge. However, Yang et al. (2018) have cautioned that runoff is much more sensitive to changes in precipitation than to changes in atmospheric water demand, and that many localities with apparent increases in the aridity index are in fact experiencing increases in runoff. Given this warning, it is prudent to examine the scanty evaluations of trends of runoff that are available for our area.

At the large scale of the entire western United States, Gudmundsson et al. (2021) indicate that runoff has decreased between 1971 and 2010 at about 4% per decade. They compare this finding with runoff simulated by models that include global warming forcing and by ones that exclude its effects. Those including the observed global warming forcing predict a decrease in runoff, albeit smaller than the actual, whereas those where it is excluded indicate an increase in runoff. This allows the runoff decline to be clearly attributed to global warming. At the scale of the Upper Colorado River basin, Xiao et al. (2018) found that the discharge of the Colorado River at Lees Ferry decreased by 17% between 1920 and 2014, or about 1.4% per decade, which they principally attributed to warming. At the headwaters of the Rio Grande, Chavarria and Gutzler (2018) did not find a significant decline in annual discharge, which they attributed to recent small increases in precipitation during the snowmelt season, but they did detect a significant decline in spring snowpack that they project will drive reductions in Rio Grande flow in the near future as temperature continues to increase. In contrast, annual discharge of the Rio Grande at Otowi, south of the Colorado border, has decreased by almost 20% per decade since 1985. However, this dramatic reduction is clearly strongly influenced by variations in snowfall that are driven by sea-surface temperature patterns that fluctuate over decades (Pascolini-Campbell et al., 2017). Since 1997, within a relatively stable ocean-temperature regime, the flow at Otowi has decreased by 4% per decade, about the same as was inferred for the entire U.S. West by Gudmunsson et al. (2021). However, this decline is small in comparison to the standard deviation of annual flows, which is about 30%. In summary, changes in runoff over the watersheds that include New Mexico are difficult to separate from natural, year-to-year variability, but to the extent that they can be separated, they consist of declines in runoff, not increases.

Trends in soil moisture, which are a measure of the partitioning of precipitation into subsurface infiltration, have been relatively little studied. Unlike streamflow, soil moisture is not routinely monitored, and the monitoring that has been done mostly covers only a few decades, or less, so there is much less data on which to base evaluation of trends with time. Instead of actual observations, global reanalyses of meteorological and remote sensing data, using land-surface and atmospheric models, are often used to reconstruct environmental conditions. Deng et al. (2020) used the output of the ERA Interim/Land reanalysis by the European Centre for Medium-Range Weather Forecasts to evaluate trends in soil moisture over the period 1979–2017. In the area of New Mexico, they inferred a reduction of water content of the soil (top 5 cm) of 3 to 5 volumetric percent per decade. Soil drying was the predominant trend worldwide. Deng et al. (2020) felt that the main driver of this drying was increasing temperature. For the Upper Colorado River basin, Scanlon et al. (2015) used standard land-surface model outputs to evaluate changes in soil moisture storage from 1980–2015. Focusing on their results from the 1997–2015 interval, for the reasons described above, reveals a steady decline in soil moisture storage amounting to about 22 mm water depth. This is roughly equivalent to 5 to 10% of the typical water storage capacity of the soil and thus appears similar to the result from Deng et al. (2020). Total basin water storage includes both soil moisture and groundwater, and can be monitored using satellites. Scanlon et al. (2018) estimated that between 2002 and 2014 the Rio Grande basin lost between 2.2 and 3.5 cubic kilometers (1.8 to 2.8 million acre-feet) of water storage, equivalent to 4.5 mm over the basin. However, the VIC simulation for the same period only registered 0.5 cubic kilometer loss. Similar underestimates by the VIC model were found for other basins worldwide.

Two conclusions can be drawn from the summary of observational evidence above. The first is that, over the area of interest to the state of New Mexico, any recent trends in precipitation, runoff, and soil moisture/recharge are small enough that, with only about 20 years of clear temperature signal, they are difficult to separate from natural year-to-year and decadal fluctuations. The second is that, insofar as they can be separated from natural variability, they almost universally indicate soil drying and reduction in runoff primarily as the result of water lost to the atmosphere through increased evapotranspiration caused by warmer air temperatures. There is very little evidence to support an upward trend in these parameters. Thus, responding to the concern of Yang et al. (2018) that the projected strong increase in aridity index might not necessarily correspond to reductions in runoff and recharge, the available observational evidence does indeed support the modeled projections of quite significant downward trends in surface water, groundwater, and soil moisture over the next 50 years. The observed evidence indicates that New Mexico is at high risk of significant increases in surface aridity in a warming climate.

Summary of Future Water-Balance Changes

As reviewed above, published studies on climate-driven changes in the water balance in New Mexico watersheds have yielded projections with wide uncertainty bounds. In general, the median hydrological model output generated by using as input multiple runs by multiple GCMs indicates declines in both runoff and recharge over the next 50 years, typically amounting to 3 to 5% per decade for both quantities. However, the published uncertainties around these median projections are generally quite large, often two to three times the projected median change, with the uncertainty encompassing both large increases in runoff and recharge, and large decreases. Such large uncertainties render the projections of limited value for water-resource planning and management. In most cases, this wide uncertainty does not arise from the variability inherent within the hydrological models used to make the projections, but rather from the variability in projected precipitation in the GCM simulations used to drive the hydrological models. Although there is generally a fairly strong clustering of GCM precipitation outputs within the bounds of no precipitation change to a decline of about 5% per decade, some individual runs from some models fall well outside these bounds, indicating either a large increase in precipitation or a fairly drastic decrease. Inclusion of these extreme runs widens the uncertainty bounds of the runoff/recharge output a great deal.

We have attempted to evaluate the value of these wide uncertainty bounds by comparing model projections (both GCM outputs in terms of precipitation and hydrological model outputs in terms of runoff and recharge) with actual data from the period of detectable global warming—the past 50 years. These data show that any inferred changes in precipitation since ~1970 are quite small and can be either negative or positive, depending on the geographical area and the time intervals compared. The available data thus do not support the validity of GCM outputs showing either substantial increases or decreases in precipitation over the New Mexico area. One cannot a priori rule out such shifts over the coming 50 years but we suggest that for planning purposes we should not place much confidence in these outlier simulations. Instead, the lack of precipitation trends over the past 50 years of pronounced warming argues that models in the median cluster are most likely to provide reliable projections for the next 50 years.

Evaluation of the data for changes in runoff or recharge yields somewhat stronger evidence for trends. Although, once again, the trends depend on location and time interval, there is significant support for declines of 3 to 5% per decade for both runoff and recharge. These decreases are on the order of the projections from the hydrological models driven by the median GCM outputs. Declines in runoff and recharge with increasing temperature can be expected so long as precipitation is not actually increasing (Yang et al., 2018). Given the likely existence of these declines during the first 50 years of global warming, their continuation into the next 50 years also seems likely.

Knowledge Gaps

The summary in this chapter of water-balance research under global climate change, pertaining to New Mexico, shows both strengths and weaknesses in our state of knowledge. Strengths include an ever-increasing capability in global climate modeling, and data to drive such models that enable a highly sophisticated approach to the problem, and the accumulation of ~50 years' worth of hydroclimatic data against which to compare the outcomes of GCM simulations. The weaknesses we address below.

1. *Lack of adequate soil-moisture and groundwater-level data*—The availability of long-term data for temperature, precipitation, and surface-water runoff is at least adequate, along with other basic hydrometeorological data. However, these present only a part of the information needed to understand changes in the surface-water-balance over time. Two critical components, soil moisture and groundwater level, are largely missing. We note that although groundwater is monitored at numerous localities in New Mexico, these are nearly all selected in response to heavy pumping. For assessing changes in groundwater recharge, water levels in remote areas with minimal human extraction are needed, but repeat water-level measurements are rarely performed in such settings.

   Using traditional methods, collection of soil-moisture data has been labor intensive and typically yields only a point measurement of a parameter that can vary a lot over short distances. However, newer technologies such as the COsmic-ray Soil Moisture Observing System (COSMOS) (Zreda et al., 2012) can sense soil moisture at a large spatial scale and a time scale of a few minutes and telemeter the data to a central location. Another relatively simple but very powerful technology is the use of fixed global-positioning system (GPS) receivers to monitor vertical changes in the land-surface elevation, from which changes in soil-water and groundwater storage can be evaluated (Larson et al., 2008; Borsa et al., 2014). As hydrological changes due to global warming increase, the state of New Mexico is increasingly going to need regional hydrology and climate data against which to calibrate and compare the results of models. Ensuring that adequate data sets of all relevant parameters are available in order to make use of these model results for management purposes would be a wise investment.

2. *Criteria for evaluation of GCM output*—Traditionally, atmospheric modelers have tended to use strongly inclusive measures to quantify the possible spread of model outputs (e.g., for GCM outputs used as input to hydrological models, wettest and driest GCM runs, see Elias et al., 2015). Although such wide bounds are conservative in the sense of bracketing the entire range of possibilities, they render the model output of limited practical value for management purposes because they do not adequately distinguish between "possible outcomes" and "likely outcomes." With a current database of about 50 years of observable warming of global temperature available, it is quite likely (though not provable) that model runs that have succeeded in predicting the *regional* hydroclimatic history over that time period will also be more successful at predicting the following 50 years. We suggest that effort be invested in developing a set of quantitative criteria for evaluating the output of GCM runs, and on that basis, selecting the ones most likely to predict future climate (a procedure commonly known as "post-processing").

3. *Lack of New Mexico-focused hydrological models*—A large number of the studies reviewed above are global in scope. Others covered the entire United States or the western U.S. Such models inevitably make compromises in attempting to reproduce the hydrological effects of global warming under climate regimes ranging from cold and humid to hot and hyperarid. They typically do not have adequate spatial resolution to simulate processes on the highly varied topography of New Mexico. When regional-scale modeling has been performed, it has often by default used the VIC model, even though there are indications that VIC systematically underestimates the magnitude of the hydrological response to climate change (Scanlon et al., 2015; Niraula et al., 2017). Given that New Mexico is one of the most water-short states in the union, and that the water supply is shrinking under climate change, development of a state-scale model should be a priority. As discussed above, a wide variety of models are potentially available, ranging from simple and straightforward, capable of being run on a laptop, to highly comprehensive and complex, requiring supercomputers. We suggest a thorough evaluation process in light of in-state capabilities, model suitability for management objectives, and availability of data to parameterize models, followed by a comprehensive projection of changes in the hydrological system of New Mexico over the next 50 years, using the selected model or models.

IV. CLIMATE CHANGE: TERRESTRIAL ECOSYSTEM RESPONSES AND FEEDBACKS TO WATER RESOURCES IN NEW MEXICO

Craig D. Allen

Climate is a fundamental driver of ongoing and future vegetation changes in New Mexico. Future changes in vegetation will affect the distribution and abundance of water resources in New Mexico. Major shifts in climate and vegetation across New Mexico's landscapes have occurred in the past, but the scale and rate of recent and projected climate change is probably unprecedented during the past 11,000 years. Recent warming, along with frequent and persistent droughts, have amplified the severity of vegetation disturbance processes (fire, physiological drought stress, insect outbreaks), driving substantial changes in New Mexico vegetation since the year 2000. Ongoing and projected vegetation changes include growth declines, reduced canopy and ground cover, massive tree mortality episodes, and species changes in dominant vegetation—foreshadowing more severe changes to come if current warming trends continue as projected. Such major alterations of New Mexico vegetation likely will also have substantial ecohydrological feedbacks with New Mexico water resources. Since water-related environmental stresses occur in parallel with water supply shortages for people, such climate-change driven water stress could lead to increasing conflict between management of declining water availability for human use (e.g., irrigation) versus "wild" water retained for the maintenance of historical ecosystems.

Introduction

Ongoing climate change—a mix of both natural climate variability and directional anthropogenic climate change—is a major driver of recently changing vegetation patterns in New Mexico, ranging from drought-induced forest die-offs and extreme wildfires to desertification of grasslands. Vegetation changes, in turn, affect various ecosystem processes that interact with and modify the geomorphology and hydrology of our landscapes—in this way, climate-induced vegetation changes have consequences for the water resources of New Mexico that affect all state citizens. "Ecohydrology" is the interdisciplinary scientific field that addresses the interactions between ecosystems and hydrology. This chapter reviews the effects of climate change on terrestrial ecosystems in New Mexico, focusing on vegetation and associated linkages to ecohydrology, to provide important context for statewide assessment of water-resource issues. Although important, aquatic ecosystems and biodiversity considerations are outside the scope of this chapter.

Globally, the main limiting environmental factors that determine the distribution and productivity of dominant vegetation types are combinations of water, temperature, and sunlight (Boisvenue and Running, 2006). In warm tropical rainforests, sunlight limitation (from intense inter-plant competition for canopy space and clouds) is usually the main constraint on vegetation productivity, while in cold

Arctic and high alpine settings temperature is most limiting. However, in semiarid warm-temperate regions like New Mexico, water is generally the most limiting factor, with seasonally varying temperature constraints (e.g., frost and extreme heat) being important secondary drivers. Ongoing regional climate change toward warmer temperatures and more severe droughts therefore threatens vegetation types that are sensitive to hotter, drier conditions.

The modern spatial distributions of New Mexico's diverse plant species and vegetation communities (Dick-Peddie et al., 1993) are generally structured by these same broad climate factors of precipitation and temperature, although at local sites the patterning of vegetation is substantially modified by other abiotic and biotic environmental factors, and human land use practices. Major human land use practices include agriculture, livestock grazing, forestry activities, fire suppression, watershed modifications and water management actions, and urbanization. Important abiotic factors include topographic characteristics that affect local microclimate (e.g., elevation, slope, aspect, landform, slope position), soil and bedrock physical properties, nutrient availability, and various ecosystem disturbance processes (e.g., fire, floods, wind). Subsurface water storage in soils and fractured bedrock is increasingly recognized to be critically important for deep-rooted plants (Rempe and Dietrich, 2018; Klos et al., 2018; Bales and Dietrich, 2020). Key biotic factors also interact to influence local vegetation patterns, including soil microbiota, competition between plants, herbivory by animals, insect and disease pests, parasites, etc. As a result, there are sharp differences in microclimate and vegetation between cooler-moister north-facing slopes versus the microclimate and vegetation found on directly adjoining hotter-drier, south-facing slopes (Fig. 4.1). At even finer spatial scales, similar microclimate and understory vegetation contrasts also occur between the cooler ground-surface conditions underneath tree or shrub canopies versus plants adapted to exposed hotter conditions in open intercanopy sites.

Paleo-environmental and Historical Perspectives on Climate-Vegetation Relationships in New Mexico

Climate is a fundamental driver of vegetation patterns and processes—but how do we rigorously determine how ongoing and projected climate changes are likely to alter future vegetation? One approach is to reconstruct the linkages between past climate variability and vegetation, providing evidence to infer likely future changes.

Past climate-vegetation relationships are particularly well-documented for many thousands of years in New Mexico, because the southwestern U.S. contains an unusual abundance and diversity

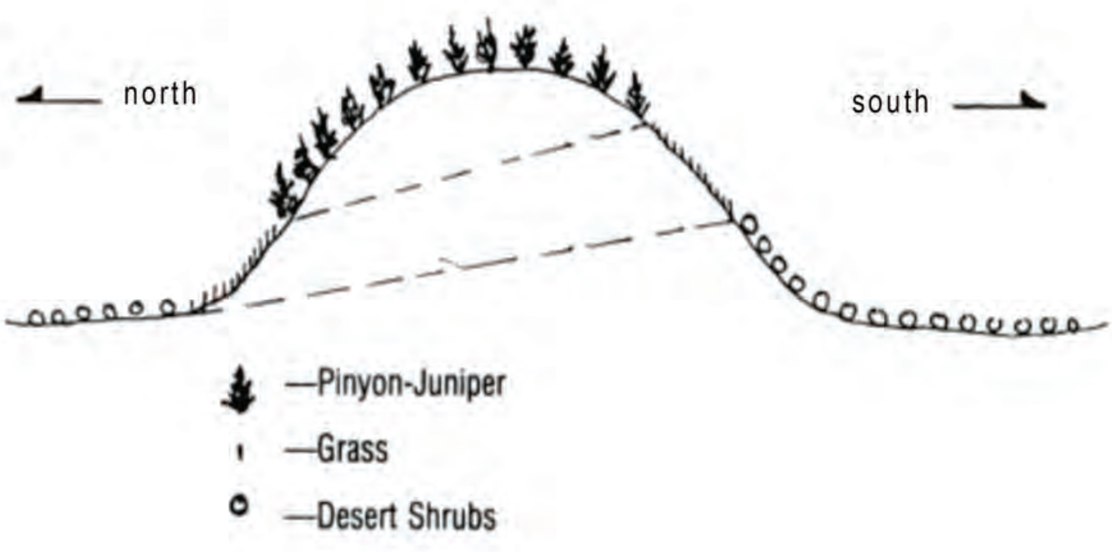

Figure 4.1. The strong effects of south versus north topographic aspect on vegetation pattern. Modified from Figure 3.1 in Dick-Peddie et al. (1993).

of paleo-environmental data sources that allow reconstruction of detailed information on linkages between climate and vegetation through time (Swetnam and Betancourt, 1998; Swetnam et al., 1999). For example, ancient lake sediments from the Valles Caldera (Jemez Mountains) provide multiple lines of evidence for major oscillations in climate and water balance (between colder-wetter versus warmer-drier) across multiple glacial-interglacial cycles over hundreds of thousands of years in northern New Mexico, with close linkages between climate and vegetation patterns (Fawcett et al., 2011). For the last 40,000 years, plant macrofossils preserved in packrat middens provide powerful species-specific information on major changes in the biogeographic distribution of vegetation and climate across the Southwest (Betancourt et al., 1990; Swetnam et al., 1999). Similarly, the pollen, macrofossils, charcoal, chemical isotopes, and numerous other paleo-environmental indicators found in the sediments of multiple New Mexico mountain lakes and bogs reveal greater detail on linked changes in climate and vegetation over the past 20,000 years, particularly as the world transitioned from the last ice age (the Pleistocene epoch) to the Holocene about 12,000 years ago (e.g., Anderson et al., 2008b). These paleo-sediment studies also provide long-term perspectives on the environmental effects of relatively recent historical land-use changes like Euro-American livestock grazing and fire suppression in New Mexico (Allen et al., 2008; Brunelle et al., 2014). Overall, these deep-time paleo-environmental studies consistently document that warmer periods in southwestern North America tend to be more arid—resulting in the drying of lake and bog environments, transitions to vegetation communities dominated by species better adapted to warm and dry conditions, and more fire activity.

Tree-ring research in the Southwest U.S. and New Mexico provides well-replicated and diverse paleo-environmental evidence that is spatially widespread, precisely located, and dated at annual to seasonal resolution. Tree-ring widths, wood density, and isotope measurements are used to produce calibrated reconstructions of past precipitation (Touchan et al., 2011), temperature (Salzer and Kipfmueller, 2005), tree drought stress (McDowell et al., 2010; Williams et al., 2013), annual streamflow (Routson et al., 2011; Margolis et al., 2011), and floods (McCord, 1996). Additionally, tree-ring-dated fire scars and other dendroecological observations document the environmental histories of New Mexico's forest fires (Falk et al., 2011; Swetnam et al., 2016; Margolis et al., 2017), insect outbreaks (Swetnam and Lynch, 1993), and forest establishment, growth, and mortality (Guiterman et al., 2018). The southwestern United States is the most intensively sampled region of the world in terms of tree-ring reconstructions of climate and fire history, with numerous chronologies extending back more than 1,000 years before present (Grissino-Mayer, 1995; Cook et al., 2007; Woodhouse et al., 2010; Williams et al., 2013). Southwestern climate reconstructions, based on tree-ring analyses, universally document high natural variability in precipitation at all timescales—annual, decadal, and even centennial (Grissino-Mayer, 1995; Williams et al., 2020a, b). There also has been recent success in separating cool-season precipitation from warm-season monsoonal precipitation in tree-ring reconstructions for New Mexico (Griffin et al., 2013), comparing reconstructed seasonal precipitation and Rio Grande streamflows back to 1659 CE (Woodhouse et al., 2013); and in assessing cool versus warm season precipitation effects on past fire occurrence (Margolis et al., 2017). Similarly, tree-ring temperature reconstructions for the Southwest also show significant variability through time (Salzer and Kipfmueller, 2005). These often well-replicated tree-ring studies quantitatively demonstrate the effects of both climate variability and human land uses on diverse forest ecosystem patterns and processes (Swetnam and Betancourt, 1998; Swetnam et al., 2016; O'Connor et al., 2017; Guiterman et al., 2019; Roos et al., 2021).

In addition, substantial historical ecology research (Allen, 1989; Swetnam et al., 1999) and numerous environmental history studies (Rothman, 1992; deBuys, 2015) have documented relatively recent (Anglo-American era, since ca. 1850) vegetation changes in New Mexico using historical observations and multiple other lines of evidence (Allen and Breshears, 1998)—ranging from General Land Office Survey field notes (Yanoff and Muldavin, 2008), repeat photography of century-old ground-based landscape photographs (Fuchs, 2002; deBuys and Allen, 2015), photo-interpretive mapping of vegetation from stereographic aerial photographs as far back as 1935 (Allen, 1989; Miller, 1999), and compilation and interpretation of diverse historical maps and text documents (e.g., Hillerman, 1957; Scurlock, 1998). These historical ecology studies are particularly useful in documenting and illustrating the major effects of extended droughts versus extended wet periods upon New Mexico's forest and rangeland vegetation (Swetnam and Betancourt, 1998; Allen and Breshears, 1998).

Finally—and most powerfully—direct measurements of climate and vegetation changes from a variety of long-term monitoring and research efforts over roughly the past century provide a solid foundation of quantitative observational data to assess recent and ongoing linkages between climate and vegetation in New Mexico. The effects of climate on vegetation change and ecosystem dynamics in New Mexico have been particularly well studied through long-term ecological research at three large and environmentally varied fieldwork localities that collectively represent a big portion of New Mexico's diverse landscapes:

1. The USDA Jornada Experimental Range (established 1912) and associated Jornada Long-Term Ecological Research (LTER) site (run by New Mexico State University since 1982)—in southern New Mexico's Chihuahuan Desert, focusing on subtropical desert grasslands and shrublands, and rangeland issues in general (https://jornada.nmsu.edu/ltar; https://lter.jornada.nmsu.edu/).
2. The USDI Sevilleta National Wildlife Refuge (established 1983) and associated Sevilleta Long-Term Ecological Research site (run by the University of New Mexico since 1988)—extending from the Rio Grande to adjoining low mountains in central New Mexico at the intersection of four biomes: Colorado Plateau Shrub Steppe, Great Plains Short Grass Prairie, Chihuahuan Desert, and Piñon-Juniper Woodland (https://www.fws.gov/refuge/Sevilleta/; https://sevlter.unm.edu/).
3. The Jemez Mountains, a volcanic "sky island" in northern New Mexico at the southern end of the Rocky Mountains, where the Valles Caldera National Preserve (est. 2000), Bandelier National Monument (est. 1916), and the USGS New Mexico Landscapes Field Station have collectively fostered long-term ecological monitoring and research since the 1980s on diverse montane forests, woodlands, grasslands, and streams along a 6,000-foot elevational gradient from the Rio Grande to Redondo Peak. These groups are partners in a new National Park Service (NPS) Research Learning Center (the in-development website address is: https://www.nps.gov/rlc/jemezmountains/index.htm).

All three of these large research landscapes are characterized by diverse, intensive, long-term studies and datasets; multidisciplinary research teams; and abundant published scientific research—documenting ongoing vegetation and ecosystem responses to climate variability and change.

These recent observations of linked climate-vegetation variability include documentation of multiple wet and dry periods since 1900 CE, ranging from a particularly wet window in the 1910s–1920s that favored a huge pulse of successful tree regeneration across the Southwest U.S. (Pearson, 1950; Swetnam and Betancourt, 1998) to the regionally severe 1950s drought that caused great stress to vegetation and water resources in New Mexico (Hillerman, 1957; Thomas, 1963; Allen and Breshears, 1998). More recently, another wet period from the late 1970s to mid-1990s was a time of abundant water resources and extremely productive tree growth (Fig. 4.2). Since ca. 2000, New Mexico and the Southwest U.S. have been in the midst of an increasingly severe regional drought (Williams et al., 2013, 2020a, b; Cook et al., 2021). Although this current multi-decadal period of lower precipitation is not unusual relative to past patterns of natural precipitation variability, the drought stress effects on both vegetation and water resources are increasingly amplified by substantial recent climate warming (Fig. 1.1; McKinnon et al., 2021). This is one of the two most severe regional "megadroughts" in the past 1,200 years (Williams et al., 2020a, b; Cook et al., 2021). The ongoing "hotter drought" in New Mexico is consistent with projected climate changes for the Southwest (Chapter 2; Williams et al., 2013; Cook et al., 2015, 2021). As New Mexico's environment has undergone this period of substantial warming and aridification, long-term ecological monitoring and research programs here have been able to precisely document and interpret the direct and indirect impacts of warmer "global-change-type drought" on both vegetation and water resources in New Mexico.

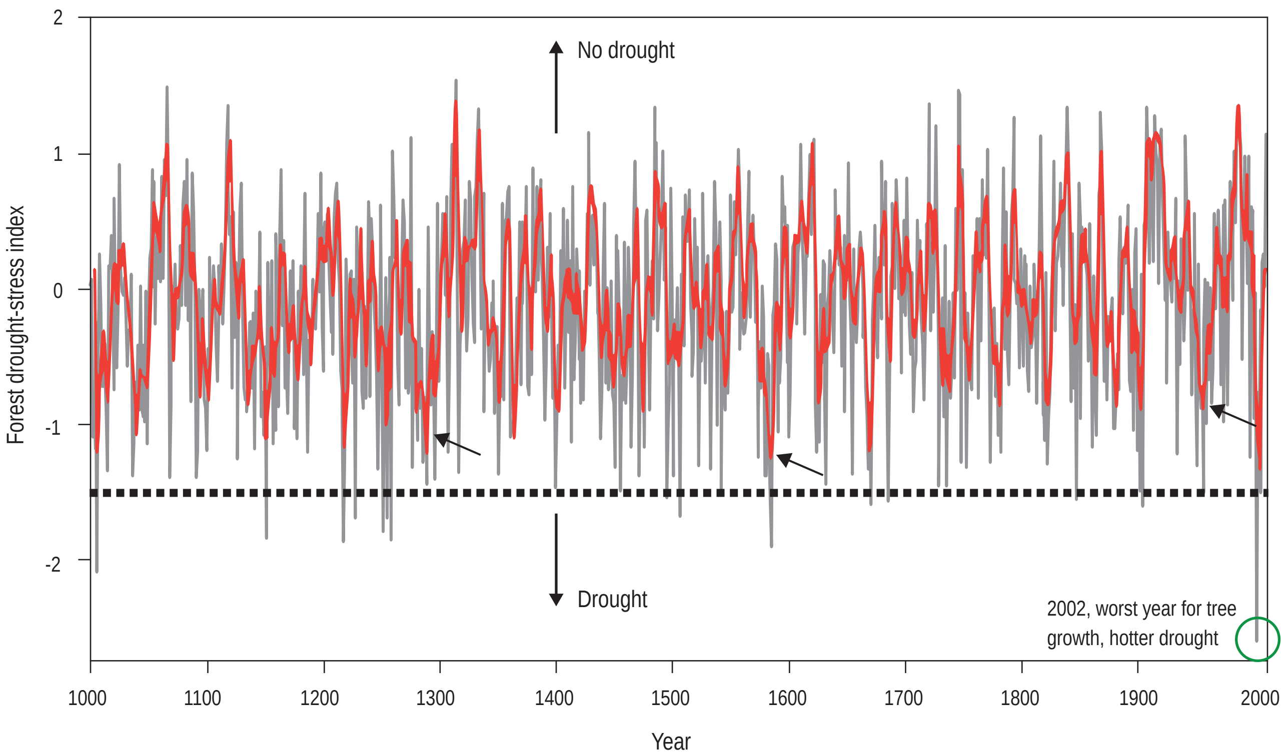

Figure 4.2. A 1,000-year reconstruction of a regional "forest drought stress index" (FDSI) from tree rings in the Southwest U.S. Annual FDSI values in gray, 10-year moving average in red, for 1000–2007. Arrows mark megadroughts in the late 1200s and late 1500s, and the well-documented 1950s historical drought. The -1.5 FDSI dashed line indicates an approximate historical threshold for tree mortality. The green circle highlights the unprecedentedly extreme FDSI in 2002, reflecting amplified drought stress from recent warming, which triggered extreme regional tree die-offs and wildfires. Modified from Williams et al. (2013) and Allen (2014).

Direct and Indirect Climate Effects on Vegetation and Ecohydrology

As described in Chapters 1–3, climate change in New Mexico is projected to continue recent trends toward warmer and thus generally more arid conditions, as well as to amplify wet, dry, and hot extremes.

Climate variability and directional climate changes in precipitation and temperature modulate New Mexico's vegetation cover in two general ways:

1. **Directly** through moisture and temperature effects on plant reproduction, growth and productivity, and mortality; and
2. **Indirectly** by altering ecological disturbance processes such as fires, insect and disease outbreaks, and floods.

Direct Climate Effects on Vegetation—Climate changes directly alter New Mexico's vegetation through effects on the demography of plant populations, including:

1. *Reproduction*—Plant populations in warm semiarid regions like New Mexico are characterized by episodic reproductive success linked to relatively infrequent, often multi-year, periods of favorable climate to sufficiently support abundant flowering, seed development (e.g., Parmenter et al., 2018), germination and seedling establishment. As a result, many dominant plant species establish primarily in pulses during the favorable climate periods, resulting in episodic even-aged cohorts of the dominant vegetation, whether Southwest U.S. trees (e.g., Swetnam and Betancourt, 1998) or grasses (e.g., Neilson, 1986; Collins et al., 2014). Note that the range of climate conditions

that support successful vegetation regeneration (the "regeneration niche") is generally narrower than the broader climatic range in which adult plants can grow and persist, and that due to warming-induced aridity, the regeneration niche is likely now shrinking for many plant species (e.g., Bailey et al., 2021).

2. *Growth*—The moisture and temperature conditions of both the atmosphere and soils directly control plant growth and productivity (Fig. 4.1); globally, soil moisture stress dominates vegetation productivity, particularly in semiarid ecosystems (Liu et al., 2020). In mostly semiarid New Mexico, the high natural variability in precipitation (and soil moisture) (Fig. 4.2) drives the similarly high variability in growth of both woody and herbaceous vegetation (Rudgers et al., 2018; Koehn et al., 2021). When water is not a limiting factor, slightly warmer temperatures can be beneficial for plant growth (e.g., longer growing seasons); in addition, the substantially elevated atmospheric concentrations of CO_2 can support increased water-use efficiency of photosynthesis (and thus good plant growth) when water stress is not extreme (De Kauwe et al., 2021). Also, atmospheric CO_2 enrichment tends to favor C3 plants like woody conifers and shrub species over C4 plants like many warm-season grasses (Archer et al., 2017; although see Reich et al., 2018). However, warming the last several decades has been enough to increase the frequency and severity of more arid atmospheric and soil conditions, thereby decreasing the supply of plant-available water (Breshears et al., 2013) and even beginning to approach thermal limits of photosynthesis (Duffy et al., 2021). These climate warming effects apparently are increasingly overcoming CO_2 enrichment benefits (Peñuelas et al., 2017; Jiao et al., 2021; although see Lian et al., 2021)—particularly in spring—and thereby reducing Southwest U.S. plant growth (Koehn et al., 2021; Munson et al., 2021). For example, warming has amplified conifer forest drought stress in the Southwest U.S., generally squeezing tree growth in New Mexico since ca. 2000 (Fig. 4.2; Williams et al., 2013), particularly in the warmer and drier low-elevation portions of the elevation distribution of individual tree species (McDowell et al., 2010). Similarly, warming-amplified drought stress and increases in precipitation variability also are linked to observed declines in the growth and productivity of perennial grasses in arid desert grasslands of New Mexico (Gherardi and Sala, 2015; Bestelmeyer et al., 2018; Rudgers et al., 2018; Munson et al., 2021).

3. *Mortality*—Extremes of drought and/or heat can lead to pulses of amplified vegetation mortality, which can rapidly change the sizes, ages, and species composition of the dominant vegetation (Allen et al., 2010; McDowell et al., 2020). While drought- and heat-induced vegetation mortality is a natural response to historical climate variability (e.g., Allen and Breshears, 1998), the emergence of hotter "global-change-type" droughts in recent decades (Breshears et al., 2005) is linked to increasing observations of more extensive and severe episodes of tree mortality in diverse ecosystems regionally and globally (Allen et al., 2015 [especially Appendix A of that paper for New Mexico observations]). While forest die-offs have received the most attention scientifically, hotter drought events also are causing mortality pulses in southwestern shrublands and grasslands (Jacobsen and Pratt, 2018; Winkler et al., 2019). Climate variability, particularly oscillation between increasingly wet and dry climate extremes, leads to "structural overshoot" of woody plants during growth-favorable (wet) climate windows at both individual and stand scales, which can increase vulnerability to forest dieback during the inevitable subsequent swing to an unfavorable climate window (hotter drought) (Allen, 2014; Jump et al., 2017; Zavala, 2021).

Because each plant species has its own particular set of climate requirements, changes in climate cause demographic changes in plant populations that drive wide-ranging incremental shifts (both contractions and expansions) in the biogeographic distribution, abundance, and community dominance of essentially all plant species (e.g., Collins et al., 2014; Rudgers et al., 2018).

Expected direct effects of future climate warming on New Mexico's vegetation include:

1. The vegetation communities historically found on warmer, drier south-facing slopes will tend to "shift" (through colonization) onto adjoining north-facing slopes;
2. More warm/dry (xeric) adapted plants from lower-elevation sites will shift their distributions upslope (Kelly and Goulden, 2008; Brusca et al., 2013); and
3. Less cold-tolerant plants from southerly portions of New Mexico will shift their distributions northward and perhaps upslope (although note the recent documentation of warming temperature and dryness constraints on alpine tree establishment in northern New Mexico—Bailey et al., 2021).

While plant individuals, populations, vegetation communities, and ecosystems have substantial capabilities to adapt to some degree of climate change (cf. Allen et al., 2015), these adaptive capacities are limited and may be overwhelmed by the speed and magnitude of projected climate change—warming in particular.

Thresholds—*(cf. Chapter 1 "critical threshold" - or "tipping point" - events)* Climate variability and change is one important driver of nonlinear **threshold** dynamics in ecosystem patterns and processes (Turner et al., 2020)—prominent New Mexico examples include drought-induced tree mortality, wildfire behavior, and water and wind erosion processes (Allen, 2007; Field et al., 2010; Bestelmeyer et al., 2018). Abrupt vegetation transitions can result from both incremental climate changes and unprecedented climate extremes (Fig. 4.3; Allen et al., 2015); such vegetation changes from aridification may be reversible, or not (Berdugo et al., 2020; Munson et al., 2021). Note that even modest incremental shifts in the average value of a climate variable (e.g., daily maximum temperature) can result in substantial increases in the probability of the most extreme events at the far tail-end of the distribution (Fig. 4.4)—e.g., the extreme heat records set in June 2021 in the Pacific Northwest and Canada. Similarly, a shift in the sensitivity of a climate-related threshold (e.g., a warming-caused decrease in the duration of drought needed to trigger tree mortality [Fig. 4.5]), can greatly increase the probability that threshold-level extreme events occur. Increasingly extreme, unprecedented climate events—particularly

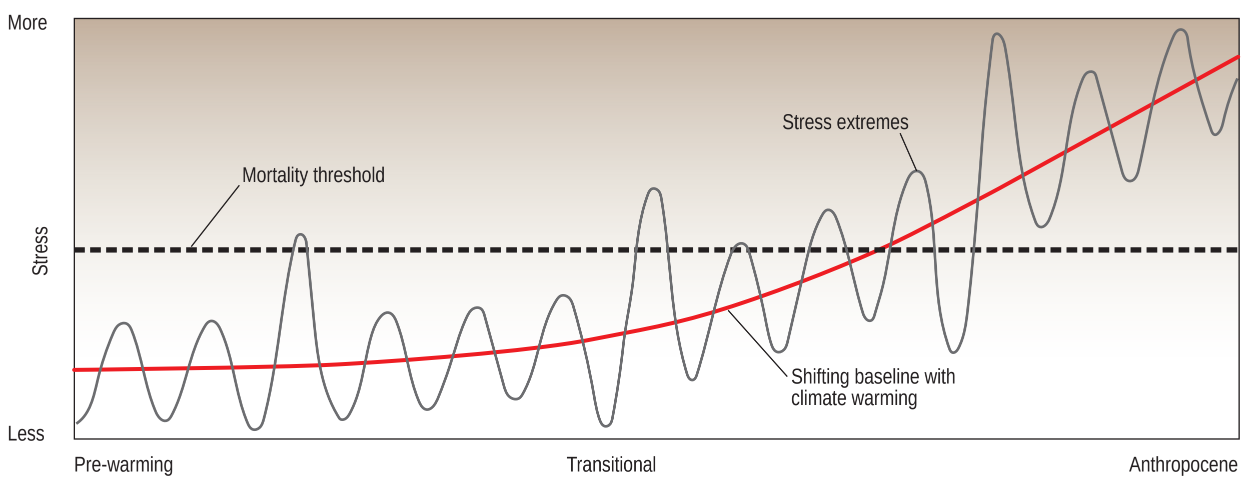

Figure 4.3. Ecosystem stress results from both general incremental trends and particular extreme events in climate (Jentsch et al., 2007). The red line indicates a shifting baseline level of forest stress through time due to an increasing trend in temperature; the gray line represents stress changes due to substantial multi-year oscillations in precipitation and temperature that are inherent in the climate system, producing stress events like extreme droughts and heat waves. Atmospheric warming increases both baseline and extreme drought stresses through time, thereby driving elevated tree mortality vulnerability. Increasing temperature alone drives greater forest drought stress (Adams et al., 2009; Williams et al., 2013), and because temperature is increasing chronically, so is forest stress. Swings in forest drought stress push forests closer (or further) from the historical mortality threshold (dashed black line), but given the chronic increase in forest stress associated with ongoing anthropogenic warming, the frequency, magnitude, and duration of these swings above the mortality threshold increase through time. If unabated, chronic warming eventually will cause even relatively wet periods to exceed the mortality stress threshold for present-day forests. From Allen et al. (2015).

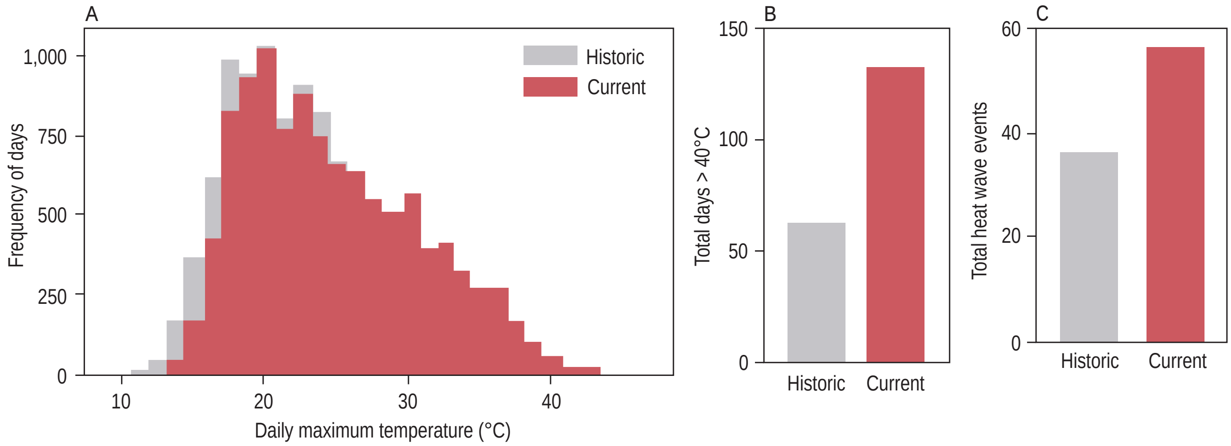

Figure 4.4. Warming greatly increases the frequency of extreme temperature days and heat waves. Daily maximum temperature (a), number of days over 40°C (b), and number of heat wave events (c) for Perth, Western Australia, for historical (1910–1939; gray) and current (1989–2018; red) 29-year periods. A small change in the overall distribution has led to more than a doubling in days > 40°C and a 59% increase in heat wave events. From Breshears et al. (2021).

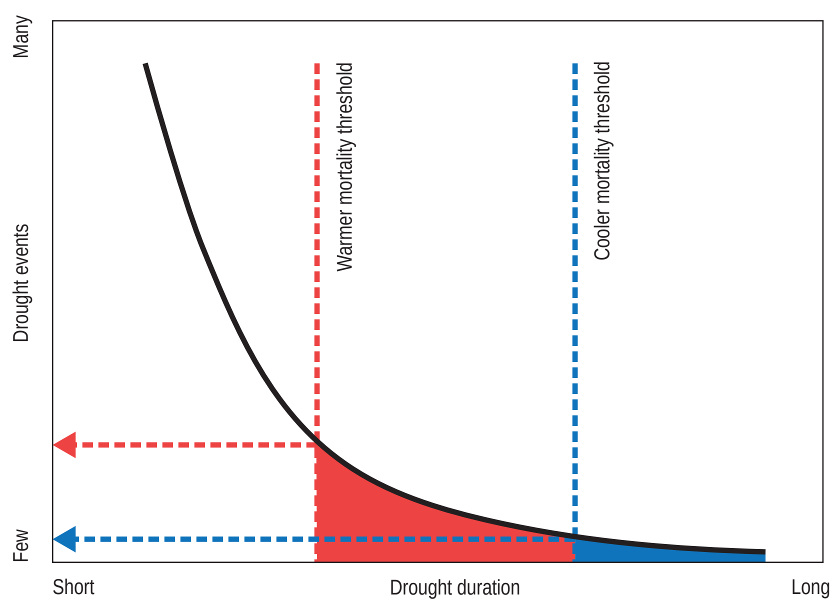

Figure 4.5. Warming greatly increases frequency of tree-killing drought events. Drought frequency (black line) increases nonlinearly as drought duration decreases, as there are many more short-duration droughts than long ones (Lauenroth and Bradford, 2009), and during cooler historical times only a few extremely long-duration drought events were long enough to exceed the historical tree mortality threshold (blue dashed vertical line). Under warmer recent and future drought conditions, trees die faster (red dashed vertical line, warmer mortality duration threshold) than with cooler droughts (blue dashed vertical line, cooler mortality duration threshold), resulting in more tree-killing drought events at the minimum duration mortality threshold for hotter drought (horizontal red arrow line) than for cooler drought (horizontal blue arrow line). This cumulatively translates into more total tree-killing droughts under hotter drought conditions (filled red + blue areas) than under cooler drought conditions (filled blue area only) because many additional shorter duration droughts become lethal with warming (Adams et al., 2009). From Allen et al. (2015).

droughts and heat waves—are emerging as ever-more important drivers of severe ecosystem disturbances and abrupt vegetation changes in the Southwest U.S. (Allen, 2014; Breshears et al., 2021).

Indirect Climate Effects on Vegetation through Altered Ecosystem Disturbance Processes— Recent, ongoing climate change also is indirectly, but profoundly, altering vegetation patterns by amplifying a variety of ecosystem disturbance processes that also affect water and watersheds. Documented effects of these climate-amplified disturbances on vegetation in New Mexico include:

1. More extreme pulses of tree mortality and forest die-offs (Fig. 4.6) from physiological stress due to hotter-drought (Breshears et al., 2005; Williams et al., 2013; Allen et al., 2015 [Appendix A of that paper]), often with associated bark beetle and other insect outbreaks (Raffa et al., 2008; Anderegg et al., 2015)—also including novel insect outbreak dynamics linked to recent warming (Figs. 4.7a, 4.7b; Elliott et al., 2021).

2. Warming has substantially altered recent wildfire activity in the Southwest U.S. and New Mexico (Fig. 4.8), with changes in frequency, severity, area burned, seasonality, and longer fire seasons (Westerling et al., 2006; Abatzoglou and Williams, 2016). Wildfire activity has recently increased upslope into cooler-wetter forest types (Higuera et al., 2021) as well as downslope into semiarid woodlands (Floyd et al., 2000, 2021; Romme et al., 2009). Recent increases in the extent and frequency of high-severity fire (Parks and Abatzoglou, 2020) are strongly filtering which species are able to regenerate post-fire (Johnstone et al., 2016; Coop et al., 2020). One result is an increase in vegetation "type conversion" from gymnosperm conifer forests that require nearby fire-surviving trees for seed regeneration to shrublands and grasslands (Fig. 4.9; Allen, 2014) dominated by resprouting angiosperm species that can regenerate after severe fire from surviving below-ground roots, tubers, etc. (Guiterman et al., 2018; Coop et al., 2020).

3. High-severity wildfires also cause extreme alterations of watershed vegetation cover and surface soil properties that can trigger post-fire floods and debris flows (Fig. 4.10); these disturbances are addressed in Chapters 6 and 9.

4. Ongoing warming-induced aridification and disturbances drive widespread reductions in vegetation cover below critical thresholds in many New Mexico landscapes (Davenport et al., 1998; Breshears et al., 2009; Field et al., 2010), resulting in generalized upland soil erosion by water (Wilcox et al., 2003) and wind (Munson et al., 2011; Duniway et al., 2019); these disturbances are addressed in Chapter 5.

5. Warming-induced desertification of desert grasslands (Fig. 4.11) is contributing to declines in perennial grass cover and increases in subtropical woody shrubs (Bestelmeyer et al., 2018).

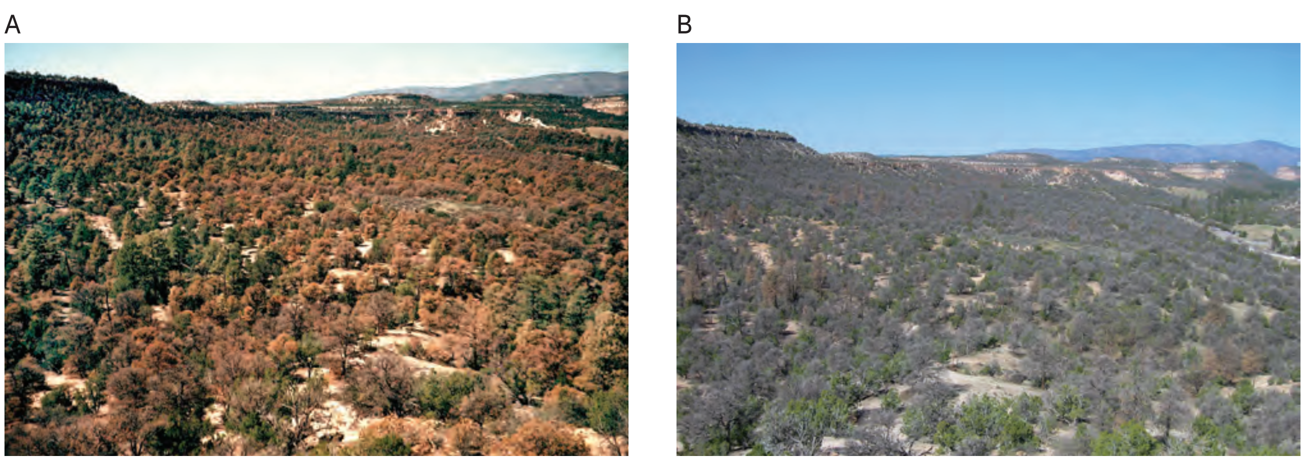

Figure 4.6. Repeat photos of landscape-scale mortality of piñon (*Pinus edulis*) from hotter drought and an associated bark beetle outbreak. (a) Rust-colored dying piñon, eastern Jemez Mountains, October 2002. (b) The same scene 18 months later, with gray piñon skeletons and remaining live junipers, May 2004. *Photos by Craig D. Allen*

Figure 4.7. (a) Novel insect outbreak dynamics. Aerial photo of Janet's Looper outbreak during 2017–2019 in the Sangre de Cristo Mountains near Santa Fe, with red-rusty-gray tree canopies from winter herbivory of Douglas-fir and Engelmann spruce tree needles by caterpillars (inset photo) of this inconspicuous moth. Recent warmer winters allowed the first recorded outbreak of this native insect in northern New Mexico. *Photos by U.S. Forest Service*

Figure 4.7. (b) Novel insect outbreak dynamics. Photos of extensive and unusually high-elevation Engelmann spruce (*Picea engelmannii*) mortality at and near upper treeline, caused by a combination of warming-amplified drought stress and an associated outbreak of the native spruce bark beetle (*Dendroctonus rufipennis*) killing over 80% of mature spruce trees across thousands of hectares in the headwaters of the Pecos River in the Sangre de Cristo Mountains. *Photos by William deBuys (October 2020)*

Figure 4.8. (a) Start of the Las Conchas Fire, 26 June 2011. *Photo by Craig D. Allen*

Figure 4.8. (b) Upper Cochiti Canyon in the Jemez Mountains seven weeks after being burned in the 2011 Las Conchas Fire. High-severity fire affected almost the entire Cochiti Canyon watershed, from upper-elevation mixed-conifer forests along the rim of the Valles Caldera down to near the confluence with the Rio Grande. This extensive loss of vegetative cover across the watershed led to substantial flooding from 2011–2013. *Photo by Craig D. Allen*

Figure 4.8. (c) High-severity fire effects in desertified piñon-juniper woodland in the southeast Jemez Mountains, taken August 2011, two months after being burned in the Las Conchas Fire. Note complete exposure of soil surface from fire consumption of all live and dead plant cover. *Photo by Craig D. Allen*

Figure 4.9. (a) Fire-caused type conversion from conifer forest to oak shrubland, Dalton Fire footprint near Pecos, NM. There is evidence that the increasingly large extent of post-fire conversions of forests into potentially quite-persistent, shrublands is a novel recent development in New Mexico conifer ecosystems. *Photo by Craig D. Allen*

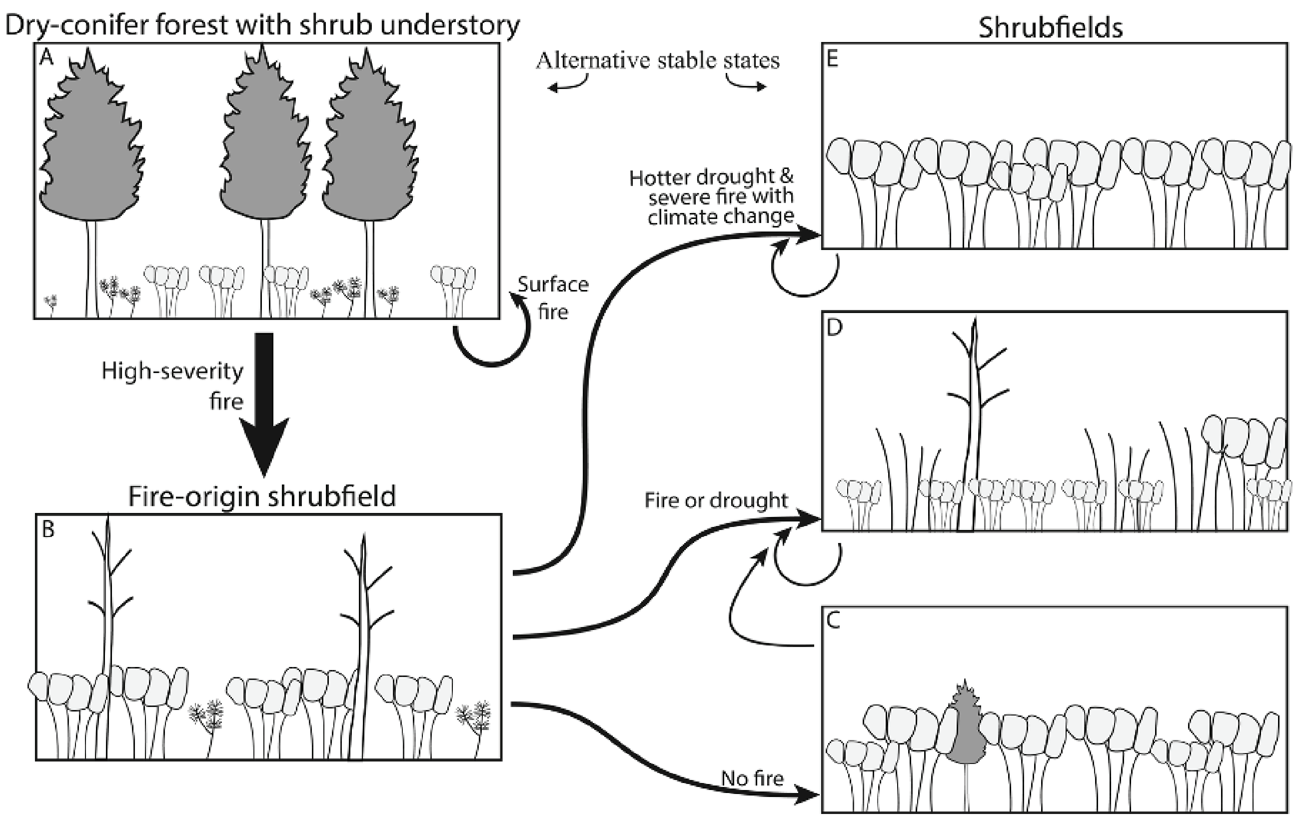

Figure 4.9. (b) Conceptual model of alternative post-disturbance stable states in dry conifer forest and shrub ecosystems of New Mexico, depending upon histories and combinations of disturbances. From Guiterman et al. (2018).

Figure 4.10. Gullies eroded by debris flows in upper Santa Clara Canyon, triggered by the 2011 Las Conchas Fire. *Photo by Craig D. Allen (2015)*

Note the importance of synergistic interactions among ecosystem disturbances, both within and across spatial scales (Allen, 2007; Turner et al., 2020). For example, warming drives the increased atmospheric-vapor pressure deficit (Williams et al., 2013), leading to greater drying of vegetation and soils that can amplify multiple individual disturbance processes (e.g., dieback, fire, erosion), which in turn also can interact with each other through diverse feedbacks (Allen, 2007), such as post-fire debris flows (Fig. 4.10).

Anticipated Effects of Ongoing and Future Climate Change on New Mexico's Ecosystems

Aquatic Ecosystems—Although aquatic ecosystems are outside the scope of this chapter, several broad assessments of climate change effects on the aquatic ecosystems of New Mexico are listed here. The New Mexico State Wildlife Action Plan (NMDGF, 2016) reviews the characteristics and climate change vulnerabilities of New Mexico's diverse aquatic ecosystems, including a broad range of perennial systems (cold and warm water streams, lakes, cirques, ponds, marshes, cienegas, springs, seeps, cold and warm water reservoirs) and ephemeral systems (marshes, cienegas, springs, playas, pools, tinajas, kettles). In a separate effort, the U.S. Forest Service (USFS) recently conducted an "Aquatic-Riparian Climate Change Vulnerability Assessment" (ARCCVA) of ongoing and potential effects of climate and drought at subwatershed-scale (HUC12) for perennial and intermittent/ephemeral waters on all lands of Arizona and New Mexico (Wahlberg et al., 2021), built upon existing data for over two dozen intrinsic and climate-related indicators associated with watershed condition, riparian and aquatic habitat, and the presence of warm- and cold-water fish that represent both impact risk and adaptive capacity. The ARCCVA geodataset can be downloaded at: https://www.fs.usda.gov/detailfull/r3/landmanagement/gis/?cid=stelprdb5201889&width=full.

***Biodiversity Considerations*—**New Mexico harbors an exceptional diversity of plants and animals, ranking fourth in the U.S. in the number of species (https://nhnm.unm.edu/). Climate change will have a broad range of effects on the plant and animal biodiversity of New Mexico that are beyond the scope of this chapter; however, several key sources of information relative to climate change effects on biodiversity in New Mexico are noted here. Natural Heritage New Mexico (https://nhnm.unm.edu/), a division of the Museum of Southwestern Biology at the University of New Mexico, does climate-change-related research on the conservation and sustainable management of New Mexico's biodiversity, and serves as a portal for acquiring and disseminating biodiversity conservation information for New Mexico. The New Mexico State Wildlife Action Plan (NMDGF, 2016) reviews the climate change vulnerabilities of New Mexico's terrestrial and aquatic ecosystems, with a focus on habitats for wildlife and fish. This State Wildlife Action Plan (SWAP) also addresses the climate change vulnerabilities of animal "species of greatest conservation need." Much additional detailed information on climate change implications for New Mexico's biodiversity is contained in a SWAP-associated online background document (Friggens, 2015). The "New Mexico Rare Plant Conservation Strategy" (NMEMNRD, 2017) is focused on 235 rare and endangered plant species in New Mexico, including 109 endemic species that only occur in New Mexico and nowhere else in the world. The overall goal of the New Mexico Rare Plant Conservation Strategy is to protect and conserve New Mexico's rare and endangered plant species and their habitats, which are distributed among 135 Important Plant Areas (IPAs) across the state. The associated "New Mexico Rare Plant Conservation Scorecard" provides an analysis of the current conservation status of the 235 rare plants, including threats such as climate change.

***Forests and Woodlands*—**Future climate warming and increased precipitation variability are anticipated to directly depress regional woody-vegetation productivity (Williams et al., 2013; Munson et al., 2021) and promote Southwest forest die-offs from hotter droughts (McDowell et al., 2015; Goulden and Bales, 2019). In concert with the associated intensification of ecosystem disturbances, particularly high-severity wildfire (Bowman et al., 2020; Pausas and Keeley, 2021), ongoing warming in New Mexico montane forests and upland woodlands is expected to increasingly constrain tree regeneration (Davis et al., 2019; Rodman et al., 2020; Bailey et al., 2021; Nolan et al., 2021) and further amplify widespread vegetation type-conversion from tree-dominated forests and woodlands to non-forest ecosystems (Allen, 2014; Guiterman et al., 2018; Coop et al., 2020; Davis et al., 2020). Drier, low-elevation distributions and ecotone margins of individual tree species and particular vegetation communities will tend to respond to growing drought and heat stress with early, rapid, and pronounced mortality-induced upslope range retraction (Allen and Breshears, 1998; Davis et al., 2019; Parks et al., 2019).

***Grasslands and Shrublands*—**Long-term research in southern New Mexico's desert grasslands finds that projected future climate warming and increased variability of wet/dry years will affect grass production and grass-shrub relationships (Peters et al., 2010; Gherardi and Sala, 2015; Gremer et al., 2015; Petrie et al., 2018). Multiple lines of evidence (from climate/vegetation monitoring, experiments, models) indicate that these warm semiarid/arid grasslands will see additional declines in perennial grasses and increases in shrubs (Fig. 4.11; Archer et al., 2017; Bestelmeyer et al., 2018), reflecting a documented ongoing conversion of New Mexico's temperate drylands (e.g., desert and plains grasslands) to subtropical drylands (Schlaepfer et al., 2017; Bestelmeyer et al., 2018). However, in some grassland settings there may be drying of deep soils that could reduce shrub cover (Schlaepfer et al., 2017).

***Riparian Forests*—**As perennial streamflows decline and become more intermittent and ephemeral, riparian gallery forests of cottonwoods in areas like the Middle Rio Grande probably will become increasingly vulnerable to growth reductions and dieback from more variable and generally lower water-table depths (Rood et al., 2013; Thibault et al., 2017; Condon et al., 2020; Varney et al., 2020; Kibler et al., 2021). Meanwhile, opportunities for post-flood pulses of native riparian tree regeneration will diminish (Molles et al., 1998; Perry et al., 2012). Reductions in riparian vegetation canopy cover will have substantial warming effects on stream temperatures (Wondzell et al., 2019).

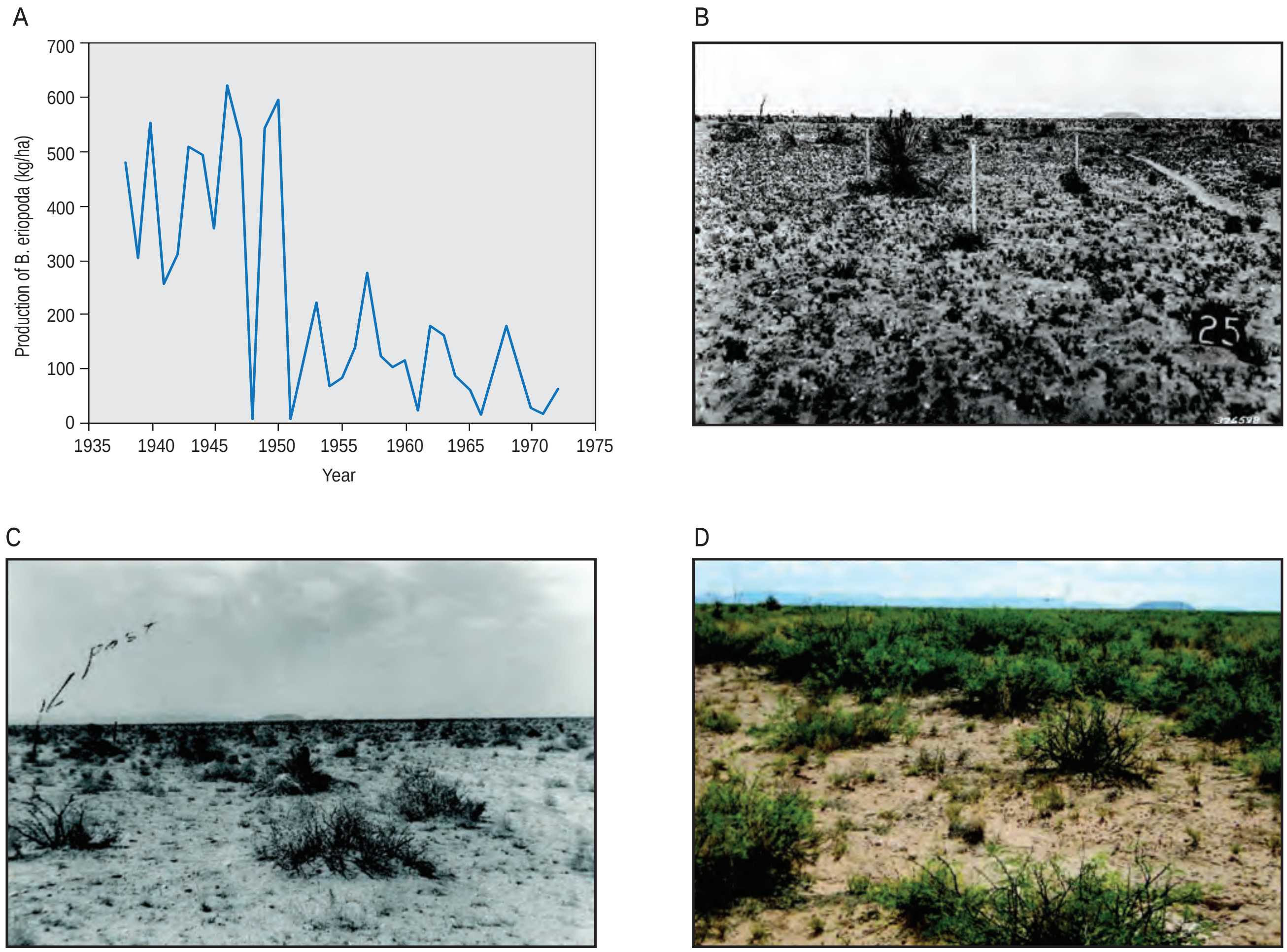

Figure 4.11. Evidence for a major historical grassland–to-shrubland transition in the Jornada Basin of southern New Mexico. (a) The initial collapse of black grama (*Bouteloua eriopoda*) production during the 1950s drought. (b) A 1936 photograph illustrating the effects of overgrazing during the 1930s drought. (c) The appearance of small honey mesquite (*Prosopis glandulosa*) shrubs in 1956. (d) The site in 2009, dominated by mesquite shrubs and with evidence of significant soil erosion exposing an indurated petrocalcic soil horizon (caliche). From Bestelmeyer et al. (2018).

Overall, globally as well as regionally in New Mexico, currently there are substantial uncertainties regarding the specifics of how rapidly and profoundly New Mexico ecosystems will reorganize in response to these direct and indirect climate change effects, as well as the particular outcomes of potentially novel post-disturbance vegetation trajectories (e.g., Figs. 4.7a, 4.7b, 4.8b, 4.8c, and 4.9a). In addition, we should expect that many of the newly transformed vegetation communities that are emerging today will be ephemeral, subject to further reorganization as ongoing climate-change drives continued direct and indirect ecosystem responses for the foreseeable future (Jackson, 2021).

Ecohydrological impacts of these climate-induced vegetation changes include—

1. Effects on the hydrological cycle of decreased vegetation cover such as increased evaporation, drier soils, and decreased transpiration, leading to positive feedbacks on regional warming and aridification in the Southwest U.S. (McKinnon et al., 2021).

2. Canopy change impacts to snowpack and spring snowmelt runoff (e.g., Belmonte et al., 2021). This effect began with twentieth century declines in snowpack and water yield due to regional forest densification (cf. McDonald & Stednick, 2003; Broxton et al., 2020) but subsequently transitioning to twenty-first century declines in water yield from excessive forest cover loss from wildfire and forest dieback processes (Harpold et al., 2014; Biederman et al., 2015; Stevens, 2017; Moeser et al., 2020 [although see Bales et al., 2020, and Bart et al., 2021]). In addition, direct effects of climate warming on snowpack dynamics is a factor (Milly and Dunne, 2020).
3. Direct or indirect reductions in forest biomass (e.g., through drought-induced dieback, fire, or mechanical thinning treatments) can substantially alter evaporation and transpiration, with potential to increase streamflow in some water-limited systems (Bart et al., 2021).
4. Fire-driven changes in watershed runoff and erosion processes; these are addressed in Chapter 6 and Chapter 9.
5. Changing connectivity of upland bare soil surfaces, affecting runoff, infiltration, geomorphic wind/water erosion processes (both directly through changes in vegetation cover, and indirectly through disturbances); these are addressed in Chapter 5.
6. Recent warming-related land cover changes (woodland tree dieback and shrub encroachment) in New Mexico alter site-level biophysical conditions (including aerodynamic conductance, albedo, and canopy conductance) in ways that can further increase surface temperatures (Duman et al., 2021)—with potential for further intensification of surface warming with expected future reductions in soil water availability.

Summary of Ecosystem Impacts and Responses

Climate is a fundamental driver of ongoing and future vegetation and ecosystem changes, with resulting effects on ecohydrological patterns and processes that will affect the distribution and abundance of water resources in New Mexico (Wilcox, 2010). While paleo-ecological evidence clearly demonstrates major past shifts in climate-vegetation across New Mexico's landscapes, the large magnitude and rapidity of recent and projected climate change is thought to be unprecedented during the past 11,000 years at least, and probably much longer. Recent chronic warming, along with increasingly unprecedented episodes of extreme hotter drought stress, have already driven substantial changes in New Mexico's vegetation over the past twenty years, foreshadowing massive reorganization of vegetation distributions and reductions in vegetative ground cover if current warming trends continue as projected (e.g., Jennings and Harris, 2017; Triepke et al., 2019). Such major alterations of New Mexico's vegetation would also have substantial ecohydrological feedbacks with New Mexico water resources. Since water-related environmental stresses occur in parallel with water-supply shortages for people, such climate-change driven water stress could lead to increasing conflict between management of declining water availability for human use (e.g., irrigation) versus "wild" water retained for the maintenance of historical ecosystem values and services (e.g., Grant et al., 2013; NMDGF, 2016; Wahlberg et al., 2021). However, through collaborative translational approaches (Jackson, 2021), thoughtful anticipatory planning (Bradford et al., 2018), and forward-looking ecosystem management actions (e.g., Schuurman et al., 2020), there is also the potential for creative adaptive conservation strategies that increase resilience to water shortages for both New Mexico ecosystems and our intimately linked human societies.

Knowledge Gaps, Uncertainties, and Strategic Areas Where New Mexico Might Want to Invest in Further Research

1. Further research is needed on the hydrological responses (e.g., changes in watershed evapotranspiration, timing and magnitude of surface-water runoff) to observed and anticipated watershed vegetation changes and ecosystem disturbances. For example, watershed research in California's Sierra Nevada shows that direct or indirect reductions in forest biomass (e.g., through drought-induced dieback, fire, or mechanical thinning treatments) can substantially alter evaporation and transpiration in overgrown forests, with potential to increase both forest resilience and streamflow in some water-limited systems (Bart et al., 2021). Are these findings potentially relevant to our somewhat similar but also substantially different higher-elevation montane forest watersheds in New Mexico and southern Colorado?

2. The usefulness of today's complex process-based models that are used to project vegetation dynamics in response to changes in climate drivers is currently limited by large uncertainties from several sources, including the lack of realistic ecosystem disturbance processes. Thus one essential research need is to develop and incorporate more realistic, well-parameterized, and better validated representations of ecosystem disturbance processes (e.g., climate-induced vegetation mortality, insect pest outbreaks, wildfire) into process-based vegetation models, including synergistic interactions among disturbance processes.

3. A general complementary approach to constrain the large uncertainties associated with projections of future vegetation dynamics from current process-based models is the development of empirical models that are directly based upon observational data. One Southwest U.S. example is the "forest drought stress index" of Williams et al. (2013), which is an empirical model of climate relationships to forest growth that also turns out to be strongly predictive of the regional extent of climate-related, tree-killing, bark beetle outbreaks and high-severity fires.

4. Further research is needed to sort out variability in findings regarding the effects of shrub dominance on deep soil moisture and potential shrub-related aquifer recharge in some desert landscapes (Sandvig and Phillips, 2006; Schlaepfer et al., 2017; Schreiner-McGraw et al., 2020).

5. Long-term ecological monitoring and research that is field-based in, and representative of, the diverse range of New Mexico landscapes is needed to adequately document, sufficiently understand, and effectively address: (1) current uncertainties and the expectation of many further tipping-point surprises over the rate, magnitude, patterns, and drivers of ecosystem reorganization in New Mexico relative to projected climate changes over the next 50 years; (2) associated ecohydrological responses; (3) modeling needs for better parameterization and validation of climate-ecosystem process models; and (4) effective societal adaptations to anticipated climate change impacts to land and water resources (Bradford et al., 2018).

V. IMPACTS ON SOILS

Leslie D. McFadden, Anne C. Tillery and Craig D. Allen

Soils play a strong role in determining how New Mexico's diverse landscapes will respond to climate change. Soil cover acts like a sponge, holding in water that falls as rain or snow. The presence of soil supports vegetation, and substantially reduces runoff and erosion. Soil enhances other processes such as infiltration of water and aquifer recharge. But soils can be damaged by a warming climate. Loss of vegetation in the northwest high desert and eastern plains, where soils are not well developed and easily damaged, will lead to dustier conditions in much of the state. On mountain hillslopes, the loss of vegetation cover in response to ongoing climate change will increase soil erosion, which then increases hillslope runoff. This, in turn, causes additional increases in soil erosion and bedrock exposure, which can largely prevent widespread recolonization by most plants, including trees. Soils on mountain hillslopes that face south, which are typically hotter and drier, will be damaged sooner by a warming climate than those on generally north-facing hillslopes that are slightly cooler and moister. Soils take many thousands of years to form, so these hillslopes will increasingly support sparse forests, or, in some circumstances, be entirely deforested. These changes are already well underway in some mountains in New Mexico.

Introduction

This chapter considers how climate change will impact soils, landscapes, and water resources in New Mexico. Many recent studies have concluded that sustained periods of drought and extensive wildfires are causing significant erosion of hillslopes and soils in areas of New Mexico (see Chapters 4 and 6, this report). The absence of soils on hillslopes is important because soils store water over large and continuous areas of hillslopes, and this fundamental aspect of soils supports recruitment by vascular plants. Moreover, the root networks of plant communities established in soils increase surface cohesion and enhance the infiltration-runoff ratio, thereby reducing erosion.

Two major questions concerning soils in New Mexico should be addressed:

1. Will climate-driven loss of soils, trees, and other vegetation in diverse landscapes of New Mexico (e.g., stable landforms of the eastern plains, hillslopes of mountain ranges) result in permanent changes to our landscapes, including increased runoff, irreversible soil erosion, and large-scale exposure of bedrock?
2. If soils over extensive areas of different landscapes are removed by erosion, how long will it take to form a new soil?

The presence of soils in landscapes impacts water resources because soils play an important role in the hydrologic cycle. The surfaces of most of Earth's landscapes are associated with a soil, or loose, unconsolidated sediment, the latter of which is formed through weathering processes that break down bedrock. When it rains or snows, water can either move into the soil or sediment ("infiltration") and sink through the soil or sediment ("percolation"), or it may accumulate at the surface and move downslope across the surface ("runoff"). Some of the water that moves below the soil may ultimately join deeper groundwater, a process referred to as "recharge" (see Chapter 3). Surface runoff may also cause erosion of soil, sediment, or even bedrock. In some circumstances, the saturation of the soil or weathered rock can trigger different kinds of mass movements such as debris flows, slumps, or slow downhill soil "creep" (see Chapters 4 and 6). Eroded material is eventually transported to streams or rivers that ultimately deposit the sediment onto river floodplains, and into lakes, reservoirs, and oceans.

The magnitude of runoff, infiltration and recharge following precipitation on hillslopes is dependent on several variables, including the steepness of the slope, the types and amounts of vegetation, the types and thicknesses of the soil and/or weathered surface materials, the amount of water in the soils prior to a precipitation event, and the overall surface area that is capable of producing runoff (Bierman and Montgomery, 2019). Thus, the distribution of various soil and sediment characteristics on hillslopes (such as soil thickness) plays an important role in the processes that directly or indirectly impact water resources in New Mexico. For example, future changes in climate that affect the spatial extent of soils in New Mexican landscapes (e.g., through increases in soil erosion, see Chapter 6) will have immediate impacts on water resources, as the removal of soil will strongly impact surface hydrological processes, as well as substantially increase hillslope erosion (see Chapter 6) by increasing the proportion of runoff relative to infiltration. Climate changes that result in increases in soil temperature, evapotranspiration, and the depth of soil moisture movement will also have a significant impact on water resources, although these impacts will likely play out over longer time scales.

In considering these important questions, it is useful to understand the nature of the soils that exist in the diverse landscapes of New Mexico. A few key factors most strongly influence the rates, processes, and magnitude of soil development in our landscapes. Two important factors are "relief" (or "topography") and "parent material" (the materials in which a soil forms) (Jenny, 1941; Birkeland, 1999). Also, the length of time that a soil has been forming is important, as many soil properties change with time. Finally, an especially important factor is climate. A conceptual approach that has been used for several decades to demonstrate how these soil-forming factors affect the development and evolution of soils on different kinds of landforms, or in different climate regimes, is called the "Factors of Soil Formation," or the CLORPT approach (Climate, Organisms, Relief, Parent materials and Time; Birkeland, 1999). Appendix B provides helpful background materials concerning the scientific study of soils and landscapes, including: (1) overviews of the CLORPT approach, (2) studies that show the lengths of time over which many types of soils form, and (3) different hillslope types and how surface processes associated with hillslope affect soil development. In this chapter, studies of soils and their relationships in diverse landscapes, climatic regimes, and geologic settings are described to show how they provide the basis for considering the impacts of ongoing climate changes on New Mexico's diverse landscapes over the next five decades. Studies of how soil landscapes responded to past changes in climate during the past few centuries extending to about fifteen thousand years ago (i.e., including global changes in climate following the last great "ice age" and those that have occurred since then) are also essential for increasing the reliability of predictions largely made on the basis of numerical modeling. Such studies are essential in predicting the consequences of ongoing climate changes that are already impacting the landscapes of New Mexico, but that may well ultimately cause irreversible changes over the next several decades and beyond.

Impacts of Climate Change on Soil Landscapes in New Mexico

An increasing number of studies address the direct impacts of climate change on soil properties and soil formation, especially considering the potential contributions of carbon from the uppermost, organic-rich soil horizons to the atmosphere (e.g., Varney et al., 2020). In New Mexico, where global climate models indicate a high probability of significant warming (see Chapter 2), some likely impacts on soil development and water resources can be predicted. Although changes in average annual precipitation over the next several decades will likely be relatively minor (see Chapters 1 and 2), increases in annual temperature and therefore soil temperatures in dryland environments, coupled with diminished vegetation cover, favor decreases in soil organic matter. This decrease is related to processes such as increased carbon mineralization caused by increased microbial activity and elevated CO_2 in the uppermost soil horizons (e.g., Pritchard, 2011), slight decreases in the average depth to which soil moisture will descend in the current climate based on measurements made by staff employed by the Natural Resources Conservation Service, and diminished soil-water availability (cf., Birkeland, 1999; McFadden, 2013). Coupled with predicted increases in the frequency, intensity, and length of droughts (see Chapters 2 and 8), studies indicate that these changes will in turn change the rate at which carbonate (sometimes called "caliche") forms in soils (McFadden and Tinsley, 1985; McFadden et al., 1991; Breecker et al., 2009).

***Impacts on Eolian Landscapes and Eolian Processes*—**Climatic changes over the next 50 years are likely to impact surface processes in ways that may substantially influence the distribution and thickness of many soils in New Mexico. For example, windblown (eolian) sediments cover many areas of New Mexico, especially in northwestern New Mexico and in large areas of the High Plains. At present, these particular eolian landscapes have been stabilized by vegetation (Lancaster and Marticorena, 2008), which has enabled relatively weakly developed soils to form. A future loss of the plant community, mainly in response to warmer, sustained periods of drought, will likely lead to widespread destabilization of eolian landforms (Muhs and Maat, 1993; Madole, 1994; Forman et al., 2008; Ellwein et al., 2018). Although the presence of more well-developed soils will slow destabilization (Ellwein et al., 2018), research shows that destabilization, essentially a form of desertification (the transformation of a vegetated landscape to a largely barren desert), is already underway in parts of northeastern Arizona (Bogle et al., 2015). Desertification of the vast eolian landscapes on the Colorado Plateau, a large part of which occurs in northwestern New Mexico (see Fig. 6.1 in Chapter 6 of this report) will allow large quantities of windblown dust to be transported long distances by wind. The deposition of such dust on top of the snowpack on downwind mountain ranges has already led to early melting of snowpack (Painter et al., 2012).

Once these eolian landforms are destabilized, stabilization at some future time will require, at minimum, changes to an effectively less arid climate that enables colonization of active eolian landforms. Formation of soils that provide increased resistance to destabilization will require at least a few thousand years, as shown by the results of studies of soil development in the eolian landscapes in different parts of the American Southwest (Wells et al., 1990; Ellwein et al., 2018)

The extensive drylands of eastern New Mexico are dominated by soils that have either fine-grained thin surface horizons or thicker and more organic-matter-rich horizons of the short-grass prairie soils. Such soils are especially vulnerable to deflation (erosion by wind of loose sediment) when subjected to extended drought-caused losses in vegetation and/or certain types of ground disturbance and/or heavy tilling. Lambert et al. (2020) reported that given the expansion of agriculture in many parts of the Great Plains, increases in drought and associated crop losses are already causing increases in erosion and dust emission. Farmers in Curry County and other parts of eastern New Mexico, observing drought-stricken fields, are concerned that future increased windiness would result in significant erosion and dust emission, essentially establishing a "new Dust Bowl" (Land, 2021). The rapid decline of the Ogallala Aquifer may force the abandonment of agriculture in parts of eastern New Mexico (Rawling, 2018, in the summer edition of *New Mexico Earth Matters*), which will further increase deflation and dust emission, especially if warm season grasses are unable to effectively recolonize such landscapes in the increasingly warmer and more arid climate (e.g., Winkler et al., 2019).

Some researchers attribute the development of large areas characterized by small sand dunes formed around clumps of vegetation in arid regions of south-central New Mexico to increases in grazing pressure coupled with drought on formerly grassland-dominated landscapes (Gile et al., 1981). Even if grazing pressure on these landscapes is reduced over the next several years, given the inexorable increase in temperature and drought length and severity, reestablishment of native grasslands is unlikely, as noted above. Whether the substantial diminishment of plant cover occurs on sandy or finer textured surfaces of landscapes in the drylands of New Mexico, a significant increase in deflation of unconsolidated surficial materials by seasonally strong winds is virtually assured. Accordingly, the response of large regions of eastern and south-central New Mexico to the next 50 years of climate and environmental change is almost certainly increasing desertification, accompanied by increasing dust emission, and increased erosion on hillslopes, as described in the following section.

***Increased Erosion on Hillslopes*—**Over the next five decades, climate change will alter the soils that currently exist on the hillslopes of New Mexico. Climate change substantially affects many hillslope processes in hot, arid landscapes that have basin-wide impacts on soil and landscape evolution (Bull, 1991 [Fig. 5.1]). Bull (1991) proposed that significant increases in temperature and aridity would cause increases in hillslope runoff and erosion by reducing vegetation cover. Such a climate change occurred during the transition between the cooler climate of the late Pleistocene (the last glacial period of the 2.6-million-year-long Pleistocene "Epoch") and the much warmer Holocene (approximately the last 12,000 years, referred to as an "interglacial period"). The soil and weathered rock eroded from hillslopes ultimately caused ephemeral streams to deposit the sediment on alluvial fans.

Substantial increases in average annual global temperature have occurred during all previous glacial-to-interglacial transitions. Changes in climate of a smaller magnitude have occurred during the Holocene. Paleoclimatic research in the southwestern U.S. also demonstrates that during previous interglacial periods there have been shorter intervals of increased warm temperatures (Fawcett et al., 2011), a pattern somewhat analogous to present circumstances. As noted above, and as will be addressed below, in addition to insights that geomorphological and paleoclimatological studies provide concerning the behavior of eolian landscapes, these studies provide insights into how an increasingly warmer climate in New Mexico over the next several decades might affect hillslopes and soils.

An important aspect of the Bull (1991) model is that diminished hillslope vegetation substantially increases the erosion of soils, thus increasing bedrock

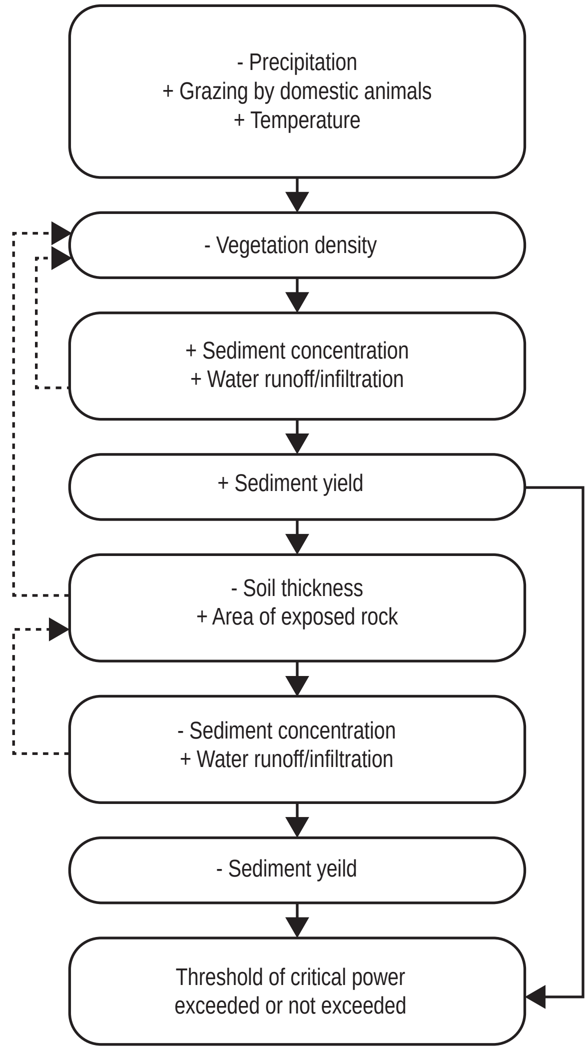

Figure 5.1. A flow diagram showing increases (+) and decreases (-) in variables involved in processes associated with sediment transport on hillslopes and deposition on alluvial fans in deserts (after Bull, 1991). "Critical power" signifies the power associated with water flowing in a stream channel needed to transport the sediment load. Feedbacks are indicated by dashed lines.

exposure. Ongoing research in the eastern Mojave Desert provides important new insights concerning the impacts of climate change on hillslopes associated with rocks resistant to chemical weathering in a high desert setting (Persico et al., 2016; McAuliffe et al., 2019; Persico et al., 2019; Persico et al., 2022). This body of research generally confirmed the Bull (1991) model, showing that climate changes after the end of the last ice age caused substantial increases in erosion, substantial loss of soil mantle, and substantial increases in bedrock exposure on hillslopes. However, these responses to climate change are most strongly expressed on south-facing hillslopes and they occurred several thousand years following the end of the last Great Ice Age. The contrast between a north-facing and south-facing hillslope in the same geographic area are illustrated in Figs. 5.2a and b. The south-facing hillslopes have large areas of bedrock and/or a thin layer of unconsolidated, weathered material that can move downslope under the influence of gravity (colluvium) over the bedrock (Fig. 5.2b). Isolated remnants of much thicker, but stabilized colluvium on which a soil has developed that supports warm season grass occur on these hillslopes. Field studies show that these hillslopes once had a continuous cover of colluvium and soil. Because soil horizons in many dryland soils contain a large amount of accumulated eolian dust (cf., McFadden, 2013; Persico et al., 2022) the timing of the accumulation of the dust can be dated. This enables determination of the timing of the formation of the soil and the age of the formerly continuous hillslope cover of colluvium. The dates show that the soils started forming over 20,000 years ago, at a time

A

B

Figure 5.2. a) Smooth vegetation and soil mantled, north-facing hillslopes in a semiarid region of the eastern Mojave Desert, California. Such hillslopes are regarded as “transport-limited slopes.” See text for details. b) Close-up of a sparsely vegetated and locally bedrock-dominated “detachment-limited” hillslope located on south-facing hillslopes only a few hundred meters from north-facing hillslopes shown in Figure 5.2a. *Photos by Leslie D. McFadden*

when paleobotanical studies show that a pinyon-juniper woodland with intercanopy grass was present. The warming and increasingly more arid climate after the end of the ice age caused the loss of the woodland. However, the only extensive alluvial deposit and associated river terrace present in this area is about three thousand years old. This indicates that the presence of a grass community in the semiarid climate of the Holocene acted to resist erosion until well into the Holocene.

On smooth, curvilinear, north-facing slopes (Fig. 5.2a) the soil is nearly continuous and supports a grass-dominated vegetation community. This type of hillslope develops when the rate of weathering and soil formation exceeds the rate of hillslope erosion. Why did the north-facing hillslopes respond so differently than the south-facing hillslopes, despite the fact that they have identical rock types and are subject to the same regional climate? The answer is that in the northern hemisphere, south-facing hillslopes receive a greater amount of sunlight than the north-facing hillslopes. Burnett et al. (2008) showed that this topographically driven difference in climate (referred to as “topoclimate”) is large enough to cause differences in soil temperature and moisture content. Thus, although the north-facing hillslopes lost the pinyon-juniper woodland at the beginning of the Holocene, the slightly cooler and moister conditions (referred to as a “mesic” condition) enabled the retention of a grass community. Accordingly, in marked contrast to the warmer and drier south-facing hillslopes (referred to as a “xeric” condition), the continuous grass cover greatly minimized erosion.

This research demonstrates how consideration of hillslope aspect allows assessment of the varied impacts of climate change on the magnitude of erosion and sediment production from hillslopes that have different kinds and thicknesses of soils and contrasting plant communities. Research in dryland regions shows that the development of moderately developed soils that support plant communities and resist erosion requires many thousands of years (see Appendix B). Once stripped from hillslopes, their formation on hillslopes will require substantial lengths of time, as long as many thousands to tens of thousands of years.

Changes in climate during the last 12,000 years (since the end of the last glaciation) have resulted in episodes of increased wildfire frequency and severity on the higher-elevation-forested hillslopes of the Southern Rocky Mountains, the Jemez Mountains and the Sacramento Mountains (Anderson et al., 2008a; Fitch and Meyer, 2016; Frechette and Meyer, 2009; Chapters 4 and 6, this report). Both tree-ring (dendrological) studies and assessment of fire-related alluvial deposits show that these episodes are correlated with periods of climate warming and/or drought severity over the past 5,000 years. Observed increases in sediment deposition during the Holocene in these areas are interpreted to reflect increased erosion of hillslope soils (see Chapter 6 for extended discussion of impacts of wildfires on hillslopes and river channel responses). The strongly correlated radiocarbon-dated fire-related deposits and paleoclimatic evidence for periods of warming and/or extended droughts show that the erosional response of the hillslopes to periods of wildfire is extensive and occurs over a short period of time. Numerous studies in the Bandelier National Monument area located on the Pajarito Plateau also provide evidence of the impacts of recent warmer temperatures, drought, land use, and wildfire on hillslopes and soils (see Chapters 4 and 6 and associated citations).

Fitch and Meyer (2016) demonstrated that climatic differences related to hillslope aspect strongly influenced the postfire erosion response to the 2002 “Lakes Fire.” Whereas fire-related alluvial deposits constituted over three-quarters of the fan sediments derived from north-facing basin hillslopes, fire-related deposits made up only about forty percent of fan sediments from the south-facing and more xeric basin hillslopes. They concluded that south aspects produce more runoff and sediment given their sparser vegetation and increased bedrock exposure; the north-facing and more mesic hillslopes mantled by soil produce much less runoff and sediment, unless they are severely burned. In addition, they also concluded that the magnitude of the erosion and deposition produced by this fire was larger than any other postfire response in the Jemez Mountains in the last several thousand years. They attributed this to extreme drought and fuel loading associated with fire suppression.

Effects of Bedrock Type on Hillslope Erosion— Research in semiarid, pinyon-juniper-dominated hillslopes in different areas of the southwestern United States demonstrates that the type of bedrock in drainage basins strongly influences rates of weathering, soil development, vegetation and erosion (McFadden and McAuliffe, 1997; Persico et al., 2011). Accordingly, climate changes affect drainage basins associated with different rock types in different ways. For example, studies show that the sandstone of the Jurassic Morrison Formation and the Bluff Sandstone are especially sensitive to changes in climate, as they are rapidly weathered by wetting-drying cycles (McAuliffe et al., 2006). When rainwater soaks into this kind of bedrock, the water interacts with some of the clay minerals that bind the sand grains together. The clay absorbs the water and expands, but when soil temperatures increase, this causes loss of the water from clay (a process called "dehydration") and the clay shrinks. Over time, many expansion-contraction cycles cause weakening of the clay cement and disintegration of the sandstone bedrock (Tillery et al., 2003). This process favors the rapid weathering of the clay-cemented sandstone and the formation of weakly developed soils in only a few decades on north-facing hillslopes (McAuliffe et al., 2006, 2014), because, as noted above, the north-facing hillslopes favor cooler temperatures and a moister, mesic environment than the south-facing, xeric hillslopes. The mantle of soils on the former hillslopes is continuous and is able to support a pinyon-pine community on a smooth, curvilinear hillslope. Geoscientists who focus on studies of the origin and evolution of landscapes refer to this type of hillslope as a transport-limited hillslope (Fig. 5.3; Appendix B). The south-facing hillslopes in these areas that formed on the same sedimentary rocks are very different; they are generally much steeper, have a much greater area of exposed bedrock and much less vegetation cover. This kind of hillslope is referred to as a weathering-limited hillslope (Fig. 5.4; Appendix B). As in the eastern Mojave Desert study area, the contrasts in hillslope form and soils in the northeastern Arizona site and their responses to climate change also can be attributed to differences in aspect-related temperature and soil moisture,

Figure 5.3. Smooth, soil- and vegetation-mantled, north-facing "transport-limited" hillslopes with a pinyon forest formed on Jurassic sandstone in a semiarid climate in northeastern Arizona. After figure 9 in McFadden (2013).

conditions that in turn influence soil development and hillslope character (Burnett et al., 2008).

Evaluation of soils and vegetation, studies of tree-ring growth (Scuderi et al., 2008; McAuliffe et al., 2006, 2014), and studies of erosion associated with large monsoon storms (Wawrzyniec et al., 2007) show that the smooth soil and vegetated hillslopes are very quickly changing into steeper and sparsely vegetated hillslopes (Fig. 5.5). On the basis of detailed dendrological, soil and other studies, McAuliffe et al. (2006; 2014) attribute this change to sustained periods of drought during the last few centuries that were abruptly followed by monsoonal storms and/or tropical cyclones. Their studies documented substantial losses of perennial grasses and perennial herbaceous plants caused by the 1999–2002 drought in this area and over much of the Southwest. Substantial reduction, or even complete loss, of these plants and their root networks allowed significant soil erosion and bedrock exposure that was caused by an unusually large monsoonal storm (Wawryzniec et al., 2007). Longer droughts and warmer temperatures over the next 50 years will likely accelerate similar changes to hillslopes in southwestern drylands on similar rock types. In New Mexico, the smooth, soil- and vegetation-mantled hillslopes shown in Fig. B.5 in Appendix B are northwest facing, whereas the southwest-facing hillslopes formed on identical sedimentary rocks in the same field area are essentially bare of soil and vegetation and have many steep cliffs (Fig. B.6 in Appendix B). Geologic maps of New Mexico show that rocks like the sedimentary rocks of northeastern Arizona, rock types that are very sensitive to climate warming and droughts, are also present in New Mexico. Over time, as climate change reduces vegetation, and soil erosion accelerates, the northwest-facing hillslopes will assume the form of the southwest-facing hillslopes. Given the results of the studies in northeastern Arizona, these changes will occur rapidly, likely over decades to centuries.

The study by Persico et al. (2011) in the foothills of the Sandia Mountains provides another example of the important role rock type plays in soil- and hillslope-forming processes as they are affected by climate changes (see Appendix B, Fig. B.8). The Sandias are composed mainly of the Sandia Granite and are characterized by bedrock-dominated (weathering-limited) "core-stone" hillslopes, which consist of bare, fractured, ellipsoidal blocks of granite, as illustrated in the lower left corner of Fig. 5.6. Core-stone hillslopes have small patches of thin, weakly developed soils between the large core-stones. Where small tabular bodies (geologists call these features "dikes") of a rock type called "aplite" (a fine-grained, granite-like igneous rock) occur in the granite, the aplite breaks down to large blocks that accumulate on hillslopes below the dikes. The blocks efficiently entrap windblown dust, a process that eventually causes the formation of a thick, well-developed soil (as described in Appendix B, Fig. B.8) (McFadden, 2013). These smooth, soil-mantled hillslopes (Fig. 5.6) have been stable for tens of thousands of years. Ongoing shifts in climate that reduce vegetation cover will accelerate erosion of these soils, although far more slowly than the very rapid soil erosion rates of soils formed on the sedimentary rocks in the northeast Arizona study area. The results of the Persico et al. (2011) study indicates the soils could potentially persist for several thousand years, unless the hillslope vegetation and soils are subjected to wildfire, as discussed in the following section and in Chapters 4 and 6 in this report.

***Changes to High-Elevation Soils and Hillslopes: The Next 50 Years*—**What insights do soil studies at lower-elevation, pinyon-juniper forests, in a semiarid climate provide about the possible impacts of the next 50 years of climate change on forested, higher-elevation settings in New Mexico? There is little doubt that there will be continued changes in vegetation in response to future increases in temperature, drought, and wildfires (see Chapter 4). As many studies have already demonstrated, this will both substantially reduce soil infiltration rates and canopy cover and increase soil erosion. This, and other research, suggests that at higher-elevation settings, many hillslopes with continuous soil mantles and vegetation will begin to shift to hillslopes with discontinuous soils, generally thinner soils, and larger areas of exposed bedrock. In some areas, virtually complete loss of soils and most vegetation is possible. As noted in the introduction to this chapter, such changes will have large impacts on surface hydrology, shallow-subsurface water flow, groundwater recharge, and the behavior of streams and rivers. Hillslopes in many areas of the state will become bedrock-dominated hillslopes that are largely incapable of

Figure 5.4. Steep, bedrock-dominated, south-facing, "weathering-limited" hillslopes formed on Jurassic sandstone in a semiarid climate in northeastern Arizona. These south-facing hillslopes are located less than 50 meters from the north-facing hillslopes shown in Figure 5.3. *Photo by Leslie D. McFadden*

Figure 5.5. Recent erosion and exposure of Jurassic sandstone on east-facing hillslopes located between hillslopes shown in Figures 5.3 and 5.4. Erosion is rapidly removing a once-continuous soil associated with formerly transport-limited hillslopes and transforming them into steep, bedrock-dominated, detachment-limited hillslopes. Dr. Joe McAuliffe is examining the recently exposed roots associated with cliffrose plants that are established on remnants of the soil visible on the right side of the photograph. Mr. Matt King is standing on a calcite-cemented concretion that is more resistant to weathering and erosion than the clay-cemented bedrock. This observed very rapid change in hillslope form is most likely caused by the impacts of recent decade- to centennial-scale climate changes. After figure 11 in McFadden (2013).

enabling widespread recruitment of plants that are better adapted to future, higher average temperatures. More xeric conditions are a virtual certainty.

Local bedrock types are, as described above, an important factor. Rocks that are less resistant to weathering and erosion are abundant in the landscapes of New Mexico, and they will likely respond to climate changes rapidly, leading to major losses of associated soil mantle after the stabilizing vegetation canopy has withered. Recolonization may take considerable time (see Chapter 4). As soils are eroded on hillslopes, exposed bedrock will generate more runoff than soil- and vegetation-covered hillslopes. Increased runoff will erode the remaining soils, further increasing bedrock exposure, and constituting self-reinforcing positive feedback. Trees may eventually be able to colonize certain areas of these future hillslopes, but the forests will likely be sparse (see Chapter 4). Formation of new soil takes a minimum of several centuries and more likely, many thousands of years. Even many of those plant species adapted to future warmer conditions will be unable to quickly recolonize cooler, higher-elevation environments that lack substantial soil cover.

What conditions would potentially prevent or perhaps minimize soil erosion in higher-elevation hillslopes subject to drought and wildfire? Such conditions would be present on those hillslopes with thick deposits of coarse colluvium, talus and glacial till. These parent materials: (1) favor accumulation of fine, windblown sediment and development of soils over a generally greater thickness; (2) have generally higher infiltration rates and permeability relative to bedrock; and (3) have relatively lower

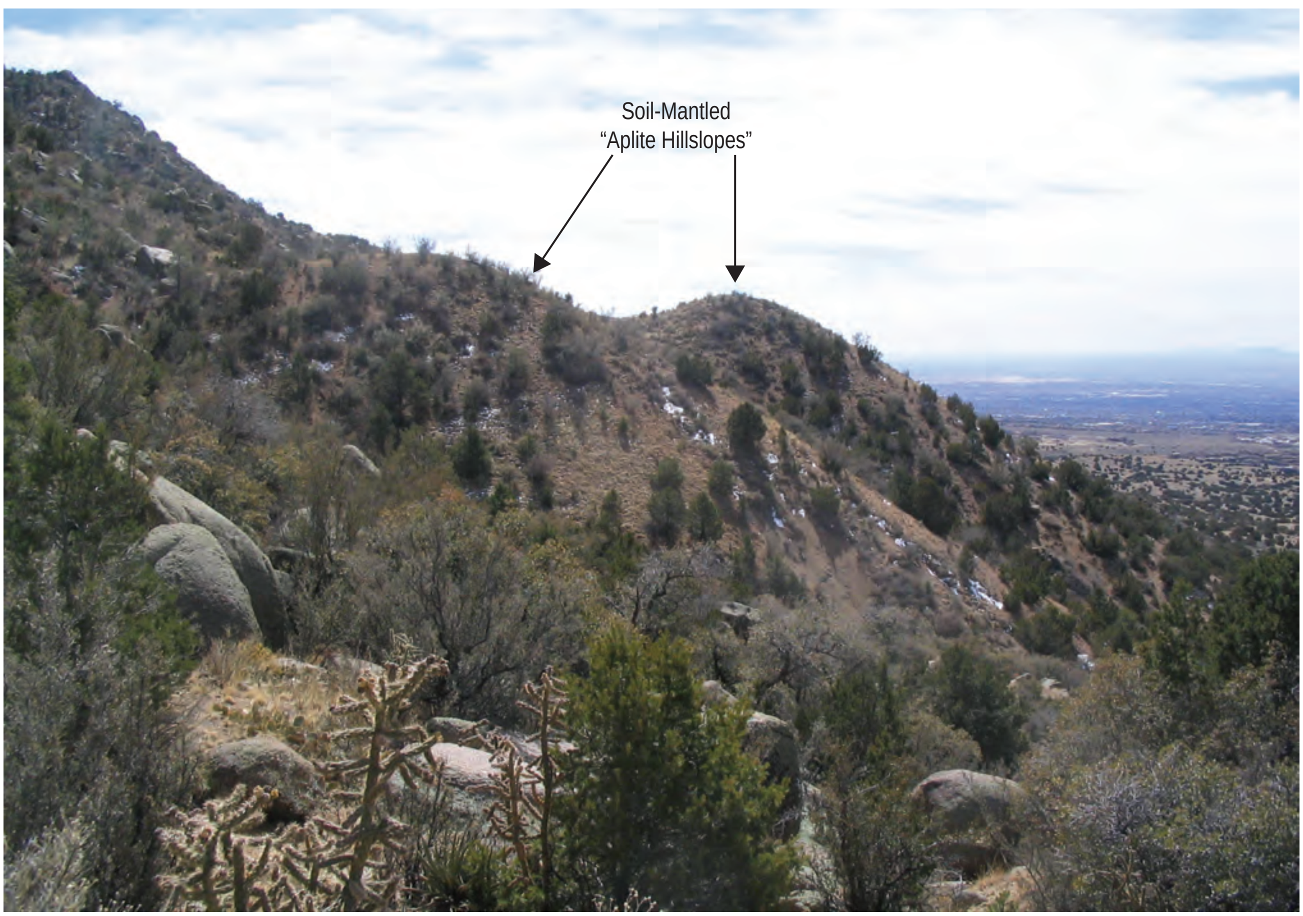

Figure 5.6. Core-stone-dominated hillslopes (in left foreground) are the dominant kind of hillslope in the Sandia Mountain foothills formed on granitic rocks. Two smooth, soil-mantled, transport-limited hillslopes are labeled. Understanding how such soils and hillslopes form provide the basis for predicting how they have responded to past climate changes and how they may respond to the next 50 years of climate change. *Photo by Leslie D. McFadden*

erosion potential. To some extent, the abundance of colluvium and talus on these hillslopes reflects the presence of steep, bedrock-dominated topography in much of the highest elevations of these mountain ranges (Fig. 5.7). Such mountain ranges, including the Sangre de Cristo and the San Juan mountains, have been subject to alpine glaciation during at least the last few million years. The legacy of the imprints of long durations of glacial climate on the surface processes during the Pleistocene greatly complicate studies and evaluation of the soils and landforms of high-elevation mountains, and the impacts of ongoing climate changes in these areas (cf., Aldred, 2020). For example, shattering of bedrock in high-elevation alpine zones is an efficient mechanism for producing large volumes of colluvium, talus and scree, accumulations of angular rock debris that form along and at the base of a hillslope (Bierman and Montgomery, 2019). Frost shattering, undoubtedly, was an important weathering process at elevations that in the currently warmer climate of the Holocene are no longer subject to this kind of weathering. The combination of high relief and strong rock types, such as granite, is also conducive to the generation of steep, bedrock dominated hillslopes, especially in high-elevation mountains that supported large glaciers during the Pleistocene. Many hillslopes in formerly glaciated mountains in New Mexico formed as a result of the deposition of glacial till and the resultant development of ridges and hummocky landforms called moraines in the Pleistocene (see Appendix B). The presence of soils that have formed in the last 12,000 years in hillslopes composed of bouldery morainal sediment or talus that resist erosion and stripping following wildfires may enable recolonization by some plants, including trees

Figure 5.7. Alpine hillslopes, Sangre de Cristo Mountains. The steepest, largely unvegetated hillslopes in the midground are an excellent example of rock-dominated "detachment-limited" hillslopes (see Appendix B for explanation). The dominance of such hillslopes at the highest elevations of this mountain range is largely attributable to previous periods of glaciation. Frost shattering is a key physical weathering process operating on such hillslopes, and the products of this process (talus and colluvium) are accumulating on the hillslopes. The lower elevation, smooth and vegetated hillslopes in the background are examples of "transport-limited" (or "weathering-limited") hillslopes (see Appendix B). Photograph taken from the summit of Wheeler Peak at an elevation of 13,160 feet. *Photo by Leslie D. McFadden*

(see Chapters 4 and 6 for an in depth overview of ecological succession and wildfire impacts).

These changes in the soils and geomorphology of higher-elevation hillslopes may result eventually in the development of increasingly sparse vegetation on hillslopes that are characterized by a discontinuous, patchy pattern of soil cover, and a more extensive exposure of bedrock. These conditions will be irreversible over time scales of thousands or more years. The climate of New Mexico has been subject to major glacial-to-interglacial changes during the last 2.6 million years. Throughout the western U.S., major mountain plant communities responded by migrating to higher altitudes during changes to warmer conditions, and to lower altitudes during changes to cooler temperatures (Betancourt et al., 2016). The average elevation change of these shifting communities was as much as 2,500 feet (Spaulding, 1990). We should expect New Mexican plant communities to shift upward in elevation in response to future warming. Of course, migration to higher-elevation hillslopes will not be a practical option for those plant communities that already occupy the highest elevations of any mountain range, or where yet, higher-elevation hillslopes are completely dominated by bedrock. In the state's highest mountains, soils and sediments that can support plants may survive the after effects of wildfire (see Chapter 4 for an extended discussion of ecological dynamics and related topics).

It is highly likely, however, that in 50 years the hillslopes will be exhibiting the initial, if not a more advanced, stage in a transformational shift from soil-mantled to more bedrock-dominated slopes. Cooler and effectively moister conditions exist at increasingly higher elevations in mountain ranges, or, in the northern hemisphere, at increasingly more northerly latitudes. Thus, species of trees that now exist at lower elevations that are subject to a warming climate (see Chapter 2, this report) could potentially thrive at higher-elevation settings (or more northerly latitudes). However, the changing nature of the hillslopes, as specifically reflected in the diminished cover of soil, will likely favor the development of a sparser, patchy forest. The results of soil geomorphological research strongly suggest that the changes in hillslope character described in this chapter will be irreversible on human time scales.

Summary

1. Soils influence how New Mexico's diverse landscapes have responded, and are responding, to climate change.
2. Soil cover acts like a sponge, holding water during times of rain and snow. Because many soils retain much of the infiltrated water, they also support vegetation. The presence of vegetation also intercepts rain, reducing runoff, and the presence of soils also increases evapotranspiration and favors shallow-subsurface flow. The lack of soils substantially increases surface runoff and reduces recharge.
3. In the drylands of New Mexico, loss of vegetation (caused by climate change) increases erosion, in many cases caused by wind. In the High Plains of northeast New Mexico, large amounts of dust will be produced, essentially creating a new Dust Bowl. The landscapes of northwest New Mexico, home of many Navajo people, are covered by windblown deposits of sand (i.e., sand dunes). Those dunes not stabilized by well-developed soils are undergoing reactivation. Desertification will only increase as temperatures rise in New Mexico over the next 50 years, resulting in many negative agricultural and health impacts.
4. At the end of, and following, the last ice age, climate changes characterized by increases in global temperature occurred, which for New Mexico resulted in increased frequency and intensity of drought and wildfires, and overall aridity. Studies that show how New Mexico's landscapes responded to those climate changes provide deep insights into how ongoing climate changes and future changes will affect New Mexico water resources over the next 50 years and beyond.
5. On mountain hillslopes, the loss of substantial vegetation cover in response to ongoing climate change is increasing soil erosion. On some hillslopes, soil erosion is increasing the area of exposed bedrock, which then increases hillslope runoff. This in turn causes additional increases in soil erosion and bedrock exposure.

6. Mountain hillslopes that have effectively hotter and drier "topoclimate" (i.e., generally south facing) will respond sooner to a warming climate than hillslopes with slightly cooler and effectively moister topoclimates (i.e., generally north facing).
7. Bedrock-dominated hillslopes largely prevent widespread recolonization by most plants, including trees. Other impediments to recolonization are presented in Chapter 4.
8. Soils take many thousands of years to form, so loss of soil on hillslopes will lead to fewer or more sparse forests, or, in some circumstances, total lack of tree colonization. These changes are already well underway in some mountains in New Mexico. This is the future for most of our mountain landscapes over the next several millennia.

Knowledge Gaps

1. New Mexico's high-elevation mountain ranges provide much of the surface flow to our rivers, and groundwater recharge to our aquifers. Therefore, more soils and geomorphic research in high-elevation mountains is essential. Unfortunately, outside of the Jemez Mountains, a survey of the relevant literature in peer-reviewed journals and other publications reveals that relatively little soils and geomorphological research has been conducted in the mountains in the state of New Mexico. Accordingly, future research efforts in these mountains should include characterization and evaluation of hillslope aspect-related contrasts in soils, plant communities, and geomorphology. Data provided by these studies can be input into numerical models to calculate the net soil loss from hillslopes as functions of topography, vegetation, and other variables. Models such as the Water Erosion Prediction Project (WEPP), the Erosion Risk Management Tool, (ERMiT), which determine potential soil loss and sediment delivery following wildfires, and the Universal Soil Loss Equation (USLE) have been successfully used to calculate potential soil erosion and sediment production from drainage basins in the Upper Santa Fe Municipal Watershed (Lewis, 2018).
2. New Mexico's upland forests are a precious state resource. Ongoing paleoclimatic and paleobotanical research (Fawcett et al., 2011) is shedding new light on the impacts of episodic intervals of increased warming during past interglacial periods on forest communities, a pattern of climate change that serves as a potential analogue for present and future warming. More such research is needed.

VI. LANDSCAPE CHANGE, FIRE, AND EROSION

Anne C. Tillery, Leslie D. McFadden and Craig D. Allen

New Mexico has a dynamic landscape; climate change and increasing fire frequency over the next 50 years will amplify recently observed instability. As the climate changes to warmer conditions, less rainfall will infiltrate into aquifers, leading to increased overland runoff. Landform processes can be complex but, in general, the predicted changes in climate and precipitation will lead to increased upland erosion caused by runoff and increased downstream sediment deposition. Canyons, mesas, and small basins or valleys filled with sediment will be particularly affected. Rapid rearrangement of sediments by water is disruptive and potentially hazardous to ecosystems and societies. Dramatic examples of accelerated erosion following the Whitewater–Baldy, Las Conchas, and other wildfires here in New Mexico illustrate the types of hazards created when forested landscapes are severely burned. Post-wildfire erosion is typically initiated by intense rainfall events. Given that both the number of wildfires and rainfall intensities are likely to increase as the climate warms, New Mexico can expect to see increases in widespread erosion and sedimentation across and downstream from upland forested areas in the state. The large volume of sediment predicted to be on the move will be of concern for many reasons, including filling reservoirs, choking channels, and blocking or destroying infrastructure. Positive feedback loops lead to further reductions in slope stability.

Introduction

Past changes in climate have left behind records of dramatic landscape changes. This is because landforms, of which landscapes are composed, are, in part, a function of the specific climates in which they form. Large dune fields, for example, are common in arid and semiarid regions, as in New Mexico. When a stable climate undergoes a transition to a new and different climate setting, landforms will respond to the changed climate (Bull, 1991). The period of time during which the landscape is adjusting to a climatic shift is typically characterized by a period of change until the landscape reaches a new equilibrium with the new climate. As discussed in Chapter 5 of this report, hillslopes covered with soils that took centuries to form in stable conditions can be stripped in years to decades due to changes in precipitation patterns or amounts.

Records of past landform responses to changes in climate provide clues to possible landform response adjustments to future changes in climate. The geomorphic, or landform, record indicates that changes in the current climate of New Mexico will likely bring about modifications to New Mexican landforms as they respond to the new climatic conditions (Bull, 1991). The timing and manifestation of these landscape modifications will vary based on a variety of factors including the morphology of and position on the initial landscape (McFadden and McAuliffe, 1997; Tillery et al., 2003; Chapter 5 of this report). Also important are the strength of the underlying bedrock material, changes in temperature, moisture, and precipitation, and feedbacks with changes in vegetation cover, which includes the geomorphic state of the fluvial system (Gellis et al., 2017). Using the record of past geomorphic responses as a key, we can infer that landscape responses will likely include wide-scale erosion in some locations and deposition of large volumes of sediment in others. The speed at which these landscape modifications might occur is difficult to estimate, but during the period of landscape adjustments, large scale movement of sediment and debris will continually disrupt local communities and ecosystems until landscape equilibrium is achieved.

This chapter looks at examples of past manifestations of climate change on fluvial or riverine landscapes in New Mexico and other western states, to estimate the response of our current landscapes to anticipated warming, drying, and changes in precipitation regimes documented in other chapters of this report (Chapters 1, 2, 3, and 8). We also detail recent, large scale and devastating erosion events in New Mexico as an illustration for what could be expected moving forward. The insights provided on landscape response to climate change in New Mexico can help in addressing future water resource concerns such as flood risks, reservoir sedimentation, and water supply.

New Mexico is the fifth largest state and encompasses a large range of physiographic and climatic settings (Fig. 6.1). Because it is not practical to look at every possible geomorphic process in New Mexico, we will look specifically at those three processes where landscape responses to climate change have been well documented, including: cycles of erosion and deposition; ephemeral (intermittently

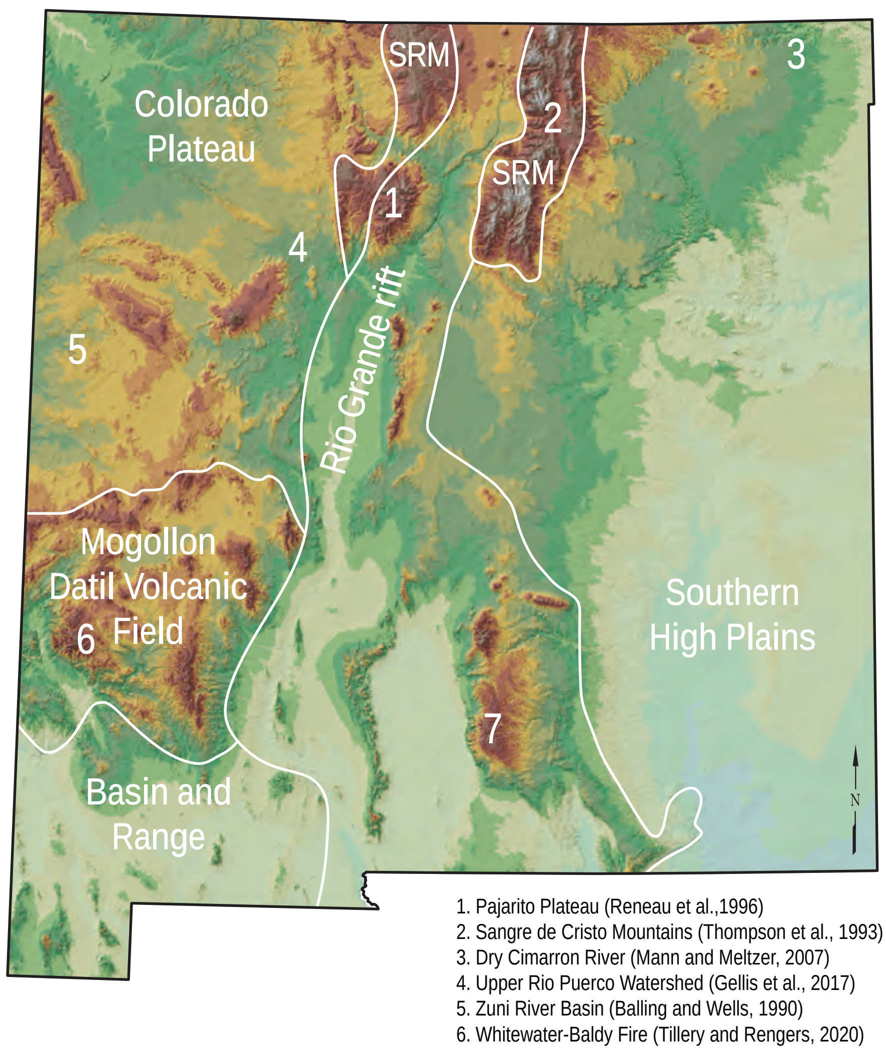

Figure 6.1. Color shaded-relief image of New Mexico showing physiographic provinces. SRM=Southern Rocky Mountains. From NMBGMR, Geologic tour of New Mexico (accessed 2021).

wet and dry) stream channels or arroyos; and post-wildfire erosion. Finally, we will discuss the role that precipitation type plays in erosion.

Cycles of Erosion and Deposition

The Pajarito Plateau in north-central New Mexico is formed primarily of volcanic ash that was lithified into a solid rock called tuff (Griggs and Hem, 1964; Smith et al., 1970). Tuff is a relatively soft rock that is easily erodible. These erodible rock types are sensitive to changes in erosive agents such as rainfall, freeze-thaw processes, groundwater sapping, bioturbation, and wind removal. The transition from the Pleistocene epoch to the Holocene epoch 12,000 years ago is defined by a change in climate that is reflected in the geomorphic record of the Pajarito Plateau. Before 12,000 years ago, temperatures were cooler and wetter in the southwestern United States, glaciers spread in the Sangre de Cristo Mountains, large precipitation-fed lakes dotted the state and precipitation occurred mostly as snowfall (Thompson et al., 1993). Approximately 12,000 years ago, the Holocene brought warming temperatures, accompanied by melting glaciers, disappearing pluvial lakes and precipitation that transitioned from snow dominated to rainfall dominated. In the Pajarito Plateau of north-central New Mexico, and other locations in the Southwest, the transition from the cooler and moister Pleistocene epoch (before about 12,000 years ago) to the warmer and drier Holocene epoch (between 12,000 years and now) is associated with a decrease in vegetative cover, and a major increase in sediment supply within some drainage basins (Reneau et al., 1996; McAuliffe et al., 2006). Reneau et al. (1996) documented increased filling (aggradation) in alluvium in canyon bottoms and rapid losses of soils on the mesa surfaces of the Pajarito Plateau soon after the cool Pleistocene ended and as the warm Holocene began. This indicates a major change in fluvial systems driven by climate change. Canyons dissecting the Pajarito Plateau aggraded (filled) with sediment derived from the adjacent mesa tops during the Holocene (Fig. 6.2). Mesa-top soil loss was mostly due to overland (surface) flow that is generated more quickly in "intercanopy" areas or open areas between trees where raindrops are not intercepted or slowed by interference from tree canopies. Local abundance of natural charcoal in some deposits suggests that erosion following fires may also have contributed to some of the mesa-top erosion. Similarly in recent times, up to ten feet of sediment was deposited in canyon bottoms in the decades between the 1940s (when Los Alamos National Laboratory was established) and the mid-1990s, giving an indication of how rapidly these changes can happen.

In the northeastern corner of New Mexico along the Dry Cimarron River west of Folsom, Mann and Meltzer (2007) used radiocarbon dating to study the alluvial histories in small (<15 mi^2) watersheds finding multiple periods of valley aggradation separated by incision episodes, some of which correlated with climatic fluctuations and intrinsic processes.

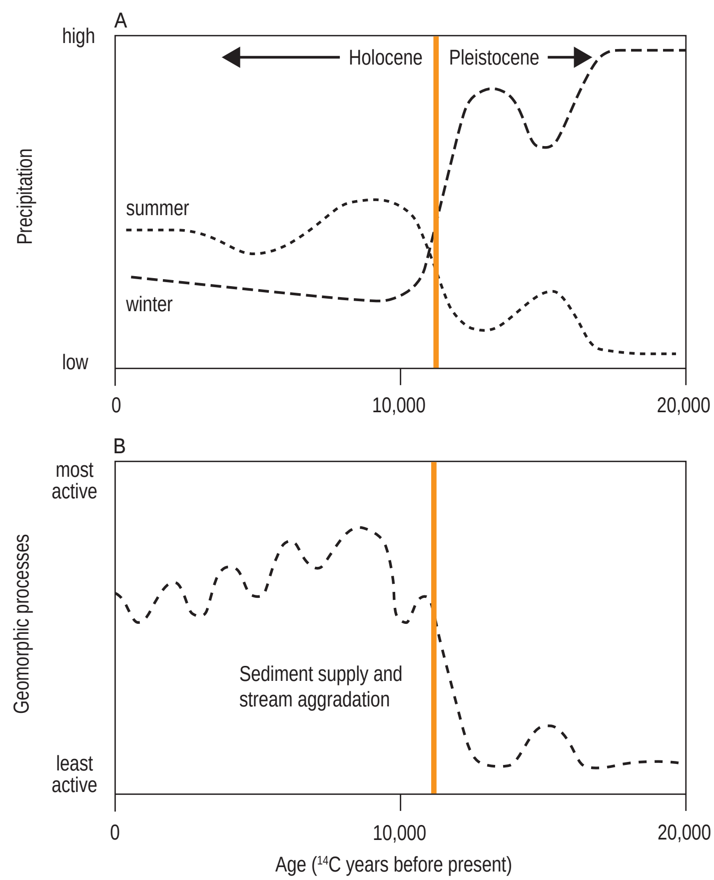

Figure 6.2. Graph showing geomorphic processes active in the Pajarito Plateau with time (in years before present from carbon-14 dating) and precipitation. Adapted from Reneau (1996). Panel A shows the precipitation regime changing from a winter precipitation (snow) dominated regime to a summer precipitation regime at the Pleistocene/Holocene boundary approximately 11,700 years before present. Panel B shows the increases in geomorphic processes, including sediment being supplied to the canyon stream channels that coincides with the change in precipitation regime at the Pleistocene/Holocene boundary.

In contrast to the Pajarito Plateau example, Mann and Meltzer (2007) found aggradation occurred during past cooler and moister periods such as during the Younger Dryas (11,000–10,000 ^{14}C yr B.P.) and Little Ice Age (A.D. 1300–1880).

The Pajarito Plateau and Dry Cimarron examples highlight landscape response to major climatic transitions, but less extreme and more frequently occurring climate shifts have also led to geomorphic responses in highly erodible settings. McAuliffe et al. (2006) used tree-ring analyses to document hillslope and basin-floor dynamics in a small, semiarid alluvial drainage basin formed in the highly erodible Morrison Formation on the Colorado Plateau and Arizona. They found erosion episodes during the last 300 years that were triggered by decadal changes in precipitation regimes, most notably, following periods of drought.

These examples illustrate how canyon, mesa, and small valley landscapes have responded to past climate changes in New Mexico and the southwestern U.S. The differences documented in the responses of landscapes along the Pajarito Plateau and the Dry Cimarron River illustrate the variability in landscape response to changing climate. The variability in landscape responses to similar historical climate changes indicates it is difficult to generalize how New Mexico landscapes might respond to future climate change. Even so, we do know that with climate change, landscapes will go through some period of adjustment that has the potential to be disruptive to sediment flux (erosion and deposition).

Ephemeral Channels (Arroyos)

Interest in arroyos in New Mexico is related to the various and destructive societal impacts caused by widespread incision of arroyos across previously stable valleys in areas of New Mexico beginning in the late nineteenth century, in some portions of the watershed, continuing through the twentieth and into the twenty-first centuries. The appearance of arroyos has led to the loss of land for grazing and farming, resulting in the loss of a way of life for some communities. Arroyos can undercut and otherwise damage or destroy roads, dams, railroads, bridges, culverts, fences and irrigation works. Arroyo incision leads to increases in downstream delivery of sediment, which can clog culverts and reservoirs and reduce floodplain capacity. Sediment from upstream arroyo erosion aggrades downstream floodplains, reducing floodwater storage capacity and leading to increased flood severity (Cooperrider and Hendricks, 1937). Arroyos provide a pathway to drain marshes and wetlands, detaching those areas from the groundwater table and leading to vegetation desiccation (Bryan, 1925). Arroyo cutting can remove as much as 25% of valley floor area (Cook and Reeves, 1976), decreasing agricultural productivity. Additionally, flood flow paths are shortened by arroyo incision, increasing stream velocity and erosive potential, creating a positive feedback that leads to further increases in erosion. The combined effects of these issues can have devastating impacts on local communities.

Arroyos and ephemeral channels are complex systems. Sediment pulses move episodically along the basins with timing and magnitude that vary not only with climate signals but also with land use, vegetation changes, and factors such as basin size, sediment grain size, base-level lowering (Schumm and Parker, 1973), channel straightening (Simon, 1989), artificial channelization, or decreases of sediment supply from upstream (Schumm and Hadley, 1957; Patton and Schumm, 1981; Bull, 1997; Friedman et al., 2015). The temporal and spatial variability in arroyo incision and filling is termed the "arroyo evolution" (Elliott et al., 1999; Gellis et al., 2012), where the rate of arroyo changes is dictated by both intrinsic and extrinsic factors (Gellis et al., 2017). As a wave of erosion happens in the upstream part of an arroyo, downstream areas that have incised and widened from bank erosion, transition hydraulically from erosion to aggradation. Upstream areas, which are undergoing head-cut erosion, transport sediment to those downstream aggradational areas. This wave of aggradation may subsequently progress upstream. The channels change as they alternate between aggradation or incision with periods of equilibrium lasting only briefly or as long as a millennium (Friedman et al., 2015). Numerous studies have shown that changes in geomorphic processes such as hillslope erosion and valley-fill aggradation are linked to changes in climate (Bull, 1991; Kochel et al., 1997; Eppes, 2002), while others cite non-synchroneity in the stratigraphic record with climate that may be due to intrinsic factors (Elliott et al., 1999).

Because of the complex history of arroyos, researchers have been investigating episodes of arroyo incision in the lower and drier elevations of western and central New Mexico for over a century (Bryan, 1925; Schumm and Hadley, 1957; Schumm, 1973; Cook and Reeves, 1976; Karlstrom and Karlstrom, 1987; Graf, 1988; Balling and Wells, 1990). Many of the studies of these inherently unstable streams were focused on dating the cycles of arroyo incision and aggradation, which are sensitive to short-term climatic changes and to human impacts. Other studies documented twentieth century arroyo changes using benchmarked channel cross sections.

In the late nineteenth century, a combination of drought and agricultural activity (i.e., grazing) led to declines in vegetation density in the Rio Puerco Basin (Gellis et al., 2017). Periods of high flows also occurred. The geomorphic state of the arroyo systems at this time were described as discontinuous or filled (Aby, 2017; Gellis et al., 2017). Runoff eroded valley-fill sediment and soils and carried them downstream to the Rio Grande. Starting in the early twentieth century, transported material reached and began to enter Elephant Butte and other reservoirs on the Rio Grande (Cooperrider and Hendricks, 1937). As a consequence of arroyo incision, groundwater levels declined throughout the Rio Puerco Basin. Channels became deeply incised and floodwaters did not inundate adjacent agricultural fields on the floodplain. Incision of the Rio Puerco in the late 1880s forced the desertion of three towns and earlier episodes of incision may have been a factor leading to abandonment of some areas by ancestral Puebloan peoples (Bryan, 1925).

In the Zuni River drainage, western New Mexico, Balling and Wells (1990) found downcutting of intermediate and small arroyos for a 20–30 year period near 1905 coincided with a long and severe drought from 1898 through 1904 that ended with three years of unusually frequent, high-intensity, summer rainfall events.

These results support the connection between periods of arroyo incision and short-term climatic perturbations. Initiation of arroyo incision, however, may be too complex to attribute to a single cause such as change in precipitation or grazing, but it is likely associated with a decrease in vegetation density. Future climate change is anticipated to lead to declines in vegetation density throughout valleys and low-elevation areas of New Mexico beginning in the next few decades, changes that, depending on the state of the fluvial system could lead to renewed arroyo incision with the accompanying reductions in water supplies for floodplain irrigation.

Post-wildfire Erosion

Wildfires can dramatically increase the probability and magnitude of flooding and debris flows. The reduction of infiltration rates on severely burned slopes results in post-wildfire floods that can be orders of magnitude beyond the normal variation seen in unburned systems. Additionally, consumption of vegetation by wildfire enhances the erosive power of overland flow, resulting in accelerated erosion of hillslope material (Cannon and Gartner, 2005; Meyer and Wells, 1997) frequently resulting in debris flows. A debris flow is a type of landslide that is composed of a slurry of water, rock fragments, soil, and mud that can travel rapidly down hillslopes. Debris flows in particular can be one of the most dangerous post-wildfire hazards because of their unique destructive power (Cannon, 2001) to structures due to their momentum and considerable impact forces. Not only is watershed response to rainfall greatly amplified following a wildfire, but the timing between onset of rainfall in the headwaters and resulting floods or debris flows downstream can be substantially reduced, giving people downstream of the burned area less time to react.

To discuss post-wildfire erosion, we look to the forested high-elevation areas in New Mexico. In September of 2013, a near-record storm produced widespread, historic rainfall amounts throughout the Southwest (cf. Moody, 2016). The heavy rainfall led to extensive and damaging flooding and erosion throughout New Mexico and surrounding states, but most severely, in areas that had been recently burned, such as the 298,000-acre Whitewater–Baldy fire that burned the previous summer in Gila National Forest in southern New Mexico. Thirty-minute rainfall intensities on the night of September 14 in the area near Whitewater Creek were equivalent to a 1,000-year recurrence-interval storm, that is, a storm that has a 0.1% chance of being exceeded in a single year, or exceptionally rare (Tillery et al., 2019). The heavy rainfall led to extensive and damaging flooding and debris flows within and around the Whitewater–Baldy burn scar. Tillery and Rengers (2020) documented 688 debris flows initiated by a series of storms in the area near Whitewater Creek, 352 of which were in the Whitewater Creek watershed (Fig. 6.3). Field reconnaissance confirmed that debris flows were ubiquitous at virtually every culvert and road crossing in the area and that they ranged from smaller than 1 ft wide to over 15 ft wide. The sediment mobilized during this single event was estimated to be over 5,000,000 ft^3, or 0.04-in. basin-average erosion depth in the 54 mi^2 Whitewater Creek watershed alone (Tillery et al., 2019). For some context, this is enough sediment to fill 295 railroad box cars, or a train 3.4 miles long. The sediment load produced by the debris-flow response was deposited in downstream channels, clogging or damaging local roadways, bridges, and culverts. Constant remobilization of sediment by subsequent rainfall events impacted local residents, the U.S. Forest Service, which manages the land, and the New Mexico Department of Transportation, which maintains the roadways in the area, for years following these events. Beyond the downstream impact from extensive sediment mobilization, the number of new channels and scarps cut into the freshly burned Gila Mountains altered the landscape in other long-lasting ways, such as destabilizing hillslope soils, decreasing length of overland flow paths, and increasing runoff and sediment supply to downstream channels. This effect could last for years or even decades, demonstrating the importance of rare events in shaping sensitive landscapes.

Earlier during the summer of 2013, a monsoon rainstorm with a maximum 10-minute rainfall intensity of 3.75 in/hour (USGS station 354711106251330, Cochiti Canyon Headwaters near White Rock, NM; U.S. Geological Survey, 2016) crossed over Frijoles Canyon, in Bandelier National Monument at 11:30 p.m. on July 25. The majority of Frijoles Canyon had been burned two years earlier by the 153,000-acre Las Conchas fire. The flood wave generated in Frijoles Canyon on the night of July 25, 2013 instantly initiated a gage-height of 18 ft at an early-warning stream gage 6 mi upstream from the park Visitor Center. In the upper portions of the canyon, trees left standing after the fire two years earlier were knocked over and carried downstream to be deposited in log jams 20 ft high and 50 ft long (Fig. 6.4). Shortly after alerting park employees of the impending flood, the stream gage infrastructure was irretrievably buried by approximately 7 ft of sediment (USGS station 08313300, Rito de Los Frijoles near Los Alamos, NM; U.S. Geological Survey, 2016).

As these two examples show, wildfires can influence the evolution of the physical landscape by dramatically increasing the probability and magnitude of post-wildfire, rainfall-induced debris flows and flooding. These events can result in catastrophic damage and loss of life (Neary et al., 2003; Moody et al., 2013), as well as changes in channel morphology (Moody and Martin, 2001; Benda et al., 2003). Numerous studies have been conducted looking at the magnitude and causes of post-wildfire mass wasting by way of debris flows in New Mexico, including studies following the Dome and Cerro Grande fires in the Jemez Mountains (Cannon and Reneau, 2000; Cannon, 2001) and studies following

A

B

Figure 6.3. Photos taken in Whitewater Creek Canyon following rains of September 2013. (a) Debris flow scarp in tributary to Whitewater Creek Canyon, see person for scale, (b) debris backed up behind ranch gate in tributary to Whitewater Creek Canyon. *Photos by Anne C. Tillery*

Figure 6.4. Photo of log jam in Frijoles Canyon, 2013. *Photo by Anne C. Tillery*

the Whitewater–Baldy and Buzzard fires in the Gila (Tillery and Rengers, 2020; McGuire and Youberg, 2020). Rain falling on areas burned by wildfires can produce stream-peak discharges orders of magnitude beyond the typical values seen in systems with fully vegetated conditions (Anderson et al., 1976; Veenhuis and Bowman, 2002). Previous studies have shown a large range (5- to 870-fold) of increases in peak discharges following wildfire, depending upon fire severity (Rich, 1962; Anderson et al., 1976; Campbell et al., 1977; Moody and Martin, 2001; Veenhuis and Bowman, 2002; Wine and Cadol, 2016). The factors that best distinguish between drainages prone to post-wildfire flooding and those prone to post-wildfire, debris-flows are the lithology and basin characteristics such as channel gradient, hillslope angles, and availability of loose sediment (Cannon and Reneau, 2000).

Post-wildfire increases in runoff and associated flooding, and debris flows are attributed to a variety of factors that work together to enhance the propensity for, and magnitude of, surface-runoff generation and to elevate surface-water velocities (Swanson, 1981). Many of these factors are strengthened with higher severity fire. According to studies by Robichaud et al. (2000) and Mishra and Singh (2003), surface runoff can increase by a factor of 1,000 when vegetation cover is reduced from 75% to 10% in some settings. The cumulative effects of these changes can increase runoff, flooding, erosion, mass movements (such as debris flows), and dependent upon bed steepness, lead to channel incision or channel aggradation (Seibert et al., 2010). Additionally, decreased response time (time between rainfall and flood peak) of streams to rainstorms combined with increased runoff potential can contribute to an increased number of floods for a given period after a wildfire. In other words, flooding hazards are substantially increased and the time for people to respond or evacuate is decreased.

Debris flows, in particular, can accomplish a tremendous amount of work to transport sediment and reshape hillslopes very quickly by cutting new channels into hillslopes and dumping large volumes of eroded material into low-lying areas (Wohl and Pearthree, 1991). Videos of debris flows from runoff following large fires in the Jemez Mountains of New Mexico can be found on the internet at (https://www.youtube.com/watch?v=_OWwrln4oeo and https://www.youtube.com/watch?v=sstvu_aRfqA).

Wildfire Frequency and Climate

The link between climate and wildfire frequency, size, and severity, particularly in the western U.S. has been demonstrated repeatedly over the last several decades (Meyer et al., 1992; Meyer et al., 1995; Westerling et al., 2003; Littell et al., 2009; Luo et al., 2013; Westerling et al., 2014; Mueller et al., 2020). In the western U.S., wildfire in federally managed forests has increased since the 1970s and early 1980s, with large fires (greater than 1,000 acres) in the decade through 2012 over five times as frequent and burned areas over ten times as large. These increases in wildfire numbers and acreages are closely linked to increased temperatures and a greater frequency and intensity of drought (Westerling et al., 2014). Climate projection modeling through the middle of the twenty-first century suggest a longer wildfire season in the western U.S. deserts as temperatures rise (Abatzoglou and Kolden, 2011). A 2020 study in Arizona and New Mexico (Mueller et al., 2020) found that increasing temperature and vapor pressure deficit (a function of humidity and temperature) and decreasing precipitation were associated with increasing area burned regionally, and particularly area burned at high severity since 1984. Additionally, they found that the relationship between climate and fire activity in the Southwest has appeared to strengthen since 2000.

As could be expected, the accelerated landscape change that follows wildfires has also been linked directly to changes to warmer and drier climates when wildfires are more common. Postfire sedimentation is projected to increase for nearly nine-tenths of burned watersheds by more than 10% and for more than one-third of burned watersheds by more than 100% by the middle of the twenty-first century in the western U.S. (Sankey et al., 2017).

One of the longer records of wildfire and post-wildfire erosion with climate comes out of Yellowstone National Park (Fig. 6.5). Studies conducted in the park were able to link a 3,500 year record of wildfires with climate signals. Meyer et al. (1992) examined a record of sediment deposited by flowing water and debris flows, and found that aggradation and erosion were both strongly modulated by climate, with fire acting as a catalyst for sediment transport. Alluvial fans aggraded during periods of frequent fire-related sedimentation that were interpreted to be related to drought or small-scale climatic fluctuations. In a subsequent study, Meyer et al. (1995) estimated that 30% of late Holocene fan alluvium is from fire-related sedimentation. In the last 100 years in Yellowstone National Park, "small-scale" climatic fluctuations during the Holocene had a substantial impact on landscapes in the study area. Additionally, summer precipitation intensity and interannual variability were likely greater during warmer periods, which increases the potential for severe short-term drought and associated major forest fires, and storm-generated alluvial fan deposition.

Similar examples have been documented in New Mexico. Frechette and Meyer (2009) found a record of episodic sedimentation throughout the Holocene following severe wildfires in the mixed conifer forests of the Sacramento Mountains. Generally, they found that not only did the fire-related sedimentation correspond to generally warmer conditions, but also that the post-wildfire erosion contributed significantly to Holocene valley fill. They concluded that given the efficiency of fire-related geomorphic processes, even rare, severe fires were likely to significantly impact the Holocene evolution of the Sacramento Mountains. The latest period of sedimentation, about 1300 CE, corresponded to documented widespread severe drought in the southwestern USA.

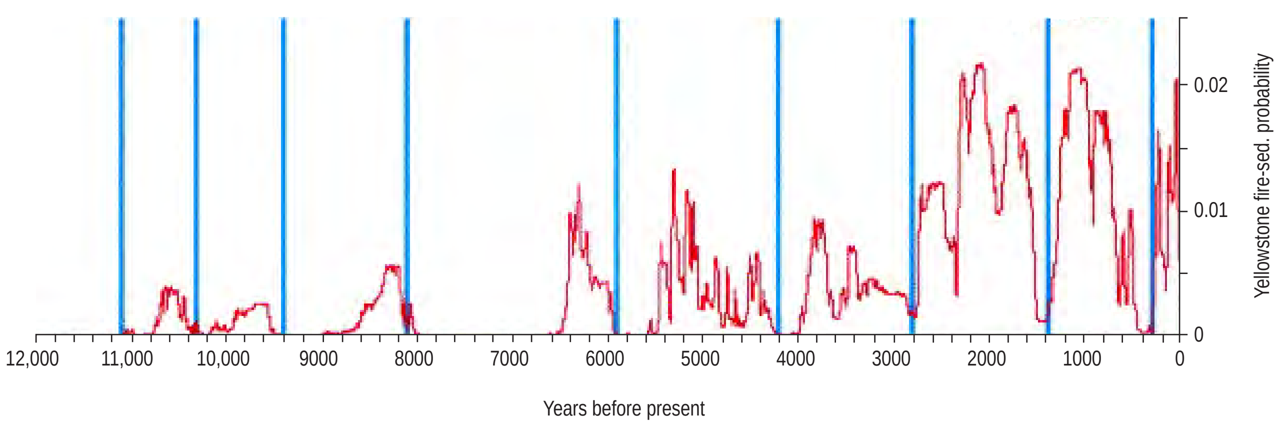

Figure 6.5. Graph demonstrating the connection between wildfire activity and temperature in Yellowstone National Park. Radiocarbon based wildfire sedimentation probability curve (red line) is plotted with time in calendar years before present. The present is on the right end of the axis. North Atlantic minimum temperatures (Bond et al., 1997) are shown as vertical blue lines. Plot demonstrates how wildfire sedimentation drops to a minimum when sea surface temperatures are at a minimum. Modified from Meyer and Pierce (2003).

More recently, the debris flows in the northern Valles Caldera following the 2011 Las Conchas fire were of unprecedented magnitude in the last few thousand years, despite the well-documented occurrence of past megadroughts (Chapter 2). The extreme extent and abundant large boulders of the postfire debris-flow deposits below Cerro del Medio in the Valles Caldera were unlike other sediments accumulated in the valley during several millennia prior to the Las Conchas fire (written comm., G. Meyer, University of New Mexico, 10/22/2021). While fire suppression and change in forest composition associated with heavy logging probably increased the severity of the Las Conchas fire on Cerro de Medio, extreme drought with high temperatures was clearly a major factor in the high severity of this burn (written comm., G. Meyer, University of New Mexico, 10/22/2021).

As discussed in this section, wildfire frequency and intensity are expected to increase across the U.S. as the climate warms, potentially meaning that the types of geomorphic responses following recent fires are likely to also become more frequent and larger. The U.S. has experienced a marked upward trend in the duration of the wildfire season, wildfire frequency, and wildfire extent since the mid-1980s attributed in part to earlier snowmelt (Stewart et al., 2005; Liu et al., 2010; Westerling, 2016). Changes in wildfire severity in the desert Southwest have also been linked to increasing variability in spring precipitation as well as increases in the vapor pressure deficit (Holden et al., 2007; Williams et al., 2013; Jolly et al., 2015).

Post-wildfire geomorphic responses may be similar to geomorphic responses to climate change, but happen on much shorter time scales. Based on 80 years of data from the literature, Moody and Martin (2009) determined that wildfires in the western United States have been an important geomorphic agent of landscape change when linked with sufficient rainfall. Because of their large magnitude and short time scales, post-wildfire erosion events have been and continue to be important agents of landscape change (Wohl and Pearthree, 1991).

Losses or reductions in vegetation due to reasons other than wildfires can lead to similar accelerated landscape change. Tillery and Rengers (2020) found that rather than burn severity from the 2012 Gila wildfire, it was the coverage of vegetation at the time of the rainfall that had the greatest correlation with location and density of post-wildfire debris flows one year after the fire. This indicates that loss of vegetation due to drought will leave landscapes more susceptible to erosion by debris flows. Additionally, given sufficient rainfall intensity and slope angles, debris flows can be initiated in most settings, including burned and unburned areas, and in both drier south-facing slopes and moister north-facing slopes.

Precipitation Type and Erosion

Precipitation type directly influences the magnitude of erosion. Rainfall is a stronger driver of erosion than snowfall, due to the potential for high-intensity rainfall, flashy overland flow and channel discharge (Leopold, 1951; Hereford and Webb, 1992; Hereford, 1993; Reneau et al., 1996; Etheredge et al., 2004). A transition of precipitation from snow to rain as is predicted (Knowles et al., 2006; Earman and Dettinger, 2011) is therefore likely to lead to an increase in rates of erosion and associated downslope aggradation.

Rainfall intensity is a measure of how fast rain is falling and is reported in depth per time. Common rainfall intensities for summer monsoons are reported in inches for time periods such as 15 or 30 minutes. It is unclear how precipitation intensity will vary with climate change in New Mexico, (see summaries in this report, Chapters 2 and 8). But in general terms, the total amount of precipitation, as a long-term average, is not expected to change significantly from historical averages (see summaries in this report, Chapters 2 and 8). However, interannual variability may increase, including the intensity of individual precipitation events. Significant vegetation declines on hillslopes during extreme drought make hillslope soils more prone to erosion if heavy precipitation follows soon after drought (McFadden and McAuliffe, 1997; Davenport et al., 1998; Wilcox et al., 2003). Erosion of sediment from hillslopes can be part of a positive feedback loop. As discussed in Chapter 5, erosion of sediment and soils from hillslopes can expose bare bedrock, increase drainage density and local relief, which further increases runoff and erosion (Etheredge et al., 2004).

Post-wildfire debris flows have been shown to be triggered from relatively short-duration (as little as 6 minutes) rainfall events with intensities ranging from 0.04–1.3 in/hr in Colorado and California (Cannon et al., 2008). Rainfall intensities in this range are common for New Mexico monsoonal storms. Following the 2018 Buzzard Fire in the Gila National Forest of southwestern New Mexico, McGuire and Youberg (2020) found that 15-minute rainfall intensities of as little as 0.6 in/hr were sufficient to initiate debris flows in some watersheds. Rainfall intensities in this range would not be considered rare or extreme. Figure 6.6 shows an example relationship of flood and debris-flow responses to a series of rainstorms of varying intensities and durations following the 2018 Buzzard Fire (McGuire and Youberg, 2020). Understanding and constraining the threshold specific to debris-flow hazards as distinct from flood hazards can help in establishing early-warning systems for debris-flow hazards that have the potential to be much more destructive than floods. The diagram illustrates that it takes more time to initiate debris flows at lower rainfall intensity levels. Predicted increases in rainfall intensities with climate change in New Mexico will lead to decreases in the time to initiate and respond to debris flows.

Summary

Each of the three geomorphic processes detailed in this chapter, cycles of erosion and deposition, ephemeral channels, and post-wildfire erosion, occur in many places throughout the state. Looking forward 50 years for each of these three geomorphic processes, we envision a New Mexican landscape with potentially disruptive geomorphic changes occurring. When canyons, mesas, small basins or valleys filled with alluvium experience a change in climatic variables such as temperature, moisture or precipitation regime, they will respond by rearranging sediment rapidly relative to rates of change during stable climatic conditions. Sediment mobilization within channels depends on the hydraulic state of the channel (e.g., incised, over widened, or filled in). Channels that are not filled in may continue to erode, and those that are completely filled in may re-incise or continue to aggrade. Rapid rearrangement of sediment through fluvial processes is potentially hazardous to ecosystems and societies. Geomorphic processes linked to climates changing to warmer conditions include reduced infiltration of rainfall, increased overland runoff during high-intensity rainfall leading to increased flooding, increased

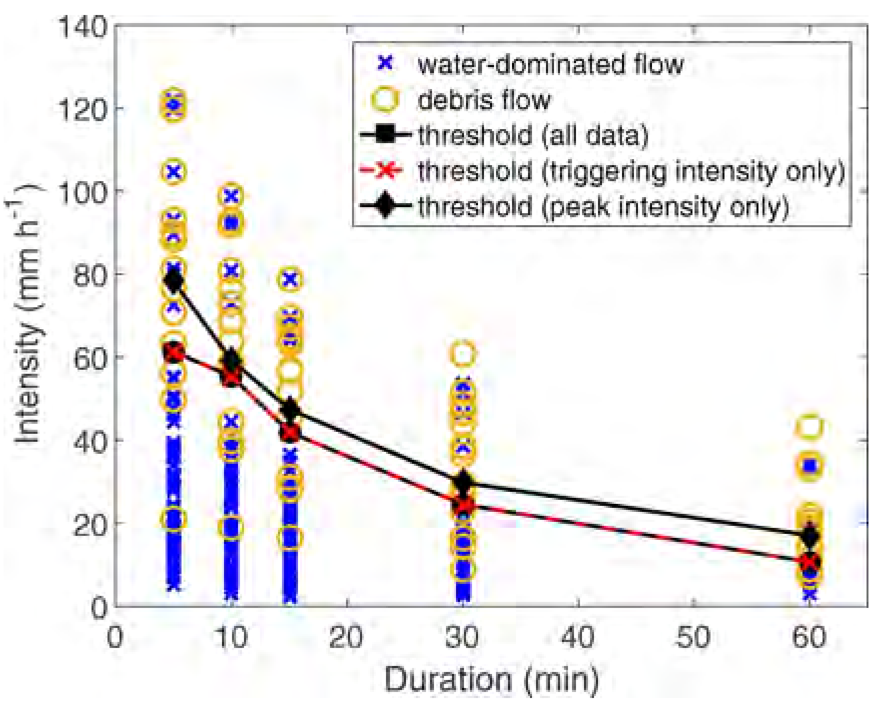

Figure 6.6. Rainfall intensity-duration thresholds to produce water-dominated flow and debris flows in small watersheds following the Buzzard Fire in southwestern NM. The black and red lines represent threshold intensity-duration values for a calibrated model (McGuire and Youberg, 2020).

upland erosion by overland flow, and depending on hydraulic state of channels, increased downstream sediment deposition and aggradation where downstream channels are filled in and erosion where downstream channels are incised. We should expect these geomorphic changes to occur across New Mexico in association with the climate changes described in Chapter 2.

The dramatic examples of accelerated erosion following the Whitewater-Baldy, Las Conchas, and other wildfires in New Mexico illustrate the types of hazards created by wildfires that have severely burned across forested landscapes in the state. Post-wildfire erosion is typically initiated by short-duration, high-intensity rainfall events. The geologic records showing increases in post-wildfire related sedimentation with past periods of warming illustrate the long-term connection between wildfire and past changes in climates. Linking these specifics with predicted future increases in temperature in New Mexico and possible increases in rainfall intensities, it becomes clear that New Mexico is likely to see increases in widespread erosion and sedimentation across and downstream from upland, forested areas in the state. The large volume of sediment predicted to be on the move will be of concern for many reasons including filling reservoirs, choking channels, blocking or destroying infrastructure and positive feedback loops that lead to further reductions in slope stability.

The most dramatic geomorphic responses to a warming climate in New Mexico will likely initiate in steep, upstream hillslopes and mountain settings and progress downstream in pulses and waves. The downstream distance affected and duration of landscape response are not currently possible to predict. Climate-response geomorphic processes could be active for years or decades as the landscapes will continue to adjust unless or until they have reached a new steady state.

In light of the proposed impacts of future climate change on New Mexican landscapes, some steps could be taken to alleviate those impacts. Design of future culverts, bridges, and reservoirs could be modified to account for increases in sediment delivery and options for removal of that sediment. Existing rainfall intensity-duration thresholds (Staley et al., 2017) can be applied for locations of concern in New Mexico in the prediction of high-hazard areas and for establishing early flood and debris-flow warning systems. Pre-fire assessments of post-wildfire hazards, such as those by Tillery et al. (2014) and Tillery and Haas (2016), can be used to help managers identify basins with the greatest potential hazards for implementation of mitigation measures such as forest thinning. Slope (25–40 degrees), vegetation greenness index (Rengers et al., 2016), and upstream drainage areas (<1,000 m^2) most commonly linked with runoff generated debris flows are well defined (Tillery and Rengers, 2020). This information could be used to create a map of New Mexico highlighting those areas with the corresponding slope, upstream drainage areas, and vegetation index indicative of debris-flow initiation locations. The New Mexico Multi-Hazard Risk Portfolio gives examples of similar hazard maps produced for New Mexico (New Mexico Multi-Hazard Risk Portfolio).

Knowledge Gaps

Substantial gaps exist in understanding the length of time it takes for different landscapes to adjust after a major disruption such as climate change. Depending on scale, runoff and conditions prior to a disruption, some fluvial systems may reach a new equilibrium in as little as a few years to a decade after the disturbance comes to an end. Other fluvial systems may continue undergoing a complex response as the channel continues to evacuate or aggrade large volumes of sediment with each major rainstorm for multiple decades or longer following the end of a disturbance before the system has reached equilibrium. Studies designed to document "recovery" time frames for different fluvial systems across the state of New Mexico would help in constraining and planning for periods of geomorphic instability following disturbances such as drought or wildfires in the various geomorphic settings around the state. However, recovery time is only meaningful in relation to a punctuated disturbance, such as a wildfire, that has a distinct conclusion. If a disturbance continues indefinitely or over long periods of time relative to human time scales, fluvial systems may not achieve true equilibrium at all. Additionally, field studies are needed that investigate sediment transport between debris-flow-producing headwaters and downstream rivers to quantify location and amounts of downstream sediment delivery.

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VII. CHANGES IN SURFACE-WATER AND GROUNDWATER SUPPLIES AND IMPACTS ON AGRICULTURAL, MUNICIPAL, AND INDUSTRIAL USERS

J. Phillip King

Surface-water supply shortages induced by climate change will drive both agricultural and municipal/industrial water users to rely more heavily on groundwater. Less surface water will lead to lower recharge to some groundwater aquifers. The Lower Rio Grande is an in-progress example of this effect, with prolonged surface-water shortage leading to plunging groundwater levels. All water users in the state will experience decreased water availability as the climate warms and aridification occurs. This decrease in water availability will likely trigger changes of use from lower-value uses to higher-value uses, and this generally means a migration from agricultural water use to municipal/industrial uses. New Mexico has a rich and diverse history of water use that is central to its collective identity. This permanent shift towards a more arid climate will upset the hydrologic balance that has weathered cyclical drought. The declining mean and increasing variability in the surface-water supply is not cyclical, and recovery periods will be fewer and farther between. This will require difficult and divisive policy and management decisions, undoubtedly accompanied by an increase in disputes and litigation. New Mexico is by no means alone in facing these daunting challenges.

Introduction

This chapter examines the likely effects of climate change on water availability for agricultural water users, primarily for irrigation, and for domestic, commercial, municipal, and industrial (DCMI) water providers. Previous chapters highlighted the uncertainty inherent in predicting how the climate will change in coming decades (Chapter 2), resulting effects on the land-surface water budget (Chapter 3), and the effects on ecological systems (Chapter 4), soils (Chapter 5) and landscapes (Chapter 6). Adding to the complexity of water-user response is the highly diverse climate, landscape, and water-use cultures in New Mexico. Prediction of climate change effects on surface water and groundwater supplies for human use inherits all the uncertainty in those areas, then overlays perhaps the greatest source of uncertainty of all—human behavior. Specifically, the way in which water users, concerned with health, economic, environmental, and social consequences of water-use patterns and climate change, respond to the highly likely reductions in runoff and recharge described in Chapter 3, will develop positive feedback cycles within positive feedback cycles, creating chaotic systems both in the scientific and colloquial sense of the word.

New Mexico has a long and rich history of water management, particularly for irrigation, going back centuries. Periods of severe and sustained drought have happened before, as have relatively wet conditions. Water managers have managed to weather the drought periods and recover in the wet periods. The focus of this report certainly includes drought considerations, but more importantly, it considers something fundamentally different—a permanent shift to a more arid climate, as opposed to the past cyclical pattern of drought and wet periods. The recovery periods will be fewer and farther between, and the drought periods will be more severe. This is not the climate in which New Mexico water use and management developed, and status quo management is not an option.

Hydrology of Water-Supply Systems

From the climate perspective, an increase in temperature is clearly underway and highly likely to continue, resulting in, among other things, an increase in potential evapotranspiration (PET), resulting in an increasingly arid climate throughout the southwestern United States (see Chapters 2 and 3). While the trend in precipitation is less predictable, both in terms of annual quantity and spatial and temporal distribution, it is highly unlikely that any increases in precipitation will be sufficient to overcome the deleterious effects of temperature rise on the quantities of runoff and recharge available to water users. Rumsey et al. (2020) described the decline in baseflow and total streamflow in the Rio Grande upstream of Albuquerque for the period 1980–2015, a clear indication that the hydrologic balance in the state is shifting.

One of the most basic concepts in hydrology is the conservation of mass (or volume) of water, which can be stated, for a given control volume:

Inflow – Outflow = Change in Storage

The control volume can be a water tank, a reservoir, an aquifer, a watershed basin, or even an entire state. The common analogy for this statement is a bank account, where deposits minus withdrawals must equal change in balance. In terms of the state's hydrologic balance, discussed in Chapter 3, inflow consists of precipitation and interstate stream and aquifer inflows, including imported water. Outflows consist of evapotranspiration (ET) and interstate stream and aquifer outflows. Change in storage consists of aquifer and surface reservoir gains and losses, as well as changes in instream storage.

In broad terms, this notion of hydrologic balance provides a structure for conceptualizing and quantifying the likely effects of climate change, in spite of the inherent uncertainty. Rising temperatures will have a dramatic effect on both the inflow and outflow terms. The highly likely reduction of snowmelt runoff and groundwater recharge means that the deposits in the hydrologic bank accounts of both irrigation and DCMI systems will be reduced, in terms of surface-water reservoir inflows as well as aquifer recharge. Outflows, the withdrawals from the hydrologic bank accounts, consist of diversions of surface water and groundwater and deliveries to downstream users, which may be subject to legal obligations. Rising temperatures lead to higher PET, which will increase hydrologic depletions from existing uses. Unless water uses are modified to reduce outflow in a like amount through human intervention (management), the simple math suggests that either storage in reservoirs and aquifers will decline, which is unsustainable, or downstream deliveries will be reduced, shorting other water-supply systems. In fact, both of these negative outcomes are already happening in the state. Described in terms of our metaphor, failure to act to rebalance the inevitable reduction in inflows by reducing outflows will inevitably result in hydrologic bankruptcy. Reducing the outflows is a difficult and painful process, and one that will likely change the character of the state.

Discussion of these effects has been ongoing for decades, and is reflected in the forecasts for increasing water stress, represented in Figure 7.1 for the period 2040–2061, as compared to the water stress for the historical period of 1900–1970 (by Lindsey, 2013). While increased stress is a safe bet for the southwestern United States, New Mexico is at or near the epicenter.

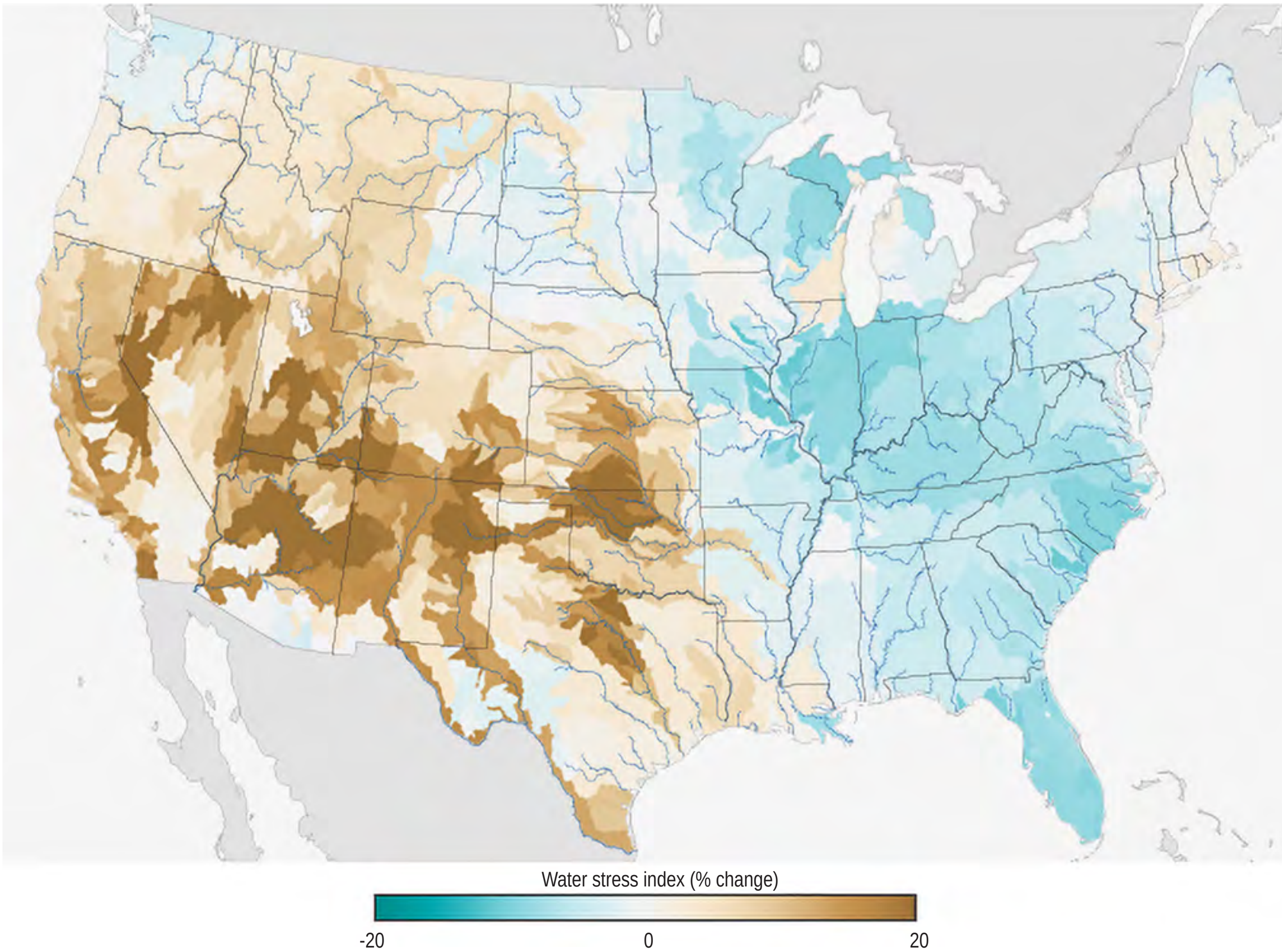

Figure 7.1. Projected change in water stress by mid-century (2040–2061) compared to historical average (1900–1970). Lindsey (2013).

Water-Supply Sectors and Typology

New Mexico has perhaps the most diverse water culture in the United States, and a broad range of water-supply systems (Table 7.1). For the purposes of this discussion, we will greatly simplify the characterization of water-use sectors and water-supply types. Distilling the sectors down to DCMI and irrigated agriculture misses much detail, and in fact industrial water use and irrigation are highly interrelated, through such activities as post-harvest processing and dairy production. While we frame the sectors as binary for discussion purposes, we recognize that water-use sectors are a continuum.

Water use for agricultural activities other than irrigation is not discussed at length. Stock wells for ranching are a common use of water in the state in a very important industry, but their water consumption is small relative to irrigation or DCMI. Effects of climate change on rainfed pasture are also not discussed at length here.

Aside from effects on irrigation water-supply sources—rivers, streams, and aquifers—climate change will produce effects on crop behavior. Higher temperatures may make some crops unsuitable for areas in which they were historically grown, due to heat sensitivity or dependence on a winter

Table 7.1. Sources of New Mexico's water-supply systems.

Water-supply Typology	Agriculture Examples	DCMI Examples
Groundwater Dominant	Pecos Valley Artesian Conservation District, High Plains	Las Cruces, Carlsbad
Surface-Water Dominant	Acequias, Middle Rio Grande Conservancy District	Las Vegas, Farmington
Conjunctive Surface Water/Groundwater	Carlsbad Irrigation District, Elephant Butte Irrigation District	Albuquerque, Santa Fe

freeze. Other more heat-tolerant crops will likely deplete more water, as increases in PET and longer growing seasons make it possible to produce more evapotranspiration, and increase crop yields (Seduto et al., 2012). Ironically, some water conservation measures intended to reduce applied water actually increase the depletion by evapotranspiration, since the crop's water needs can be more fully and efficiently met with drip or sprinkler irrigation. The reduction in applied water with precision-irrigation systems is due to reduction in evaporation, which is a depletion, but also in deep percolation or release of tail water, which are non-consumptive losses, and contribute to aquifer recharge and streamflow.

In terms of water-supply sources, most of the state's water systems can be described as some combination of surface water and groundwater dependent. As with the water-use sectors, for the sake of clarity, we will define the state's water-supply systems in terms of their relative dependence on surface and underground sources, while recognizing that conjunctive use of water can be quite complex and varied.

It should be noted that water conservation will certainly be a response to reduced water supply in all sectors. Several DCMI users have formal drought response plans in place that specify water conservation measures to be implemented in various levels of drought. Agricultural users routinely scale their cropped acreage to meet available supply, and implement more aggressive water conservation measures, both at the farm level and the system level. In the discussion below, it is assumed that conservation measures will be part of the response to climate change. The specific means of conserving water are highly dependent on site-specific hydrology and water uses and users.

In selecting appropriate water conservation measures, water managers and policy makers should consider the concept of "wet" water conservation versus "dry" water conservation, characterized by Seckler (1996). Seckler pointed out that water conservation measures may not have the intended effect due to hydrologic complications. For example, lining irrigation canals with concrete reduces seepage, and pressurized irrigation systems can reduce deep percolation losses relative to flood irrigation. However, the seepage and deep percolation losses are, in many cases, major sources of groundwater recharge, and reducing them does not reduce the net hydrologic depletion to the basin. This is the concept of dry water conservation. Wet water conservation reduces net hydrologic depletion. Examples would be lower water use crops, elimination of incidental evaporation, or fallowing crop land, which reduce atmospheric losses to the local hydrologic system. While Seckler's (1996) focus is on agricultural water conservation, the same hydrologic principles apply to DCMI water conservation.

The focus in this chapter is on availability of water supply. It should be kept in mind that availability can be constrained by more than just physical access to water. Environmental impacts of both increasing aridity, and agricultural and DCMI withdrawals of water will further constrain the functional availability of water supply. Johnson et. al. (2016) examined the impacts of climate variability and groundwater withdrawals on the La Cienega wetlands southwest of Santa Fe and suggested that timing and location of groundwater withdrawals would have to be modified to maintain the hydrologic balance of the wetlands. Similar constraints will apply to a broad range of ecosystems and water supplies around the state, including surface water and groundwater, impacting agricultural and DCMI water sources.

Groundwater-Dominant Agricultural Systems

Agricultural water-supply systems that are dependent primarily on groundwater include groundwater-only irrigation systems such as the Pecos Valley Artesian Conservancy District (PVACD), irrigators in the High Plains aquifer in eastern New Mexico, and several smaller systems in the southwestern part of the state. There are fundamental differences among these systems.

For example, PVACD draws water from an aquifer that is recharged by regional groundwater flow, which is recharged by precipitation in the Sacramento Mountains and flows toward the Pecos River (Rawling and Newton, 2016). While it is beneficial to have a recharge source (which will be reduced by climate change, as discussed in Chapter 3), there are drawbacks in this case. The extraction and depletion of groundwater in PVACD captures water that would otherwise discharge to the Pecos River, and contribute to the water supply of downstream senior rights in the Carlsbad Irrigation District (CID). This decrease in available surface water raises the possibility of a priority call on the river by the New Mexico Office of the State Engineer (OSE), which could require curtailment or offsets of groundwater withdrawals in PVACD. The Pecos River Compact also requires water delivery to Texas in the Pecos. Failure to make adequate deliveries triggered U.S. Supreme Court litigation, the outcome of which now compels full compliance with the Compact on an annual basis (Texas V. New Mexico, 1988). This illustrates the complexity not only of climate change effects on a given water system, but also the propagation of climate change impacts through the hydrologic and institutional connections between systems.

In contrast, groundwater-dominant irrigation in the High Plains region of New Mexico does not have stream connection issues, so avoids impairment of surface water. However, it has been depleted far faster than it is being recharged for many years. The extraction of groundwater for irrigation is essentially a mining operation, with little recharge reaching the source aquifer over the societal time scale (Rawling and Rinehart, 2018). As aquifer levels decline, well production, and possibly water quality, will decline (Lane et al., 2019); and pumping with higher lifts gets more expensive. At some point, the cost of pumping or the cost of deepening wells to reach the dwindling aquifer may make continued irrigation economically unviable for some irrigators. The inevitable decline in water use for irrigation in the High Plains Aquifer region is described in Mrad et. al. (2020), and while climate change may accelerate the process, it is likely in any case. Eventually, as with mining operations, when the resource plays out, the miners (farmers) move on.

Groundwater-Dominant DCMI Systems

Groundwater-dominant DCMI water suppliers face many of the same dilemmas that irrigators do. Water-supply systems that pump from aquifers that are hydrologically connected to surface-water systems often benefit from recharge from those rivers and streams into aquifers that serve their systems (Terracon et al., 2003). However, much of the surface-water use in New Mexico was developed initially for irrigation, hence irrigators typically have water rights that are senior to those of DCMI systems. As surface water dwindles with a changing climate, priority calls requiring offsets or curtailment by junior groundwater users affecting surface flows may become necessary. Through administrative schemes like Active Water Resource Management, shortage sharing schemes may be developed for basin-specific conditions, including market-driven temporary or permanent transfers between water-use sectors. These schemes provide management alternatives to the "blunt instrument" of strict priority administration. If DCMI groundwater users are required to offset their impact on senior surface-water users (some already are), water will become more expensive, which will be an inevitable consequence of climate change. Acquiring offsets from senior irrigators will require retirement or rotational fallowing of agricultural land, which may affect the viability of agricultural economies in heavily impacted areas.

In the case of mined aquifer supplies, DCMI users are more constrained. They could acquire, through market mechanisms, rights currently used for irrigation in their shared aquifer. Taking agriculture out of production is not without downsides. It will presumably be expensive, and may have negative impacts on local economies, increasing the economic disparity between urban and rural parts of the state. It would however, increase the lifetime of the aquifer if withdrawals and depletion are reduced.

Importing water is also an adaptation strategy that many municipalities, including those on the High Plains Aquifer, are using. On the Rio Grande north of Elephant Butte Reservoir, sixteen project contractors have been using imported water from the San Juan watershed in the Colorado River system through Reclamation's San Juan–Chama Project since the 1970s. An additional contractor, the Pojoaque Regional Water System, is now being added. Additional water importation projects are now being proposed or constructed. The Ute Pipeline Project aims to bring water from Ute Reservoir on the Canadian River into eastern New Mexico communities, especially Clovis (Montoya Bryan, 2017). The Navajo Gallup Water Supply project will divert a portion of New Mexico's water allocation under the Colorado River Compact from the San Juan River and deliver it to communities on the Navajo and Jicarilla Apache Nation lands and to the City of Gallup. While importation can bring in new water to water-short locations, it is taking it from the location or basin from which it originated, which can lead to shortages, or lack of economic opportunities there. In addition, water importation projects are very expensive. The climate changes discussed in Chapters 1 and 2 are large in scale (affecting all of southwestern North America), so the sources of imported water are facing the same negative climate change effects that the end user is facing. Hence ongoing climate change is likely to compromise availability of imported water. Developing new importation projects will become increasingly difficult, as users looking to import water find source options increasingly stressed. It may be the case that the interbasin transfers that can be done, have been done, and future importation projects are simply infeasible.

Surface-Water-Dominant Agricultural Systems

The practice of irrigating with surface water in New Mexico is far older than the state itself, and is a key pillar in New Mexican culture. From pre-Columbian indigenous farmers to acequia parciantes under Spain, to Mexican and American farmers, irrigation from New Mexico's rivers and streams led to the development of the state. Surface water is, of course, the hydrologic resource most immediately vulnerable to climate change impacts, but in most cases, surface-water rights are quite senior due to their early development. New Mexico's acequias are virtually completely dependent on surface water, and many have little potential for supplemental groundwater due to farm economics and hydrogeologic limitations. Furthermore, the spring runoff is occurring earlier in the season, so those irrigation systems that lack large storage reservoirs must operate "run of the river," and the early spring runoff begins before crops are ready and finishes while crops still need water. The Middle Rio Grande Conservancy District (MRGCD) is primarily dependent on the water rights to surface water of the Rio Grande, but some farmers have invested in groundwater wells, many of which were drilled during the drought of the 1950s.

Because surface-water flow is so vulnerable to drought and climate change, as described in Chapter 3, surface-water-dependent farmers have few choices when shortage strikes. Storage reservoirs built over the previous century (e.g., Elephant Butte, Brantley, Santa Rosa) provided a buffer, storing water in wet years and carrying it over in storage for use in dry years. In the current drought, most reservoirs have very low storage due to the prolonged nature of the shortage. The "bathtub rings," high water marks more than one hundred feet above current reservoir water surfaces, are evident in reservoirs throughout the southwestern United States and indicate vast volumes of unused storage. If no other source is available, surface-water irrigators have to reduce cropped acreage to fit the available supply at a given time. In earlier times this could lead to famine; now it tends to lead to economic hardship for commercial farmers, some of which could go permanently out of production, and potential collapse of local or regional agricultural economies.

Surface-Water-Dominant DCMI Systems

Due to the long-understood inherent vulnerability of surface-water supplies to drought (and now climate change), most DCMI providers that were previously solely reliant on surface water have diversified their water portfolios to include a groundwater component, although some still remain heavily dependent on surface water. Some examples of such systems are described in this section.

The City of Farmington draws its water supply from Lake Farmington, which is fed by the Animas and San Juan rivers. Recognizing the current drought conditions and resulting drop in reservoir inflows, the City of Farmington is asking residents to voluntarily reduce their water use (KRQE, 2021). On June 1, 2021, the City of Farmington enacted Drought Stage 1, which calls for voluntary conservation measures.

The cities of Farmington, Aztec, and Bloomfield, along with the County of San Juan and the San Juan Rural Water Users Association, formed the San Juan Water Commission in 1986 (SJWC JPA, 1986) to facilitate the implementation of the Animas–La Plata Project. In dealing with climate-driven persistence of water shortage, such organizational infrastructure will certainly help in implementing coordinated, cooperative water management among water users rather than the default competitive, zero-sum-game approach.

One of the most surface-water-intensive cities in the state is Las Vegas, deriving about 90 percent of its water from the Gallinas River, which has been dramatically affected by drought, and presumably a permanent shift to a more arid climate. While farmers using only surface water can fallow fields to match their cropped acreage to the available supply in a shortage, as the old saying goes, “It’s a lot easier to fallow a field than to fallow a neighborhood.” Las Vegas is implementing a tiered response that is the DCMI equivalent of staged fallowing. Using a 10-step scale based on water in reservoir storage, going from routine water conservation measures and voluntary use reductions at level 1 (when 1,000 acre-feet or more is in reservoir storage) to emergency shut off for non-essential services at level 10 (when storage drops below 100 acre-feet) (CLV, 2021). The city has also taken measures to develop groundwater capacity, with mixed results (Martino, 2012).

The dire outlook of spending more time at the higher response levels (lower storage) due to climate change suggests that Farmington, Las Vegas, and other surface-water-reliant DCMI providers will have to make significant investments to diversify their water portfolios.

Conjunctive Surface-Water/Groundwater Agricultural Systems

Where the hydrogeology and legal institutions allow it, farmers, particularly those for whom farming is a primary or major source of income, invest in groundwater wells as a back-up supply in times of surface-water shortage. Most surface-irrigation systems are established in the fertile soils deposited by river systems, which also provides access to divert water from a river or stream. Drawing groundwater from the alluvial aquifer underlying a river for irrigation may get a farmer or an irrigation district through a drought, but ultimately the aquifer must be recharged by the flow of the river. Instead of the aquifer producing a new source of water, it functions akin to a reservoir in that it stores water that can be withdrawn but must be recharged by future surface-water flows.

Farmers in the Elephant Butte Irrigation District (EBID), with 90,640 assessed acres, relied nearly completely on surface water from the Rio Grande Project (RGP) until the severe drought of the 1950s, which motivated them to invest in wells to provide a backup supply during times of surface-water shortage. These farmers have been getting more water from groundwater than surface water in most years during the current drought of 2002–2021 (Chermak et al., 2015). During the current drought, aquifer storage was depleted significantly, particularly in the critically short years of 2011–2015, when the surface-water allotment dipped to 3.5 acre-inches per acre in 2013, the lowest allotment and release from reservoir storage in the 105 year history of the RGP, and about one-tenth of the full surface-water allocation of 3 acre-feet per acre. While farmers pump groundwater to get through the drought, groundwater levels decline, causing increased loss of surface water from the river and the irrigation network into the groundwater system to make up for the loss. The lowered groundwater levels also causes a drastic reduction in drain flow, which once recycled surface-water supply so it could be used again downstream, because groundwater levels have dropped below the inverts of the drains. It is a positive feedback system, where the more groundwater the farmers pump, the less surface water there is, and the less surface water there is, the more groundwater the farmers pump.

Aside from loss of aquifer storage and surface water availability, periods of heavy reliance on groundwater in EBID produce water quality problems. Groundwater salinity increases dramatically in certain areas of the district under heavy groundwater pumping, particularly in the Rincon Valley. Declining groundwater levels also reduce drain function (specifically the flow of water into the drain that removes the salts that enter the aquifer with irrigation water), a critical aspect of irrigated agriculture. Source water from the Rio Grande contains salt that, if it is not removed by drain flow, will accumulate in the crop root zone and aquifer. If drain function is not restored, salt accumulation will have disastrous effects on agriculture and potentially DCMI groundwater users.

Like EBID, the Carlsbad Irrigation District (CID) is a Reclamation project with 25,055 acres of assessed land that started as a surface-water system. In response to the regional drought of the 1950s to the 1970s, many farmers installed supplemental groundwater wells (Polly, 2019). Groundwater salinity is a limiting factor to how much groundwater farmers can use, and many CID farmers have been leasing their supplemental groundwater rights to oil and gas producers (Davis, 2013). A significant portion of CID is fallowed each year, with about 4,600 acres of water rights purchased by the New Mexico Interstate Stream Commission to fallow land and help ensure the delivery of water to Texas as required by the Pecos River Compact. Dale Ballard, the former manager of CID, estimated that 16,000 to 17,000 acres of the district are farmed in a given year, leaving 8,000 to 9,000 acres—or roughly a third of the district—out of production (Polly, 2019). This is an example of how progressive aridification can transform a formerly, highly productive agricultural area into a marginal one.

With the comparative water-supply reliability provided by the development of conjunctive surface-water and groundwater sources for irrigation, many farmers have invested in high-economic-return permanent crops such as pecans. Pecans require an initial investment of both capital, to establish the trees, and time, because the trees take a few years of growth after transplanting before they produce a commercially viable crop. While annual crops can be fallowed in response to water-supply shortages, permanent crops cannot. This hardens the water demand for those crops and could drive the farmers raising them into competition with DCMI users to acquire—on a temporary or permanent basis through leases or purchase—water from land growing more flexible crops. The worst-case scenario is that a combination of prolonged, severe drought that curtails surface-water supply with legal restrictions on groundwater pumping has the potential to reduce irrigation deliveries below the survival limit of pecan trees. Loss of the pecan orchards would be a catastrophe for the agricultural economy and the communities that depend on it.

Conjunctive Surface-Water/Groundwater DCMI Systems

As discussed earlier, the inherent variability in surface-water availability has motivated surface-water-dominant DCMI suppliers to diversify and develop groundwater-supply sources. In addition, the effects of extended groundwater pumping on aquifers and surface-water supplies have motivated groundwater-dominant DCMI providers to develop a surface-water component. However a DCMI provider arrived at conjunctive surface-water/groundwater use, the very likely reaction to a climate-induced surface-water shortage will be more heavily reliant on groundwater.

The City of Santa Fe is a conjunctive system, deriving about 78 percent of its water supply from surface water (the Santa Fe River and imported San Juan–Chama water) and 22 percent from groundwater sources. Effects of the current drought illustrate the vulnerability of the Santa Fe River to shortage. In January 2021, the Rio Grande Compact Commissioner for Texas requested that New Mexico release all water it could into the Rio Grande (Wylander, 2021), a provision provided in the Compact when New Mexico is in deficit status on its downstream delivery to Texas. While the immediate concern was flooding caused by the rapid release, this illustrates how downstream demand and delivery obligations exacerbated by aridification can drastically reduce available surface-water supply. For a given level of demand, even one reduced by aggressive conservation measures, any reduction in surface-water availability and use must be made up with groundwater.

The Albuquerque Bernalillo County Water Utility Authority (ABCWUA) added surface-water treatment to its water portfolio in 2008 to treat imported San Juan–Chama water for DCMI use within the agency's service area. The short surface-water supply conditions of 2020 and 2021 are reducing the duration for which the surface-water treatment plant can be operated, shifting demand back to the groundwater supply.

In the late 1990s and early 2000s, the City of Las Cruces planned to develop a surface-water treatment plant. Water users in the Lower Rio Grande developed the statutory basis for the Special Water Users Association (SWUA), an organizational structure that allowed DCMI users to acquire EBID surface-water rights to provide Rio Grande Project water for surface-water treatment plants to be built in the future, providing DCMI an alternative to groundwater. Under the SWUA, farmers would receive the same allotment per water-righted acre as the farmers in EBID, and take delivery during the surface-water irrigation season. Planning and policy development were underway (Terracon, 2003) when the drought of the 2000s hit. The plant was never built due to the drought of the 2000s and the shortened season of surface-water availability, and reduced allocations to EBID. A treatment plant that looked like a logical diversification of water supply in the very wet 1980s and 1990s was no longer attractive in the arid 2000s.

Summary of Overarching Themes

Surface-water supply shortages induced by climate change will drive both agricultural and DCMI water users to rely more heavily on groundwater. In those areas where groundwater is recharged by surface-water sources, that recharge will be reduced by the reduction in surface water. This increased reliance on groundwater and reduction in recharge (colloquially termed a "double whammy") on the groundwater system is a classic case of a positive feedback system discussed in Chapter 1. The Lower Rio Grande is an in-progress example of this effect, with prolonged surface-water shortage leading to plunging groundwater levels (Chermak et al., 2015).

One very likely outcome of this feedback loop will be an overall decrease in water availability for both irrigation and DCMI uses. This decrease in water availability will likely trigger changes of use from lower-value uses to higher-value uses, and this generally means a migration from agricultural water use to DCMI. This too is already underway. The Albuquerque Bernalillo County Water Utility Authority acquired agricultural water rights to offset the impact of groundwater pumping on the Rio Grande, and the City of Las Cruces acquired surface-water irrigation water rights from the Reclamation's Rio Grande Project for a surface-water treatment plant that was never built. Any large-scale movement of water from agriculture to DCMI use would certainly change the character of the state.

While policy development and implementation move rather slowly, the positive feedback effects created by climate change are happening very quickly. The Lower Rio Grande has been in shortage conditions since 2002. That shortage is now spreading upstream into the Middle Rio Grande, with shortened seasons for river diversion for both agricultural and DCMI users.

New Mexico has a rich and diverse history of water use that is central to its collective identity. The notion of prior appropriation, included in the State Constitution, suggests that those that first put water to beneficial use can continue to do so for all time, protecting the status quo. The unpleasant reality of climate change is that the status quo is no longer an option. The simple inviolable mass balance concept suggests that a permanent shift toward a more arid climate will upset the hydrologic balance that has weathered cyclical drought. The declining mean and increasing variability in the surface-water supply is not cyclical, and recovery periods will be fewer and farther between. This will necessarily require difficult and divisive policy and management decisions, undoubtedly accompanied by an increase in disputes and litigation. New Mexico is by no means alone in facing these daunting challenges.

VIII. EFFECTS OF CLIMATE CHANGE ON EXTREME PRECIPITATION EVENTS AND STORMWATER MANAGEMENT IN NEW MEXICO

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A warming climate could increase the magnitude of future storms, leading to extreme precipitation events and increased flooding in New Mexico. Warmer air can hold more water vapor, approximately 7% more moisture for each 1°C (1.8°F) increase in temperature. Global climate models (GCMs) used to predict future conditions are not detailed enough to simulate individual storms. Three major types of storms occur in New Mexico: short-duration, high-intensity local storms in summer (usually monsoonal); long-duration general storms (caused by winter weather fronts); and occasionally the remnants of tropical storms. The principal risk from extreme precipitation events will be flooding in small watersheds from high-intensity local storms, precisely the storms that are hardest to simulate in climate models. Large-scale regional studies have corroborated the hypothesized increase in extreme precipitation with warming temperature, but few such studies exist on the impact on local storms in the four-corner states. A study of extreme precipitation events in Colorado and New Mexico was recently completed and has updated estimates of the magnitude of severe storms possible in our state. Data and modeling studies suggest that while the risk of the most severe storms might not increase beyond current estimated values, less severe (but still high-intensity) storms may occur more frequently than at present, which could impact existing stormwater management infrastructure.

Introduction

Knowledge of the characteristics and magnitude of future extreme precipitation events and their frequency of occurrence is vitally important to stormwater management agencies. The major risk posed by runoff from extreme precipitation events is the threat to human safety and infrastructure, particularly in urban locations. Furthermore, about 16% of the dams in New Mexico store hazardous mine tailings or wastewater and their failure would pose a serious environmental risk to downstream watersheds. However, extreme precipitation events also present a threat to undeveloped watersheds, especially those damaged by catastrophic wildfires (see Chapter 6).

There are several phenomena associated with a warming climate that may affect the intensity and magnitude of storms: a warmer atmosphere can hold more water vapor (see Appendix C), a warmer atmosphere may produce stronger storms, and the type of storm events may change as a result of changing weather circulation patterns. The objective of this chapter is to review the current state of knowledge of extreme precipitation events in New Mexico in order to determine how such events may change, discuss possible impacts on the state's stormwater management infrastructure, and identify areas where new information is needed to improve stormwater management. Understanding how future extreme precipitation may change is critical to planning for future storm events. This section focuses on the frequency, occurrence, and characteristics of extreme precipitation events and stormwater management. Note that whether a particular storm results in flooding depends on the hydrologic conditions of the watershed (especially its topography, land cover, and antecedent conditions), as well as the characteristics, duration, and track of the storm. Because these characteristics and conditions are location and storm specific, it is not possible to predict the magnitude and consequences of individual future storms.

Extreme Precipitation in New Mexico

Extreme precipitation events in New Mexico that pose the greatest risk of flood damage to infrastructure and the environment are often very intense, short duration, local storm events that are difficult for dynamical models to simulate. Coarse-resolution climate models do, however, attempt to simulate atmospheric conditions that will enable the understanding of potential changes in precipitation events. Those changes are discussed in this section.

Due to its location in the Southwest and its varied topography, weather patterns in New Mexico are highly variable and influenced at times by regional weather patterns from the Pacific Northwest, Arctic synoptic events from northern Canada and Alaska, and tropical weather from the Gulf of Mexico, the eastern Pacific Ocean and the Gulf of California. Three types of storms that may cause extreme precipitation events in New Mexico were considered in the Colorado-New Mexico Regional Extreme Precipitation Study (CO-NM REPS): local storms, general storms, and remnant tropical storms. The general characteristics of each are (CO DWR and NM OSE, 2018; AWA, 2018):

Local storms:

- Main rainfall accumulation within 6 hours or less
- Not associated with overall synoptic patterns leading to regional rainfall
- Generally limited in extent to 100 square miles or less
- High-intensity rainfall
- Occur during the appropriate season, April through October

General storms:

- Rainfall that lasts for 24 hours or longer
- Occur with synoptic environments associated with frontal events or atmospheric rivers
- Extent ranges from hundreds to thousands of square miles
- Lower rainfall intensity compared to local storms
- Generally strongest from fall through spring

Tropical storms:

- Rainfall that is a direct result of a landfalling tropical system
- Occur during the appropriate seasons, June through October

Storms may exhibit characteristics of more than one storm type and are classified as hybrid storms. In New Mexico, the storms that pose the greatest threat to both urban and most natural watersheds are very-high-intensity local storms, typically associated with convective activity (i.e., thunderstorms).

Extreme precipitation events are usually measured by three characteristics (termed IDF): their intensity (I), which is the depth per hour of precipitation produced by the storm; the duration (D) of the storm event measured in minutes, hours, or days; and the frequency (F) at which they occur, the inverse of the probability of occurrence over a specified time interval (often expressed as the probability of an event occurring in a single year). For example, the intensity from a 100-yr, 6-hr storm is the amount of rain, reported as depth of rain, that falls over a 6-hr period from a storm with a 1% probability of occurring in a given year (i.e., a storm that occurs on average once every 100 years). The total amount of precipitation produced by a storm, the storm's magnitude, is obtained by multiplying the intensity times the storm's duration. One other factor that affects the impact of storm events is its areal extent. This is particularly important for summer thunderstorms in New Mexico, which are frequently very intense but of such limited extent that they do not produce major flooding. Information on IDF characteristics of storms throughout the country are available from a variety of sources but most commonly are obtained from NOAA Atlas 14 published by the National Weather Service (NWS) (NWS, 2005a).

The complexities associated with multiple storm types occurring in New Mexico and the state's widely varying topography contribute to a high degree of uncertainty in identifying extreme precipitation events. The complicated weather patterns in New Mexico are illustrated in the rainfall map for the 100-yr, 6-hr storms (Fig. 8.1), which shows large variations in rainfall depths over a distance of a few tens of kilometers. This variation is particularly notable in the upper Rio Grande watershed where the influence of topography is especially important. For example, the rainfall magnitude from a 100-yr, 6-hr storm at the crest of the Sandia mountains is 2.8 in (71 mm), which is 25% greater than that at the Albuquerque airport 2.23 in (57 mm) though these sites are only 15 miles apart. The difference is even greater for longer duration storms, for example, a 53% difference for a 24-hr storm.

There are two basic ways to attempt to estimate how climate change might affect extreme precipitation events. One approach is to analyze historical records to test for changes that may have occurred in the recent past. Two recent studies examined observational records of extreme storm events to test for the existence of a long-term trend, using very different approaches. Kappel et al. (2020) assessed trends in large storm events across the United States controlling the most extreme precipitation amounts, so-called "Probable Maximum Precipitation" (PMP) events (discussed further in the Design Standards section below). Roughly 10 such events occur nationally each year. They found no significant trend in decadal averages of these extreme storms through the twentieth century.

Towler et al. (2020) assessed daily summer precipitation amounts, spatially averaged over the entire Rio Grande corridor north of Elephant Butte Reservoir, using a modest threshold to define "extreme events" of just 0.2 in/day (5 mm/day), which includes ~10 events each summer. They also found no significant trend over a short (40 year) record (Fig. 8.2), although one wonders if there is a trend in extreme events if the threshold were changed to just the top 1% of precipitation days, those which are more likely to cause flooding (above the red line in Fig. 8.2). The large variation in precipitation for these storms illustrates the difficulty in assessing historical trends of extreme events based on the available data and considering the variable results obtainable using different criteria for unusually large storm events.

The second approach is to conduct dynamical modeling experiments. Computer models based on equations describing atmospheric physics can be employed to simulate changes in extreme precipitation, or at least changes in the large-scale mechanisms that promote extreme precipitation (Fig. 8.3). The effect that is best understood is moisture availability, often referred to as precipitable water. This is the depth of liquid water in a column of the atmosphere, if all the water in that column precipitated as rain. Increasing temperature, even modestly, leads to a large increase in the capacity of the atmosphere to hold water vapor, hence moisture availability (see Appendix C). Each of the mechanisms listed in Fig. 8.3 is discussed in Chapter VI of the CO-NM Regional Extreme Precipitation Study (AWA, 2018). This study is discussed in more detail below. As shown in Fig. 8.3, the mechanisms that are best understood should promote future increases in extreme precipitation through increases in moisture availability and convective intensity. However, although increased energy is associated with warmer air, it is actually temperature differentials (i.e., temperature gradients) that result in atmospheric instability and increased convective intensity. There is some evidence that climate warming may cause increased atmospheric stability, which may reduce monsoonal rainstorms (Pascale et al., 2017).

The uncertainties inherent in simulating future storm events described in Chapter 2 all apply to the assessment of extreme precipitation, although the future trends are much less certain. However, as a group, multiple GCMs suggest that extreme precipitation events (such as those with less than 1% probability of occurring each year) will become more frequent and more intense in New Mexico (Janssen et al., 2014; AWA, 2018; see Fig. 2.5). Further, Donat et al. (2016) conclude that the effects of a warming climate on extreme precipitation events will be felt more in arid regions compared to wet regions. However, this conclusion is not quantified nor is it supported by all storm research in the Rocky Mountain states.

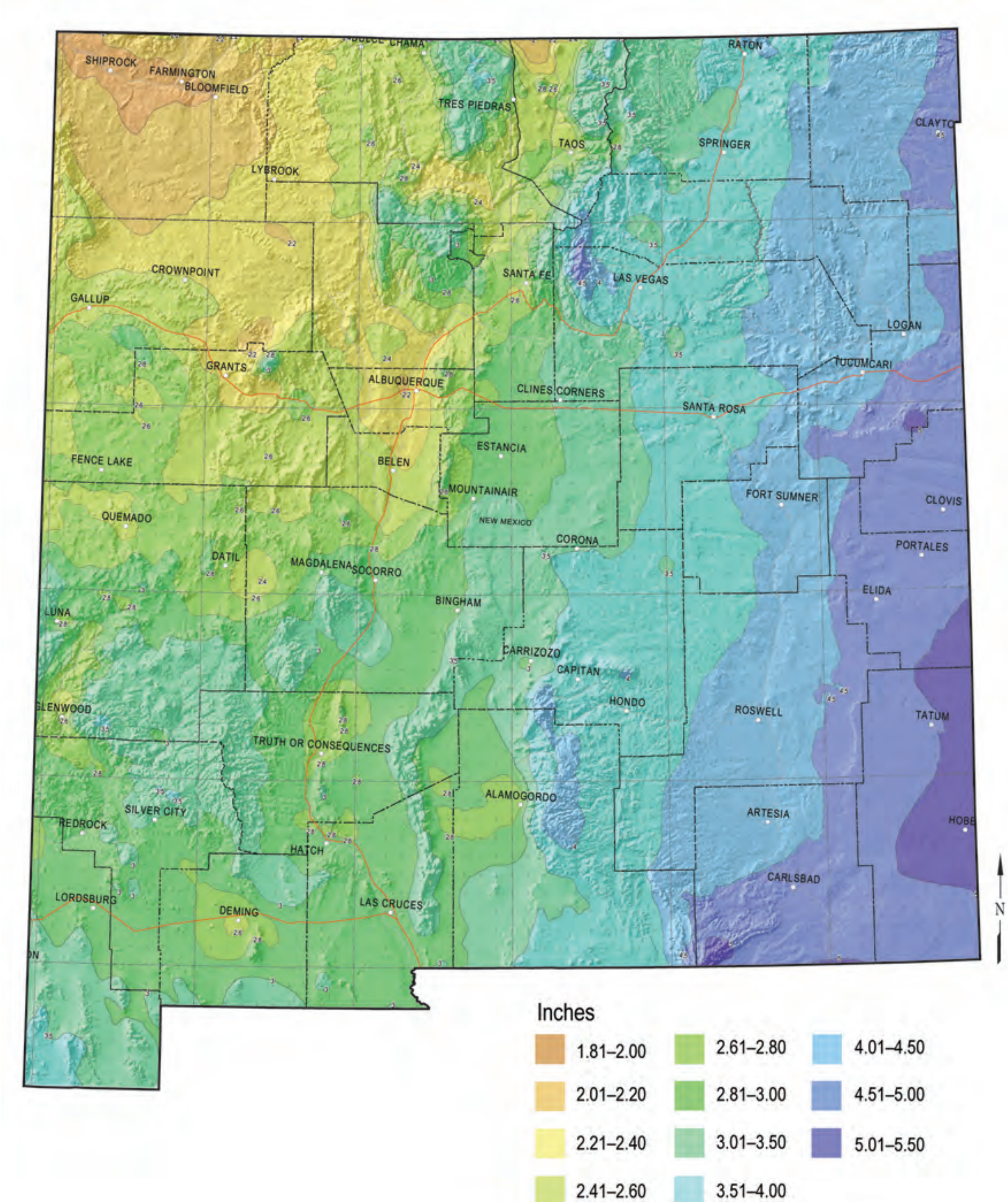


Figure 8.1. Map of rainfall depth produced by 100-year, 6-hour storms in New Mexico (NWS, 2005a).

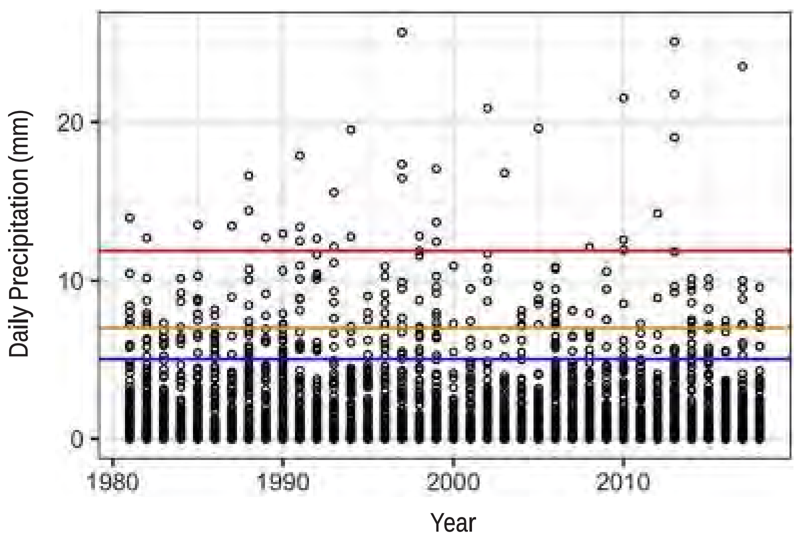


Figure 8.2. Monsoon season (Jul–Sept) daily precipitation across the upper Rio Grande watershed in northern New Mexico from 1981 to 2018 (from Towler et al., 2020). Horizontal lines are select quantiles: Q91 = 5.0 mm/d (0.20 in, blue), Q95 = 7.0 mm (0.28 in, orange), and Q99 = 11.9 mm (0.47 in, red). Thus the most extreme daily precipitation amounts, in the 99th percentile, occur above the red line with amounts >11.9 mm (0.47 in). Towler et al. (2020) used a precipitation threshold of 5 mm/day (0.20 inch/day) to define extreme events.

Emori and Brown (2005) suggest that climate change will affect extreme precipitation in two ways, simplifying the list shown in Fig. 8.3. Dynamical changes may result from a change in atmospheric circulation patterns, whereas thermodynamic change is due to increased moisture content in warmer air. Storm events in New Mexico will be subject to both effects, and both are expected to change the environment in such a way as to generate storms that will be more frequent and more intense. The topography of New Mexico is an important factor that influences the characteristics of precipitation events in New Mexico. The prominent mountain ranges in New Mexico generate orographic effects that can either enhance or decrease precipitation depending on whether it forces air to rise (upslope effect) or descend (downslope effect). In addition, these mountain ranges affect the storm track and velocity of local, general, and tropical storms.

Nevertheless, significant uncertainties remain. The historical correlation between convective storm intensity and rainfall amount is not strong (Mahoney et al., 2013; AWA, 2018). The discussion by Mahoney et al. (2013) of the difficulties in downscaling from regional climate models to mesoscale (i.e., local) convective storm events is especially relevant to storms in New Mexico. Thus, though New Mexico may experience more thunderstorms in the future, it is not clear that they will increase the risk of flooding.

Instead of trying to predict the effects of the physical mechanisms shown in Fig. 8.3, Towler et al. (2020) assessed model-simulated twenty-first century changes to large-scale summer weather patterns in order to identify trends in extreme precipitation events in New Mexico. Their analysis suggests little change in the frequency of extreme events over the next few decades but predict an increase in summer storm events after 2050, using 0.24 in/day (6 mm/day) as the threshold for large precipitation events. Furthermore, there were no increases in the probability of daily precipitation exceeding 1 in/day (25 mm/day), which was interpreted as evidence that the frequency of extreme daily precipitation was more likely to change in coming decades rather than increase the amount of rain produced. Towler et al. (2020) caution that their technique does not directly consider trends in physical mechanisms such as precipitable water, which might limit the scope of their conclusions regarding (absence of) trends in extreme events.

Lu et al. (2018) investigated the effect of increased water vapor in the atmosphere (moisture availability) and changes in the jet stream affecting storm tracks to determine the impact of atmospheric rivers on future extreme precipitation events in the western U.S., such as occurred in the wet winter of 2016/2017. Atmospheric rivers are winter storms often associated with El Niño events that generally produce heavy snowfall in the mountains of New Mexico and southern Colorado. Runoff from these storm events are not typically associated with regional flooding due to the presence of conservatively designed large federal dams on all large rivers and streams in northern New Mexico that protect downstream agricultural land and urban areas. The only large

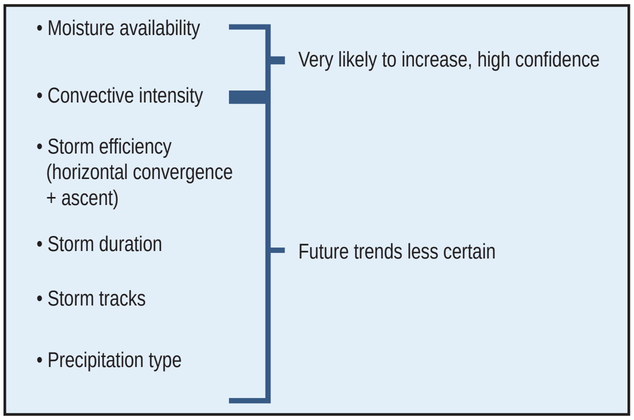


Figure 8.3. The principal mechanisms that may increase precipitation from PMP events and summary of current confidence in future changes of these mechanisms (McCormick et al., 2020).

perennial river in New Mexico without a dam to protect downstream areas from flooding is the Gila River in southwestern New Mexico. Lu et al. (2018) note that while wet winters may become more frequent in a warmer world, diminished winter snowpack will reduce the volume of spring runoff, a phenomenon that is already occurring in New Mexico (see Fig. 1.5 and Chapter 2).

Criteria for Flood-Sensitive Infrastructure

Most stormwater infrastructure in New Mexico is designed to manage runoff from 100-yr storms for durations of 24 hours. However, critical infrastructure, defined as that which would cause a major loss of life in the event of failure, is designed to withstand flooding from much greater storms, usually those that result from storms that produce the "probable maximum precipitation" (PMP). Probable maximum precipitation is the maximum depth of precipitation that may fall over a defined time for a given storm area at a particular location based on the most extreme atmospheric conditions possible at that location. These are extremely rare events with probabilities of occurrence ranging from 0.01% (a 10,000 year storm) to 0.000001% (a 10,000,000 year storm).

NOAA Atlas 14 (NWS, 2005a) only has IDF data for storms with expected return periods up to 1,000 years, which is considered to be insufficient for designing critical infrastructure. In the 1970s and 1980s the NWS prepared information on PMP storms for the entire country and published them as Hydrometeorological Reports (HMRs) (Fig. 8.4a). Probable maximum precipitation rainfall depths for New Mexico are described in HMR 49 and HMR 55a (Fig. 8.5). Rainfall depths for PMP storms predicted by HMR 55a are much greater than depths of 100-yr storms, in many cases three or four times greater (see Table 8.1), so that facilities designed to accommodate the PMP storms are large and expensive.

Estimation of PMP storms has traditionally been done using a variety of historical information including behavior of nearby extreme storms, atmospheric conditions, and weather patterns. In recent years numerical modeling of storm events is included as well. Storm and meteorological

Table 8.1. Comparison of rainfall depths at selected New Mexico locations for 100-yr, 6-hr storms (NWS, 2005a), PMP storms predicted by hydrometeorological reports (Hansen et al., 1984; Hansen et al., 1988), by the CO-NM Regional Extreme Precipitation Study (CO DWR and NM OSE, 2018) and storms occurring once every 10 million yrs (CO DWR and NM OSE, 2018).

RAINFALL DEPTH FOR 6-HR 10-MI^2 STORM (INCHES)					
Location	100 year[a]	PMP (HMR 55a)[b]	PMP (CO- NM REPS)	Ratio PMP/100 yr[c]	10 Myr storm[d]
Albuquerque	2.60	12	11	4.6	7.14
Hobbs	7.06	25	23	3.5	21.4
Las Cruces	3.74	14.5	15	3.9	9.5
Roswell	5.22	24.5	21	4.7	22.4
Santa Fe	3.21	14	19	4.4	7.3
Taos	2.88	11.5	15	4.0	5.9
Farmington[e]	2.43	10.6	8	4.4	10.7

Notes:
a – NOAA Atlas 14 (NWS, 2005a), which is most commonly used for storm precipitation estimates in New Mexico
b - HMR 55a (Hansen et al., 1988)
c – Calculated using HMR 55a & HMR 49 data
d – HMR 49 (Hansen et al., 1984)
e – CO-NM REPS web utility (CO DWR and NM OSE, 2018)

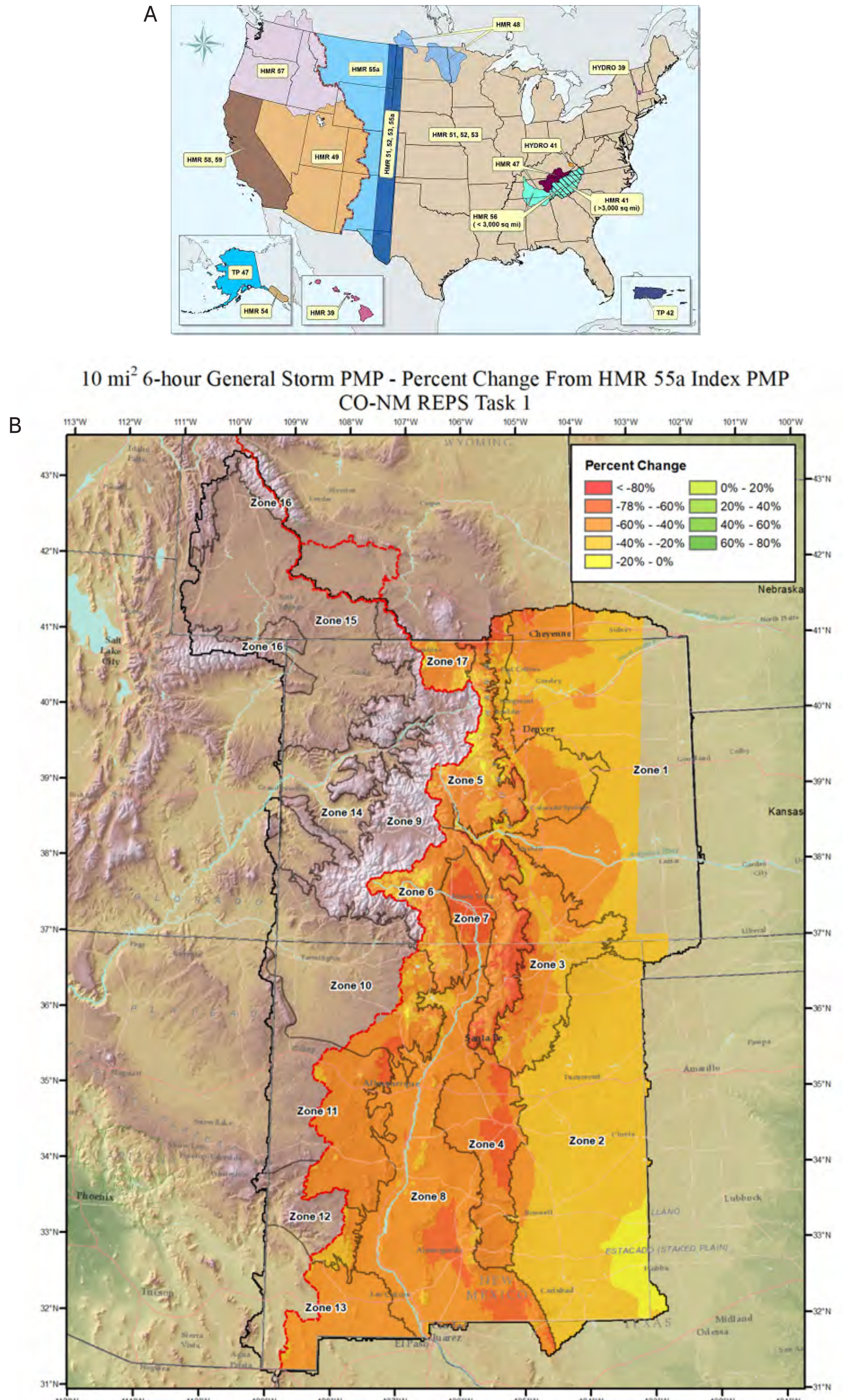


Figure 8.4. (a) National map showing the coverage of Hydrometeorological Reports (HMR) describing the characteristics of extreme precipitation events in the U. S. (Hydrometeorological Design Studies Center, (https://www.weather.gov/owp/hdsc_pmp)). (b) Percent change between 6-hr 10-mi^2 PMP storms predicted by HMR 55a (Hansen et al., 1988) and the CO-NM REPS (CO DWR and NM OSE, 2018).

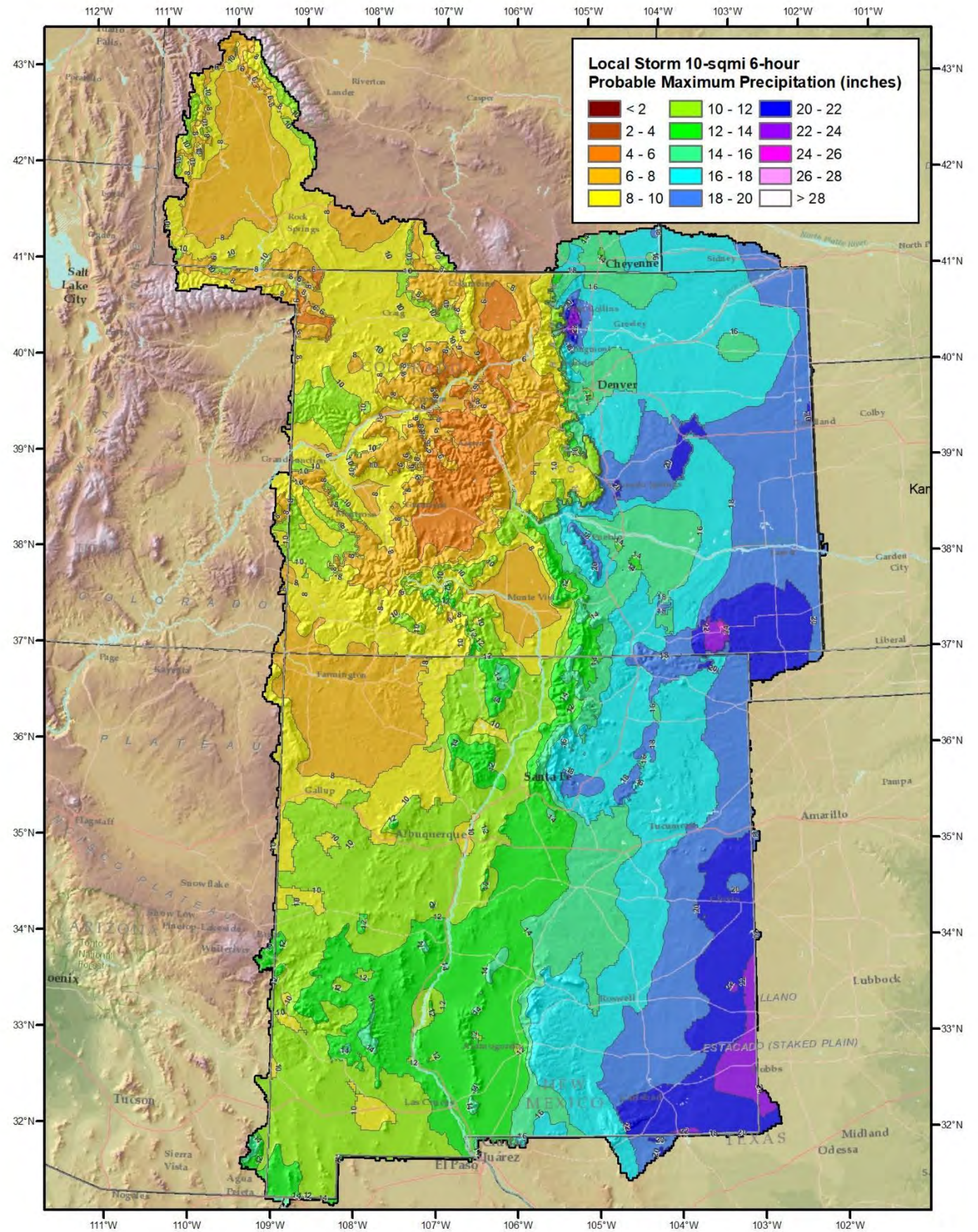


Figure 8.5. Probable maximum precipitation (PMP) for a local storm (10 square miles) of 6-hour duration (CO DWR and NM OSE, 2018).

information and modeling technology used to determine PMPs have all greatly improved in the last 40 years and have increasingly called into question the accuracy of the HMRs. Accordingly, the states of Colorado and New Mexico contracted for development of the CO-NM Regional Extreme Precipitation Study (CO-NM REPS) (CO DWR and NM OSE, 2018). This study examined historic storms, considered meteorological conditions including the effects of topography, and evaluated the current state of the art in storm modeling. Both a web-based tool and a GIS-based tool are publicly available for predicting extreme precipitation events with frequencies ranging from once every 100 yr to PMP events.

The CO-NM REPS study found substantial differences compared to extreme storms predicted by the HMRs, in some cases a nearly 50% reduction (Fig. 8.4b and Table 8.1). At some high-elevation locations, the local PMP storm precipitation depth increased. The analysis of extreme precipitation events in the CO-NM REPS did not consider the effects of a warming climate because "...no methodologies for estimating PMP or precipitation-frequency-analysis (PFA) under climate change have as yet been elevated to an official or preferred status" (Mahoney et al., 2018). However, the study did provide a separate chapter containing a descriptive analysis of these effects (Mahoney et al., 2018).

Salas et al. (2020) recently provided a state-of-the-art review of the impacts of climate change on extreme precipitation events, specifically PMP storms. Though this review was for worldwide PMP storms, their conclusion that the effects of climate change on extreme precipitation events may be significant is relevant to New Mexico, where so much of our flood protection infrastructure is aging, built to older design criteria, and in poor condition. In particular, they note that traditional methods of determining PMP storms should be re-evaluated as recent experience has shown that changing climate conditions may influence the type and nature of storms in different ways than in the past.

In New Mexico storms that pose the greatest risk of causing flooding are short-duration, high-intensity, local storms (usually monsoonal thunderstorms) and less frequently, long duration general storms, especially those associated with synoptic events that produce atmospheric rivers and are modulated by Madden-Julian oscillation changes (Maloney et al., 2019). In some cases, notably in urban areas, the greatest challenge is posed by storms of high intensity but very short duration, often two hours or less. The infrastructure to control short-duration, high-intensity storms is the greatest number of stormwater management systems in New Mexico. Furthermore, because most are designed only for 100-yr storms, they constitute the infrastructure that is most vulnerable to storms of increasing magnitude that may result from a warming climate.

Lynker Technologies (2019) discussed methods of modifying IDF curves for the Colorado Water Conservation Board to aid in developing design criteria for future flood protection infrastructure. Three methods were discussed:

- Physically based scaling methods in which the IDF curves were adjusted for the increased maximum moisture capacity of warmer air.
- Delta method wherein the historical climate record is modified by a change factor calculated from raw or downscaled GCM results.
- Nonstationary globalized extreme value (GEV) distribution method in which the probability density function of annual maximum precipitation events is adjusted based on projected changes in temperature, mean precipitation, or other physical parameters.

Lynker Technologies (2019) used these three methods along with physical data and modeling results near Denver, Colorado to investigate the impact of climate change on IDF precipitation events through 2050. They found that the 100-yr, 24-hour precipitation intensity is likely to increase by 10 to 20% across the state of Colorado by 2050. However, uncertainty in historical IDF curves could result in an up-to-30% increase at some locations. This uncertainty is much larger than often recognized and the study concluded that the true precipitation from the 100-yr storm may actually be closer to that which is currently projected for a 500-yr storm.

A conundrum occurs when considering design requirements for stormwater infrastructure. Flood insurance programs and building restrictions require (or at least provide strong incentives) to minimize flood risks within the 100-yr floodplain, but ignore adjacent areas. However, adjacent areas are vulnerable to flooding from less frequent but larger events. The question that must be considered in developing long-range, flood-management strategies is whether protection should be designed for storms of greater intensity, longer duration, or increased frequency of occurrence that may result from a warming climate?

Aside, one should recognize that requiring stormwater management systems to provide protection from 100-yr storms provides a level of protection rather than a measurable reduction in risk. For example, a dam built to limit flooding from a 100-yr storm in a watershed provides the same level of protection regardless whether the downstream watershed consists of agricultural fields or high-density urban development with elementary schools and hospitals. There is increasing agreement within the stormwater management profession that infrastructure should be designed to reduce the risk posed to life and property rather than simply provide a specified level of protection. Thus, a greater amount of protection would be required for a developed urban watershed than for an undeveloped area.

Regional Flooding

The discussion in this chapter has primarily focused on flood protection from localized storm events impacting watersheds a few hundred square miles or smaller. However, historically, much greater floods, often resulting from spring snowmelt runoff that affected large areas of the state, have occurred. Historical records show flooding from the Rio Grande during the following years: 1828, 1851, 1865, 1874, 1886, 1903, 1905, 1911, 1920, 1928, 1929, 1935, 1941 and 1942 (USACE draft, 2017). The 1941 flood was particularly severe with peak flows being estimated at 24,600 cubic feet per second (cfs). Construction of large dams on the Rio Chama (Heron, El Vado, and Abiquiu), Rio Grande (Cochiti), Pecos (Sumner) and others have nearly eliminated the chance of regional flooding from large rivers in the future. For example, the capacity of the channel downstream from the Cochiti dam, 7,000 cfs, limits controlled releases to that amount, which is less than one-third of the flow during the 1941 flood. Reduced spring runoff resulting from decreasing snowpack in the future (discussed in Chapter 2) will further limit the occurrence of extremely high flows from spring runoff. While flooding from snowmelt runoff poses a small risk for a few communities in New Mexico, it is largely unquantified and most urban stormwater management facilities are designed for high intensity, local storms. However, there is still risk of flooding from unregulated tributaries. The 1929 flood that obliterated San Marcial in southern Socorro County resulted from a monsoon outburst that came down the unregulated Rio Salado and Rio Puerco (Phillips et al., 2011).

Though the risk of extremely high flows in the Rio Grande is reduced, many of the levees along the river, between Cochiti Reservoir and the state line, are at risk of failure from moderately high flows that may occur once every decade or two. Most of these levees are simply spoil-bank levees constructed by piling sand and soil excavated from the riverside drains next to the Bosque. They have none of the features included in engineered levees such as an impervious core, erosion protection along the toe, or careful selection of soils and their proper emplacement to assure stability. As a result of levee failures associated with Hurricane Katrina in 2005, FEMA and the US Army Corps of Engineers re-evaluated levees around the country and decertified most of the levees in New Mexico in 2009. Recent evidence of the vulnerability of these levees was provided in the summer of 2019 when two months of flows above 5,000 cfs caused severe damage and near failure of a spoil bank levee on the west side of the river near Los Lunas, New Mexico. The damage was not caused by erosion or scour but simply by sloughing of weak soil material in the levee due to the presence of standing water at its toe for a period of several weeks. Levee stability along the lower Rio Grande has been a long-time concern of the International Boundary Waters Commission (IBWC, 2021).

Impacts of Precipitation on Burned Watersheds

There is a large and growing body of literature on the post-wildfire impacts of large precipitation events. The overarching effects of storm events in a burned watershed are increased volume and water velocity of stormwater runoff. These lead to debris flows (high density slurries of rocks, mud, sediment, and burned and unburned vegetation that are transported by runoff at high velocities), landslides, hillside soil loss and rill formation, erosion of stream channels, reduced infiltration, and degraded water quality. More details on these processes are discussed in Chapter 6.

Wildfires increase runoff volumes and velocity by destroying vegetation and ground cover, which in turn increases the flow of water, decreases infiltration, and increases erosion. The increased flow and velocity coupled with the lack of vegetative cover to hold soils in place may result in debris flows from even modest storm events. Due to the high velocities and large amounts of material entrained in debris flows, which range from mud and silt to boulders and large trees, these flows can be extremely damaging to stream channels and any infrastructure in the channels such as culverts, roads, bridges, or reservoirs.

Two notable examples of the infrastructure damage caused by debris flows are cited here. Monsoon rains following the 2011 Las Conchas fire produced heavy debris flows that filled small ponds and stock tanks, damaged roads, stream crossings and agricultural fields, plugged the Rio Grande downstream from Cochiti Reservoir, and forced the Albuquerque Bernalillo County Water Utility Authority (ABCWUA) to stop drawing water from the river for 40 days (Tillery and Haas, 2016; USACE, draft 2017).

Further south, late summer monsoon rains following the June 2012 Little Bear fire in the Lincoln National Forest of south-central New Mexico resulted in large debris flows from the watershed (Tillery and Matherne, 2013). These completely filled Bonito Lake, the principal source of drinking water for Alamogordo, causing it to be taken out of service. Restoring the water supply requires removal of all of the sediment and debris as well as repairs and improvements to the dam and are not expected to be completed until summer of 2022, nine years after the fire (Maxwell, 2021).

Concerns about the impact of postfire debris flows on water supplies and urban stormwater management systems led local agencies in Bernalillo, Sandoval, and Santa Fe counties to support studies by the USGS of the potential threats posed by fires and subsequent debris flows on watersheds in the Jemez, Sandia, and Manzano Mountains (Tillery et al., 2014; Tillery and Haas, 2016).

Summary of Existing Stormwater Management Programs in New Mexico

There are about 400 large dams in New Mexico, most of which were built for stormwater management and flood protection. In this discussion, large dams are those at least 25 ft (7.6 m) tall and retain at least 15 acre-ft (18,500 m^3) of water, or dams 6 ft (1.8 m) tall and retain at least 50 acre-ft (62,000 m^3) of water. About 215 of the dams in New Mexico are classified as high hazard dams, which means that failure or improper operation will probably cause loss of human life. The location and ownership of large dams in New Mexico is presented in Figure 8.6.

The average age of large dams in New Mexico is about 60 years, which means they were designed when hydrologic conditions were not nearly as well defined as they are now. Furthermore, it is likely that these conditions have changed in the intervening decades and may change even more with a warming climate in future decades. A further complicating factor is that many of the dams that were built to protect undeveloped watersheds have experienced downstream suburban and urban development that has increased the risk to the public presented by possible dam failure. This is a form of “hazard creep” that stormwater management agencies do not have the resources to address.

Stormwater management in New Mexico is provided by a diverse set of federal, state and local organizations. At the federal level the Bureau of Indian Affairs owns 27 large dams, the Corps of Engineers 7, the Bureau of Land Management 34, the Bureau of Reclamation 15, and the Forest Service owns 5 dams. The state of New Mexico owns 15 dams. Local governments, including cities, counties, irrigation districts and flood control districts own 174 dams, and 105 state regulated dams are privately owned. Thus, responsibility for managing flood control infrastructure falls upon a large number of federal, state, and local organizations as well as private companies and individuals.

Federal dams are not subject to state regulations, but instead separate design and operations requirements are established for each of the agencies that own them. New Mexico regulations for design, construction and operation of dams are contained in 19.25.12 NMAC and are administered by the Dam Safety Bureau of the Office of the State Engineer. The state of New Mexico does not identify the level of protection that must be provided for a watershed vulnerable to flooding. The level of protection is generally determined by the requirement that mortgages from federally approved lending programs obtain flood insurance. Flood insurance is available under the National Flood Insurance Program (NFIP) in Special Flood Hazard Areas (SFHA) that are most commonly defined as areas with a 1% annual chance of flooding, in other words, a flood resulting from 100-yr storm (also known as the 100-yr floodplain). Most stormwater infrastructure is designed to minimize the 100-yr floodplain. Thus, knowledge of how climate warming will affect the 100-yr storm is important to stormwater management agencies and local governments.

New Mexico dam safety regulations require that all high hazard dams, regardless of size, must have spillways designed to pass a flood from the probable maximum precipitation (PMP) storm (NMAC, 19.25.12.11.C.3.d). The extremely large nature of PMP storms in comparison to 100-yr storms often creates a difficult design challenge for dam owners. For example, the John Robert Dam owned by the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA) provides protection from the 100-yr storm in northeast Albuquerque (Fig. 8.7). This dry dam is 65 ft (20 m) tall and retains a 659 acre-ft (813,000 m^3) reservoir on the Bear Canyon Arroyo that drains the western slope of the Sandia Mountains. Flow in the arroyo from a 100-yr, 6-hr storm (2.3 in) is estimated to be 7,840 cfs (813,000 m^3/s), but the spillway is designed for the flow from a 6-hr PMP event (17.5 in at the dam and assumed to be 10.2 in over the entire watershed), which

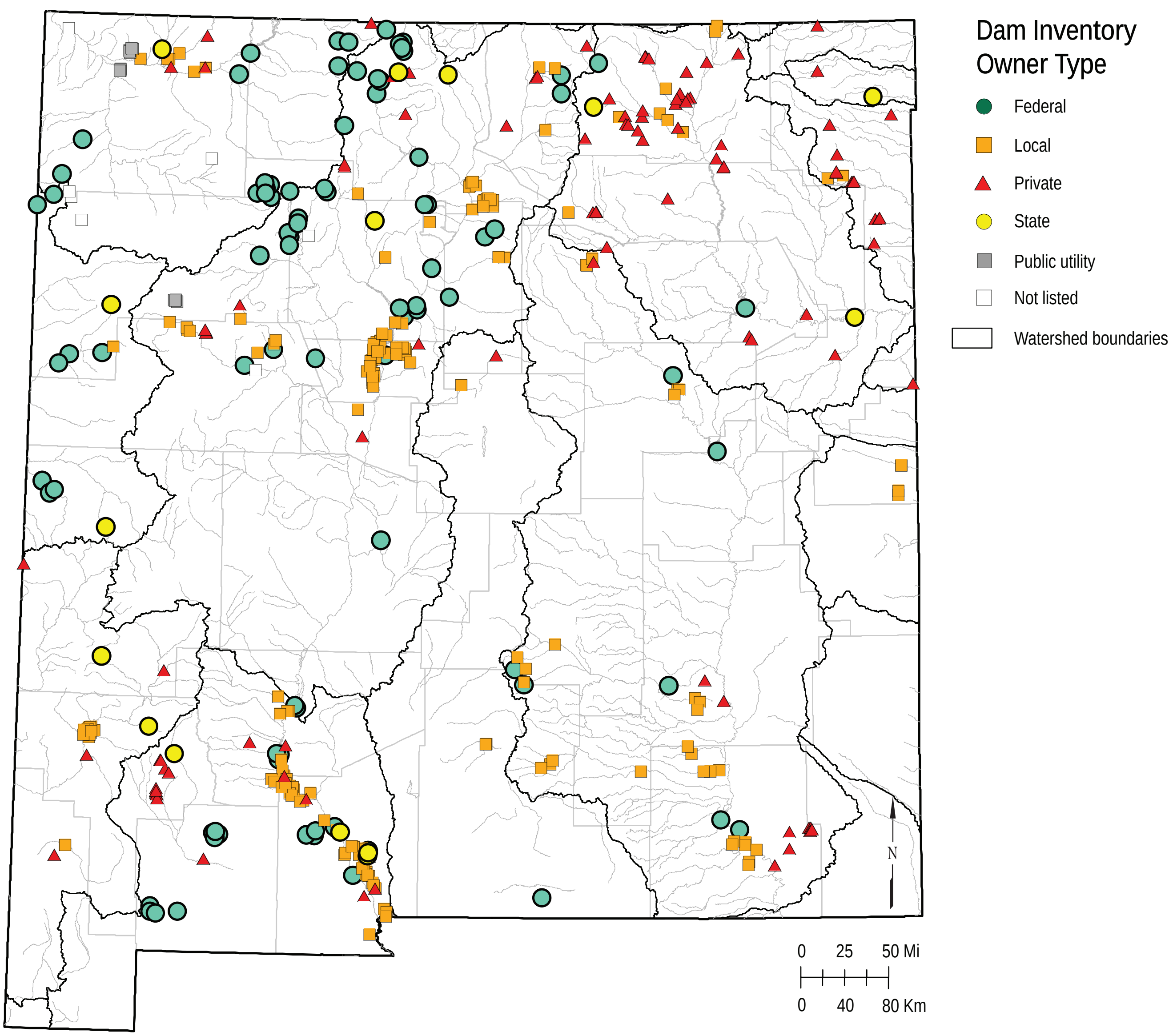


Figure 8.6. Location of all large dams in New Mexico showing ownership. (Data from USACE, 2021)

produces a flow of 23,600 cfs (668 m^3/s), hence the dam must have a very large spillway. The dam was designed so that water from a 100-yr storm event would not pass over the spillway. If a 6-hr PMP storm ever occurs, the flow would be so large that only a small portion would be retained by the dam. The rest would flow over the spillway such that a reservoir-filling volume of water would pass over the dam every 20 minutes. Under these extreme conditions the dam would provide virtually no downstream protection from flooding, illustrating the challenges of urban stormwater management considering the range of flows that could occur from extreme precipitation events.

The impact of a warming climate on dam design criteria for the state of Colorado has recently been discussed by McCormick et al. (2020) based on the CO-NM REPS (2018), other published research papers, as well as expertise from climate scientists

Figure 8.7. Photo of the emergency spillway for the John Robert dam owned by the Albuquerque Metropolitan Arroyo Flood Control Authority (AMAFCA). The spillway was designed to convey a flow of 23,600 cfs from a PMP storm. *Photo by Bruce M. Thomson*

Stormwater cannot be captured for subsequent use without a water right (see Thomson, 2021). Stormwater capture is addressed in state law, which states that "the water shall not be detained in the impoundment in excess of 96 hours unless the state engineer has issued a waiver to the owner of the impoundment (NMAC 19.26.2.15.B)." This allows an entity to detain stormwater for the purposes of attenuating a flood wave but all of the water must be released within 96 hours unless it is associated with a water right. This is known as the "96-hour rule."

The 96-hour rule brings to light a subtle but important distinction between two terms used in arid region stormwater management; retention and detention. Retention refers to capturing and retaining runoff indefinitely whereas detention refers to capturing then releasing all stormwater within a short period. In New Mexico retaining water for later use requires a water right. Detention requires releasing it within 96 hours.

An important consequence of the 96-hour rule is that nearly all flood control dams in New Mexico are "dry dams" meaning they are not designed to hold water for more than a few days. Dry dams are much simpler and less costly than wet dams because they do not have an impervious core; they are usually not keyed into an underlying impervious geologic structure to prevent underflow; they do not have operable flood gates that can be closed to retain water; and they have little or no erosion protection on their upstream and downstream faces (Thomson, 2021).

at the University of Colorado, and NOAA's Physical Sciences Laboratory, both located in Boulder, Colorado. Based on this study, Rule 7.2.4 of the Colorado Rules and Regulations for Dam Safety and Dam Construction was adopted to require that future stormwater management projects be designed to accommodate a 7% increase in rainfall to account for a warming atmosphere and associated increase in atmospheric moisture over the period from 2020 to 2070 (McCormick et al., 2020).

Knowledge Gaps

While there is an intensive, international research effort to model climate change and detect signals confirming its occurrence, there is considerably less research into predicting the frequency of occurrence and magnitude of individual storm events. Furthermore, little of the research on this topic is focused on storms in New Mexico and its neighboring Rocky Mountain states. As has been discussed in this chapter, New Mexico storms result from distinctly different types of weather and the characteristics of these storms are influenced by factors that are somewhat unique to this state. The storms that present the greatest challenge to stormwater managers are short-duration, high-intensity local storms, which are especially difficult to predict and model. Accordingly, suggested knowledge gaps are presented below:

- Data analysis and/or modeling results are needed to determine if the intensity of low probability (i.e., 100-yr storms) is changing or will change in the future as these are the storms that most stormwater infrastructure is designed to manage.
- Improvements in storm models are needed to provide better prediction of the intensity, duration and track of local storms (i.e., monsoonal thunderstorms) to assist the development of infrastructure design criteria and provide real-time data to assist in storm warning systems.
- Improved downscaling from GCMs to regional climate models to mesoscale weather models to develop better estimates of the frequency of occurrence and intensity of extreme storm events resulting from a warmer climate.
- There is an inconsistent understanding of the risk to the public as a result of current flood protection systems. While infrastructure in large urban areas is generally well designed and maintained, public knowledge of the status of stormwater management systems elsewhere is less complete.
- The stormwater management community and regulators should establish a dialogue with elected officials and the public to determine what level of risk might be acceptable for different watersheds that are subject to flooding from storm events.

Conclusions

As the climate warms, the atmosphere can contain more moisture, and warmer air has more energy if the thermal contrast also increases. Together these factors lead to the concern that future rainfall events may be more intense and drop more water, thus leading to more frequent and larger flood events. Storm events are characterized by their rainfall intensity, the duration of the storm, and the frequency at which they occur (IDF). The magnitude of a given storm is the factor that affects flooding and is the product of precipitation intensity and duration. Quantitative metrics of extreme precipitation vary depending on choices made regarding IDF. Assessments of historical trends in extreme precipitation are limited by the length and quality of observed data, particularly for defining trends in the most extreme, and therefore rarest, event. Furthermore, simulation of extreme events in dynamical models presents a very difficult challenge for climate models that have insufficient spatial resolution and time increments that are too long to capture the physics of individual local storms. This is further complicated by incomplete physical representation of key atmospheric processes and topographic influences in current models.

These analysis challenges mean that assessments of past or future trends in extreme precipitation are inherently subject to large quantitative uncertainties. The most recent National Climate Assessment used climate models to project that extreme storms with a 20-year return period would become significantly more intense across the U.S. as climate warms this century. Other studies discussed in the chapter use different techniques for defining and projecting trends in extreme storms or extreme precipitation. Recent studies reach inconsistent conclusions, with some projecting an increase and others projecting no detectable change in extreme precipitation—based on huge variations in the definition of "extreme" from study to study.

The characteristics of future large precipitation events have recently been the subject of a collaborative study funded by the states of Colorado and New Mexico (CO-NM REPS, 2018). This study identified three storm types that affect New Mexico—short duration (<6 hrs), local storms; long duration (>24 hrs), general storms; and tropical storms. Hybrid storms involve more than one of these characteristics. Storms that present the greatest threat of flooding are intense local storms, sometimes combined with tropical weather patterns, and most stormwater management infrastructure is built to provide protection from these events. Most infrastructure is designed to manage the 100-yr storm, which has a probability of occurring once every 100 years. Critical infrastructure is designed to withstand more rare events up to the probable maximum precipitation (PMP) event, defined as an event that produces the maximum amount of precipitation that is meteorologically possible; such events by definition are expected to occur much less frequently than the 100-yr storm.

By updating the methodology and data used to define PMP storms, the CO-NM REPS (2018) found that for current climatic conditions the maximum possible rainfall from PMP storms in most of the state are similar to but slightly less than that predicted by older studies (see Table 8.1). Perhaps more importantly, this study allows estimation of the magnitude of storms with average recurrence intervals of between 100 and 10,000,000 years, a feature that will facilitate development of risk-based stormwater management strategies.

As the climate warms and wildfires increase in burn area and severity, the frequency of debris flows will increase. These are high density slurries of rocks, mud, and vegetation resulting from destruction of vegetation and soil litter that retain runoff, and decreased infiltration from a burned watershed, which increases the runoff volume and velocity of surface flow. Debris flows are extremely destructive due to their high velocities, the abrasive nature of the bed and sediment loads and the amount of debris they transport. Following a wildfire, debris flows will result from short duration intense storms that are common during the monsoon season; they do not require extreme precipitation events. Thus, they are likely to follow most large fires in New Mexico. Given that wildfires are projected to increase with global warming (Chapter 6), increased numbers of debris flows can be expected.

Most large dams in New Mexico are designed for flood control and therefore do not retain a permanent pool of water. The average age of these dams is about 60 years, hence they were designed to different standards and for different hydrologic conditions than are likely in the future. It will be important to review the design, performance, operation, and maintenance of these dams and other stormwater management infrastructure to ensure that they will serve their intended purpose of protecting the safety and welfare of the state as the structures age under conditions of potentially enhanced flood risk. In particular, state regulators may consider establishing dam safety regulations that are based on risks posed to downstream communities, infrastructure and the environment rather than simply requiring protection against a 100-yr storm.

The high level of scientific uncertainty of future extreme precipitation events leaves policymakers and water managers without clear, quantitative guidance regarding future trends in extreme precipitation—or even what the current risk of these events might be. From a risk management perspective, a conservative policy approach would seem to be to accommodate the possibility of increased extreme precipitation events in a warmer climate. This is the approach taken recently by the state of Colorado (McCormick et al., 2020). A similar approach should be considered by the state of New Mexico. Progress in narrowing the uncertainties in quantifying likely extreme precipitation, and estimating future trends in extreme precipitation and flooding events, represents a first-order need for continuing future research.

IX. IMPACTS OF A WARMING CLIMATE ON WATER QUALITY IN NEW MEXICO

Bruce M. Thomson and Fred M. Phillips

A warming climate may affect the quality of both surface and groundwater resources in New Mexico; the most likely effects may include increased temperature along with concentrations of nutrients, dissolved oxygen, and pathogenic organisms. Although the quality of groundwater may be affected, it is likely to be limited to locations with shallow groundwater depth and where surface water recharges the aquifer. The New Mexico Environment Department publishes an assessment of the quality of the state's surface waters every two years. This recent assessment finds that the major causes of impairment of streams and rivers are temperature, nutrients (nitrogen and phosphorous compounds), *E. coli* bacteria, turbidity, and dissolved aluminum. The parameters most likely to be affected by a warming climate are temperature, nutrients, and *E. coli* concentrations. Studies suggest that loss of riparian vegetation is the biggest factor affecting water temperature. Modeling studies of the effects of climate warming on nutrient concentrations are somewhat inconclusive. Recent investigations suggest that *E. coli* concentrations may increase as a result of microbial regrowth in warming stream sediments in slow moving stream reaches. A future threat to water quality is runoff following wildfire events. Postfire runoff can cause depletion of dissolved oxygen far downstream from the burned watershed.

Introduction

Total water withdrawals in New Mexico in 2015, the latest year for which data are available, constituted 3.1 million acre-feet (MAF) (Magnuson et al., 2019). Surface-water sources made up 52% of this amount, while 48% was groundwater. Surface-water resources are especially vulnerable to the effects of a warming climate, as both the quantity and quality of the resource may be negatively impacted by a warming climate. The quantity of surface-water resources is likely to be diminished principally by increasing amounts lost to the atmosphere through evapotranspiration and the amount of water diverted for agricultural, municipal and industrial uses, as discussed in Chapters 3 and 7 of this report. The impacts of a warming climate on water quality are likely to be important to water supply in the state and especially to the quality of aquatic and riparian environments. However, these impacts have not been studied nearly as much as the impacts on the magnitude of the resource.

Surface water in New Mexico occurs in streams and rivers; ponds, reservoirs and lakes; and wetlands. Table 9.1 gives the length of perennial and non-perennial streams, and the surface area of lakes, reservoirs, and freshwater wetlands. This information is from a bi-annual report prepared by the New Mexico Environment Department (NMED) and submitted to the EPA to satisfy the requirements of sections 303(d) and 305(b) of regulations under the federal Clean Water Act (CWA), hence this report is known as the "Clean

Table 9.1. Summary of New Mexico surface-water resources (NMED, 2021a).

Resource	Value (US Units)	Value (SI Units)
Total length of perennial non-tribal rivers & streams	6,677 miles	10,750 km
Total length of non-perennial non-tribal rivers & streams	190,225 miles	306,100 km
Number of significant public lakes & reservoirs	170	170
Area of significant public lakes & reservoirs	85,455 acres	34,580 hectares
Area of freshwater wetlands	845,213 acres	342,500 hectares

Water Act 303(d)/305(b) Integrated Report" (NMED, 2021a). This comprehensive report forms the underpinnings of this chapter, the purpose of which is to discuss how surface-water quality may be affected by a warming climate.

While the magnitude of groundwater resources will be impacted by reduced recharge and increased diversions in a warming climate scenario (Chapters 3 and 7), it is not clear how the quality of these resources will change, as there have been no studies of possible impacts in the Southwest. One possible impact may be increased concentration of total dissolved solids (TDS) in aquifer-recharge water due to salinity increases caused by evaporation and evapotranspiration, but this effect is expected to be localized to shallow groundwater in a limited number of recharge zones. A second impact may result from enhanced microbial activity in warmer soil that could increase the concentration of CO_2 in groundwater, resulting in a decrease in pH and release of metals such as manganese (Riedel, 2019). Currently, however, it is not known if this might affect groundwater quality in New Mexico. Finally, although there is a formal process for periodic review of the state's surface waters, there is no comparable monitoring program for its groundwater resources. Thus, the focus of this chapter is on the quality of surface-water resources.

Summary of Surface-Water Quality in New Mexico

Water-quality requirements for surface waters are based on their designated use as identified in 20.6.4 NMAC, Standards for Interstate and Intrastate Surface Waters. The designated uses include: supporting aquatic life, fish culture, primary and secondary contact recreation (including cultural, religious or ceremonial purposes), public water supply, industrial water supply, domestic water supply, irrigation, livestock watering and wildlife habitat. In addition to state standards, 10 New Mexico tribes and pueblos have developed their own EPA-approved stream standards to protect the quality of their surface-water resources (EPA, 2021a). Other water-quality standards that may be applicable include groundwater standards in 20.6.2 NMAC, Ground and Surface Water Protection, and federal safe drinking water act (SDWA) standards (EPA, 2021d). State drinking water standards adopt the federal standards by reference as established in 20.7.10 NMAC, Drinking Water. As noted, this section focuses on whether surface-water quality complies with state stream standards. The stream standards constitute a convenient and accepted set of criteria by which to measure surface-water quality.

The New Mexico surface-water quality standards consist of both descriptive criteria and numeric values that have been developed to support the designated use for each lake or reach of stream in the state. The Surface Water Quality Bureau (SWQB) of the NMED conducts an assessment of a fraction of the state's streams each year with the objective of evaluating all lakes and streams every seven years. This assessment is published every two years and identifies whether each lake or stream reach has sufficient water quality to support its designated use (NMED, 2021a). The assessment results are characterized by assigning each reach a numerical category as summarized in Table 9.2.

Possible recent trends in stream and lake water quality can be determined by plotting the percent of each assessed unit in the five assessment categories from data in the biannual 303(d)/305(b) reports (NMED, 2021a). The plots (Fig. 9.1) suggest little change in the number of impaired streams or lakes, those that are in assessment category 5. The number of stream reaches that have incomplete assessments has declined (category 2) while those reaches that

Table 9.2. Summary of New Mexico's 303(d)/305(b) Integrated Report Categories for streams and rivers (NMED, 2021a).

Category	Description
1	All designated uses are supported.
2	Available data and/or information indicates that some designated uses are supported.
3	There is insufficient data and/or information to determine if the designated uses are supported (3 subcategories).
4	Available data and/or information indicate that at least one designated use is not supported and a TMDL* is either in place or may not be needed (3 subcategories).
5	Available data and/or information indicate that at least one designated use is not supported and a TMDL* may be needed (4 subcategories).

* TMDL is the total maximum daily load of a constituent, which is "the maximum amount of a pollutant allowed to enter a water body so that the water body will meet and continue to meet water-quality standards for that particular pollutant" (NMED, 2021a).

support their designated use (category 1) and those that do not support their designated uses (categories 3 and 4) have increased commensurately. Sixty-five percent of the lakes in New Mexico are impaired, meaning that their water quality does not support the lakes' designated use. Figure 9.1 shows that there has been virtually no change in the fraction of lakes that are impaired since 2008.

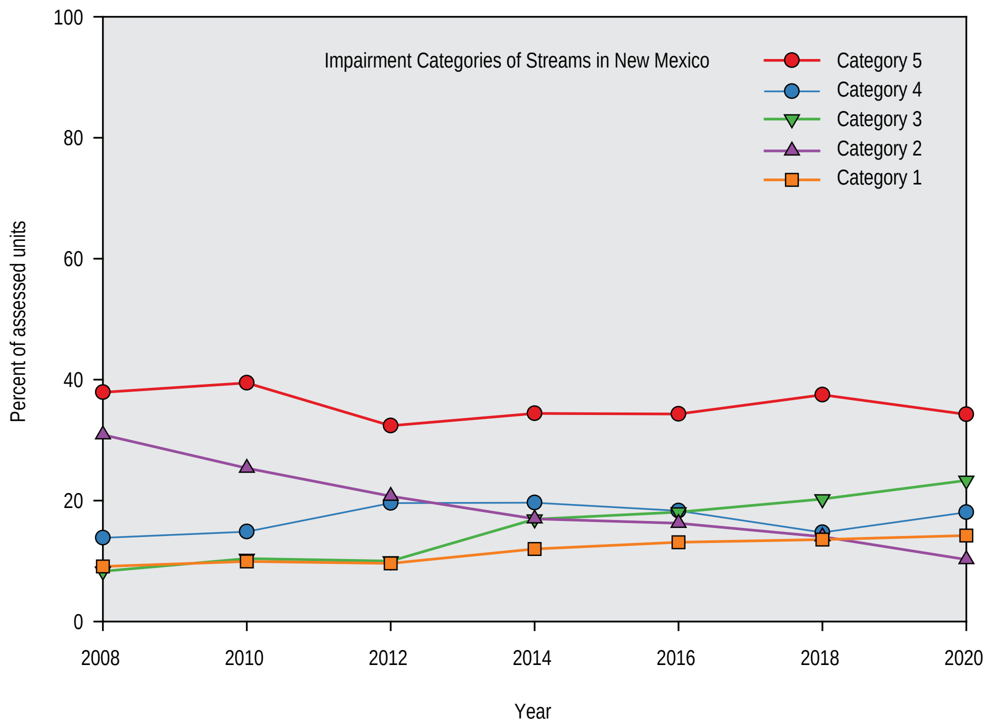
The principal causes of impairment of streams and rivers are shown in Figure 9.2 and the causes of impairments of lakes and reservoirs are shown in Figure 9.3 (NMED, 2021a). The three primary causes of stream impairment are excessive temperatures, high concentrations of nutrient and eutrophication, and high concentrations of *E. coli* bacteria. All are likely to be affected by a warming climate, especially temperature. Excessive temperature has caused impairment of over one-third of the state's streams. Temperature limits are primarily established to protect fish and related aquatic life. The maximum temperature limits to support each type of aquatic life are summarized in Table 9.3 (20.6.4.900 NMAC). Temperature is an especially important parameter because it affects the type of organisms that can survive in the stream. In addition, the solubility of oxygen in water is inversely dependent on temperature; as the temperature rises the maximum dissolved oxygen (DO) content of water decreases. Elevated water temperatures therefore contribute to impairment caused by low DO.

The principal causes of impairment of New Mexico lakes and reservoirs are mercury and polychlorinated byphenyls (PCBs) in fish tissue and temperature. Sources of mercury in New Mexico waters may include atmospheric deposition from coal-fired electric power plants, legacy impacts of gold and mercury mining, and natural leaching of mercury-containing minerals (Wentz et al., 2014). Deposition of mercury in Caballo Reservoir from a distant forest fire was documented by Caldwell et al. (2000). Polychlorinated byphenyls can occur in aquatic systems from releases of hazardous wastes or atmospheric deposition (EPA, 2021b). Except

Table 9.3. Maximum temperature limits and minimum dissolved oxygen (DO) concentrations to support aquatic life in New Mexico streams, rivers, lakes, and reservoirs (20.6.4.900 NMAC).

Designated Use	Maximum Temperature	Average Temperature	Criteria for Average[1]	Minimum Dissolved Oxygen conc. (mg/L)
Cold-water aquatic life	23°C (73°F)	20°C (68°F)	4T3	6.0
Marginal cold-water aquatic life	29°C (84°F)	25°C (76°F)	6T3	6.0
Cool-water aquatic life	29°C (84°F)	-	-	5.0
Marginal warm-water aquatic life	32.2°C (90°F)	-	-	5.0
Warm-water aquatic life	32.2°C (90°F)	-	-	5.0

Note: 1-The average temperature limits for cold-water and marginal cold-water aquatic life are based on temperature for 4 (4T3) or 6 (6T3) consecutive hours in a 24 hr period on more than 3 consecutive days.



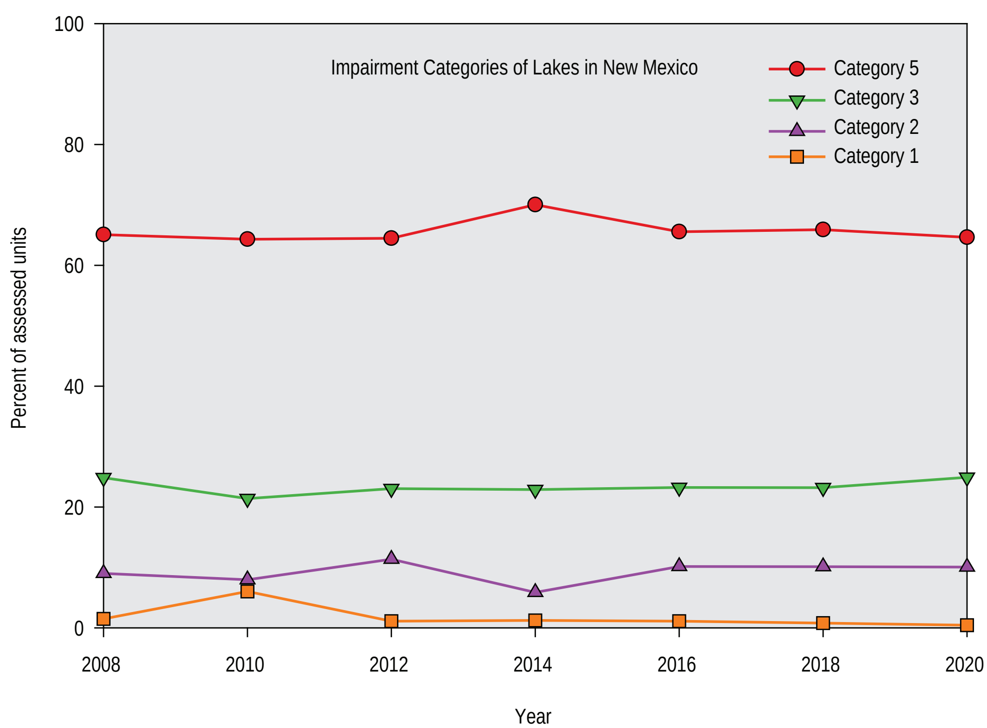


Figure 9.1. Summary of the impairment categories of assessed streams and lakes in New Mexico (NMED, 2021a). A description of the assessment categories is provided in Table 2.

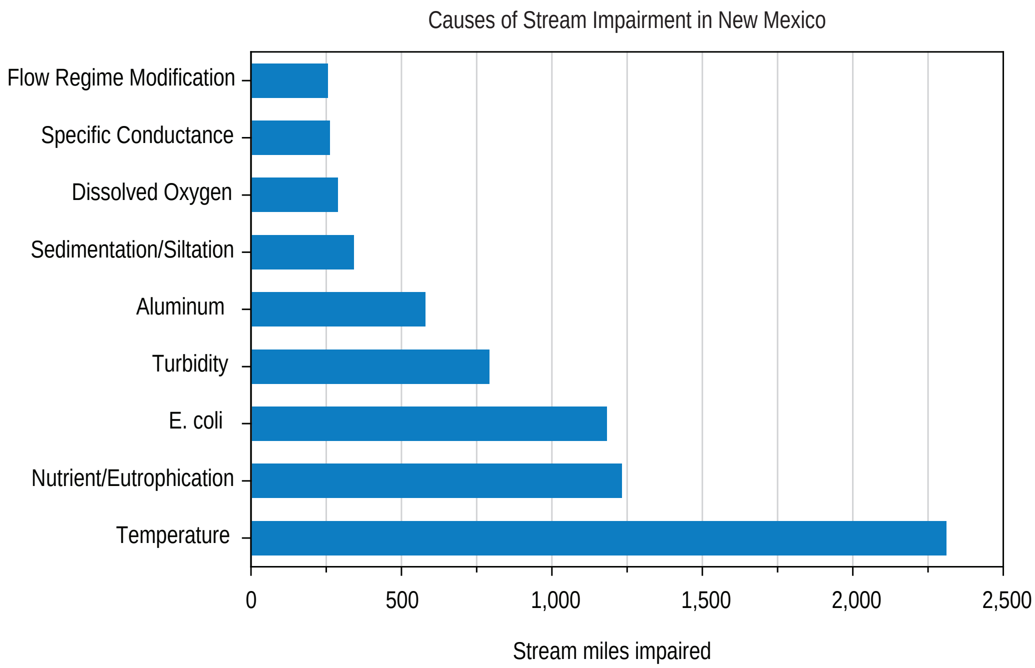


Figure 9.2. Principal causes of surface-water impairment of streams and rivers (NMED, 2021a).

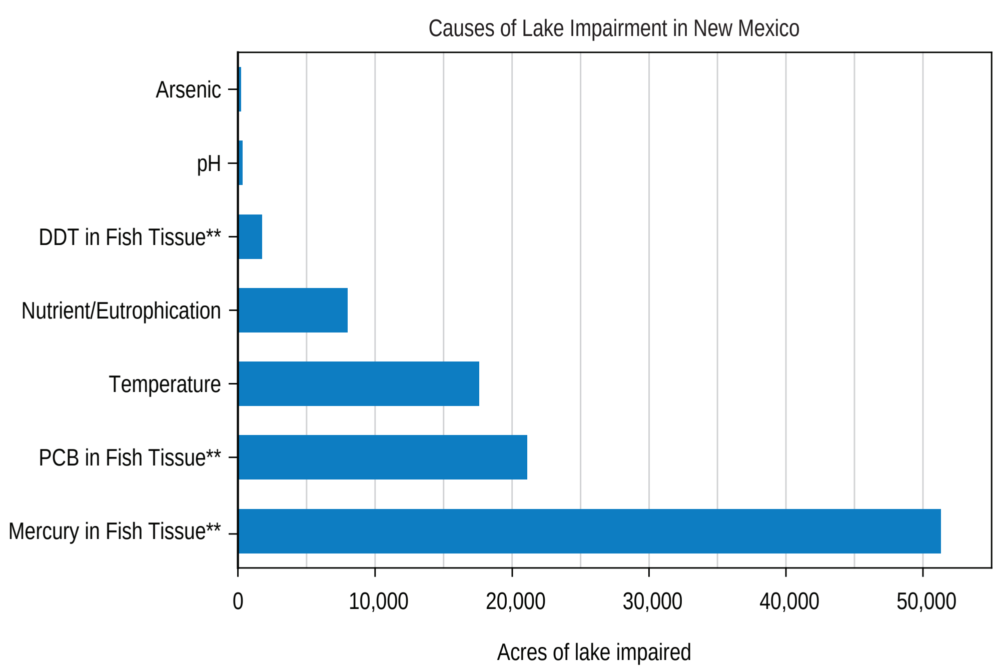


Figure 9.3. Principal causes of surface-water impairment of lakes and reservoirs (NMED, 2021a). **Based on current fish consumption advisories and 0.3 mg/kg methylmercury in fish tissue criterion.

for increasing forest fires, it is not clear that either the occurrence of mercury or PCBs will change in response to a warming climate.

The sources of impairment for surface waters include point source discharges, non-point source discharges, stormwater runoff, impacts caused by poor management of the watershed and/or the riparian environment, and runoff following catastrophic fire events. The sources of impairment of streams and rivers in New Mexico identified in TMDL reports by NMED (2021a) are summarized in Figure 9.4. Most of these sources are not directly affected by a warming climate and only 8% of the probable sources of impairment are due to drought-related impacts. However, degradation of watersheds as a result of increasing aridity, overgrazing, and increasing frequency of range and forest fires are likely.

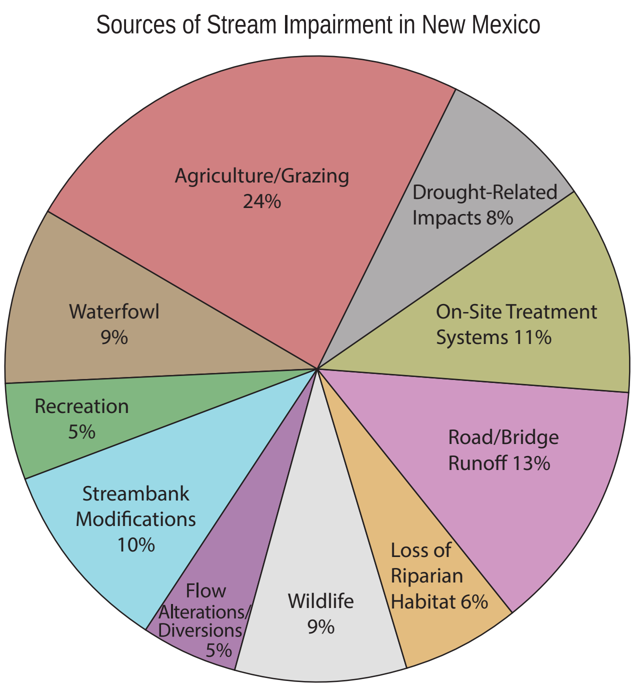


Figure 9.4. Probable sources of surface-water impairment in streams and rivers of New Mexico as reported in approved TMDLs (NMED, 2021a).

Impacts of Climate Warming on Water Quality Parameters

The 303(d)/305(b) list (pg. 52, NMED, 2021a) has a brief section on the impacts of drought and climate warming on water quality. These impacts may include increased pollutant concentrations due to reduced flows caused by evaporation, warmer water temperatures, enhanced algal production, and lower DO levels, however, the degree to which these impacts may increase was not discussed.

Nearly all of the causes of impairment of streams, rivers, and lakes identified in Figure 9.2 and Figure 9.3 are due to nonpoint-source pollution. The one exception is nutrients from wastewater discharges, although most wastewater treatment plants have discharge permits requiring them to control nutrient releases, and most reliably comply with these requirements. Nonpoint-source pollution is the primary cause of impairment for streams, rivers, and lakes in the U.S. (EPA, 2021c). Constituents that affect stream water quality include: dissolved solids, which increases salinity; inorganic contaminants including metals and non-metals; nutrients, principally compounds containing nitrogen (N) and phosphorous (P); and organic constituents, both natural organic matter (NOM) and anthropogenic compounds. Based on the assessments in the 303(d)/305(b) Integrated Report (NMED, 2021a), the principal contaminants of concern that may be affected by a warming climate are nutrients, metals (principally aluminum) and salinity (Figs. 9.2 and 9.3). Impairments caused by mercury, PCBs and DDT in fish tissue are not directly influenced by a warming climate and are not discussed here.

The EPA (2017) published the results of a national assessment of the impacts of climate change on a variety of economic and social issues including health, infrastructure, electricity generation, water resources (including both water supply and water quality), agriculture and ecosystems. The study used the results of a suite of global climate models (GCMs) as input to appropriate models to predict the effects of climate warming on each. Two water-quality models were used: Hydrologic and Water Quality System (HAWQS) and US Basins (Fant et al., 2017). The largest impacts predicted in the Southwest are loss of habitat for cold-water fish and damage to watersheds by wildfire (EPA, 2017; Fant et al., 2017).

The modeling effort by EPA (2017) shows a large increase in water temperature and moderate decrease in DO in New Mexico (Fig. 9.5). Modeling details were discussed by Fant et al. (2017). The source of nitrogen and phosphorus in the models was primarily from runoff from non-point sources. The total load of each nutrient was not projected to increase much in the Southwest through 2090. However, the nutrient concentrations were projected to increase because their load was transported by a smaller volume of water. The HAWQS model predicts a large increase in nitrogen concentrations by 2090, whereas the US Basins model predicts a decrease in nitrogen concentration. The difference between the two models is explained by the differences in flow predicted by the two water models; the HAWQS model predicts a greater reduction in river flow by 2090 than the US Basins model, thus a similar nitrogen loading will result in a higher concentration (Fant et al., 2017). Both models predict an increase in the concentration of phosphorus in New Mexico streams primarily as a result of reduced flow. Note that the scale of this modeling effort was limited to eight digit HUC watersheds, which was quite coarse. Thus, the conclusions of this study should be considered as possible consequences rather than definitive predictions.

A recent paper by Coffey et al. (2019) consists of a review of studies of impacts of a warming climate on water quality in watersheds throughout the U.S. The parameters considered were nutrients, sediments, pathogens and algal blooms. This paper also confirmed that nutrient loads are primarily from non-point sources and cited mechanisms that might increase these loads (more agricultural activity due to a longer growing season and greater runoff from more intense storms) or decrease these loads (more nutrient uptake by plants and increased denitrification as a result of warmer temperatures). They report that the effects of future changes in land use and climate on nutrient loads are uncertain.

Aqueous nutrient concentrations (N and P) and sediment concentrations were generally predicted to increase east of the 100th meridian and decrease in western states. Only a few studies were identified in the summary paper by Coffey et al. (2019) in the four-corner states and only one was done in New Mexico. All four studies predicted decreases in N and P sediment loads. The N and P loadings published by Fant et al. (2017) varied depending on the GCM used. Water-quality modeling using one set of models predicted an increased loading for both constituents while another set predicted a decrease. The difference was primarily attributable to nonpoint-source runoff, the quality of which is difficult to reliably predict. The overall conclusion from the three studies cited here is that the future effects of climate warming on nutrient loads and concentrations are uncertain.

The likely effect of a warming climate on temperature and *E. coli* is briefly discussed below, as are the water quality impacts of forest fires.

Temperature and Dissolved Oxygen—Figure 9.2 and Figure 9.3 show that temperature is the principal cause of impairments to New Mexico streams and the third most frequent cause of impairments of lakes. Although there is wide agreement that the climate of New Mexico is warming (see Chapter 2), the influence of air temperature on water temperature is difficult to predict. The EPA (2017) and Fant et al. (2017) nationwide studies regarding the impacts of climate warming on water quality predicts 2° to 5°C (3.6° to 9°F) increases in the temperature of New Mexico streams, however, the coarse nature of this study introduces uncertainty regarding how well the projections may apply to any particular locality.

Increased water temperature affects dissolved oxygen (DO) as the saturated solubility of DO in water is inversely dependent on water temperature. In addition, the saturated DO concentration decreases with elevation, a factor that is often overlooked but is especially important in high altitude New Mexico streams. The relationship between maximum DO concentration, temperature and elevation is summarized in Figure 9.6. Thus, although temperature is a frequent cause of impairment of streams, rivers, and lakes, high water temperatures are also an important contributor to low DO concentrations.

The temperature of a stream is influenced by three principal factors: air temperature, flow, and riparian vegetation. Two different approaches have been used to characterize the relationships between climate and stream-water temperature. The first is to use historical data to correlate water temperatures to changes in air temperature. This method compiles historical records of water and air temperature, streamflow, watershed characteristics and other relevant information, then uses statistical methods such as multiple regression to determine the effect that each parameter has on temperature. Isaak et al. (2012) used this method to analyze data from 1980 to 2009 to estimate the effects that a warming climate will have on cold-water streams in the Pacific Northwest. The limitations of this approach are mainly due to the large natural variations in water temperature that make detecting a long-term trend difficult. The limitations have been discussed by Arismendi et al. (2014). The second method is a mechanistic approach in which all of the heat fluxes into and out of the water are calculated and used to predict water temperature changes (see for example, Sinokrot et al., 1995). The challenge with this approach is determining values for the large numbers of site-specific input parameters needed to accurately model the temperature in a particular stream.

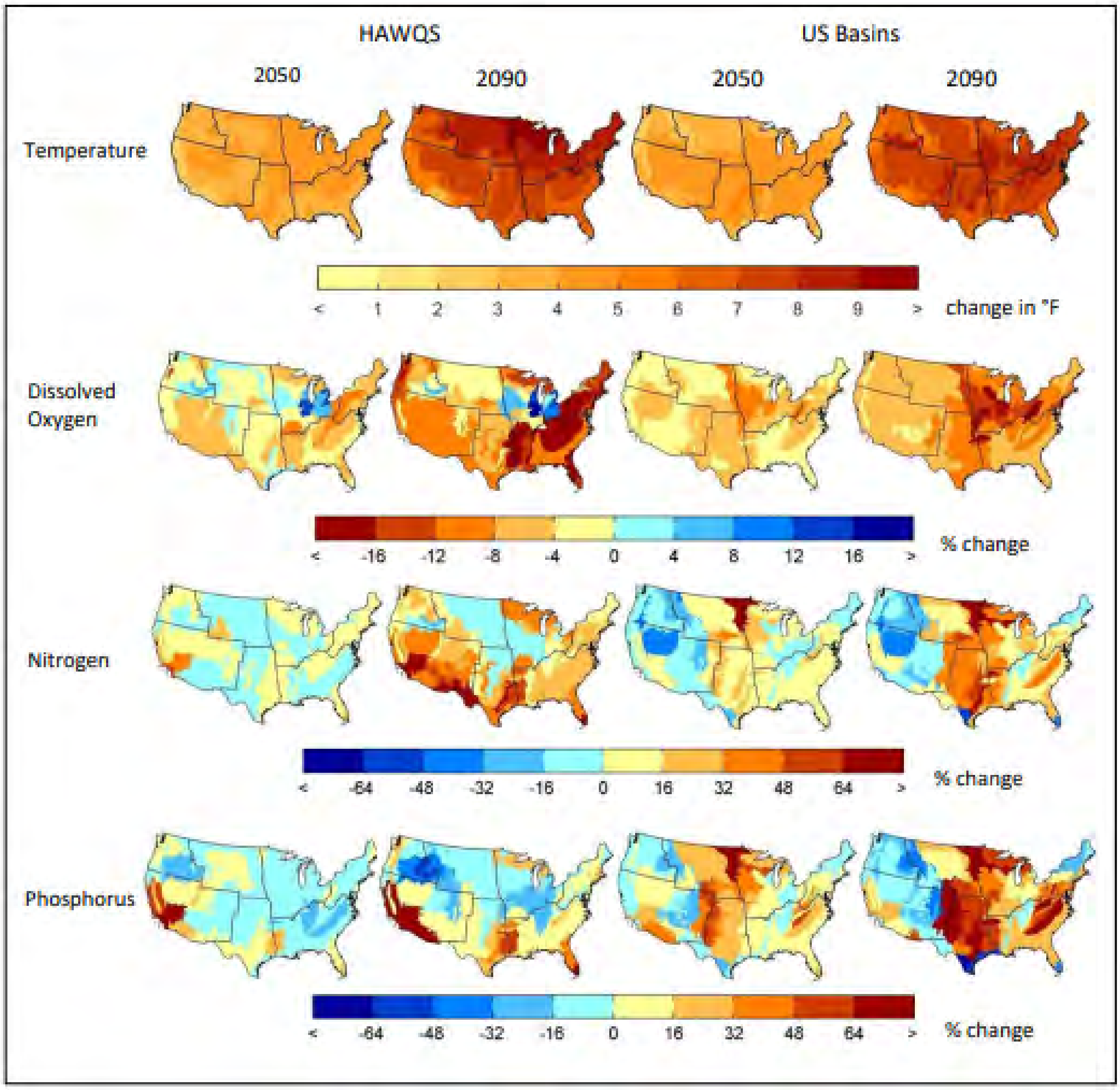


Figure 9.5. The effects of climate change in water-quality parameters under RCP8.5 in 2050 (2040–2059) and 2090 (2080–2099) relative to the reference period (1986–2005). Results for each eight-digit HUC represent the average values across the five GCMs, and are aggregated to the Level-III Ecoregions (EPA, 2017).

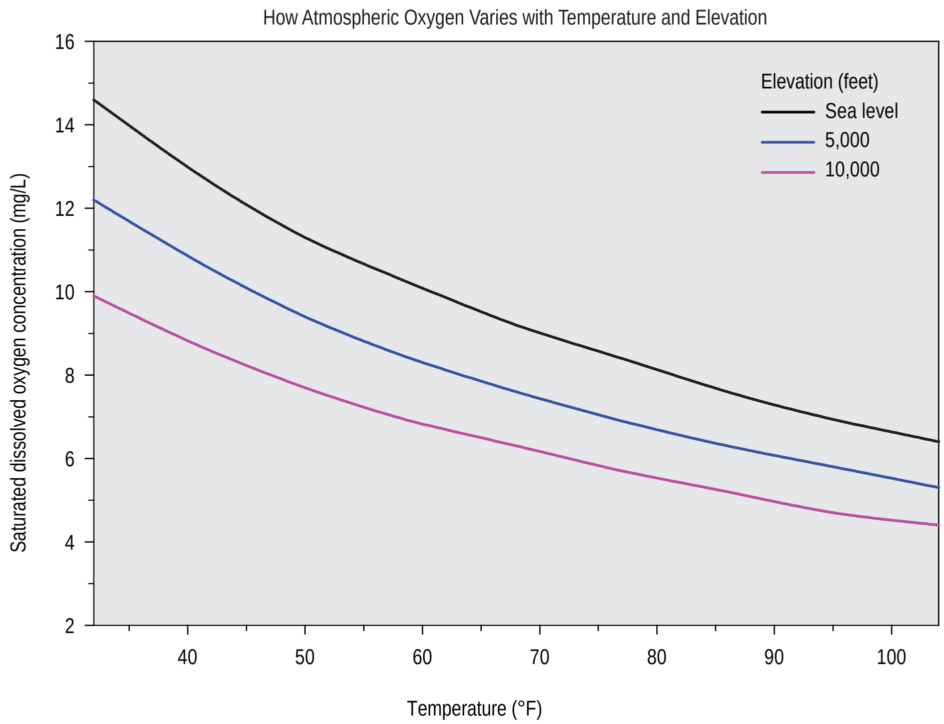


Figure 9.6. Dependence of the saturated dissolved oxygen concentration (mg/L) in equilibrium with the atmosphere on temperature and altitude.

Paul et al. (2019) published a recent review of the impacts of a warming climate on flow, water temperature and salt-water intrusion. Nearly all studies of watersheds throughout the U.S. were expecting to experience increased water temperature. No studies were found for New Mexico streams. Wondzell et al. (2019) provided a recent review of studies of the effects of climate warming on northwestern U.S. cold water streams, then used a mechanistic heat budget model to determine the effects of each factor under varying conditions of climate warming. The study area was the Middle Fork of the John Day River in northeastern Oregon, a region of the country and a stream with many similar characteristics of perennial streams in northern New Mexico. Air temperature increases of 2°C (3.6°F) and 4°C (7.2°F) were modeled and flow changes of ±30% were considered (as described in the paper and Chapter 3). The effects on water temperature of riparian shade, a 4°C (7.2°F) increase in air temperature, and ±30% change in flow for seven days, all compared to a 2002 baseline, are shown in Figure 9.7. The effect of shade was modeled by considering the loss of riparian vegetation due to a catastrophic wildfire, followed by regrowth of a young open forest.

Wondzell et al. (2019) found that “shade was by far the biggest single factor influencing future stream temperatures” as has been found in previous studies. It affects temperature in two ways. First, loss of vegetation allows direct exposure to sunlight, which increases water temperature and reduces heat loss by long wave radiation. Secondly, heat loss due to increased evaporation results in large diurnal swings as is shown in Figure 9.7a. These large daily variations resulting from loss of riparian vegetation may have an effect on aquatic cold-water organisms both as a result of afternoon high temperatures, but also because increasing the water temperature by roughly 10°C (18°F), for example from 20° to 30°C (from 68° to 86°F), would result in the saturated DO concentration dropping from 7.6 mg/L to 6.3 mg/L at 5,000 ft elevation.

The study by Wondzell et al. (2019) considered loss of riparian vegetation as a result of wildfire. However, in New Mexico a much more frequent cause is destruction by grazing animals, including

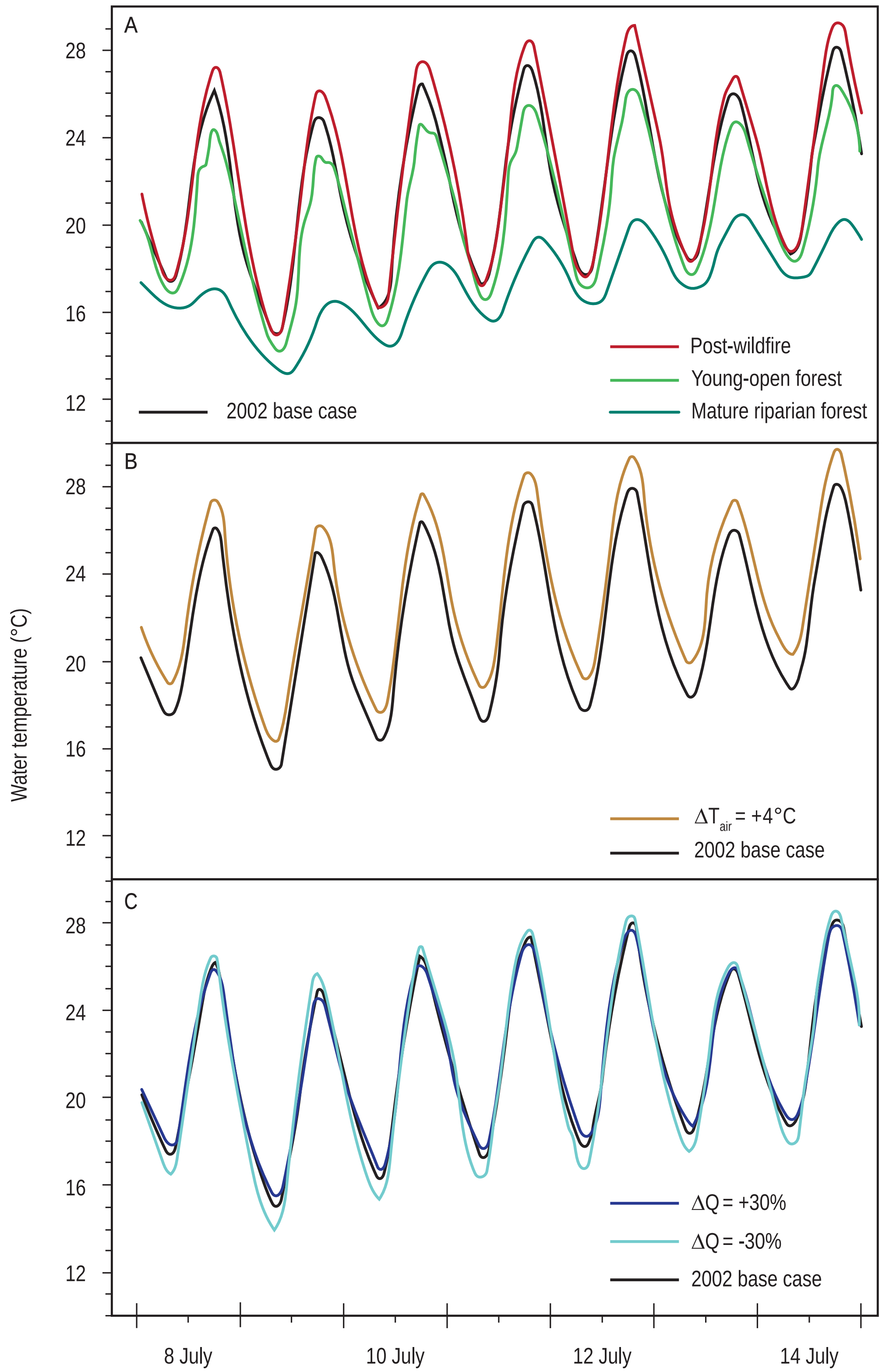


Figure 9.7. Hourly stream temperature time series at RKM 14.05 for the seven-day period over which the heat budget is summarized (from Wondzell et al., 2019, fig. 3). (a) Four riparian vegetation scenarios with 2002 base-case conditions for air temperature (T_{air}) and discharge (Q). (b) Two air temperature scenarios with 2002 base-case conditions for riparian vegetation and Q. (c) Three discharge scenarios with 2002 base-case conditions for riparian vegetation and T_{air}.

cattle, sheep, and wildlife (Lucas et al., 2004; Lucas et al., 2009; Clary and Kruse, 2004; Thibault et al., 1999). The NMED nonpoint-source management program supervises an extensive watershed improvement program using federal funds under Section 319 of the Clean Water Act (NMED, 2021b). Much of the effort is devoted towards restoring a healthy riparian environment through construction of grazing animal exclusion zones (i.e., fencing) (Swanson et al., 2015; Nusslé et al., 2015). The benefit of these programs is illustrated in Figure 9.8, which shows the effect of different range management strategies on riparian vegetation on the Sapello River north of Las Vegas, New Mexico. The ranch in the right side of the photo allows animals to graze and wander into the stream, whereas that on the left side limits access of cattle and other ungulates to the river. Limiting grazing access to the river on this ranch has resulted in growth of a rich and diverse riparian forest that helps control water temperature and also improves the habitat for fish, birds, and aquatic mammals (i.e., beaver and muskrat) (Thomson and Ali, 2008).

***E. coli* Concentrations—**High concentration of *E. coli* bacteria is the third leading cause of stream impairments in New Mexico, especially in lower elevation, slower flowing warm streams (see Figure 9.2). *E. coli* is an enteric bacteria that lives in the gut of warm blooded animals and is regulated as an indicator of fecal contamination. This organism and other enteric bacteria are often referred to as fecal indicator bacteria (FIB). Since human waste may contain pathogenic microorganisms, the presence of FIB in water is a suggestion that the water may be a threat to human health. The sources of *E. coli* may include discharges from improperly functioning

Figure 9.8. Photograph of the boundary between two ranches on the Sapello River showing the effects of different management strategies on riparian vegetation. *Photo by Bruce M. Thomson (2021)*

wastewater treatment plants, stormwater discharges, runoff from agricultural activities, leakage from on-site wastewater treatment systems (i.e., septic tank systems), and illicit discharges (EPA, 2010). Wastewater treatment plants have very stringent discharge limits for *E. coli* as well as frequent monitoring requirements and are therefore not considered a major source for this constituent. High concentrations of *E. coli* and other FIB organisms in natural waters is assumed to be due to the presence of fecal contamination from warm-blooded animals. Besides humans, this may include domesticated animals (cats and dogs), livestock, terrestrial and aquatic mammalian wildlife, and birds, especially waterfowl.

The Middle Rio Grande flowing through Albuquerque is a reach of stream that persistently is impaired as a result of high concentrations of *E. coli* that have been attributed to stormwater and nonpoint-source runoff. An EPA-approved total maximum daily load (TMDL) determination was completed for this reach of the river in 2010 (EPA, 2010), however, water-quality data continue to document exceedances of the stream standards in spite of aggressive implementation of control strategies (AMAFCA, 2018). This experience illustrates the difficulty of meeting stream standards for this constituent.

However, there is a growing body of literature that shows that *E. coli* can grow in warm organic-rich sediments in streams, rivers and lakes. A comprehensive review of growth of *E. coli* in natural environments has been provided by Fluke et al. (2019) to support their recent study that found strong evidence of natural regrowth of *E. coli* occurring in sediments of the middle Rio Grande. This study sampled river water and bottom sediments at six locations along the river from north of the town of Bernalillo to south of the discharge of the Southside Water Reclamation Plant (SWRP), a 3.33 m^3/sec (76 Mgal/d) advanced wastewater treatment plant near the southern boundary of the city.

The results are summarized in Figure 9.9 and show a strong correlation between *E. coli* in suspension and *E. coli* in stream bed sediments. The highest concentrations of both were in the summer and fall when water temperatures were highest. Furthermore, the concentrations increased at the southern sampling sites that corresponded to the flattest slope, slowest river velocities, and deepest and finest sediment accumulations.

High concentrations of fecal indicator bacteria such as *E. coli* are often present in urban stormwater runoff (Thomson, 2021) and watershed management measures need to be implemented to control this type of pollution. However, the contribution of urban runoff to most New Mexico streams and rivers is small. The results of Fluke et al. (2019) and studies cited by them suggest that *E. coli* concentrations will increase as future water temperatures increase, especially in low-energy streams with fine-grained, organic-rich, bottom deposits. Exceedances of stream standards for this parameter will therefore cause increased surface-water impairments in New Mexico.

***Impacts of Forest Fires*—**As the climate warms, the number and size of forest and range fires is expected to increase, as discussed in Chapter 6 of this report. This has three major effects on watersheds, primarily resulting from the increased volume and velocity of runoff from burned land. These effects are as follows: catastrophic erosion of land, stream channels and conveyance structures by debris flows; accumulation of rock, mud, and burned vegetation in reservoirs and stream channels; and water-quality degradation by suspended sediment and dissolved constituents leached from the burned watershed. A discussion of the mechanisms and controls affecting debris flows on burned and unburned hillslopes for two forests in New Mexico has been provided by Tillery and Rengers (2020) and Tillery and Haas (2016). The discussion in this section focuses on the effects of post-wildfire runoff on surface-water quality. Other impacts are discussed in Chapters 4 and 6.

The impacts of post-wildfire runoff on water quality may include high concentrations of sediments, nutrients, organic compounds and metals. High concentrations of these constituents contribute to impairment of receiving waters. For example, nutrients and/or metals may leach from sediments transported to the stream by runoff, while biodegradation of organics in sediments and in solution can cause sufficiently low DO concentrations to result in widespread fish kills. Postfire impacts on water quality contribute to at least ten of the top twenty causes of impairments listed by the EPA (2017).

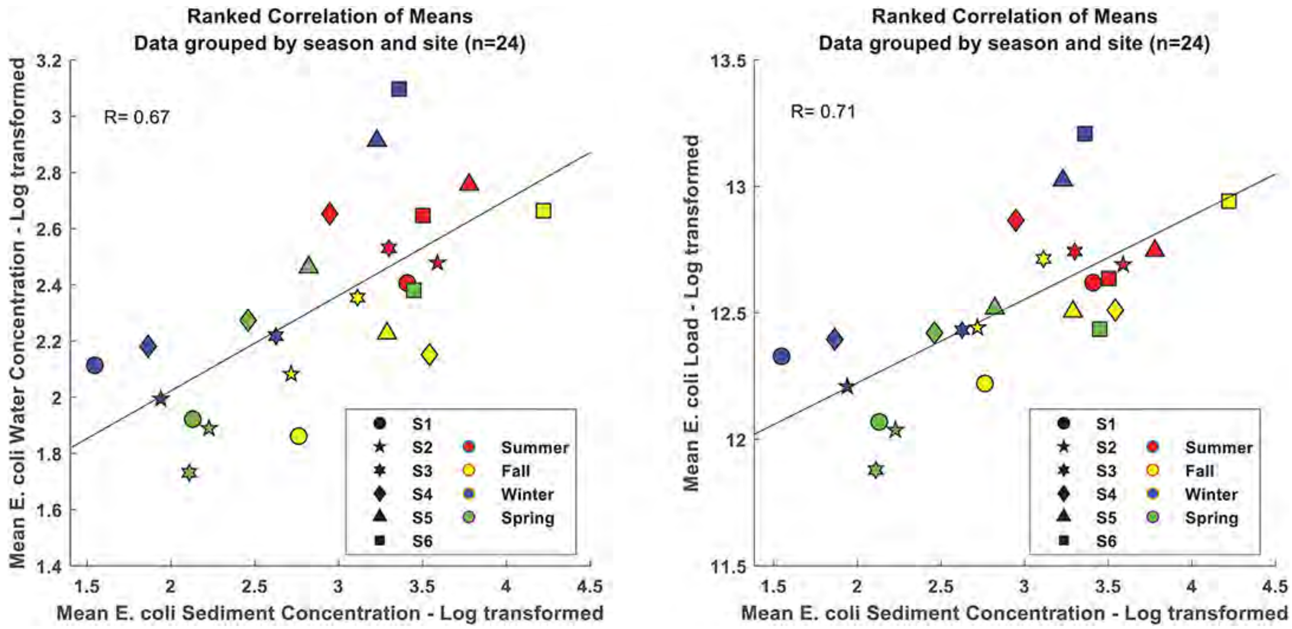


Figure 9.9. Correlation between *E. coli* water and sediment concentrations (left) and *E. coli* water loads and mean *E. coli* sediment concentrations in stream bottom sediments in the Middle Rio Grande (right). Sites are numbered from upstream extent of the watershed (site S1) to downstream extent (site S6) (Fluke et al., 2019).

While there is a growing body of literature on postfire impacts on water quality, perhaps the most relevant is a recent paper by Ball et al. (2021), which looked at spatial and temporal increases in stream impacts between 1984 and 2014 on western streams and rivers. They found that wildfires directly impact ~6% of total stream and river miles in the western U.S. and that the length of impacted streams is growing at a rate of 342 km/yr.

The effects of the 2011 Las Conchas fire in the Jemez Mountains on Rio Grande water quality received special attention (Ball et al., 2021) and built upon previous work by Reale et al. (2015). The analysis showed that monsoonal rainstorms after the fire resulted in DO concentrations dropping below the New Mexico stream standard. Data from water-quality monitoring instruments was used to calibrate a numerical model to estimate that DO sags of > 0.5 mg/L extended at least 388 km downstream from the headwaters of one of the streams in the burned area (Fig. 9.10). Transient extreme DO depletions could jeopardize aquatic life, especially cold-water game fish that require high DO concentrations to survive. They note that effects of other parameters, including ash, nutrients and metals, likely extended farther downstream than those affecting DO.

A broader analysis of the water-quality impacts of post-wildfire runoff was conducted by Gallaher and Koch (2004) following the 2000 Cerro Grande fire in the Jemez Mountains. This fire burned approximately 3,000 ha (7,400 acres) of property owned by Los Alamos National Laboratory (LANL) and about 4,000 ha (10,000 acres) of watershed above the lab that drains through lab property. The report describes four years of extensive monitoring of the hydrologic and water-quality impacts of the fire. Knowledge gained on the impacts of a large fire on a forested watershed in New Mexico are especially valuable because the watershed was well instrumented and intensively studied both before and after the fire, which allowed a thorough understanding of the nature and extent of degradation of the watershed and streams, and the impacts on water quality. Continued reported monitoring also provided information about the recovery of the watershed in the four years after the fire.

Wildfire impacts on this watershed were unusual because of the presence of the National Laboratory and the nature of the contaminants. Portions of the property owned by LANL have high concentrations of radionuclides from legacy laboratory activities, therefore special attention was paid to their concentration in runoff.

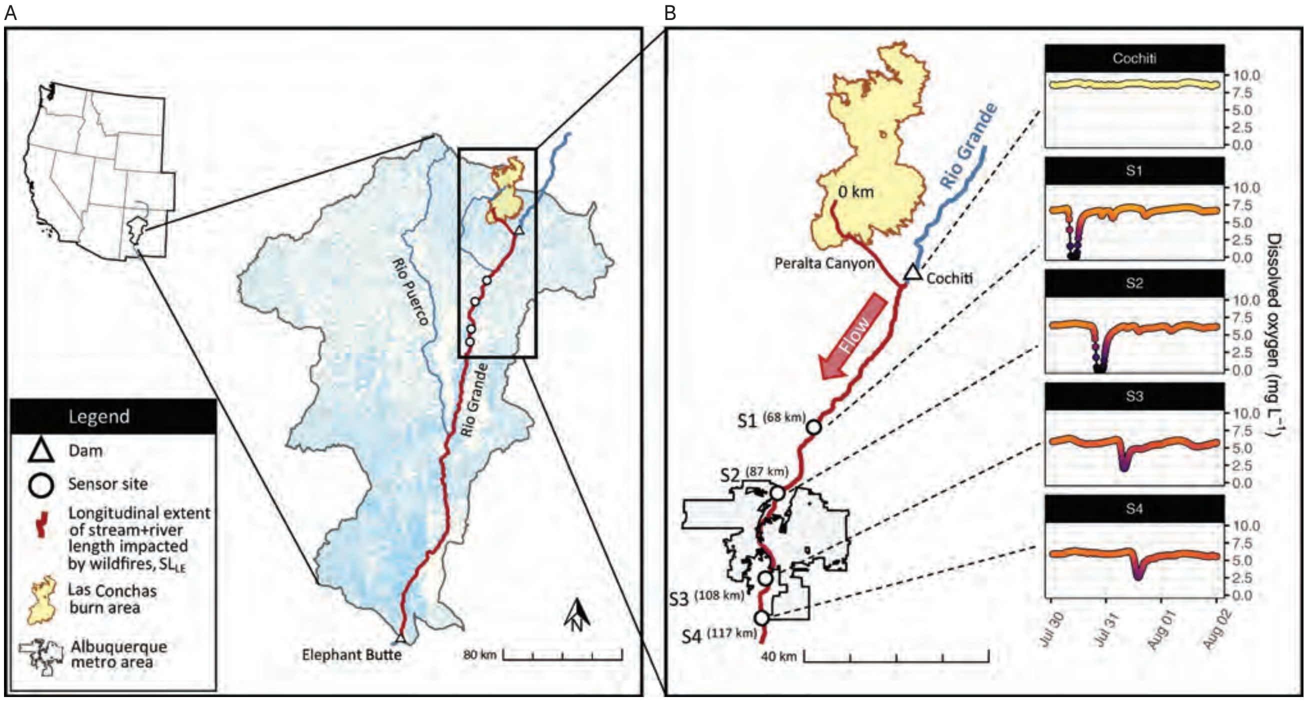


Figure 9.10. Summary of impacts of Las Conchas fire on dissolved oxygen concentrations in the Rio Grande (Ball et al., 2021).

The concentrations of major constituents (total suspended solids, major cations and anions, nutrients, and cyanide) increased immediately after the fire but dropped to near-background levels, generally within two to three years. The one exception was suspended solids, which remained high over the four-year duration of the study due to soil loss from the watershed. Concentrations of radionuclides in runoff immediately following the fire increased from 10 to 50 times those in pre-fire samples depending on the constituent. These radionuclides included radioactive isotopes of americium (Am), cesium (Cs), strontium (Sr), plutonium (Pu), and uranium (U). Ninety-five percent or greater of these contaminants were associated with suspended solids that were mobilized by the fire. Dissolved concentrations of radionuclides and minor constituents generally met federal drinking water standards. Twenty-five metals were analyzed in runoff from the watershed. All of the constituents detected at concentrations greater than surface or groundwater standards were attributed to natural sources, not laboratory activities. Most metals were associated with suspended solids. Consequently their soluble (i.e., filtered) concentrations generally met applicable water-quality standards. A broad suite of organic compounds were analyzed in runoff including explosive compounds and PCBs. Ninety percent of the samples had concentrations of organic compounds that were below applicable standards.

In addition to the effects of postfire runoff on the aquatic environment, poor water quality may affect utilities that rely upon surface water as their source of supply. In addition to mobilizing suspended solids, ash, and metals, as was reported by Gallaher and Koch (2004), runoff from burned watersheds may include pyrogenic-dissolved organic matter (i.e., dissolved combustion products) that cause color, taste, and odor problems that is difficult to remove by conventional water treatment (Chow et al., 2021). Furthermore, if the fire burns a developed rural community, subsequent runoff may contain hazardous and/or toxic compounds from combustion of cars, houses, and commercial buildings. Fire in such a community also destroys water infrastructure such as pump houses, water tanks, and above-ground components in a water distribution system.

Concern about poor water quality following the Las Conchas fire and its impact on the water treatment system caused the Albuquerque Bernalillo County Water Utility (ABCWUA) to discontinue withdrawing surface water from the river for two months. This utility was able to take this action because it has sufficient capacity of groundwater to meet its needs in the event of disruption of its surface-water supply. Utilities that rely upon surface water without an alternate source of water may face drinking-water-quality challenges that cannot be met by their water treatment systems.

Summary and Research Gaps

New Mexico and many of the Pueblos and Tribal Nations in the state have developed scientifically-based water-quality standards for the streams, rivers and lakes that have been approved by the USEPA (EPA, 2021a). These standards have been developed to protect the designated uses of these streams, including anthropogenic uses such as drinking-water supply and agricultural use, as well as to protect the quality of the aquatic environment. The NMED publishes an assessment of the quality of the surface waters in the state every two years that identifies whether the quality is sufficient to support the designated use for each identified stream segment (NMED, 2021a). The four major causes of impairment of streams and rivers include (in descending order) temperature, nutrients and/or eutrophication, the presence of *E. coli* bacteria and turbidity (Fig. 9.2). High water temperatures are especially problematic and result in impairments of roughly one-third of the total length of perennial streams in the state. The four major causes of impairment of lakes are mercury and PCBs in fish tissue, temperature, and nutrients and/or eutrophication (Fig. 9.3). The water-quality issues that are likely to be of increasing concern due to climate warming are temperature and *E. coli* concentrations. Future changes in nutrient concentrations and eutrophication are uncertain but not predicted to be problematic, however, they have not been the subject of much investigation.

The impact of wildfires on water quality is also of concern and may result in high concentrations of sediments, nutrients, organic compounds and metals. A recent study has found that the length of streams impaired by post-wildfire runoff is increasing in the western U.S. (Ball et al., 2021). Further, this study found that DO sags extended up to 388 km downstream from the burn area of the 2011 Las Conchas fire during summer monsoon rains. Because of water quality concerns from this watershed following the fire, the ABCWUA curtailed withdrawals of Rio Grande water for its public water supply for two months. This experience demonstrates that post-wildfire runoff may have effects on public water supplies as well as impacts on the aquatic environment. Intensive monitoring of a watershed on and above the Los Alamos National Laboratory following the 2000 Cerro Grande fire found elevated concentrations of major constituents (total suspended solids, major cations and anions, and nutrients), metals and radionuclides (Gallaher and Koch, 2004), however, these constituents were primarily associated with high suspended sediment concentrations. The dissolved concentrations of these constituents nearly all met applicable water-quality standards.

Knowledge Gaps

The NMED has an effective surface-water quality monitoring and assessment program that provides a considerable amount of quantitative and descriptive information on the status of lakes and perennial streams in New Mexico. However, as this chapter has shown, there has been little research to describe and quantify possible impacts of a warming climate on these bodies of water. Information and/or studies that might be implemented to address this deficiency include:

- The wealth of existing NMED surface-water quality data has not been comprehensively examined to determine if climate warming, change in watershed characteristics (e.g. urbanization or changing agricultural practices), or other factors, have impacted watershed characteristics.
- Long term water-quality monitoring stations at key locations might be correlated to a warming climate or other factors.
- Modeling studies have not been done on New Mexico water bodies that could identify impacts of a warming climate.
- It is not clear if there is an agency or organization that has responsibility for compiling, analyzing, and reporting changes in water quality with time. Such an agency or organization might also serve to coordinate cooperative investigations into future impacts.

X. SUMMARY OF STATEWIDE AND REGIONAL IMPACTS OF CLIMATE CHANGE ON WATER RESOURCES

Nelia W. Dunbar, Fred M. Phillips and David S. Gutzler

All regions of New Mexico will be affected by climate change, but the topographic complexity of the state will generate distinct impacts by location. The average temperature will warm across the state, probably between 5° and 7°F, whereas average precipitation is likely to remain constant, even if more variable from year to year, with the possibility of more extreme precipitation events. Snowpack, runoff, and recharge will decline, stressing both surface and groundwater resources. Surface-water quality will decline. Plant communities will be stressed by higher temperatures and greater aridity, leading to more extreme wildfires and increased erosion. Damage to soils, related to a number of factors, will create greater atmospheric dustiness and lower water infiltration to aquifers.

Although latitude plays a role in the effects of climate change, the bigger impact in New Mexico is related to local topography and elevation. For the purposes of this report, we are dividing New Mexico into four physiographic regions, based on projected climate change impacts and associated effects on hydrology. These four regions, which are defined by a combination of latitude and topography, are: the High Mountains (northern mountains, Gila/Mogollon–Datil, and Sacramento Mountains); the Northwestern High Desert (Colorado Plateau, San Juan Basin, and Zuni Mountain region); the Rio Grande Valley and Southwestern Basins; and the Eastern Plains.

Changes in New Mexico's climate and consequent impacts on water resources over the next 50 years will affect all parts of our state. Many effects will be felt statewide, and also across all of southwestern North America. However, as outlined in Chapters 2–9 of this report, numerous factors influence how the impacts will be felt in different parts of New Mexico. Furthermore, simply dividing the state into regions based on a map view does not capture the variability in impact that will be experienced. The elevation and presence of mountainous topography strongly influences the types of impacts that will result from climate change. Local climate varies as a function of elevation, and influences the types of vegetation present in any given place. Changes in vegetation through wildfire or climatic warming and drying strongly influence how rainfall infiltrates into aquifers or causes sediments to mobilize on hillslopes. This is especially true during extreme rainfall events that may become more common and more intense as temperature increases. At an even more granular level, in areas of moderate to steep topography, north- or south-facing hillslopes will respond differently, largely because of the relatively higher temperatures and lower soil moisture of south-facing hillslopes, and consequent higher stress on vegetation.

The previous chapters of this report examine the anticipated impacts of climate change on water resources in New Mexico. These chapters rely on examination of effects of past climate variations on natural systems in New Mexico to provide valuable clues for understanding future climate variations and their likely consequences for our state. Although not addressed in great detail in this report, we need to recognize that there are a range of potential changes that may result from different projections of greenhouse-gas increases. There may also be tipping points, feedback mechanisms, and compounding events that would be difficult to anticipate or predict.

This chapter provides a summary of climate variations and associated hydrological impacts that will affect the entire state. Following this general summary, we will highlight what may be the dominant impacts in different physiographic regions of the state (see Fig. 6.1), recognizing that even within a given physiographic region, there may be elevation- and topography-related variations. This summary directly incorporates the detailed information presented in earlier parts of the report, so readers seeking more detail and references can consult the relevant chapters.

In some parts of the world, particularly in higher latitudes, aspects of climate change may result in effects that could be considered positive. For instance, atmospheric warming can result in longer growing seasons or more precipitation as storm tracks shift poleward. Increased CO_2 in the atmosphere is generally beneficial for plant growth. However, in the semiarid climate of New Mexico, where availability of water is critical for the health of the environment, analysis of the literature suggests that the impacts of climate change are overwhelmingly negative. A reader may have the impression that only negative effects were considered in this analysis. This is not the case. Unfortunately, the instances of positive impact on New Mexico's water resources of the projected warming and aridification appear to be vanishingly few.

Overall Summary of Impacts of Climate Change and Hydrological Impacts in New Mexico

All evidence suggests that the average temperature for all parts of New Mexico will increase over the next 50 years. Models indicate that the amount of temperature increase will depend on the amount of greenhouse gases added to the atmosphere in the future. In a higher-side greenhouse-gas-emission scenario, the average projected temperature increase across the state is a staggeringly high 7°F over the 70-year period between 2000 and 2070. In lower emission scenarios, temperature will continue to climb at a rate closer to what has been observed during the past 30 years, leading to a more modest average temperature increase of about 5°F. But, in all currently envisioned cases, temperatures statewide and around all of the southwestern U.S. will rise significantly.

There is little consensus among model projections for how total annual precipitation might change over the next 50 years, although the seasonality of precipitation may be slightly different than it is today. Also, over the next 50 years, we are likely to experience more variability in precipitation from year to year, including anomalously wet years interspersed with periods of more extreme drought. Because the temperature will be rising, episodic droughts will be hotter than in the past, and will therefore have a more detrimental effect on vegetation. The impacts of a warming climate on frequency and intensity of extreme precipitation events in the southwestern U.S. is an area of current research and considerable uncertainty. Our knowledge of atmospheric processes, as well as some models, suggests that extreme precipitation events will happen more frequently and be more intense in New Mexico, going forward. However, this projection is difficult to quantify and is supported by limited and inconsistent evidence.

Another robustly projected impact of warming temperatures over the next 50 years is that the average snowpack in the mountains on April 1, typically the time of maximum snowpack, will steadily decrease. This effect will likely be exacerbated by increased dustiness in parts of the state, which also promotes early melting of snow. This decreased snowpack will, in turn, impact the timing and quantity of runoff, reducing flow in the Rio Grande and other major snow-fed rivers. Furthermore, increased evaporation and sublimation of snowpack and subsequent runoff in a warmer climate further reduces the amount of snowmelt water that reaches rivers.

Although average annual precipitation across New Mexico is unlikely to change significantly over the next 50 years, and the incidence of extreme precipitation events may go up, we have more confidence in projecting that the aridity of the state will increase because of rising temperatures. This is because a warmer atmosphere can absorb more moisture than cooler air, so at warmer temperatures, evaporation of available water from soil and plants increases, leading to more loss of surface moisture into the atmosphere. Despite inherent uncertainties in modeled trends, or trends projected from past observations, most studies suggest that soil drying and reduction in runoff and recharge will result from future temperature increases. Most hydrological model outputs suggest declines in runoff and recharge of around 3–5% per decade for the next 50 years, leading to total 50-year declines of between 16 and 28%.

Aridification over the next 50 years will impact vegetation throughout New Mexico. The specific impacts on vegetation vary by region of the state, but, in the longer term, vegetation communities will tend to migrate northward, to higher elevations, or from south- to north-facing slopes. Plants that cannot tolerate hotter and drier conditions, including species that now grow at high elevation or in northerly parts of the state, may disappear altogether. Although vegetation, and therefore soils, will be most affected on south-facing slopes, those on other aspects will be impacted as well.

This transformation of vegetation communities is already occurring. In the short term, generalized warming and aridification has stressed vegetation communities. Within a given region, growth and productivity of plants will decline. Although higher atmospheric CO_2 has been shown to promote plant growth, in our region this effect is offset by rising temperature and aridity. Furthermore, hotter periods of droughts are likely to lead to forest die-offs, which have already been occurring in some parts of the state. Forest die-offs have been exacerbated by high-intensity fires and disease, and similar die-off events have also been observed in grasslands or shrublands. The warmer temperatures and increased aridity lead to more wildfires of higher intensity, impacting a wide range of plant communities, some of which may not be able to regenerate once burned. In terms of impact on water resources, loss of plant communities leads to destabilization of the landscape, including loss of soil cover, which reduces infiltration and recharge of surface water into aquifers. And, as outlined below, loss of vegetation also may promote increased runoff and flooding, with associated destructive effects.

Landscapes and soils are impacted by, and change in response to, changes in climate. As New Mexico's climate warms, landscapes, soils, and water resources will be impacted. These effects will vary throughout the state, as discussed in more detail below. In general, these impacts include reduced infiltration of rainfall, increased overland runoff, increased flooding, increased upland erosion by overland flow, increased downstream sediment deposition and aggradation, and increased atmospheric dustiness. Many of these changes will be exacerbated by increased intense wildfire events.

All of the factors outlined above result in reduced and less reliable water resources for New Mexico, both in terms of quality and quantity, leading to statewide water stress. With more intense and hotter droughts and associated aridity, surface-water supplies are most at risk. But, when surface-water supplies are inadequate, groundwater from aquifers may be tapped instead, depleting aquifers that generally recharge very slowly, or not at all. Extreme precipitation events may increase, providing abundant surface water to geographically small regions of the state for brief periods of time. Putting this water to beneficial use will be a priority, after changing the rules (Thompson, 2021). The associated risk of flooding and debris flows causing damage to natural systems and infrastructure is real. The flooding risk, and associated damage, will be intensified in areas that have experienced, or are downstream of, wildfires.

The likely impacts of warming climate and associated environmental effects on water quality are less well understood than the impacts on water quantity. Declines in water quality will impact water supply for human uses, as well as the water in riparian settings. The largest impact on water quality will be in terms of increased temperature of surface water, which will rise statewide, to the detriment of aquatic ecosystems. Surface-water temperatures generally rise in response to higher atmospheric temperature. However, the areas that will be impacted most dramatically are bodies of surface water not shaded by vegetation. In a warming climate scenario, losses of streamside vegetation in response to increasing temperatures, degradation of soil, and increased incidence of wildfire can create a detrimental feedback loop. Other negative impacts of water quality associated with generalized warming include lower dissolved oxygen content of water, and high concentrations of *E. coli* in surface water. Other effects on water quality may occur as well, but have not yet been studied.

Systematics of Water-Balance Change with Increasing Aridity

Over the next half century, global warming is expected to force New Mexico's climate to become more arid. Most of this increase will likely be driven by an increase in the potential evapotranspiration rate, forced in turn by increasing temperature. Precipitation seems more likely to decrease than increase, but this inference is far from certain. Chapter 3 addressed how this increase in aridity is likely to affect runoff and groundwater recharge over the entire state, but here we seek to specify these changes by region. How will increasing aridity (as quantified by the "aridity index," which is potential evapotranspiration divided by precipitation) affect runoff and recharge in low desert areas of the state, as compared to the cooler mountain tops?

This question has been addressed from a theoretical standpoint by Yang et al. (2018), who used a very simple and generalized approach known as the "Budyko framework" to evaluate the sensitivity of runoff and recharge to changes in the "aridity index." Their findings are summarized in Figure 10.1.

For high values of the aridity index, the sensitivity is very asymmetric, with a high sensitivity of runoff + recharge (Q) to changes in precipitation (P) and almost no sensitivity to changes in potential

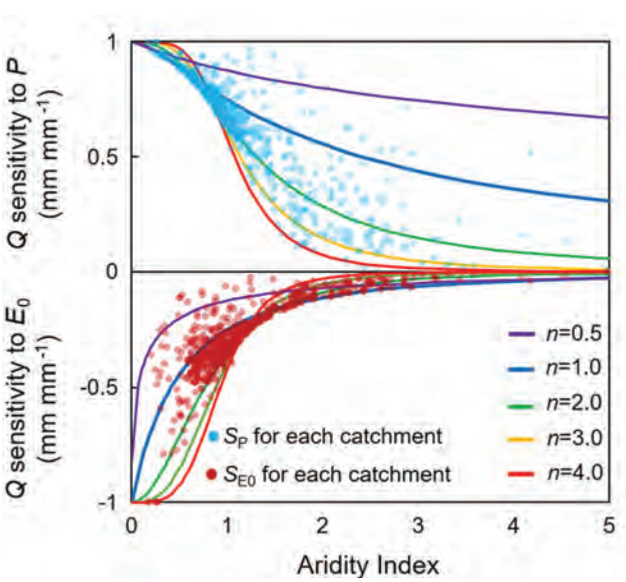


Figure 10.1. Sensitivity of Q (runoff + recharge) to changes in the aridity index (E_0/P), from Yang et al. (2018). High values of the aridity index correspond to arid climate and low values to humid climate. P is precipitation and E_0 is potential evapotranspiration (both with units of mm/yr). 'n' is a factor that accounts for the effects of processes other than P and E_0 on runoff + recharge, such as seasonality or intensity of precipitation. The red and blue dots are empirical data for change in Q as a function of change in P and E_0, from 1981 to 2010, from 710 drainage basins worldwide. They indicate the number of mm/yr that Q changed in response to a 1 mm/yr change in P or E_0. The distribution of the data points indicates that 'n' typically varies between 1 and 3 and averages about 2.

evapotranspiration (E_0). In contrast, for values of the aridity index less than one, the sensitivity of Q to the two parameters is roughly equal. Therefore, if temperature (and therefore E_0) increases (almost certain) and P decreases (likely), then areas of low aridity index will show a smaller decrease of Q than areas of high aridity index.

This graph enables us to make some region-specific predictions for runoff and recharge in New Mexico over the next 50 years. Most of the state consists of hot, high-aridity-index desert. The analysis predicts that, so long as the amount of precipitation does not change markedly, these regions will experience little change in runoff and recharge even if the aridity index increases significantly due to increasing temperature. However, if precipitation does increase or decrease, then runoff + recharge would change in the corresponding direction.

At the state level, however, such changes would be insignificant because only a small proportion of the state's runoff and recharge are generated in the low-elevation deserts. The areas of greatest interest are the relatively small areas at high elevation in the northern part of the state and in southern Colorado, where the large majority of runoff is generated. This analysis indicates that these areas are quite sensitive to both temperature and precipitation. Because we can have confidence that temperature will continue to increase, while changes in precipitation are equivocal, it seems more likely that runoff and recharge from these critical areas will decline rather than increase. Certainly, large increases in precipitation will be required to offset the reductions resulting from the temperature increases predicted by even the more optimistically modest emissions scenarios.

Regional Impacts of Climate Variability and Hydrological Impacts

For the purposes of this report, we are dividing New Mexico into four physiographic regions, based on projected climate change and associated effects on hydrology (Fig. 10.2). These four regions, which are defined by a combination of latitude and topography are:

1. the High Mountains (Northern mountains, Gila/Mogollon–Datil, and Sacramento Mountains);
2. the Northwestern High Desert (Colorado Plateau, San Juan Basin, Zuni Mountain region);
3. the Rio Grande Valley and Southwestern Basins; and
4. the Eastern Plains.

These represent a simplification of the eight climate divisions defined by the National Oceanic and Atmospheric Administration. Within these four regions the Office of the State Engineer defines sixteen water planning regions.

***High Mountains*—**The High Mountains region, as used in this report, combines three of New Mexico's most mountainous areas. The Northern mountains include the Sangre de Cristo Mountains, the Tusas Mountains, and the Sierra Nacimiento, which together constitute the southern end of the Rocky Mountains. For the purposes of this report, we also include the Jemez Mountains. Further south, the Gila/Mogollon–Datil Mountains are a rugged area of relatively high elevation. Finally, even further south and east are the Sacramento Mountains, a high-standing mountain block within the Eastern Plains region of New Mexico. Snowpack accumulates over the winter in each of these mountainous areas, generating snowmelt runoff in the spring. The impact of climate change on hydrology in these mountains will be distinct from the surrounding lower-elevation areas.

Mountainous regions of New Mexico will be particularly impacted by a warming climate, and these impacts will cause downstream effects in other regions of the state. The atmospheric temperature in mountainous regions will rise over the next 50 years at a rate similar to the rest of the state. The highest elevations are very likely to experience sharp declines in snowpack, which will melt earlier and generate less snowmelt runoff. As discussed above, higher temperatures will lead to higher levels of evapotranspiration across the state, but the relative increase in evapotranspiration rates over the next 50 years will be higher in New Mexico's mountainous regions. Less snowmelt and higher evapotranspiration lead to proportionally less water available to recharge aquifers and support plant growth. The decreased recharge in high, mountainous parts of the state will lead to decreased replenishment of downstream aquifers. This decrease in recharge will occur in a time when these groundwater resources will be stressed by increased pumping in response to the effects of hotter droughts. The loss of plant communities in mountainous terranes, as a result of higher temperatures, will also impact the stability of local soils, which may be completely lost from south-facing slopes. South-facing, and even west- or northwest-facing mountain slopes may evolve towards becoming bare bedrock, which can reduce infiltration of rainwater into local aquifers.

As in other parts of the state, average precipitation is unlikely to change substantially in mountain regions over the next 50 years. However, the seasonality of precipitation may be different than it is today. The Northern mountains region of New Mexico, including the Jemez Mountains, is projected to receive more winter precipitation, offset by less precipitation in the spring, with amounts remaining similar in summer and autumn, all subject to pronounced year-to-year and decade-scale natural variability. In contrast, the Datil–Mogollon and Sacramento Mountains are projected to receive less winter precipitation, but relatively more in the

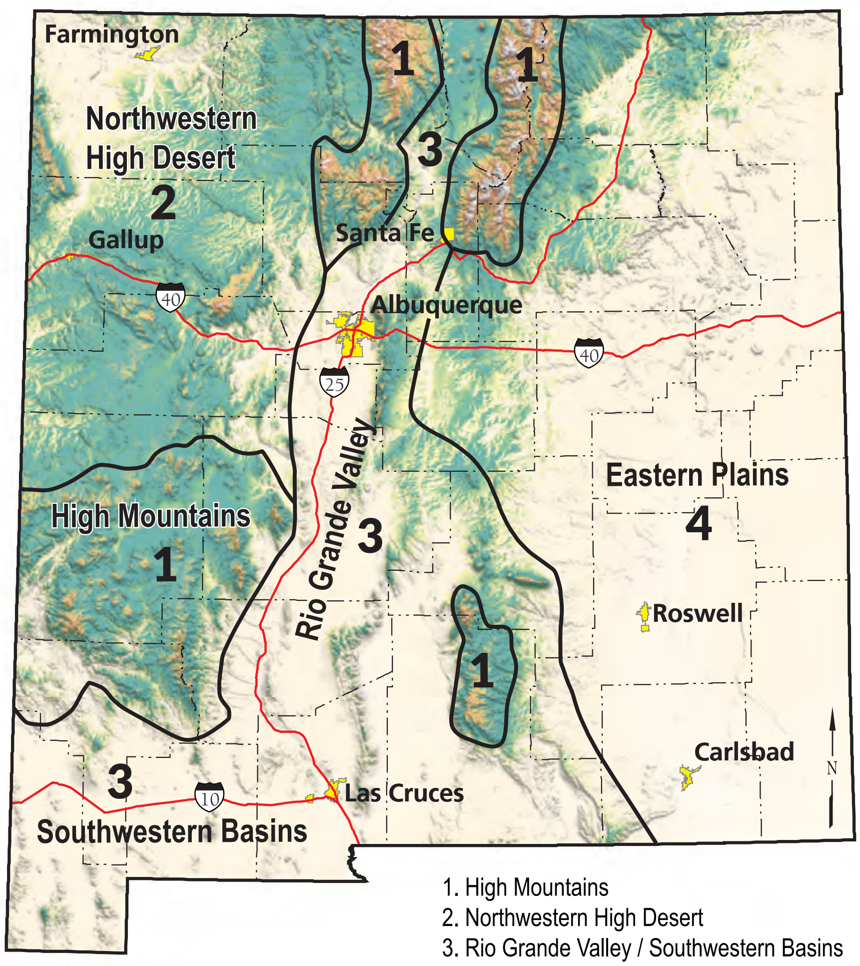


Figure 10.2. Regions of the state expected to experience similar impacts to water resources from a changing climate over the next 50 years. Modified from the New Mexico Bureau of Geology and Mineral Resources website (NMBGMR, Geologic tour of New Mexico, accessed 2021).

summer and autumn. The location of precipitation in mountainous areas may also change because variations in atmospheric circulation patterns resulting from climate change may influence where orographically controlled precipitation falls. Changes in the geographical distribution of precipitation will impact local vegetation patterns, and may also influence how local aquifers are recharged.

Even with amounts of precipitation remaining relatively constant, rainfall on landscapes and soils in mountainous regions is likely to cause increased erosion. This is because increased wildfire, as observed in New Mexico in the last decade, dramatically increases the probability and magnitude of post-wildfire, rainfall-induced flooding and debris flows. Long-term loss of vegetation associated with climate change can exacerbate this effect. Wildfire-enhanced floods tend to initiate in steep, upstream hillslopes and progress downstream in pulses and waves, carrying large amounts of sediment in the process. Soils, already negatively impacted by increasing temperatures, can be stripped off hillslopes in this process, leading to even more dramatic flood events due to unimpeded overland flow, and also reducing infiltration of water and curtailing recharge to local aquifers. Sediments mobilized in these floods move downstream and impact lower-elevation areas, filling in depressions that could otherwise sequester floodwater and promote infiltration. These climate-related landscape changes tend to remain active for years or decades, as the landscapes continue to adjust until they have reached their new steady state.

Additional downstream consequences of increased flooding due to wildfires and warming include erosion of land, stream channels and conveyance structures; accumulation of rock, mud, and burned vegetation in reservoirs and stream channels, as well as water-quality degradation due to suspended sediment and dissolved constituents leached from the burned watershed. Lastly, the loss of vegetative canopy in mountainous regions will cause the temperature of surface waters to rise and the dissolved oxygen levels to decrease, negatively impacting local biota.

***Northwestern High Desert*—**The Northwestern High Desert includes the Colorado Plateau, the San Juan Basin, and adjacent Zuni Mountains, but also stretches south to the midpoint of the state. These areas combine relatively modest topographic relief with high elevation, averaging almost 7,000 feet above sea level. This region is projected to experience the highest temperature increases over the next 50 years, about 1°F higher than the average state increase.

Increasing temperature, in the absence of increased precipitation over the next 50 years, will likely substantially influence the spatial extent and thickness of soils in New Mexico's landscapes, particularly in northwestern New Mexico. Much of this part of the state is covered with windblown deposits that are presently stabilized by vegetation and thin soil. Loss of plant communities through higher temperatures and drought will destabilize local, weakly developed soils in this region, causing emission of considerable quantities of windblown dust. The deposition of dust on snowy downwind high-elevation hillslopes will increase early melting of mountain snowpack. Additionally, loss of stabilizing soil will allow reactivation of dunes, which will impact local communities.

The high, generally flat, topography of the Colorado Plateau and San Juan Basin may also be impacted by increased arroyo formation resulting from climate change. Arroyo incision leads to increases in delivery of sediment downstream, which reduces the efficiency of floodplains, and also fills downstream floodplains that could have stored flood water, leading to increased flood severity. Arroyos can also cause draining of marshes and cienegas by lowering the local groundwater table and leading to vegetation desiccation. Increased arroyo incision is also likely to impact the Rio Grande Valley/Southwestern Basins and Eastern Plains parts of New Mexico. Vegetation in the Northwestern High Desert will be impacted by increasing temperature. Grasslands will become less productive, and will be gradually replaced by shrubs. Conifer forest drought stress will increase, particularly in the warmer and drier lower-elevation areas. Finally, trees in bosque areas associated with rivers may experience dieback because of lowered shallow aquifers, due to reduced water in formerly perennial streams and rivers. The dieback of trees along river banks will then allow water temperatures to become elevated and dissolved oxygen levels to decrease. *E. coli* concentrations may also increase, especially in low energy streams with fine-grained, organic-rich, bottom deposits.

Rio Grande Valley and Southwestern Basins—The Rio Grande Valley is a north-south trending rift zone that bisects the state of New Mexico. The northern part of the rift is relatively narrow, and is flanked by rugged mountains (Northern mountains). The valley broadens to the south. As much as 15,000 feet of rift sediment has accumulated in basins along the Rio Grande rift, forming important aquifers for some of the largest cities in our state.

The southwestern corner of New Mexico has overall low elevation, is a notably arid region of the state, and one of the areas that experiences the highest temperatures. Northerly to northwesterly-trending narrow, rugged, relatively low-elevation mountain ranges are separated by broad basins. Many of the streams have no outlet to the ocean, so water collects in the basins, forming large lakes and playas during wet years that dry up when conditions are drier.

Major warming-related impacts on the Rio Grande Valley and Southwestern Basins region will have less effect on other parts of the state include lower river flows (due to higher evapotranspiration) and changes in timing of runoff (because of earlier snowmelt). Flows in the Rio Grande are projected to be 25% less on average in the next 50 years above Elephant Butte Reservoir.

Warming temperatures will also cause dramatically increased evaporation of surface water from reservoirs and increase water demands of riparian vegetation, landscape watering and irrigated croplands. Open-water evaporation increases with temperature more strongly than on-land evapotranspiration. With an increase in average daily maximum temperature of 5°F, as is likely over the next 50 years, Elephant Butte could experience an additional two feet of annual evaporative loss. This would constitute a stunning 30% increase in evaporative water loss over the present-day rate, reducing the available water that could be used below Elephant Butte Reservoir.

This region of New Mexico would also experience a number of effects that have been described for the High Mountains and Northwestern High Desert portions of the state. These are listed here and more details can be found by consulting earlier sections of this chapter.

- Vegetation stress and transition from grasses to shrubs
- Bosque forest die-off due to dropping shallow aquifer levels
- Arroyo incision
- Sedimentation
- Loss of soils and increased dustiness
- Compromised surface-water quality (high temperature, low dissolved oxygen, *E. coli*)

Eastern Plains—The Eastern High Plains province covers the eastern quarter of the state of New Mexico, stretching from the northern to southern border of the state. The whole area is relatively flat, and is characterized by grasslands in the northern part transitioning to Chihuahuan Desert in the south. The Eastern Plains include two climate divisions as defined by NOAA (Northeastern and Southeastern), which we have combined for this report.

The average temperature increase over much of the Eastern Plains is projected to be roughly a degree lower than the state average, but evapotranspiration (ET) is likely to experience among the greatest change in the state, leading to higher aridity. This is a consequence of projected decreases in precipitation during spring and summer, when ET is highest (see Fig. 2.3). And, given that the major aquifer in this region has already undergone serious depletion (Rawling and Rinehart, 2018), the lower availability of surface water related to aridity will present a major challenge. Summer precipitation is projected to decrease slightly over the next 50 years, but autumn and winter precipitation may increase slightly—with much uncertainty inherent in these projections. But, if an increase in extreme precipitation events does occur (regardless of changes to total precipitation), the Eastern Plains will be the most strongly impacted part of New Mexico by far, even more so than the mountainous regions.

Given the relatively flat topography of the Eastern Plains, some of the most dramatic climate-related impacts will be related to vegetation and soils. The drylands of eastern New Mexico are dominated by soils that are especially vulnerable to wind deflation when subjected to extended drought-caused losses in vegetation and/or agricultural modification. The response of spatially extensive regions of eastern and south-central New Mexico to the next fifty years of climate and environmental change is most likely desertification, accompanied by significant increases in dust emission, as well as increased erosion on hillslopes.

The Eastern Plains are also likely to experience a number of effects that have been described in other parts of the state. These are listed here and more details can be found by consulting earlier sections of this chapter.

- Vegetation stress and transition from grasses to shrubs
- Bosque forest die-off due to dropping shallow aquifer levels
- Arroyo incision
- Sedimentation
- Lower flow in rivers and increased evaporation from reservoirs
- Compromised surface-water quality (high temperature, low dissolved oxygen, *E. coli*)

XI. RECOMMENDATIONS: DATA GAPS AND CHALLENGES

The process of evaluating and projecting climate change in New Mexico over the next 50 years, and examining the impacts on water resources, illuminated a number of research topics that should receive attention from the state's science community. A high-priority research target is to better understand a number of facets of precipitation that New Mexico might experience over the next half century. These would include seasonality of precipitation, snowpack dynamics, and extreme precipitation. Better understanding of the latter would allow New Mexico planners to be able to consider how to put localized, heavy precipitation to good use, and to mitigate damage associated with flooding. Climate, hydrology, and ecology numerical models, which allow projection of conditions and behaviors of these natural systems in New Mexico over the next half century, are also needed. Finally, a number of observational data gaps have been identified, most notably a thorough and geographically distributed assessment of the water levels in New Mexico aquifers. Other topics include impact of climate change on soil moisture and groundwater quality, as well as landscape and ecological responses to climate change, both in terms of magnitude and timescales of response. This can be carried out, in part, by long-term ecological monitoring.

Much remains to be learned about the interplay of climate change and water resources in New Mexico. Chapters 2–9 of this report outline the state of knowledge, based on current literature, on a range of topics that will need to be considered when developing New Mexico's 50-year water plan. Based on their career experience, or as part of the process of developing the chapters, the authors have identified fruitful research areas that could be pursued to build a more complete understanding of New Mexico's changing climate and the implications for water resources in our state. These research areas and data gaps are presented in more detail as parts of most chapters in this report, and are presented here in abridged form, for ease of reading. For more information, chapter numbers are noted.

Precipitation

The temperature changes that New Mexico can expect over the next 50 years is well understood. However, a number of aspects of how baseline and extreme precipitation patterns will change require additional research. These are summarized together below.

- Better understanding of a number of facets of the occurrence of extreme precipitation is needed. Theoretical studies suggest that more extreme precipitation events should occur, given that the atmosphere will be warmer and wetter. But, published observations of precipitation during the past 20 years, during which time warming has occurred, do not yet offer a clear signal with regard to extreme precipitation. And, with regard to New Mexico's 50-year water plan, capture and use of water from extreme precipitation events may offer some hope in an otherwise challenging situation (Chapters 2 and 8).

- Along with changes in extreme precipitation events, changes in seasonality and recurrence intervals of baseline precipitation must be better understood in order to robustly model future surface runoff and aquifer recharge. In general, trends in projected total precipitation amounts are uncertain in most seasons, with different global climate models generating significantly different projected trends. The newest generation of climate model simulations (CMIP6) needs to be examined closely to see if large-scale uncertainties in projections of total precipitation can be reduced (Chapters 2 and 3).
- On a related note, the risk associated with stormwater-associated flooding should be examined on a watershed-level basis, and information should be communicated to the public, and to public officials (Chapter 8).
- Improved understanding of the processes that determine what fraction of snowpack at high elevations becomes river discharge would decrease uncertainties in projecting flows in major snow-fed rivers in a warming climate. There is general consensus that increasing temperature will reduce snowmelt runoff but quantifying the reduction is difficult at present (Chapters 2 and 7).

Modeling

Numerical modeling is a critical element of projecting future conditions in a warming climate scenario. Deficits exist in several aspects of models and modeling techniques. Addressing these deficits (outlined below) will improve projection abilities.

- The need for development of a methodology for fine-tuning GCM methodologies, particularly for local models, to allow determination of the most probable future climate states, rather than the full range of possible states (Chapters 2 and 3).
- The role of clouds and cloud-related processes in GCM is not well understood, and improvement of this aspect of models would not only benefit New Mexico, but other parts of the world as well (Chapter 2).
- A calibrated hydrological model focusing specifically on New Mexico would improve our understanding of recharge and runoff (Chapter 3).
- A need exists to incorporate ecosystem disturbance processes into process-based vegetation models (Chapter 4).
- In a related suggestion, there is a need for less-complex empirical models of vegetation dynamics, directly based on observational data (Chapter 4).

Observational Data Gaps

Authors of several chapters noted the need for additional data on a number of water-resource-related topics. These are enumerated below.

- Water levels in New Mexico's aquifers must be more thoroughly studied, and in particular, water-level records from lightly pumped aquifers are needed to assess pumping-independent changes in recharge. The data developed for water levels must be made publicly available, using findable, accessible, interoperable, and reusable (FAIR) management principles; and this could be done through the New Mexico Water Data Act (NMSA 1978§ 72-4B) (Chapter 3).
- As a parallel to better understanding water levels in aquifers, historical trends and future projections of abundance and discharge from springs, and changes in lengths of perennially wet reaches of surface waterways, are needed.
- Little data exist on soil moisture around New Mexico, and these data are needed to assess the response of soil moisture to increasing aridity in our state (Chapter 3).
- Few comprehensive studies on the impact of a warming climate on surface or groundwater quality in New Mexico exist. Although water quality may be a less pressing need than water quantity, both parameters are important for understanding New Mexico's water resources (Chapter 9).

- Few comprehensive studies on the hydrological response to watershed vegetation changes exist. These studies will be particularly important for New Mexico's upland forests (Chapters 4 and 6).
- The length of time required for landscapes to adjust following a major climate disruption can be widely variable, and understanding the reasons for this variability requires further research, as does the process of sediment transport from headwaters to downstream rivers (Chapter 6).
- Information on sediment infill rates to New Mexican reservoirs and connections between those rates and climate is needed for accessing impacts of increased sediment infill rates on water supplies and reservoir designs.
- Additional studies are needed on soils, plant communities, and geomorphology in high elevation mountain ranges where aquifer recharge and channel discharge occur. Data provided by these studies would inform numerical models to calculate the net soil loss from hillslopes as functions of topography, vegetation, and other variables (Chapters 4, 5, and 6).
- Further research is needed on the possibility of increased aquifer recharge as a side effect of increasing shrub dominance in desert landscapes (Chapter 4).
- Long-term ecological monitoring and research are needed to document, understand, and effectively address the response of New Mexico's ecosystem to projected climate changes over the next 50 years and the associated ecohydrological responses (Chapter 4).

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APPENDIX A

Modeling Approaches for Projecting Changes in the Land-Surface Water Budget

In order to generate projections that have real predictive value at sufficient resolution to be useful, surface hydrologic models must have several characteristics. One is based on the observation that New Mexico is large and contains greatly varied topography and local climate. This means that Global Climate generalized models are of little value until their output is downscaled to finer resolution. Useful models must be capable of simulating the effects of climate change at the local scale (described below). A second is that models based on historical empirical observations are not likely to correctly predict future behavior when the system behaves differently than it does now. Rather, these models should be based on physical principles that are generally valid. A third is the degree of difficulty in constructing and running the model. Very highly resolved and complex models may be difficult to employ because of the computational demands (e.g., they run on only a supercomputer) and because it is very difficult to accurately supply all of the parameters that are needed to construct the model.

The basis for obtaining future projections of the hydrologic budget under changing climate usually starts with the output of GCMs that are driven by standardized greenhouse-gas emission scenarios developed by the IPCC. The coarse-resolution GCM outputs are converted to finer scales in a process called 'downscaling'. The outputs for the historical period are statistically adjusted to match the statistics of the observations for the same period and this adjustment is then used on the climate-model outputs for the future. The downscaled sequence of climate parameters is then used to drive the state-scale water balance models. Below we review several water-balance models that have been used for estimating recharge and runoff in New Mexico.

***Mass-Balance Accounting Models*—**To date, the only model that has been employed to empirically estimate the water balance for the entire state of New Mexico is a systems-dynamics mass-balance accounting model called the 'New Mexico Dynamic Statewide Water Budget Model' (Peterson et al., 2019). Such models use relatively simple equations that conserve mass or volume as hydrological flows that are routed or transferred, for example from the soil-water reservoir to the atmosphere via evapotranspiration. This type of model is also termed 'lumped-parameter' or 'bucket models' because models of this type do not attempt to spatially resolve the hydrological processes, but rather divide up the area into sub-units (e.g., counties or water-planning regions, which are treated like 'buckets' districts) that are treated as being homogeneous. The hydrological transfers are often quantified using empirical constants that are derived from historical studies, for example, estimation of the fraction of the snowpack that becomes runoff, based on past snow surveys and stream gaging.

Although they are a valuable tool for understanding the current water balance, their utility is limited for future projections under changing climate. This is partly because their lack of spatial resolution does not account for variations of hydrological response across a varied landscape, but more fundamentally it is because the empirical formulations that they often employ were derived by observations under constant climate and are likely to be inaccurate under different climate conditions in the future.

***One-Dimensional Surface Process Models*—** There is a large family of models that use physical formulations (as opposed to empirical ones) to simulate the division of hydrological flows at the land surface, but only as a purely vertical process. This is reasonable to a first approximation, noting that the vertical flows in Fig. 3.1 are much larger than the horizontal flows. For the most part these models employ physics-based formulations to calculate flows and transformations and should thus have predictive power under changing climate. They are computationally straightforward and can thus be used at high spatial and temporal resolution to capture effects of topography and vegetation variation and other heterogeneities. Their main limitation is that they cannot include lateral flows of water, except on the land surface. Lateral flows are important to generating runoff and to focusing shallow subsurface flow to become recharge.

The most important of these is the Variable Infiltration Capacity (VIC) model (Liang et al., 1994). It is commonly used in conjunction with GCMs to make coarse-resolution hydrological projections. It is also the most common hydrological model to be coupled with downscaled GCM output for finer resolution local projections. A significant limitation of VIC is that it, at least in the original version, does not explicitly quantify groundwater recharge. Rather, any excess water at the base of the root zone is directly routed to surface flow. This is a reflection of common hydrological conditions in humid regions.

A code that has been explicitly employed to compute groundwater recharge is the WaterGAP Global Hydrology Model (WGHM) (Döll et al., 2003; Döll and Fiedler, 2008). This model was incapable of realistically simulating groundwater recharge in arid and semiarid environments without arbitrary adjustments (Döll, 2009).

Only one such model has been developed and applied specifically to calculate recharge in the New Mexico environment: Python Recharge Assessment for New Mexico Aquifers (PyRANA) (Ketchum, 2016; Xu, 2018; Parrish, 2020). This model employs the dual crop-coefficient method of calculating evapotranspiration (Allen and Breshears, 1998) to obtain accurate water-balance in New Mexico's semiarid climate and is efficient to run at very high spatial and temporal resolution in order to meet the challenge of the state's irregular topography. However, in its current configuration, it does not incorporate interception of precipitation by plant leaves, which can significantly affect the land-surface-water balance, especially in forested areas.

Three-Dimensional Hydrological System Models—A more complex family of models attempts to mimic the entire hydrological system, including hydrometeorological, land surface, surface-water, and groundwater components, in three dimensions. This allows them to account for some phenomena that cannot be represented in more simplified models, but at the cost of much greater computational expense. They generally can only be run on supercomputers.

The most relevant of these to our purpose is ParFlow-CLM, developed for high-resolution global simulations of the hydrological cycle under current and future conditions (Maxwell and Miller, 2005).

APPENDIX B

Soil Diversity in New Mexico and the "CLORPT" Approach in the Studies of Soil Landscapes

The map of soils of the United States at the level of soil orders (the highest taxonomic level of soil classification in the U.S. Department of Agriculture [USDA] Soil Taxonomy) (Fig. B.1) illustrates the large range of very different soil types that are present in the landscapes of New Mexico (Fig. B.2). At least six of the twelve soil orders are evident at this map scale (Entisols, Inceptisols, Aridisols, Mollisols, Alfisols, Vertisols); at least one other soil classified in another order can be found locally in some landscapes in favorable circumstances (Andisols, soils with properties that reflect weathering of volcanic parent materials). The large spatial extent of Aridisols (well-developed soils that form in an "Aridic" soil moisture regime), an order that has six suborders in New Mexico (Fig. B.3) reflects the arid climate of many areas of New Mexico. The large area with Mollisols (soils typical of grassland and prairies with a thick, darkened surface A horizon - a 'Mollic' epipedon) reflect the semiarid areas of New Mexico that support shortgrass communities. Alfisol (high base-status soils with fine textured subsurface

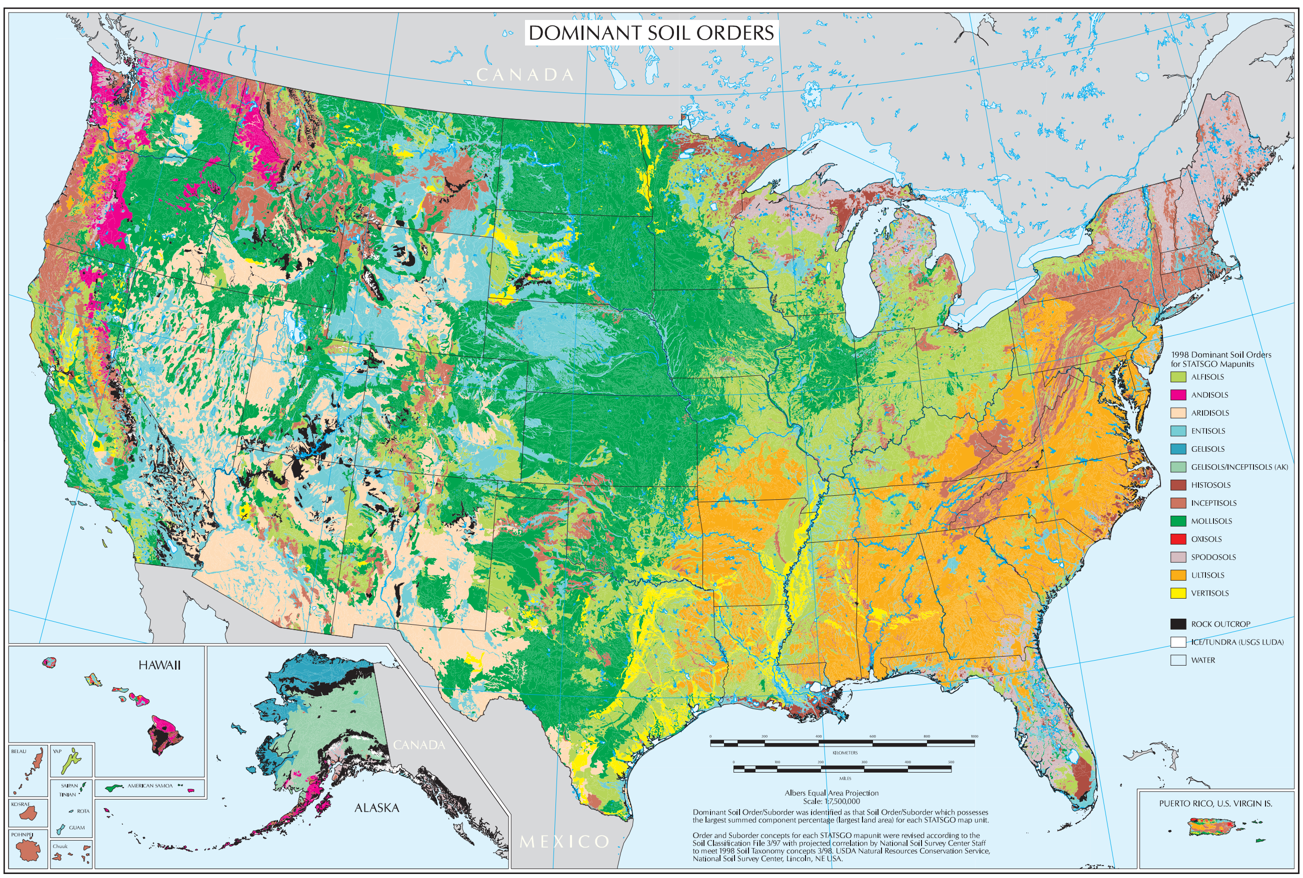

Figure B.1. Soil orders distribution map of the United States and Territories (http://www.nrcs.usda.gov/wps/portal/nrcs/)

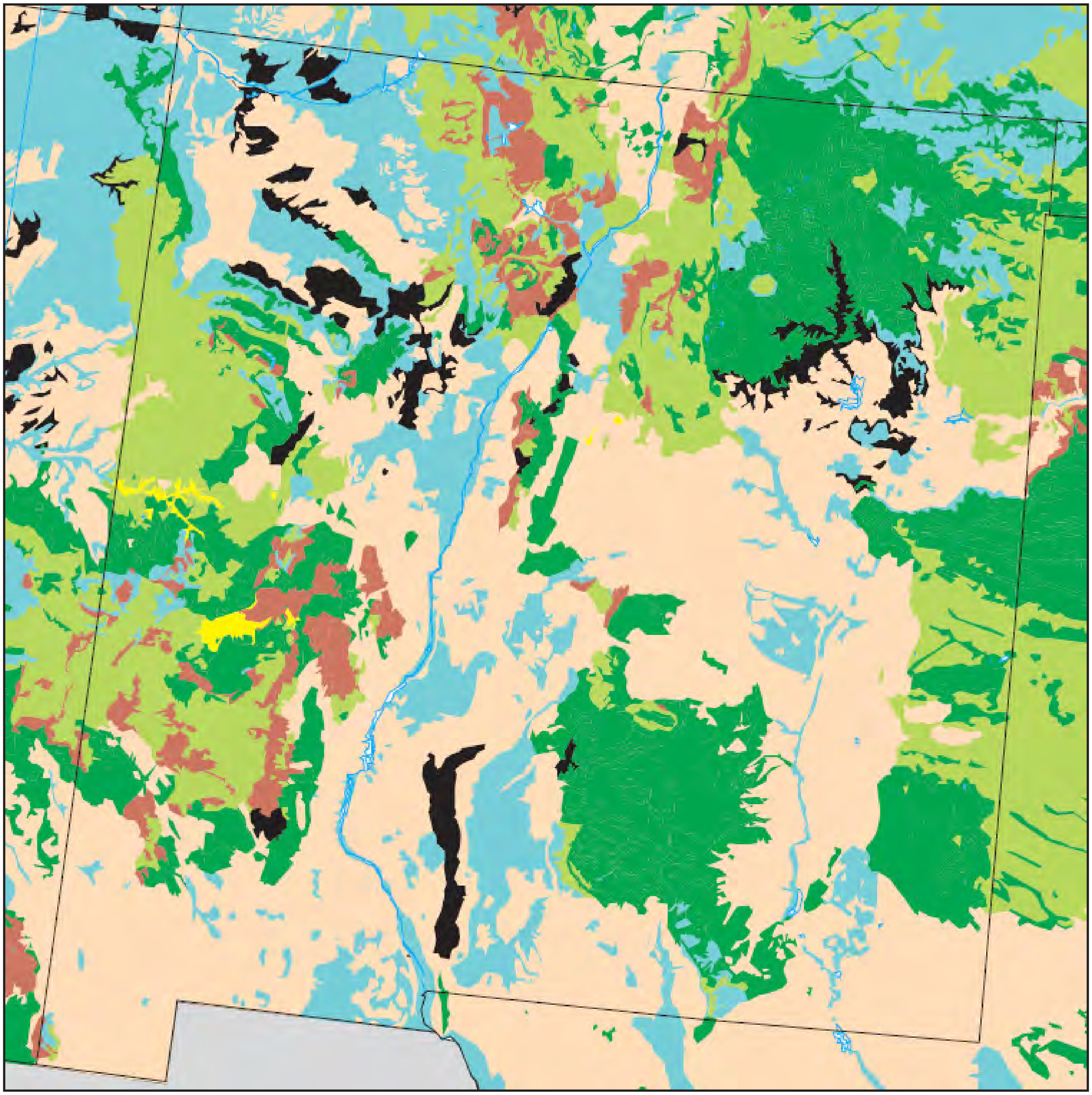

Figure B.2. Soil orders in New Mexico (http://www.nrcs.usda.gov/wps/portal/nrcs/).

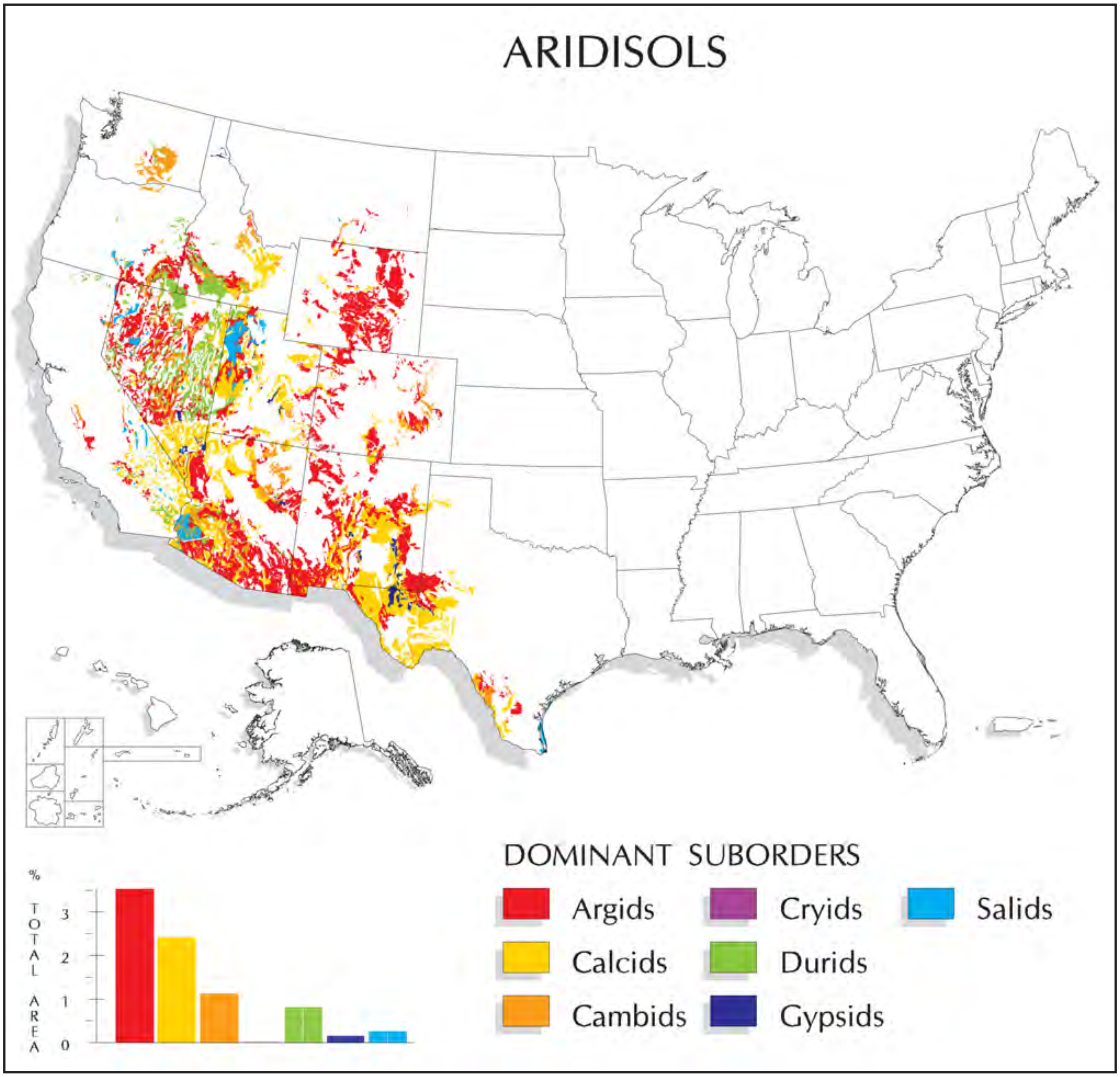

Figure B.3. Map of the suborders of Aridisols in the United States (NRCS image, https://www.nrcs.usda.gov/Internet/FSE_MEDIA/stelprdb1237729.jpg). The large spatial extent of these suborders in New Mexico as well as other regions of the western United States reflects an arid climate and associated soil-forming processes favored by an "aridic" soil moisture regime.

B horizons) can be found in areas of greater annual precipitation at typically higher elevations. Of course, at other levels of the Taxonomy or in Natural Resources Conservation Service (NRCS) soil maps of much smaller regions, literally many dozens of Suborders and much larger numbers of Great Groups, Subgroups, Series, and Types are present (USDA).

Substantial soil diversity in New Mexico reflects the highly variable topography, climate, vegetation and rock types that characterize the state. Much of this variability reflects, to a large extent, the consequences of Cenozoic tectonic processes that ultimately caused, for example, uplift of the lofty southern Rocky Mountains or the development of lower elevation dryland basin landscapes of the Rio Grande rift. Topography, climate, vegetation, and rock types constitute the most important factors that influence the many soil-forming processes and overall soil profile development.

Soil chronosequences are one of several types of sequences of soils designed to enable scientists to ascertain the influences of factors such as climate (Cl), organisms, or biotic factors (O), local and regional relief (R; essentially also characterized as "topography"), parent material characteristics (P) of processes of soil development (Jenny, 1941). A remaining attribute of soils, their age (T), enables recognition of the degree to which some processes are strongly time dependent. Although other factors certainly influence soil-forming processes, these five factors are generally regarded as the most critical ones to the extent that collectively they define the "state" of the soil (or a particular soil property) (Birkeland, 1999), and they have come to be generally known as CLORPT. This conceptual framework used in soil geomorphic research is often referred to as the "State Factor" approach (or the CLORPT approach). Through careful selection of groups of soils in circumstances such that the influences of one factor can be isolated or selectively varied, while the influences of the others are essentially held constant, different soil "functions" associated with the CLORPT factors can be determined (Jenny, 1941; Birkeland, 1999; McFadden, 2013). To identify differences amongst a group of soils that primarily reflect soil age, a soil chronosequence is established, and a time-dependent change in soil morphology (or a given property) is called a chronofunction. Soil chronosequence studies usually involve selection of geomorphic surfaces with relatively low gradients and generally low relief, features that engender geomorphically stable conditions, which in turn favor continuous soil formation and morphological property development on time scales ranging from a few hundred to several hundred thousand years (Birkeland, 1999).

Other soil sequences can be established in a given region that emphasize topography (soil toposequences, or sometimes referred to as a "catena" (Fig. B.4)). Studies of toposequences prove invaluable in the study of hillslope form and processes, as they are geomorphically unstable when compared to, for example, the surfaces of fluvial terraces (Birkeland, 1999; McFadden, 2013). Similarly, the role played by different soil parent materials (the earth materials in which soils form) substrate (e.g., weakly cemented sedimentary rocks, crystalline igneous and metamorphic rocks, alluvium) in influencing soil development can be assessed through studies of soil lithosequences (Birkeland, 1999).

Drainage Basin Hillslopes and Soils

The hillslopes of drainage basins ("watersheds") are the major areas of aquifer recharge and the primary source of water and sediment discharge to fluvial channels in most landscapes. In New Mexico and adjacent states, substantial runoff and recharge is generated from mountainous areas (see relevant sections in this report). These include the San Juan, Sangre de Cristo, Jemez, Black Range, Sacramento, Sandia, Zuni, and Mogollon Mountains, all of which have relatively extensive high elevation areas (greater than 10,000 feet) with elevations in a few cases exceeding 12,000 feet. In many drainage basin hillslopes of these mountains, weathering of exposed bedrock or bedrock beneath a cover of hillslope sediments produces "regolith". In some studies, formation of regolith, either in situ or mobile, by this process is referred to as "soil production" (Heimsath et al., 1997; Bierman and Montgomery, 2019). The formation of regolith occurs mainly through biogeochemical weathering of bedrock. The initial alteration of bedrock that is essential in influencing subsequent chemical weathering rates and the eventual development of soil that enables colonization by vascular plants involves the development of secondary porosity and resultant increased water-holding capacity (Graham et al., 2010). Some studies in New Mexico mountainous, and other high elevation study areas, that document chemical weathering of bedrock parent material include Egli et al. (2014) and Rea et al. (2020). On many drainage basin hillslopes, however, soils form in materials produced mainly by physical weathering of bedrock, such as talus and colluvium. In higher elevation areas subject to frequent freeze-thaw cycles, frost weathering is a key physical weathering process (Bierman and Montgomery, 2019). At lower, generally warmer elevations where frost weathering is not effective, other physical weathering processes are important. Recent studies suggest that solar insolation may actually play a key role in the development and extension of initial fractures (McFadden et al., 2005; Eppes et al., 2010), accelerated via subcritical formation and extension of cracks (Eppes and Keanini, 2017). Increases in the spatial extent and thickness of talus and colluvium are commonly observed in the hillslopes of mountain ranges with high relief, given the associated higher annual precipitation and lower temperatures, conditions that tend to favor an increase in the magnitude of physical weathering.

The character and spatial extent of soils on hillslopes are affected by several factors, such as relief, rock type, vegetation, climate and local base level. Given variability amongst these factors in diverse geomorphological settings, hillslopes exhibit different forms. For example, some hillslopes are dominated by relatively frequent occurrences of debris flows, rotational slumps, and other mass movements. In many drainage basins where mass movements are rare, a very common hillslope form observed is characterized by a smooth, curvilinear profile and is associated with a continuous mantle of soil and vegetation (Fig. B.5). Gilbert (1880) recognized the latter hillslope form as being one that develops in effectively wetter and colder climate regimes. These conditions are conducive to weathering and slope material production sufficient to exceed the rate of transport of weathered material on the hillslope. In the nearly 150 years since this publication, a large

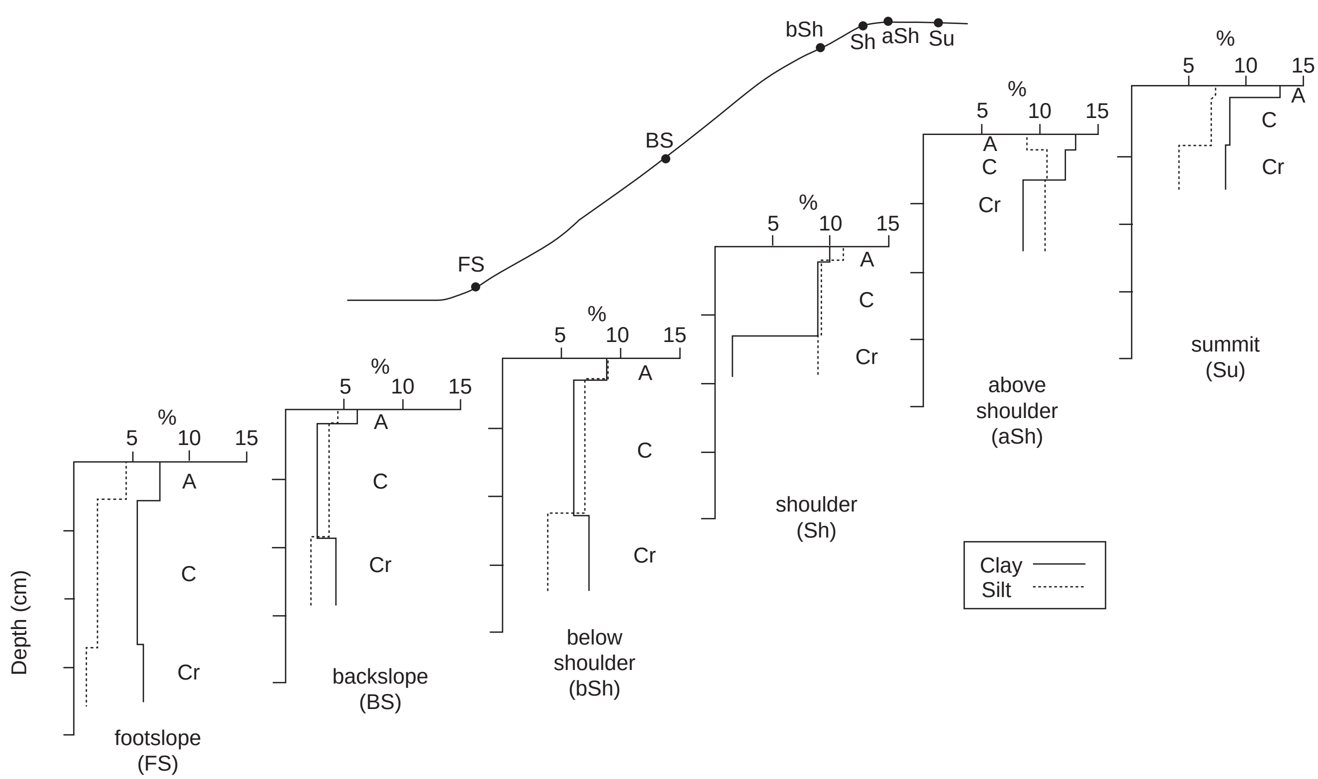

Figure B.4. A cross section (no vertical or horizontal exaggeration) showing a soil toposequence on a transport limited hillslope from a study site on the Colorado Plateau in NE Arizona. Soil horizons with depths and textural data for soils located at various hillslope positions are shown in the different plots. See text discussion of soil toposequences. After McFadden (2013).

body of published research has both confirmed and extended Gilbert's research (e.g., Heimsath et al., 1997), and these smooth hillslopes are commonly referred to as transport-limited hillslopes dominated by diffusive transport of slope materials. In contrast, typically steeper hillslopes dominated by exposure of bedrock and discontinuous weathering mantles (including soils) are now often referred to as detachment- or weathering-limited hillslopes (Fig. B.6) (Bierman and Montgomery, 2019). Gilbert noted that such hillslopes are common in generally arid climates, and he recognized that in these circumstances, the magnitude of weathering and production of colluvium and/or soils was not sufficient to exceed the rate of hillslope erosion by runoff or mass movements (e.g., creep).

In geomorphically favorable circumstances, where colluvium has accumulated in zero order drainage basins or where colluvium, sheetwash-derived sediment or debris-flow sediment has accumulated at base of hillslopes, the soil profiles are often generally thicker than those forming in bedrock. For example, published detailed NRCS soil maps of the higher elevations (8,400 to 10,500 feet) of the Sandia Mountains (Hacker, 1977) identified

Figure B.5. Smooth, soil and vegetation mantled "transport limited" hillslopes formed on weakly cemented sandstones of the Dixon Member, Tesuque Formation, Santa Fe Group. The hillslopes face to the northeast (hillslope aspect) and the area is located 35 km southwest of Taos, New Mexico at an elevation of approximately 2070 m. *Photograph by Leslie D. McFadden*

Figure B.6. Steep, bedrock dominated "detachment-limited" hillslopes formed on southwest-facing hillslopes formed on the same bedrock and in the same area as the hillslopes shown in Figure 6.5. *Photograph by Leslie D. McFadden* the "Shallow to Deep Soils" of the Kolob-Rock Outcrop Association. This association includes large areas of exposed bedrock or very thin soils (Rock Outcrop, including extragrade "Lithic" subgroups with typically thin, weakly developed A-C profiles with bedrock at shallow depths) and the thicker Kolob soils, many of which occur in thick hillslope materials and commonly exhibit B horizons. In the Sandia Mountains, these more well developed, thicker soils occur in the Alfisol, Mollisol and Inceptisol orders. Soils classified in these orders are also common in higher elevation settings in the Jemez Mountains (e.g., Nyhan et al., 1978) and in the Front Ranges in Colorado (Birkeland et al., 2003). Recent extensive geomorphological research in glaciated and unglaciated basins in the southern San Juan Mountains also show that relatively thick soils (some exceeding 100 cm) with weakly developed B horizons have formed in latest Pleistocene unconsolidated morainal till and younger Holocene alluvial deposits at elevations between 10000 and 11000 feet. Soils formed directly on steep hillslopes, however, exhibit thin soils with A-C-Cr profiles (Aldred, 2020).

Steep hillslopes commonly favor rates of erosion that enable only thin soils to form, or entirely preclude the development of soils. Additionally, the relatively low permeability of bedrock (as compared to, for example, gravelly alluvium) favors a low infiltration-to-runoff ratio, which also limits weathering and soil development. This is especially the case in dryland climates. Many other hillslopes are not so steep, and thick soils can form on these hillslopes. Their development can be attributed to the following: (1) the moister climate at higher elevations characterized by higher annual precipitation and cooler temperatures that favor deeper average depths of soil water movement and soil development in relatively permeable parent materials; (2) increasing vegetation density at higher elevations provides canopy cover and a root network that increases soil strength and cohesion, which results in increased resistance to erosion (see Chapter 4 of this publication); (3) the entrapment and incorporation of eolian dust in soils that produces net soil accretion; (4) incision of gullies into colluvial deposits and debris fan-aprons temporarily isolates soils from subsequent runoff and erosion; (5) colluvial materials, commonly far more permeable than bedrock, favor deeper soil water movement and, ultimately, development of thicker soils; and (6) thicker forest soils with thick O, A, Bw and C horizons often have relatively high infiltration rates and generally low runoff (e.g., Martin and Moody, 2001). In addition, the presence of thick soils that retain soil water provide insulation that increases soil water retention in deeper subsurface horizons. At the soil-bedrock contact, these circumstances have been proposed to favor increased chemical weathering of bedrock. As is described in Chapter 4, the presence of a continuous soil mantle is also conducive to the colonization of soil-stabilizing herbaceous plants, such as grass.

The body of soil geomorphological research conducted on drainage basin hillslopes in New Mexico is relatively limited; however, over two dozen papers in this area have been published in only the last twenty-five years (e.g., Davenport et al., 1998; Phillips et al., 1998), presumably largely reflecting the presence of a large national laboratory (LANL) and the establishment of the Santa Catalina-Jemez Mountains Critical Zone Observatory (CZO) in the Jemez Mountains (e.g., Olyphant et al., 2016). As is the case in other CZOs throughout the United States and also many other studies of hillslope geomorphology, one conceptual approach that has been adopted in the study of soil component of the critical zone is referred to as steady-state soil production (McFadden, 2013; Richter et al., 2020). The recent development and refinement of soil production represents an important extension of the definition of soil geomorphology as initially proposed by McFadden and Knuepfer (1990). The derivation of the soil production function (spf) that combines the hillslope sediment flux equation with the conservation of mass for a column of soil requires that the spf is essentially applicable only on soil mantled hillslopes with convex-up form and characterized by exclusively diffusive slope transport (i.e., abiotic and biotic creep) (Heimsath et al., 1997). In addition to the application of the steady-state spf in soil geomorphological research of hillslopes in the Jemez Mountains, this approach has been utilized in a few studies in other New Mexico mountains, including a study focusing on biochemical weathering processes in bedrock (Rea et al., 2020) and in studies of drainage basin patterns on hillslopes formed on uplifted basin fill sediments in the semiarid region west of Socorro (Gutiérrez-Jurado and Vivoni, 2013). As will be described below, however, recent studies of soils and hillslopes in some semiarid settings in New Mexico and elsewhere in the southwestern U.S. (Persico et al., 2011; McFadden, 2013; McAuliffe et al., 2014) show that steady state has been disrupted and/or that gullying and rilling (advective sediment transport processes) have played important roles with respect to erosion and sediment transport. In addition, soil-forming processes other than "production" of soil via bedrock weathering affect hillslope soils, including variable eolian sediment flux and the development of mechanically strong petrocalcic horizons not subject to creep. These geomorphic processes somewhat limit the usefulness of the conceptual framework provided by the spf in study of many landscapes subject to climate and other environmental changes.

Soil Chronosequence and Other Geomorphic Studies

Ultimately, over longer time spans, hillslopes must inevitably retreat, thereby ultimately limiting periods of geomorphic stability that enable sustained soil development and the overall magnitude of soil development. Processes of runoff, erosion, interflow, locally intensive bioturbation, and the difficulty of determining the ages of soil parent materials on hillslopes greatly complicate interpretation of strongly topographically dependent trends in soil-forming processes. However, studies of soil formation on the basis of soil chronosequence studies can in appropriate circumstances be used to evaluate some important aspects of soil development on hillslopes.

Some of the most well regarded soil chronosequence studies have been conducted in the landscapes surrounding Las Cruces in southern New Mexico, known as the Desert Project (Holliday et al., 2001). Desert Project research shows that many soil-forming processes are strongly time dependent (e.g., the development of pedogenic carbonate morphology) (Gile et al., 1981). The availability of numerical age dates for different soil parent materials or soil materials provided the basis for determining rates of soil development in this dryland region. Since these studies, new geochronological methods have been developed that provide numerical age information to help determine rates of soil development (e.g., Phillips et al., 1998). One of the most significant contributions of Desert Project research, however, was the recognition of the role of dust as a principal source of pedogenic calcium carbonate, rather than the production of dissolved calcium via chemical weathering of aluminosilicate minerals in the initial soil parent materials.

Other soil chronosequence studies in New Mexico also revealed key time-dependent soil properties including the important role the incorporation and pedogenic alteration of dust plays in the development of soil properties in addition to soil carbonate accumulation. Many other studies of soil chronosequences elsewhere in the southwest show similar results (c.f., Birkeland, 1999). Other studies that demonstrate the significant impact of dust entrapment and accumulation on soil formation in New Mexico and adjacent regions include studies of soils formed on volcanic flow surfaces (Eppes and Harrison, 1999; Van der Hoven and Quade, 2002; McFadden, 2013), and on eolian landforms (Wells et al., 1990; Reheis et al., 2005; Ellwein et al., 2018).

The entrapment and accumulation of dust in dryland soils not only plays a primary role in pedogenic carbonate accumulation, but also ultimately plays a fundamental role in the mode of soil profile development in sparsely vegetated landscapes (McFadden, 2013). In contrast to soil profile development in more humid climates (Fig. B.7a) (dominated by chemical weathering and net mass loss below the soil-atmosphere interface), dryland soil development is commonly characterized by the net **addition** of eolian sediment via cyclic soil inflation and accretion (Fig. B.7b). The formation and evolution of soils of desert pavements that dominate the landscapes of many very hot and arid regions is attributable to this mode of profile development; however, this mode of soil development can also be recognized in the soils of the semiarid foothills of the Sandia Mountains, as described below (Persico et al., 2011). A recently published study of lacustrine sediments from a site in central Arizona (Staley et al., 2021) shows that eolian dust accumulation has been occurring during much of the last 1.3 Ma, demonstrating that this process likely has strongly influenced soil development in drylands of the southwest throughout much of the Quaternary.

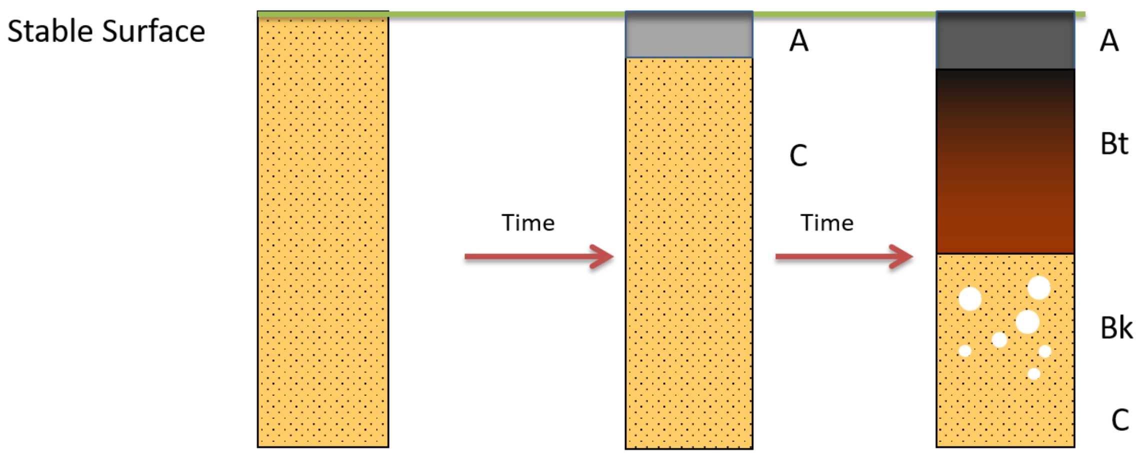

Figure B.7a. Time dependent development of the classical A/B/C soil profile developed in the 19th century by Russian soil scientists and ultimately adopted as a profile model by scientists worldwide in the 20th century. The lower case letters “t” and “k” indicated the presence of soil clay and calcium carbonate in the associated soil horizons. After Figure 1a from McFadden (2013).

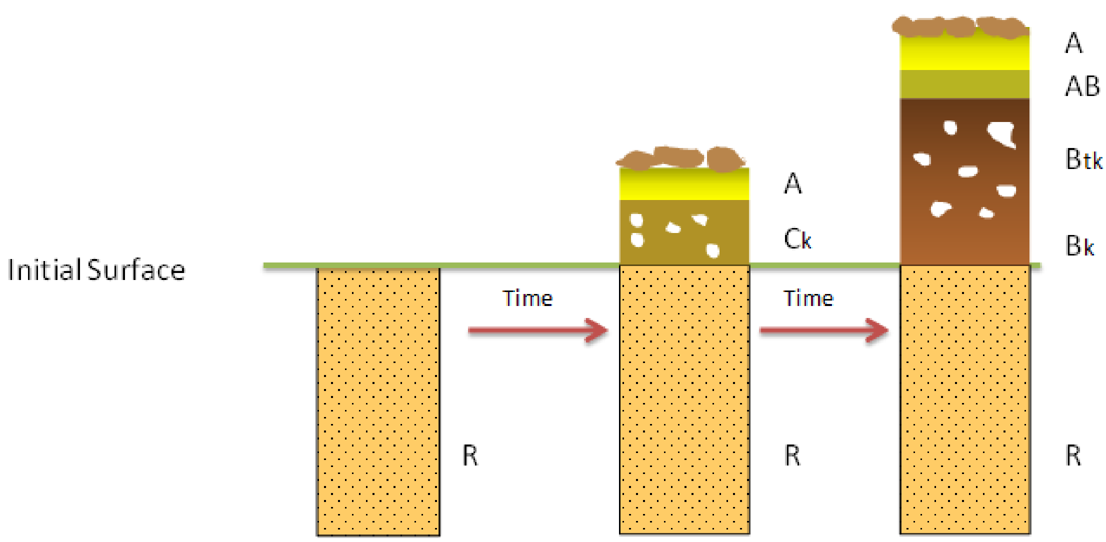

Figure B.7b. Time dependent development of a “cumulative” soil profile dominated by net accretion of slowly accumulating and pedogenically modified sediment. The light-brown irregularly shaped objects represent coarse fragments or gravel that are maintained as the surface during development of the soil. This example of a cumulative soil represents development of a dryland soil below a “desert pavement”; “R” represents fresh and/or slightly weathered bedrock. After Figure 1b, McFadden (2013).

Contributions of Soil Geomorphological Research to the Evaluation of Rates and Processes of Pedogenesis on Hillslopes in New Mexico

As noted above, the geomorphic and hydrological processes that characterize hillslope environments (e.g., interflow, soil creep) as compared to those on stable geomorphic surfaces appropriate for soil chronosequence studies complicate the interpretation of soil formed on hillslopes (Birkeland, 1999; McFadden, 2013). Certain hillslopes, however, provide more favorable circumstances. Glacial moraines found in mountainous regions subject to alpine glaciation are a good example. Unlike most hillslopes formed on bedrock, the hillslopes of a moraine initially have the same age, eliminating "T" as a soil state factor. Moreover, in some cases, morainal sediments can be dated using radiocarbon or cosmogenic surface age methodologies. The relatively limited relief, common parent material and vegetation of moraines enables development of soil toposequences. On some hillslopes formed on bedrock, dendrochronological methods and cosmogenic surface age dating also can be used in the study of hillslope soils and geomorphic processes (McAuliffe et al., 2006; Scuderi et al., 2008; McAuliffe et al., 2014).

Studies of soils of glacial moraine toposequences (Muhs and Maat, 1993; Birkeland, 1999; Birkeland et al., 2003) in the Rocky Mountains of central Colorado show that the entrapment and incorporation of dust plays a key role in soil development, despite the moist conditions and development of organic matter-rich O and A horizons. Soils in the southern San Juan Mountains formed in latest Pleistocene moraines and post-glacial colluvium and alluvium with B horizons are also strongly influenced by eolian dust (Aldred, 2020). Late Pleistocene soils formed in tundra covered soils on bedrock at elevations up to 12,000 feet in the Uinta Mountains with A-Bw-C profile development are also dominated by dust accumulation. These studies also demonstrate that soils on latest Pleistocene moraines with A-B-C profile development require at least several thousand years to form, a conclusion consistent with that of the numerous aforementioned soil chronosequence studies conducted in New Mexico and adjacent regions.

With the exception of the Jemez Mountains region, to date there have been relatively few soil geomorphic studies in high elevation mountains in New Mexico. For example, Google Scholar for publications in this area of research turned up between 0 and a maximum of 3 papers (for a given mountain range) over the last few decades based on studies in the Sangre de Cristo, Sandia, Sacramento, Black Range, and Mogollon Mountains. Although their focus is not on the development of soil properties, at least some of the published studies, such as the studies of Gierke et al. (2016) and Rea et al. (2020) in the Sacramento Mountains and Persico et al. (2011) in the Sandia Mountains foothills acknowledge the significance of dust accumulation in development of soils in their study sites.

The study by Persico et al. (2011) in the foothills of the Sandia Mountains provides another example of the important role rock type plays in soil- and hillslope-forming processes. The Sandias are composed mainly of the Sandia Granite and are characterized by bedrock-dominated (weathering-limited) "core-stone" hillslopes, which consist of bare, fractured, ellipsoidal blocks of granite, as illustrated in the lower left corner of Fig. 5.6. Core-stone hillslopes have small patches of thin, weakly developed soils between the large core-stones. Where small tabular bodies (geologists call these features "dikes") of a rock type called "aplite" (a fine-grained, granite-like igneous rock) occur in the granite, the aplite breaks down to large blocks that accumulate on hillslopes below the dikes. The blocks efficiently entrap windblown dust, a process that eventually causes the formation of a thick, well-developed soil (Figure B.8) (McFadden, 2013). These smooth, soil-mantled hillslopes (Figure 5.6) have been stable for tens of thousands of years, but ongoing shifts in climate will likely strip away the soil. As noted above, the numerous studies in the Jemez Mountains provide important contributions to the understanding of the role played by soils in the critical zone. Several of these studies also focus on soil hydrology, and in particular the impacts of wildfire on surface soil horizon alteration and erosion potential (e.g., Martin and Moody, 2001) (see Chapters 4 and 6). Employing "constitutive mass balance" analysis of a strongly developed soil atop the Pajarito Plateau, Eberly et al. (1996) strongly suggest that dust accumulation has influenced the development of soils on the hillslopes of the Jemez Mountains and other mountain ranges elsewhere in the southwest United States.

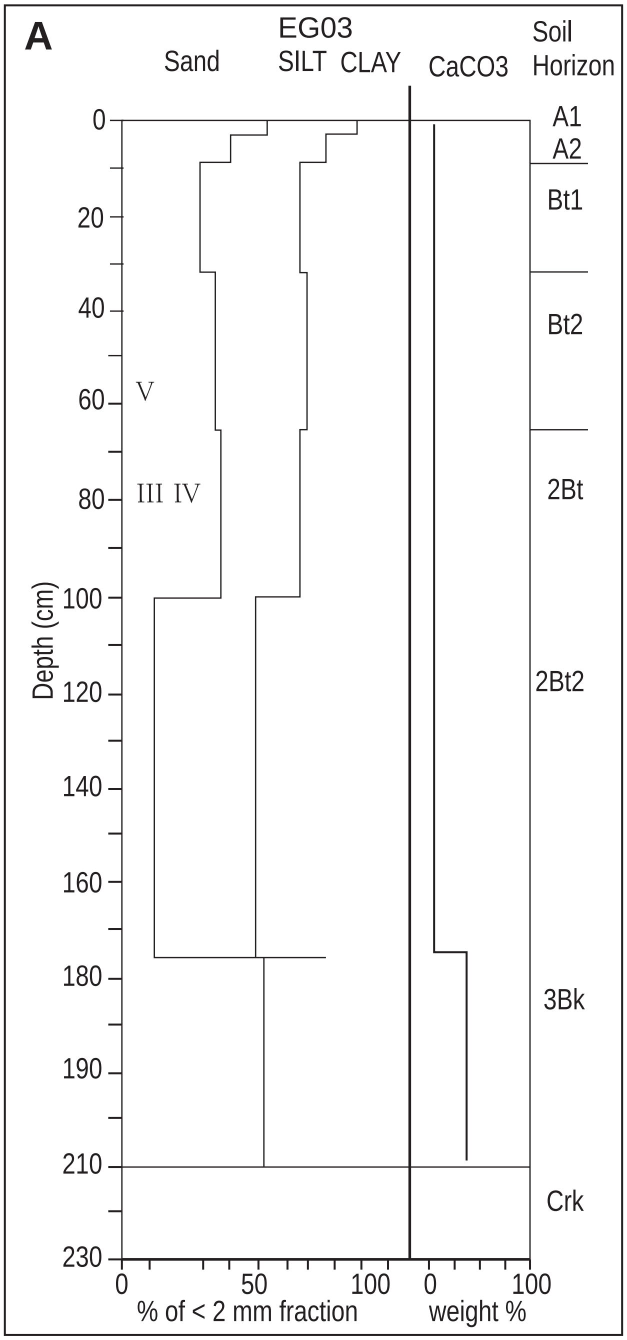

Figure B.8. Changes in particle size and soil carbonate concentrations in a thick soil on an "aplite" hillslope located in the foothills of the Sandia Mountains, New Mexico. The graph shows that soil-forming processes over tens of thousands of years have caused the accumulation of a great deal of clay and silt in the soil "B" horizon, most of which is derived from windblown dust. Only small patches of much thinner and weakly developed soils are found on the core-stone hills. Development of such soils are responsible for the emergence of smooth, curvilinear hillslopes (see text). Roman numerals signify depths at which samples for optical luminescence studies were taken. Modified after figure 8 in Persico et al. (2011).

APPENDIX C

The Clausius-Clapeyron Relationship

Most discussions of the effects of a warming climate on extreme precipitation start with a presentation of the Clausius-Clapeyron equation, which describes the saturation vapor pressure of water as a function of temperature (Donat et al., 2016; Lu et al., 2018; Lynker Technologies, 2019; Meredith et al., 2019; Kappel et al., 2020; Kunkel et al., 2020; Tabari, 2020; Fowler et al., 2021). The saturation vapor pressure of water is proportional to the maximum water content that the atmosphere can hold.

$$\ln\left(\frac{P_1}{P_2}\right) = \frac{\Delta H_{vap}}{R}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

Where

- P_1 & P_2 are the vapor pressure of water at temperatures T_1 & T_2
- ΔH_{vap} is the Enthalpy (Heat) of Vaporization of water (40.7 kJ/mol)
- R is the universal gas constant (8.314 J/(mol °K))

This relationship, plotted in Figure C.1, shows that a slight increase in temperature results in a large increase in atmospheric water content at warm temperatures. For example, increasing air temperature by only 1°C (1.8°F) allows the atmosphere to retain approximately 7% more water vapor. Consequently, increased temperature allows for the potential for much-increased water content in the atmosphere. This relationship directly implies the potential for increased precipitation from rainfall events as temperature increases.

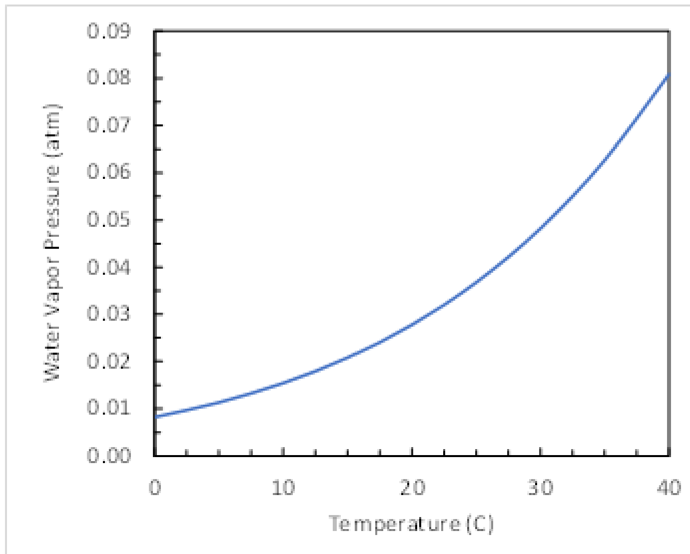

Figure C.1. Relationship between saturation water vapor pressure (over a flat surface of liquid water) and air temperature.

Of course, most of the time the actual vapor content of the atmosphere is much less than the saturation vapor pressure (the "holding capacity" of the air). This statement is equivalent to noting that most of the time the relative humidity (which is the actual vapor content expressed as a percentage of the saturation value plotted in Fig. C.1) is considerably less than 100%. On dry summer days in New Mexico, the relative humidity can be as low as 5%; on these days the temperature is typically very hot, but there just is not much water vapor in the air. For purposes of assessing future rare occurrences of extremely high precipitation, however, the huge increase in saturation vapor pressure at temperatures near 40°C in Fig. C.1 provides a compelling reason to expect that the most extreme precipitation events will be more intense in a warmer climate.

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Doug West, *Arroyo Salado*, serigraph, 1993

Doug West's limited edition serigraphs and posters are available through Leslie Levy Fine Art www.leslielevy.com; his original paintings are represented by Blue Rain Gallery, Santa Fe, New Mexico blueraingallery.com.

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