Climate Change Associated Sediment Yield Changes on the Rio Grande in New Mexico: Specific Sediment Evaluation for Cochiti Dam and Lake

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Executive Summary

Climate change is expected to have significant effects on water resources availability in New Mexico in general, and in the Rio Grande basin specifically, through alterations in the hydrologic cycle. Warmer temperatures, particularly in winter, are expected to reduce the amount of winter precipitation that falls as snow and is stored in the snowpack, reduce snow water equivalence in the snowpack, and lead to earlier spring melting of the snowpack. These changes may not only impact surface water flows, but the interaction between surface water and ground water as well. Warmer temperatures are anticipated to both drive up evaporation rates and increase the length of the growing season, contributing to lower overall soil moisture levels even without changes in precipitation. Recent climate trends suggest these processes are already underway.

Projections for precipitation are variable, primarily because there is great uncertainty about future changes to sea surface temperatures in the Pacific, which determine how much rain the Southwest gets over much of the year. In many models, winter precipitation declines because warming leads to the poleward expansion of subtropical deserts, pushing mid-latitude winter storms systems north of the catchment of the Rio Grande. However, models project wildly different futures for El Niño and La Niña cycles, some of which push the Southwest into permanent winter drought and others which create a permanent "El Niño" state in the eastern Pacific that actually increases winter precipitation in the Southwest. However, evapotranspiration increases are anticipated to outpace precipitation increases in the wettest models. A second uncertainty is whether hotter summer temperatures will drive a stronger summer monsoon, and if this monsoon will be able to tap into tropical cyclone moisture to produce large, late summer floods in the region.

This study considers the potential impact of climate-induced hydrologic changes to the Rio Grande on U.S. Army Corps of Engineers, Albuquerque District's flood control operations at Cochiti Dam and Lake, the major mainstem flood control structure in the upper basin. The specific concern being addressed is the relationship between changing climate conditions and reservoir sedimentation that might shorten the project lifetime or impact the flood control pool.

The U.S. Bureau of Reclamation provided the Corps with downscaled climate model ensembles providing projections for monthly changes to precipitation under five different climate scenarios: drier, less warming; drier, more warming; wetter, more warming; wetter, less warming; average of all model runs. Five scenarios were provided for the period 2010-2039 ("Near Future") and for the period 2040-2069 ("Far Future").

Reclamation used the data from the 10 projected climate scenarios as input to a Variable Infiltration Capacity (VIC) model to derive values for runoff, infiltration and contributions to groundwater from precipitation falling on a particular subset of the region. These data were then input by the Corps into its Upper Rio Grande Water Operations Model (URGWOM) in order to model changes in stream flow and in the amount of sediment transported to Cochiti Reservoir.

The results of the modeling effort project overall declining runoff volume, particularly in winter and spring, and a shift in the hydrograph to an earlier, lower spring peak flow. These changes drive overall reductions in inflow to Cochiti Lake, particularly in the Far Future. As a result, the rate of sedimentation in Cochiti Lake declines relative to the historic record. This may reflect the declining overall flows in the Rio Grande, and therefore its declining capacity and competence in the reaches above Cochiti. In this region, the channel bed and margins are primarily sand and coarser materials. In the future, lower peak spring flows may be less able to transport this coarse-grained material than at present, resulting in channel aggradation above Cochiti Lake rather than transport of this sediment downstream to Cochiti Lake.

Cochiti Lake is operated for flood control only, which means that native flows are typically passed without storage. Under climate scenarios in which peak floods and average inflows to Cochiti both decline, these changes in flow are expected to be passed downriver leading to declines in both average flows and flood flows downstream. These changes to flow will impact water allocations throughout the Rio Grande basin, as well as conservation flows, ground water recharge, ground water contributions to surface flows, and other hydrologic relationships.

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I. Introduction

Climate models currently project temperature increases at Earth's surface averaging 3-4°C above 1950-1999 by 2100 (and continuing to increase in the following decades), assuming that there are no radical changes in the global energy profile, and continued modest economic growth. Radical reductions in carbon emissions would reduce the temperature increase to about 2°C by 2100 (although the timeframe in which this could reasonably be achieved may be past). Rapid global population and economic growth without energy sector changes would result in more rapid temperature increases on the order of 6°C by 2100, with more beyond (Intergovernmental Panel on Climate Change (IPCC), 2007).

Although alarming, the warming itself is much less of a problem than the major consequences of this warming:

- Changes to precipitation amount and spatial distribution (annually and seasonally): many arid regions may become more arid, while many humid regions may become more humid.
- Changes will occur in precipitation intensity: precipitation is expected to fall in larger storms interspersed with longer dry spells. In particular, precipitation may vary even more on an inter-annual basis. Winter and summer storms may become more severe.
- Increases in evaporation and plant transpiration (evapotranspiration) are expected to scale with temperature. Longer growing seasons will translate into higher overall water demand among all users. Some plants may reduce transpiration in response to increases in atmospheric carbon, but this phenomenon is poorly understood. Precipitation increases may not be sufficient in many areas to offset increases in evapotranspiration, leading to a net soil moisture loss. The most vulnerable are the regions currently intermediate between arid and humid.
- Shorter, warmer winters are expected to result into less snow as a percent of total precipitation, earlier spring runoff (therefore earlier peak river flows, in advance of peak irrigation needs), and the decline and loss of glaciers and snowfields (reduced late summer runoff and river flows).
- Changes are expected to phenology (the seasonal timing of reproduction among species in response to environmental cues, affecting offspring survival) for both plant and animal species. These changes will occur on a species-by-species basis, and have the potential to disrupt food webs.
- Changes are expected in the distribution of plant and animal species, both terrestrial and aquatic. Changes to migration patterns and to the availability of food and habitat along migration routes are also expected.
- Enormous changes will occur in the Polar Regions that, for a variety of reasons, are warming at twice the rate of the world as a whole, leading melting of polar ice caps, sea level rise, and changes in Arctic weather patterns and ocean circulation. These changes will have significant impacts on midlatitude climates as well.
- Yield decreases are expected in crops that are highly vulnerable to changes in temperature and soil moisture, but also yield <u>increases</u> in some crops. Genetic engineering may be able to offset some of these declines.

Many of these changes will have profound effects on runoff and stream flow in the western United States in general and specifically the Rio Grande basin. Reductions in flow will pose special challenges for water resource managers, who must balance competing human uses against the demands of ecosystems and endangered species. Changes to stream flow in the Rio Grande also have the potential to shorten the

design lifetime of dam projects in the region through increased sedimentation. This reduction in storage capacity would increase flood risk along the river by reducing the reservoir flood space.

This research project, which is being done in collaboration with the U.S. Department of Interior, Bureau of Reclamation, assesses the effects of climate change on sedimentation at the U.S. Army Corps of Engineers' Cochiti Dam and Lake project. The amount of sediment transported to and deposited in reservoirs is dependent on the amount and type of sediment available in the catchment, and the ability of the fluvial system to transport that sediment to the reservoir. Hydrologic changes resulting from global atmospheric warming are likely to affect both sediment supply and fluvial transport. This in turn may affect the life expectancy of a reservoir and its operation with respect to storage and release of water.

Specifically, this report addresses three questions:

- How is projected climate change expected to affect watershed sediment yield?
- How would changes in sediment yield affect the rate of reservoir sedimentation and associated loss of storage capacity?
- How might these latter effects interact with hydrologic (water supply) impacts to ultimately affect water delivery reliability?

This project is part of a parallel effort led by Reclamation to understand how climate change may impact reservoir operations in the west. For this project, Reclamation provided the Corps with data for the climate scenarios and provided projections of future runoff under different climate scenarios using the Variable Infiltration Capacity (VIC) model. The Corps determined reservoir sedimentation changes using the Upper Rio Grande Water Operations Model (URGWOM).

A. About the Study Area

This report summarizes current and projected climate change, and climate change impacts, in the western U.S. and the Southwest, and describes the result of runoff modeling and sediment yield impact evaluation at Cochiti Dam and Lake, a Rio Grande mainstem US Army Corps of Engineers (Corps) project.

The Rio Grande rises in southern Colorado, in the San Juan Mountains near Creede. The river drains southeast to Alamosa before adopting a generally south-trending course through New Mexico to El Paso, then turning southeast to the Gulf of Mexico. Approximately 75% of the river flow above El Paso originates in the San Juan Mountains of Colorado, and in the Sangre de Cristo and Jemez Mountains of New Mexico.

Cochiti Dam is located at the confluence of the Rio Grande and the Santa Fe River, approximately 25 miles southwest of Santa Fe and 50 river miles north of Albuquerque. Construction on Cochiti Dam began in 1965 and was completed in 1975. The dam is a 28,815 foot-long, rolled earthfill structure with a maximum height of 251 feet above the streambed. Cochiti Dam and Lake are located on land belonging to the Pueblo de Cochiti. Cochiti Lake is operated for flood and sediment control, and maintains a permanent recreation pool. Sedimentation rates in the in the reservoir averaged about 6.6 cm/year near the dam from 1975 to 1996. Suspended sediment load at Otowi gage typically ranges from 1 million to 4 million tons/year, with loads as high as 9 million tons/year in some years (Wilson and Van Metre, 2000).

The drainage basin contributing inflow to the lake has an area of approximately 11,685 square miles. Cochiti Lake storage includes approximately 500,000 acre-feet for flood control and another 105,000 acre-feet for sediment accumulation. As of 2009, approximately 73,517 acre feet remained in the sediment reserve space. A recreation and conservation pool of 1,200 acres surface area (approximately

50,000 acre-feet) is maintained using non-native water from the San Juan-Chama Diversion Project. Annual evaporation from this pool, and seasonal flood control storage, averages approximately 4,200 acre-feet.

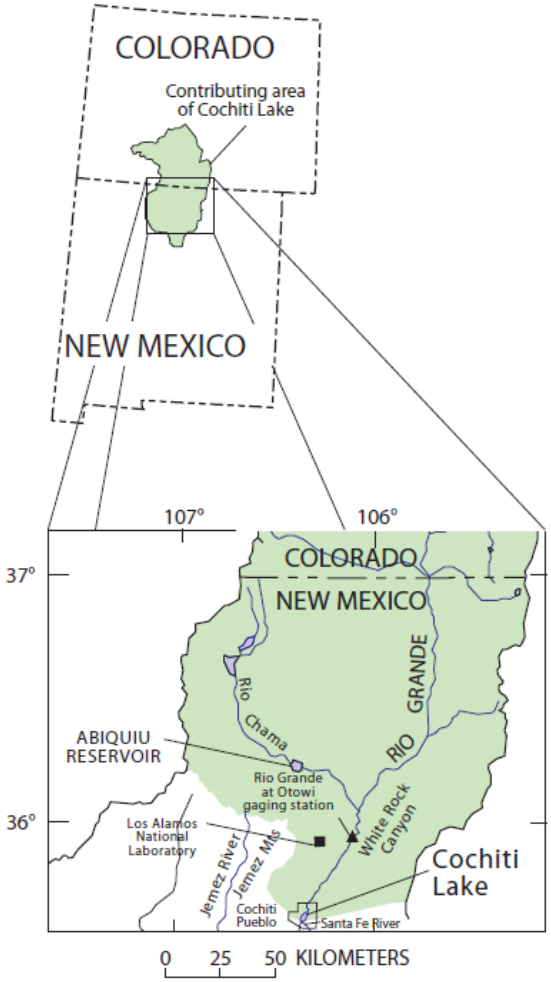


Figure 1: Map of Cochiti Lake and its catchment (from Wilson and Van Metre 2000, Fig. 1.)

The dam's current operation is to pass water rather than to store it, except during flood operations. Storage of flood flows occurs primarily in the late spring months and releases are made to maintain flows below a safe channel capacity of 7000 cfs at the Albuquerque gage at Central Avenue during snowmelt/spring runoff.

Upstream from Cochiti, water storage along the Rio Chama, the major tributary, occurs at the Bureau of Reclamation El Vado and Heron Lake facilities, and this water passes through the Corps' Abiquiu Dam on its way to downstream users. Significant sediment retention occurs at each of these facilities, dramatically reducing sediment contribution to the Rio Grande from the Rio Chama Drainage. In the Espanola Basin north of the Chama confluence, significant sediment contribution to the Rio Grande comes from ephemeral tributary streams.

B. Authority

The Bureau of Reclamation is required, under the SECURE Water Act of 2009 (Public Law 11-11, Subtitle F), to ensure that water supplies in the United States are adequate and safe. Under Section 9503, Reclamation is charged with identifying and mitigating risks to the nation's water supply posed by global climate change. As part of this effort, Reclamation is supporting research on reservoir sediment changes due to climate change (Project ID 8990). Reclamation has partnered with the Corps to understand how sedimentation is likely to affect two projects on the Rio Grande in New Mexico: Cochiti Dam and Lake and Elephant Butte Reservoir.

Participation by the Albuquerque District of the Corps in this project follows the lead set by Jo-Ellen Darcy, Assistant Secretary of the Army (Civil Works), who has advocated a proactive approach to assessing the risks posed by climate change and finding ways to mitigate or adapt to a changed climate (Darcy, 2010):

> *The US Army Corps of Engineers (Corps) recognizes that the entire portfolio of our structural and nonstructural water resources projects will be affected by climate change, necessitating not only mitigation to climate change, but adaptation as well...[The] Corps is responding to water-related risks posed by climate change to water resources infrastructure, including risk and vulnerability assessments, identification of potential adaptation strategies, and collaborative efforts supporting climate change adaptation.*

C. About this Report

This report was prepared using primary technical literature, public documents and online data.

- Chapter 1 introduces the report and the study area.
- Chapter 2 summarizes the current climate of New Mexico, paying close attention to the global and regional factors that determine spatial and season patterns of temperature and precipitation. The chapter also covers the key sources of cyclical variation in these climate factors.
- Chapter 3 discusses projected climate patterns in the western United States in general, and the Southwest and New Mexico in particular. It covers evidence for recent climate change, and emphasizes what the impact of warming on precipitation, evaporation, snowpack, snowmelt and stream runoff, among other factors. Chapter gives an overview of the literature on how river sediment load is impacted by climate change in sediment source areas (both valley alluvium and hillslopes).
- Chapter 4 provides a brief overview of climate change affects on fluvial systems.
- Chapter 5 describes the models used in this study.
- Chapter 6 presents the results of the modeling studies.
- Chapter 7 summarizes the findings.

II. Current Climate of New Mexico

Atmospheric warming over the next century will have significant impacts on the Southwestern landscape. However, these impacts will vary by place and season in ways governed by the large scale features of the modern climate system. Therefore, an understanding of how climate change will manifest in New Mexico must rest on an understanding of how the modern climate system works. This section of the report provides a brief overview of New Mexico's climate, its major features and drivers[1].

New Mexico is classified as an arid climate, with average annual precipitation approximately 13.4". That amount is greater (approaching 20") in northern areas and at higher elevations, and significantly less in southern areas and at lower elevations. Precipitation is bi-seasonal, with the major peak in summer (July to September), a secondary peak in winter (November to March), and arid spells in spring (April to June) and fall (late September through early November).

Temperature can be classified as warm. Average daily low temperatures in winter are 20°F (-7°C) while daily summer temperatures average 80 to 95°F (27 to 35°C). Again, areas to the north and at higher elevation are cooler year-round and areas to the south and at lower elevation are warmer year-round.

The basic pattern of New Mexico's climate is driven by its latitude and its position in the continental interior (Figure 2). In summer, New Mexico sits at the northern edge of the subtropics, a latitudinal zone located between approximately 20° and 40° north of the equator. Solar heating of Earth's surface along the equator causes humid air in this region to rise and to drop its moisture as rain. A portion of this air migrates northward, and eventually descends over the subtropics. As it descends, it warms and its capacity to retain moisture increases (pulling moisture out of the environment as the air mass descends)[2]. New Mexico's summer is therefore hot and largely dry.

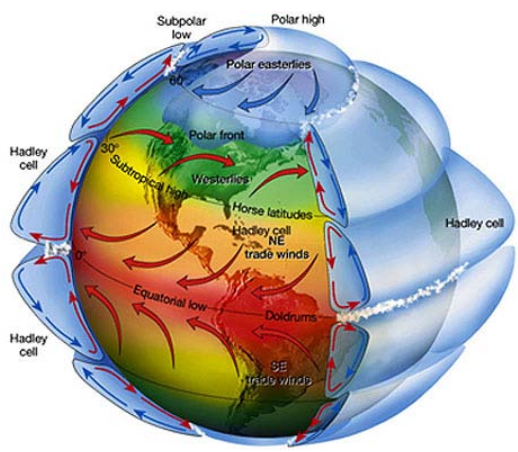


Figure 2: Map of atmospheric circulation, showing New Mexico at the boundary between the subtropics and the midlatitudes (source: SERC/Carleton College).

In winter, the area of maximum heating shifts south of the equator, which causes the zone of subtropical descending air to shift south as well. In New Mexico, this shift allows the southern movement of the temperate climate zone, bringing New Mexico into the reach of the jet stream and the alternating pattern of high pressure (clear) and low pressure (storm) systems that the jet stream drives west to east across mid-latitude North America. The weather in New Mexico in winter resembles that of Wyoming and Montana, although it is warmer and drier.

In addition to its latitudinal position, New Mexico also sits in the interior of North America: it is surrounded by dry land and is distant from warm oceans. Being in the continental interior limits how much moisture is available for precipitation. This limit is exacerbated by the region's location in the rainshadow of the Sierra Nevada mountains: much of the moisture coming off of the Pacific is wrung out of storm systems as they cross the Sierras, and is only added back in when these storms reach the Plains states and tap into humid air masses originating over the Gulf of Mexico.

1 This discussion of modern climate of the region is based on Sheppard, P. R., A. C. Comrie, G. D. Packin, K. Angersbach, and M. K. Hughes. 2002. The climate of the US Southwest. *Climate Research* 21(3):219-238.

2 As a general rule of thumb, rising air cools and as it cools, the water it contains condenses and eventually precipitates out – so areas underneath rising air get rain. Descending air warms, and as it warms it can hold more moisture, so it becomes relatively drier. Areas underneath descending air do not get rain.

A. Winter Climate

Although winter brings mid-latitude, temperate climate to New Mexico, the state is along the southern margin of this climate zone. Consequently, most storms bring cold air, wind, and clouds, but little precipitation. Some storms penetrate farther south, bringing widespread soaking rain or snow to lower elevations and, as demonstrated in February 2011, occasional subzero temperatures. Precipitation from these storms may continue on and off over a 24 hour or longer period and may impact a large region.

Winter precipitation varies from year to year depending on the temperature of the ocean surface to the southwest and west. Areas of the ocean with warm sea surface temperatures add a great deal of heat (energy) and moisture to overlying air masses, creating larger storms with greater precipitation potential[3]. Areas with cool sea surface temperatures fail to heat the air much, and produce small, weak storms with low or no precipitation potential. Ocean temperatures in areas that matter for Southwestern climate – eastern Pacific, Gulf of Mexico – vary in temperature from year to year, with direct consequences for climate in the Albuquerque District.

The most familiar variation in ocean temperature (and in the overlying atmosphere) is the El Niño-Southern Oscillation (ENSO) cycle (Figure 3). In a normal year, surface winds push warm equatorial Pacific surface waters to the west, creating a pool of warm water near Indonesia and allowing very cold, deep ocean water to rise to the surface in the eastern Pacific from northern Peru to Mexico. Over the warm pool, heat and moisture are contributed to the air, the warm air rises, and heavy precipitation occurs in the western Pacific. At the same time, the air over the eastern Pacific is comparatively cool and dry, and therefore the eastern Pacific and adjacent regions (such as the Southwest) are relatively cool and dry.

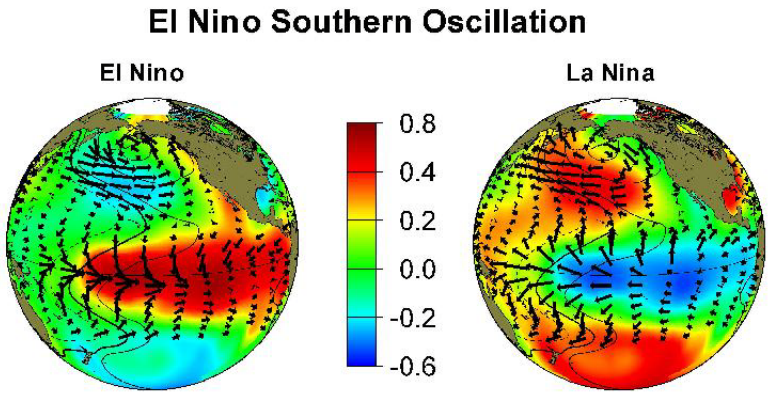


Figure 3: Changes in sea surface temperature in the Pacific as the result of ENSO cycles (source: JISAO/University of Washington).

In an El Niño year, the warm pool "migrates" to the east, leaving Indonesia cooler and drier, and shutting off the upwelling of cold ocean water in the eastern Pacific. Although most precipitation occurs out to sea, there is a significant increase in atmospheric moisture in the eastern Pacific, which brings more winter precipitation to the Southwest. Winter 2009-2010 was an El Niño year.

ENSO has a third state known as La Niña. In a La Niña phase, the warm pool migrates to the west of its normal position, bringing additional rain to Indonesia and Australia while at the same time bringing hyper-dry conditions to the eastern Pacific. Winter 2010-2011, which is a La Niña winter, has been exceptionally warm and arid in the Southwest.

The frequency of El Niño and La Niña events has increased since the 1970s. Before 1970, El Niño and La Niña events occurred in roughly equal frequencies, and were separated by several normal (ENSO-neutral) years. Since the late 1970s, the frequency of El Niño and La Niña events has increased, El Niño events

[3] Warmer air can hold more moisture and warmer seas evaporate more moisture, so air masses over warm seas become warm and humid (e.g., over the Gulf of Mexico). Cooler seas have less heat energy to drive evaporation, so evaporation is less. In addition, cooler sea surfaces also contribute less heat to the overlying air. The result is that air masses over cool parts of the ocean tend to be cooler and drier.

have outnumbered La Niña events by 2:1, the number of "normal" years separating the two have decreased, and El Niño events have increased in strength. The reasons for these changes are poorly understood. They may relate to other large-scale climate phenomena, including long-cycle changes in sea surface temperatures in the north Pacific[4] which operate on multi-decadal (50-80 year) cycles, and which can serve to amplify or dampen the different phases of the ENSO cycle.

ENSO effects on precipitation in the Southwest are primarily a winter phenomenon, and summers are usually characterized by ENSO-neutral or transition states. NOAA maintains a regularly updated discussion of current ENSO status, near-term (about 6 month) ENSO projections, and implications for how changes in ENSO will affect temperature and precipitation across North America[5].

B. Summer Climate

Summer precipitation in New Mexico has a very different origin than winter precipitation. In summer, the mid-latitude storm track migrates northward and New Mexico falls under the influence of subtropical climates. This is most evident in the hot, dry period April through June. Temperatures remain elevated through September, but in many years are moderated by the development of the North American Monsoon. A monsoon is defined as a seasonal reversal of wind and air movement of at least 120°. Whereas in winter, most weather descends on the region from the northwest, in the summer the flow is predominantly from the south.

Figure 4: Moisture sources for the North American Monsoon (source: NOAA).

Summer precipitation in the Albuquerque District is driven entirely by sunlight falling on Earth's surface, which heats the overlying air by conduction, and then the heated air rises. As this convection cycle gets repeated day after day, this eventually draws in moist air from over the eastern Pacific and Gulf of Mexico (Figure 4). As this air is drawn into this daily cycle of heating and rising, the rising air cools, water condenses from it and falls as rain over the Southwest. The monsoon onset is time-transgressive, beginning mid-June in areas to the south, and in mid-July in areas to the north.

Monsoon strength increases with elevation, in direct proportion to the amount of increase in daytime air mass rise. All things being equal, higher elevation areas will receive greater, and more consistent, monsoonal precipitation, with high mountain areas experiencing daily downpours. Lower elevation areas will tend to see less mid-day precipitation but more evening precipitation, and there will be greater day-to-day and place-to-place variation in precipitation.

The strength of the monsoonal rains depends very much on 1) how hot the Southwest gets (how much heat is available to drive air convection); 2) how warm the sea surface temperatures are the eastern Pacific and Gulf of Mexico, which serve as the principal sources for moist air and therefore determine the amount of moisture in air masses being pulled into the Southwest; and, 3) related to point 2, how active the

[4] These cycles are known as the Pacific Decadal Oscillation (PDO). ENSO cycles are also affected by multi-decadal, cyclical sea surface changes in the Atlantic (Atlantic Decadal Oscillation and others). All of these long-term climate cycles, and the effects of their interactions, are still poorly understood.

[5] This discussion can be found at NOAA's national Weather Service Climate Prediction Center, online at http://www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/ (Accessed March 16, 2011).

cyclone/hurricane season is in the eastern Pacific and Gulf of Mexico, which can push tremendous amounts of moisture into the Southwest during the late summer and early fall. Monsoon strength is also affected by sea surface temperatures at the hemispheric scale that govern large-scale movements of air masses at different altitudes.

Monsoon precipitation is typically intense but localized, and rarely has a uniform effect across a large drainage basin area. However, precipitation can be more widespread if the monsoon is able to tap moisture from a tropical cyclone in the moisture source regions.

III. Projected Climate Change in the Western United States and New Mexico

Any discussion of projected impacts of climate change on flows in the Rio Grande must take into account the range of future climate projections. Because future greenhouse gas emissions are dependent on future economic, demographic, technological, political and other considerations, any projection of future runoff must take these factors into account. This chapter begins with a discussion of future climate scenarios typically used in climate change models. It then goes on to discuss impacts to the West in general and New Mexico in particular of projected climate changes given different future atmospheric greenhouse gas concentrations.

A. Projecting Climate Warming under Different Economic Scenarios

Projecting climate change is a complex, multi-step process involving:

1. Construction of a coarse-resolution, global-scale model of Earth's climate system (atmospheric general circulation model or atmospheric GCM). Because of the tremendous influence of sea surface temperatures on climate, to more "realistically" mimic the climate system, the atmospheric GCM has to be coupled to a model of Earth's ocean circulation (oceanic GCM), producing what is known as a "coupled" model (coupled GCM). The completed model is refined by comparison with modern climate systems (e.g., "forcing[6]" the model with El Niño conditions to see if it reproduces known El Niño climate patterns), the historic instrumental record, and other records of past climate change.
2. Construction of models of future global economic, social, demographic, and technological change to project future carbon emissions. These are referred to as scenarios. These scenarios were developed by the IPCC in its *Special Report on Emissions Scenarios* (Intergovernmental Panel on Climate Change (IPCC), 2000) to use as common climate model inputs for both comparing how robust model predictions are, and assessing how sensitive climate will be to different carbon emissions levels. The SRES scenarios used for modeling are (Figure 5):
    a. The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building, and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. The A1 scenario family develops into three groups that describe alternative directions of technological change in the energy system. The three A1 groups are distinguished by their technological emphasis: fossil intensive (A1FI), non-fossil energy sources (A1T), or a balance across all sources (A1B). A1B is also called the "business as usual" scenario.
    b. The A2 storyline and scenario family describes a very heterogeneous world. The underlying theme is self-reliance and preservation of local identities. Fertility patterns across regions converge very slowly, which results in continuously increasing global population. Economic development is primarily regionally oriented, and per capita economic growth and technological change are more fragmented and slower than in other storylines. A2 has the highest carbon emissions because demand continues to rise, but

[6] In this situation, forcing a model refers to altering the input parameters to see how the model responds. In this instance, altering the pattern of sea surface temperatures in the Pacific to see if there are appropriate corresponding changes to atmospheric circulation, surface temperature, precipitation, and so forth.

lack of coordination among nations prevents the rapid spread of more efficient technologies.

c. The B1 storyline and scenario family describes a convergent world with the same global population that peaks in midcentury and declines thereafter, as in the A1 storyline, but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies. The emphasis is on global solutions to economic, social, and environmental sustainability, including improved equity, but without additional climate initiatives. B1 has one of the lowest carbon emissions of the scenarios.

d. The B2 storyline and scenario family describes a world in which the emphasis is on local solutions to economic, social, and environmental sustainability. It is a world with continuously increasing global population at a rate lower than A2, intermediate levels of economic development, and less rapid and more diverse technological change than in the B1 and A1 storylines. While the scenario is also oriented toward environmental protection and social equity, it focuses on local and regional levels.

3. The coupled GCM is then forced with the carbon dioxide (and other) emissions of one of the IPCC scenarios and run until the model stabilizes. This yields a projection for future climate at a particular point in time (e.g., 2080) under a particular scenario (e.g., A1B). Because there are stochastic elements to climate, the model is run a number of times, and what gets reported is essentially the average of all the model runs. Some aspects of projected climate change recur across model runs, and are considered “likely” or “very likely”; some aspects of projected climate change differ among model runs and are considered less likely or less certain.

4. For larger scale assessments, model ensembles are used (the results from multiple climate models for a given scenario are grouped together and treated as a single data set).

5. Computing power limits the spatial resolution of coupled GCMs. To get a more detailed representation (for instance, in areas of significant differences of relief, such as the Southwest), a finer-resolution, local model has to be tucked into the coupled model so that the larger-scale model outputs for that area of the world become inputs to the local scale model. This process is known as “downscaling”. Downscaling is essential to modeling local and regional landscape responses to climate change [such as the soil moisture changes captured using the Variable Infiltration Capacity (VIC) model (Gao et al., 2009)].

Some points to consider:

- Carbon emissions due to human actions are small compared to the natural carbon flux. However, the natural carbon flux is balanced – as much is taken up by natural processes as is given off. Human-caused emissions are unbalanced – they accumulate in the atmosphere because they are not removed by natural processes (e.g., photosynthesis, marine shell formation, burial, etc.).
- There is a lag between the emission of carbon and its effect on climate. Therefore, even if we went to zero carbon emissions today, the climate would continue to warm and the possibility exists that we are already committed to dangerous levels of warming (Armour and Roe, 2011).
- Many aspects of the climate system are imperfectly understood, so good and bad surprises await us.
- Changes can be amplified through positive feedbacks. For instance, snow and ice reflects sunlight almost like a mirror, so little heat is absorbed and little heat given off to the overlying air. Patches of bare ground and ocean water, however, are very good at absorbing sunlight, heating up, and then transmitting the heat to the overlying air so that it warms. In the Arctic, the decline in

summer sea ice means that summer air over the Arctic Ocean is much warmer and more humid than previously, which is accelerating the warming of the Arctic (Screen and Simmonds, 2010). It is therefore also contributing to a shortening of the Arctic winter; changing ocean circulation between the Arctic Sea and surrounding oceans; and changing summer climates throughout the subarctic.

- Changes can be dampened by negative feedbacks. For instance, aerosol pollutants in the atmosphere reflect sunlight back into space, and have a net cooling effect on the planet. Ironically, cleaning the air of pollutants will actually slightly increase warming.
- Climate change is not necessarily linear (gradual), but can be stepwise (rapidly shift between two very different steady-states).
- The rate of warming is a critical issue because the slower Earth warms, the longer humans, plants and animals have to adapt to climate change physiologically, or through migration, or, for humans, technology. The amount of ecological collapse can be thought of as being proportional to the rate of change. The projected rate of climate change is now faster than that at the end of the last Ice Age, which was a major (if not the major) contributor to Earth's most recent mass extinction event.
- Ocean acidification is an important problem. Increasing the carbon dioxide concentration in the air leads to increasing carbon dioxide in the ocean leads directly to a decline in ocean pH. Lower ocean pH makes it difficult for some marine animals to make shells, which not only impoverishes

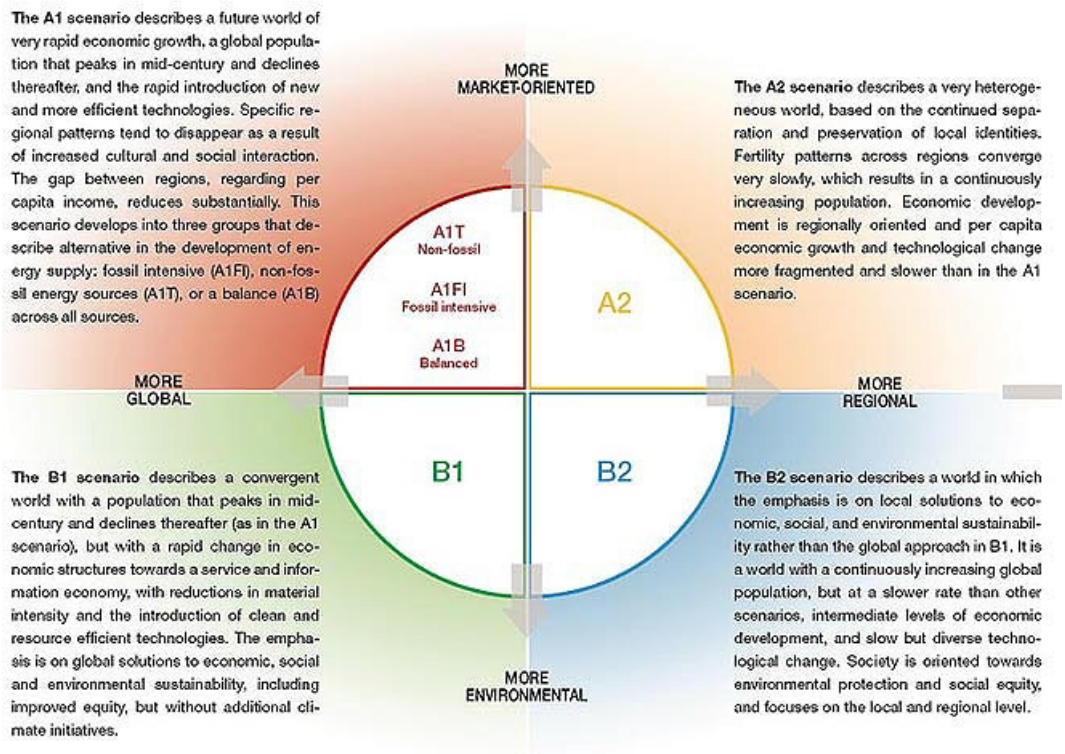


Figure 5: IPCC SRES model scenarios (source: GRID Arenal).

the ocean food chain (because most of the shell-making occurs in small ocean critters at the base of the marine food chain, such as diatoms) but reduces the ability of the ocean to remove or "sequester" carbon from the atmosphere and acts as a positive feedback to the climate system by increasing the net carbon in the atmosphere.

B. Climate Change in the Intermountain West

i. Temperature Changes

Recent Trends

Temperatures in the Intermountain West have shown a relatively steady rise beginning in the early 20th Century. The rise stalled during the middle part of the century during the post-war economic boom as increasing atmospheric pollution reduced the amount of sunlight entering the lower atmosphere, and then continued to rise following implementation of laws regulating environmental and atmospheric pollution.

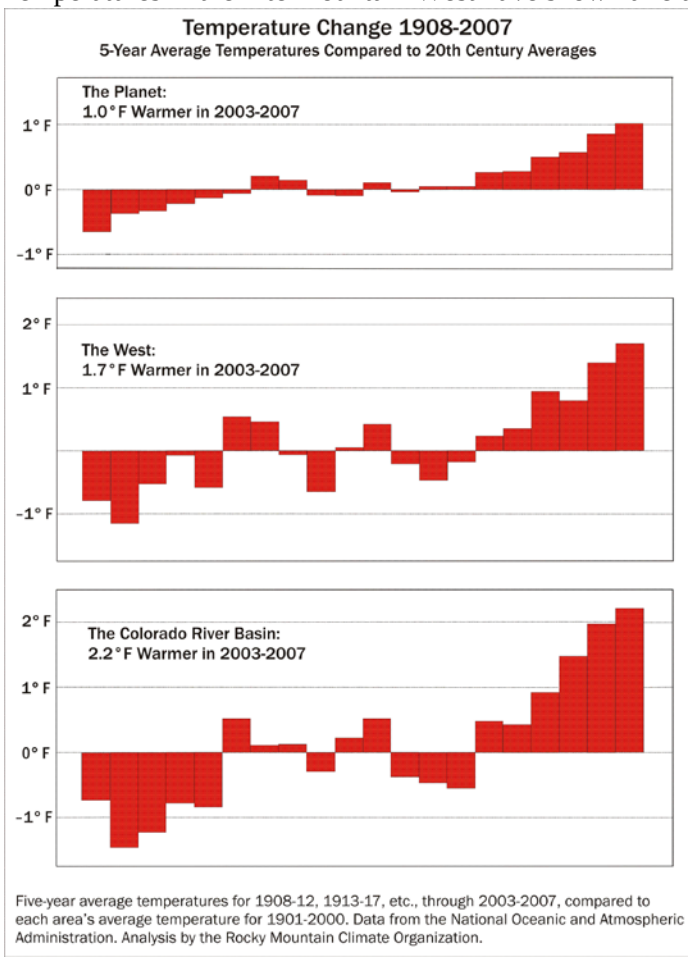


Figure 6: Five year average temperatures in the Rocky Mountains compared to the West and globally (source: Rocky Mountain Climate Organization).

Globally, 2010 is tied with 2005 as the warmest on record, continuing a trend of 34 consecutive years during which average global surface temperatures remained above the 20th Century average. The 2010 global land surface temperature average was 0.96°C (1.7°F) above the 20th Century mean (NOAA, 2011a). The first 10 years of this century constitute 10 of the 11 warmest years in the historical record, and may be warmer than it has been for millennia. In this decade, there were four wet El Niño cycles and three dry La Niña cycles (NOAA, 2011b).

The consensus view is that recent increases in temperature in the western U.S. exceed observations in the historic record, and constitute evidence for anthropogenic (human caused) climate change (USGCRP, 2009). In the mountainous West, average annual temperatures for 2001-2009 were 0.8°C (1.4°F) higher relative to the average for 1895-2000 (MacDonald, 2010). Temperature increases were greater in areas to the south and at lower elevation. In New Mexico, temperature increases over this same period were as great as 1.5 to 2 standard deviations above the 20th Century mean in the Rio Grande Valley, and between 1 and 1.5 standard deviations above on the Plains. The recent temperature increase exceeds that observed in the record for the last 400 years in the Southwest.

Particularly troubling have been increases in late winter/early spring (January, February, March, or JFM) temperatures throughout the mountainous West. The observational record of 1950-1999 shows an average increase in maximum average JFM temperatures of 1.53°C (2.8°F) and an increase in minimum average JFM temperatures of 1.72°C (3°F) (Bonfils et al., 2008). Winter temperatures are warming at rate that is faster than average temperature increases. This has resulted in a contraction of the number of days below

freezing by approximately 8 days, and a corresponding lengthening of the frost-free period. Detection and attribution modeling studies indicate that these patterns cannot be replicated in models of natural climate forcing (including ENSO, Pacific Decadal Oscillation, solar variation and changes in volcanic aerosol concentrations), but are robustly replicated in models that include anthropogenic forcing.

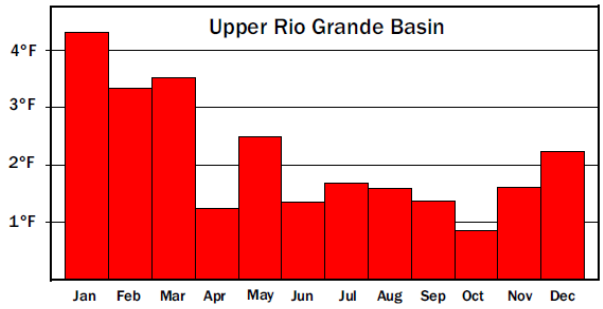
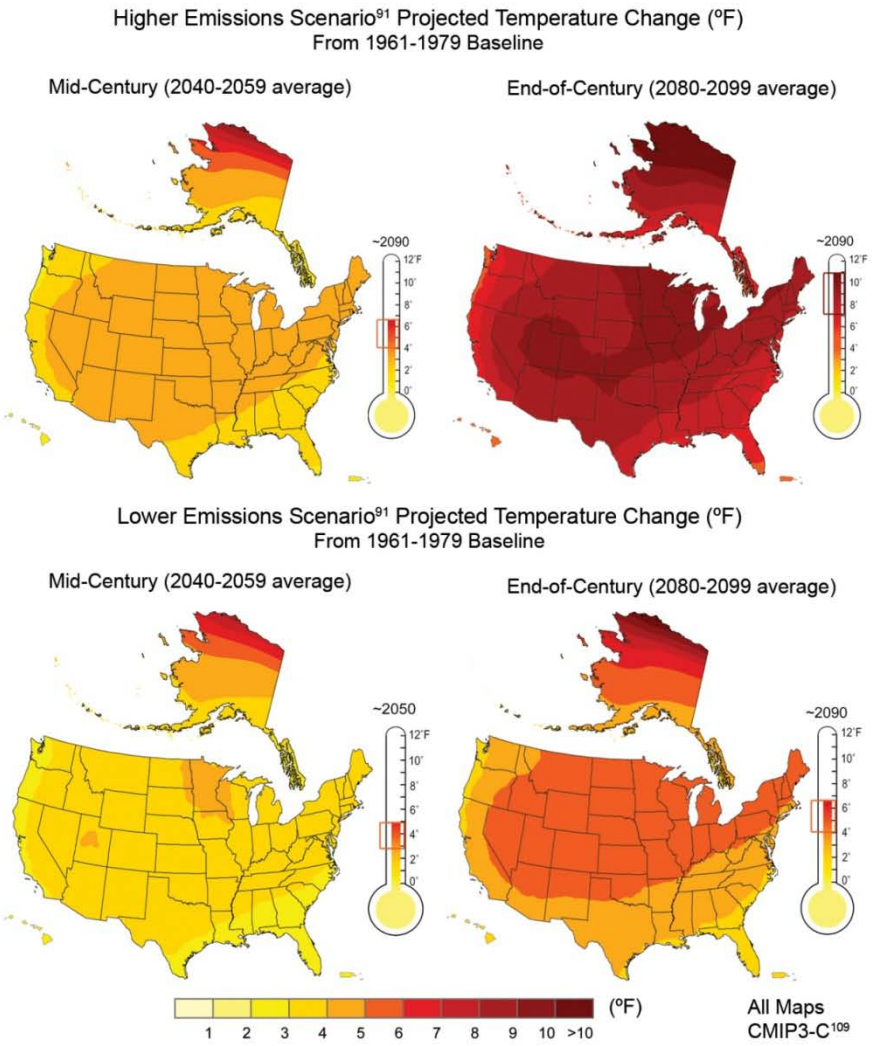


Figure 7: Average monthly temperature change in the Upper Rio Grande Basin, showing that warming is greatest in the winter months (source: Saunders et al., 2008).

Rates of warming at altitude may be considerably greater than average. In a recent analysis of National Weather Service and SNOTEL site data in the San Juan Mountains, Rangwalla and Miller detected a rate of warming of 1°C (1.8°F) ***per decade*** from 1990 to 2005 (Rangwala and Miller, 2010). Elevation played an important role in determining the season of greatest warming in the mountains. Lower elevation sites experienced greatest warming during the winter months, warming in winter at a rate of 1.5°C (2.7°F) ***per decade***. Higher elevation sites experienced their greatest warming during the summer months, with temperatures increasing at a rate of 1.5°C ***per decade*** during this season. The differences in the season of greatest warming are due to the cooling effects on air temperatures of snow on the ground. Increases in winter minimum temperatures increased faster than winter maximum temperatures at lower elevations, while summertime maximum temperatures rose faster than minimum at higher elevations.

Temperature Projections

Climate models project a warmer Southwest, with average annual temperatures by 2080 rising approximately 2 to 3.5°C (4 to 6°F) under lower emissions scenarios and 4 to 6°C (7 to 10°F) under higher emissions scenarios (USGCRP, 2009). A recent analysis suggests the higher warming scenario is more likely, with temperature increases of 2 to 4°C likely by 2050 (Barnett and Pierce, 2009). In addition, there may be seasonal and geographic differences in warming: temperature increases may be greater over the northwestern portion of the area, particularly Utah, than other parts (Dominguez et al., 2010).



The maps on this page and the previous page are based on projections of future temperature by 16 of the Coupled Model Intercomparison Project Three (CMIP3) climate models using two emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC), *Special Report on Emission Scenarios* (SRES).91 The "lower" scenario here is B1, while the "higher" is A2.[91] The brackets on the thermometers represent the likely range of model projections, though lower or higher outcomes are possible. Additional information on these scenarios is on pages 22 and 23 in the previous section, *Global Climate Change*. These maps, and others in this report, show projections at national, regional, and sub-regional scales, using well-established techniques.[110]

Figure 8: Projected average temperatures under higher and lower emissions scenarios (source: USGCRP, 2009)

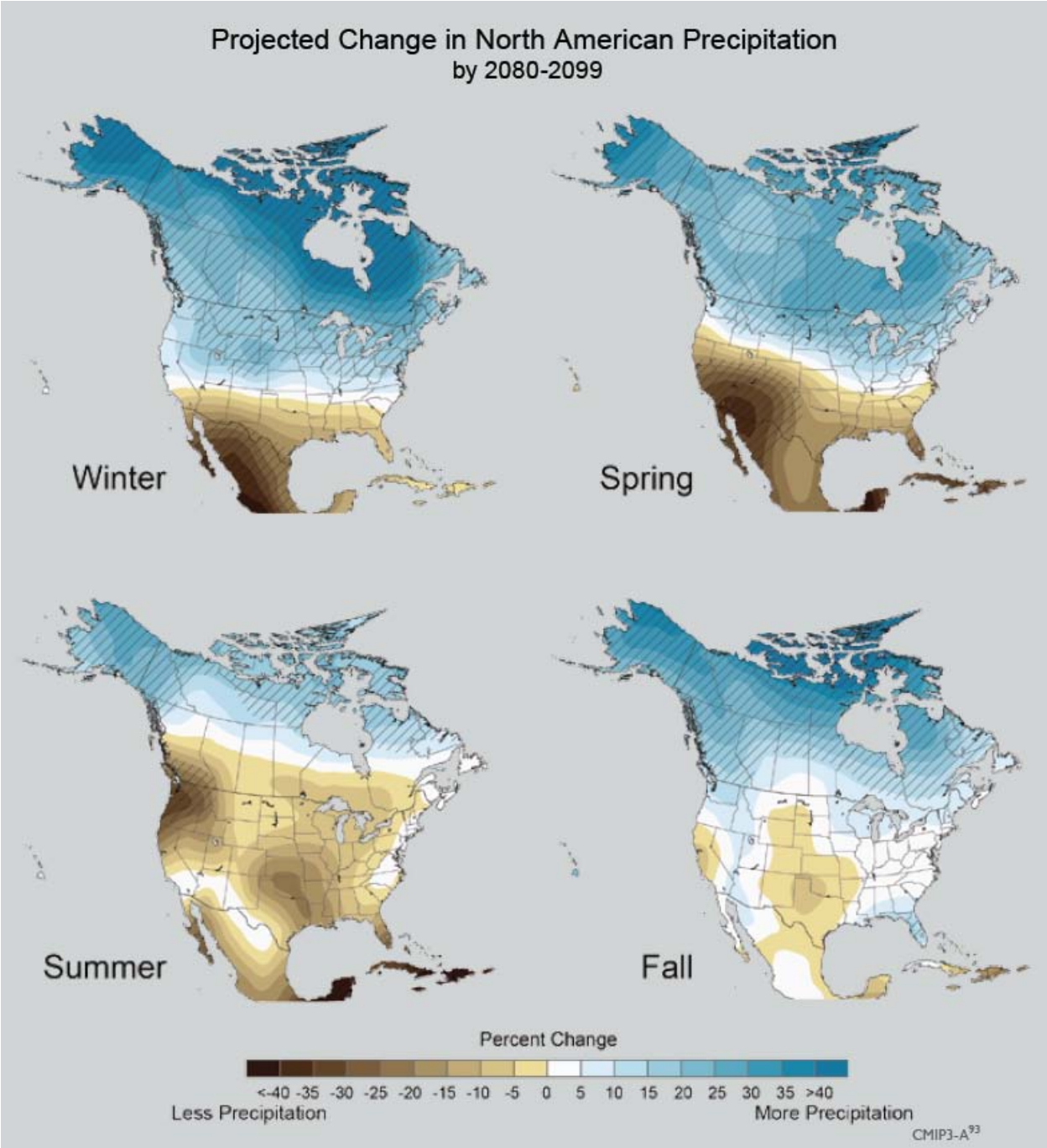


Figure 9: Projected change in North American precipitation by 2080-2090 (source: USGCRP, 2009).

ii. Precipitation Changes

Recent Precipitation Trends

Warming-driven changes to global atmospheric circulation will affect when, where, and by how much precipitation will change. These changes will be superimposed on already highly-variable precipitation patterns resulting from the interplay of long- and short-term climate cycles. Long-term wet and dry cycles in the Southwest are controlled by Pacific sea surface temperatures, particularly the multi-decadal Pacific Decadal Oscillation (PDO). Inter-annual variation in winter precipitation is controlled by the ENSO cycle, with either El Niño or La Niña amplified depending on the state of the PDO. Because of the high variability in precipitation in the Southwest at multiple scales, detecting changes in precipitation has been more challenging than detecting changes in temperature.

At the national scale, precipitation has increased 5% over the past 50 years, driven by increased evaporation from warmer ocean surfaces putting more moisture in warmer air producing bigger storms with more precipitation. Most of the precipitation gain has been in the Northeastern U.S. from the eastern Dakotas to the Atlantic Ocean, with decreases in the Southeast. New Mexico overall had a slight increase in November to March precipitation over the period 1950-1999 (Mote et al., 2005). Attribution studies have so far concluded that precipitation trends in the region currently cannot be attributed solely (or directly) to anthropogenic causes, because the magnitude of the trend so far is swamped by the magnitude of variation due to long-term and short-term shifts in Pacific and Atlantic sea surface temperatures (Barnett et al., 2008; Dominguez et al., 2010).

During the 20th century, the period 1905-1930 was wetter than average, and from 1942-1964 it was drier than average. From 1976 through 1997/1998, warm, wet winters and erratic summer precipitation were the norm (Sheppard et al., 2002), giving way by 1999/2000 to conditions that were warmer and drier than at any period in the 20th Century or the preceding 1200+ years (MacDonald et al., 2008). Since 2001, large portions of the Southwest have experienced drought, with particularly widespread & severe drying in 2002, 2003, 2007, 2009, and 2011. During these extremes, precipitation across the region averaged 22-25% below the average for the 20th Century, leading to a significant reduction in soil moisture and stream flow. For instance, at Lee's Ferry on the Colorado River, annual flow in the early 20th Century was approximately 17.0 million acre feet, but averaged only 11.2 million acre feet for 2001-2006, and for 2002 alone, flow declined to approximately 6.2 million acre feet (Reclamation, 2011).

Recent and Past Droughts

Historically, droughts are common in the Southwest. Between 1916 and 2008, there were 11 extreme drought years covering all or part of the region. An extreme drought year is a water year in which the area-averaged soil moisture falls below the 10th percentile of the 1951-1999 historical period. Extreme drought years in the 20th century "almost always have occurred in the midst of longer dry periods, in which droughts build up and subside over multiple years" (Cayan et al., 2010). These dry periods historically ranged from 47 to 123 months (approx. 4 to 10 years). Three of the 11 extreme drought years occurred in the 1st decade of the 21st Century (in 2002, 2007, and 2008), nestled within a period of elevated temperatures beginning in 2000. Water year 2011 is also likely to be an extreme drought year given projections that La Niña conditions will persist into the summer (NOAA, 2011c).

For winter 2011, in which protracted drought was exacerbated by La Niña conditions, watersheds for the Rio Grande average snow water equivalents on March 22, 2011 were: Upper Rio Grande (84% of normal); Rio Chama (77% of normal); Sangre de Cristo Mountains (53% of normal); and Pecos Mountains (40% of normal). Watersheds to the north and northwest that are tributary to the Colorado River are experiencing higher than average snow water equivalents (Reclamation, 2011). Because the

watershed for the Colorado River extends north into northwestern Wyoming and northeastern Utah, dominated by temperate, midlatitude climates – both historically and projected – flow on the Colorado may not correlate well with flows on the Rio Grande. Modeling by Seager and Vecchi (Seager and Vecchi, 2010) suggests that the current drought is within the range of natural climate variation and cannot be attributed to anthropogenic causes.

Although the 2011 water year is exceptionally dry, overall the current drought "does not have an unusual precipitation deficit", but the "warmth of the recent drought is exceptionally strong and consistent" (Cayan et al., 2010). The results are persistent soil moisture deficits and runoff levels that are below average extreme dry levels: in the first decade of the 21st Century, the Colorado has experience its lowest 5-year mean flows on record. The start of the current drought is variably placed by researchers, with some arguing for the onset of drought by late 1999 (Cook et al., 2004). It should also be noted that, if the current drought persists as expected at least through the end of the current La Niña in June 2011, the duration of this drought (>138 months) will exceed the longest duration drought of the historical record.

The duration the current drought, however, is not remarkable considering the tree ring records of climate change covering the last 1200 years (back 2000 years in some areas). In a widely cited work, Cook and colleagues (Cook et al., 2004) used centuries-long, annually resolved tree-ring records from throughout North America to reconstruct annual summer-season Palmer Drought Severity Index (PDSI) for the last 1200 years. The PDSI is a relative measure of drought and non-drought conditions. Their reconstruction extends back to a warm climate interval known as the Medieval Warm Period between approximately AD 800 and 1300 when Northern Hemisphere temperatures increased due to natural forcing[7]. In the warmest part of the Medieval Warm Period (from AD 950 to 1150), average Northern Hemisphere temperatures rose 0.2-0.4°C above the mean 1850-2006 (by comparison, late 20th / early 21st Century global average temperatures are 0.8°C above the same mean) (Mann et al., 2008). In the Southwest, average temperatures may have been double this amount, and during the warmest intervals in the Southwest, temperatures may have approached 1°C above this mean (Woodhouse et al., 2010).

They found four multi-decadal droughts occurred in the overall much drier 400 year "megadrought" interval from AD 900 to 1300, peaking in AD 938, 1034, 1150, and 1253. During the megadrought, reconstructed PDSI values show an average increase in drought area in the West of 41.3%. Droughts of considerably less magnitude occurred in the slightly cooler, wetter period from 1300 to approximately 1920 (also known as the "Little Ice Age").

Medieval Warm Period warming is thought to be the result of increased solar irradiance and reduced volcanic activity, which forced the Pacific into a persistent "La Niña"-like state. El Niño and La Niña climate swings occurred relative to this drier base state. If warming due to anthropogenic factors has a similar effect on tropical Pacific sea surface temperature patterns, a similarly more arid base state will emerge that could potentially last for centuries (the duration of projected warming).

The strongest of the multi-decadal droughts during the Medieval Warm Period megadrought occurred between 1140 and 1159 (and contributed to the abandonment of the Chaco Canyon area). Based on tree-ring records (Cook et al., 2010; Meko et al., 2007; Salzer and Kipfmueller, 2005), the warmest, driest period of the 12th Century was AD 1146-1150. During this period, reconstructed Colorado River flows are estimated to have averaged 14.2 billion cubic meters per year, 65.5% of the Southwest was under drought conditions, and average annual maximum temperatures for the region were 15.65°C. By comparison, over the 20th Century, the average flow for the Colorado River has been approximately 18.3 billion cubic meters per year, only 32.6% of the area has been under drought conditions at any one time, and the

[7] Detection and attribution studies have assessed whether the same factors responsible for the MWP (high solar irradiance and reduced volcanism [Cook et al. 2004]) might account for today's warming, and have consistently found that they do not.

average annual maximum temperature (1909-2008) has been 15.72°C (summarized and extended in Woodhouse et al., 2010). In the last decade, the average annual maximum temperature in the Southwest has been 17.54°C and the average flow on the Colorado River in the period 2000-2009 was 14.65 billion cubic meters per year. The current drought is not as extensive as the 12th Century (which impacted as far away as the Pacific Northwest, which is not affected by the current drought), and has not yet lasted as long.

While some researchers propose changes to ENSO as the primary driver of future droughts, both the intensification of tropical-subtropical circulation and the expansion of the resulting subtropical dry zone are important features projected to contribute to future aridity in climate models of the Southwest (Seager et al., 2007). Recent studies have suggested that this mechanism may have operated in the past. Recently, a team of researchers headed by Peter Fawcett (2011) have examined sediment cores from the Valles Caldera, New Mexico, dating to the mid-Pleistocene (between 368,000 and 550,000 years ago). Temperature and drought reconstructions show that centuries-to-millennia-long megadroughts occurred during warmer climate intervals, when mean annual temperatures were as high or higher than today. These droughts are marked by evidence for the collapse of drought-tolerant C4 plant communities, indicating summer aridity likely resulting from the poleward expansion of the subtropical dry zone. The authors specifically compare the characteristics of these ancient climate intervals with the modern, and conclude that it is plausible for the subtropical dry zone to expand in response to modern warming, resulting in future Southwestern megadroughts.

Some researchers see evidence in the current climate data that warming-driven expansion of the subtropical dry zone is already under way (Seager et al., 2007; Seidel et al., 2008). One study has shown that a northward shift in the jet stream began in 1978, allowing more rain to fall to the north and east, and leaving the Southwest drier in the early spring (McAfee and Russell, 2008). As a result, the northern Great Plains states have seen a small increase in spring precipitation. Another study has indicated that the drier springs in the Southwest are contributing to a later start for the summer monsoon season (Seth et al., 2011). Early in the monsoon season, moisture to initiate precipitation is typically pulled from soil moisture, with progressively greater contributions of moisture from air masses over the eastern Pacific and the Gulf of Mexico as the season progresses. Because winter/spring storm tracks are pushed to the north, resulting in drier springs in the Southwest, there is less and less soil moisture available to initiate the early monsoon. Monsoon season precipitation thus declines (because the season is shorter), although greater land surface heating is anticipated to lead to enhanced convection and stronger monsoonal precipitation once marine subtropical air masses are drawn inland.

Seager and Naik (2012) reanalyzed models used by the IPCC in order to detect differences in tropical atmospheric circulation affecting precipitation (P) and evapotranspiration (E) in the subtropics and midlatitudes. They focused on the difference between these two numbers (P-E) as a way of differentiating ENSO-driven changes from changes due to increased heating and moisture transport resulting from atmospheric warming. By subtracting the portion of P-E changes due to ENSO variation from the climate record for the period since 1979, a clear but weak trend in the P-E data emerged that is consistent with warming-forced expansion of the subtropical dry zone predicted by models used in the most recent IPCC assessment. Although still swamped by interannual variation in precipitation, they found an emerging trend indicating warming-driven expansion of the subtropical dry zone may be under way.

Detection and attribution studies have had less success with hydroclimate variables than with temperature. In the northern Intermountain West, modelers engaged in detection and attribution studies discovered a clear anthropogenic signal to earlier peak runoff during the period 1950 to 1999 (Hidalgo et al., 2009). However, the observed changes in the southern Intermountain West could not be clearly distinguished by cause: anthropogenic changes appear to be one of several causes contributing to earlier peak spring runoff, declines in snow water equivalent, and other hydroclimate changes in the region.

Model Projections of Late 21st Century Precipitation

Predictions of precipitation levels have much greater uncertainty than for temperature because there are great uncertainties with respect to how anthropogenic warming might impact ENSO and multi-decadal ocean oscillations in the Pacific, Atlantic and Arctic Oceans. Small changes in one can be amplified by small changes elsewhere in ways that are poorly understood for current systems.

The general rule of thumb is that anthropogenic warming will intensify precipitation patterns: wet areas, such as the northeastern U.S., will get wetter and dry areas, such as northern Mexico and southern Arizona, will get drier (USGCRP, 2009). But what will happen in areas lying on the current boundary between the subtropical and mid-latitude climates, such as New Mexico, west Texas, Oklahoma and Kansas, is harder to project because they depend on estimates of how far north the storm tracks may be displaced, and how far north the monsoon may penetrate. Model projections range from essentially no change in precipitation to reductions of about 10% (Barnett and Pierce, 2009).

Researchers at the U.S. Global Change Research Program project a 10 to 20% decline in precipitation by 2080-2090 primarily in the winter and spring, resulting from the northward (poleward) shift of midlatitude winter storm tracks bringing the Southwest into the subtropics year-round (Figure 9). Land and ocean warming should bring more moisture into New Mexico during the summer months, providing stronger monsoons, but this is only projected by some models. Modeling by Dominguez and colleagues (2010) suggests that the distribution of drying will be uneven across the Southwest: the southern part of the Southwest will become drier, and the northern part slightly wetter, but the modeled trends were not significant.

A key change projected by models is that precipitation will become concentrated in a smaller number of larger-magnitude precipitation events. This is borne up by data that show that the frequency and intensity of heavy downpours in the U.S. has increased, with the share of total precipitation falling in major storm events increasing by nearly 20%. This pattern has also been observed in the Southwest. From 1958 to 2007, there was a 9% increase in the amount of rainfall falling in very heavy precipitation events across the Southwest, the lowest rate in the country (the Northeast has seen a 67% increase and the Midwest at 31% increase over this same timeframe). Climate models project that the share of precipitation falling in heavy rainfall events will continue to increase, while a decreasing share will fall during low-intensity events.

C. Changes to Water Balance

Regardless of whether projections are for increases or decreases in precipitation, there is a broad agreement that temperature-driven increases in evaporation will exceed increases in precipitation, leading to a net decrease in soil moisture and a persistently negative water balance for the region.

In a review of 19 models used by the IPCC in its most recent assessment report, Seager and colleagues (Seager et al., 2007) examined trends in precipitation minus evaporation (P-E) over the period 1900-2098 (modeling included retrodicting the historic record and projecting the 21st Century climate). They found that under the A1B emissions scenario there is a sustained transition to drier climate beginning in the 1990s or early in the 21st century. In the models P decreases faster than E. Most of the reduction in P-E occurs in winter when precipitation declines but evaporation levels are not substantially changed from present. This modeling effort suggests that the average climate of the Southwest by mid-21st Century will resemble that of climate during a multi-year drought today. “The most severe future droughts will still occur during persistent La Niña events, but they will be worse than any since the Medieval period, because the La Niña conditions will be perturbing a base state that is drier than any state experienced recently” (Seager et al., 2007).

More recently, Seager and Vecchi (2010) reviewed 24 IPCC models with robust representations of precipitation and evaporation in the Southwest through 2099. They found that the median values for the model runs project a steady decline in both winter (Oct.-March) and summer (Apr.-Sept.) precipitation in the 21st Century relative to the 20th. In winter, warming causes evaporation to increase steadily, resulting in projections of an increasingly negative value for precipitation-evaporation (P-E) over the 21st Century. The model average also predicts a decline in summer precipitation, but no significant change in summer P-E. Decreases in the value of winter P-E are robustly predicted for all models regardless of precipitation trends, showing the projected dominance of temperature-forced increases in evaporation over any increase in precipitation.

Seager and Vecchi found that additional ensemble modeling indicated that the expansion of the subtropical dry zone and the poleward retreat of the temperate wet zone, driven by global-scale warming, will be the primary driver of changes in P-E. Worst case drying scenarios occur in models predicting a shift to a persistent La Niña state in the Pacific, while the wettest scenarios occur in models predicting a persistent El Niño state. However, because of the overprinting of a gradual drying in the Southwest, not even the wettest future models predict a return to the two wet decades preceding the 1997-98 El Niño. Finally, recent trends in carbon emissions exceed the levels used in this study (based on the A1B SRES scenario), so the drying may be greater than projected in this study.

D. Other Hydrologic Consequences of Climate Change in the Southwest

Rivers in the West can be considered “exotic” in that most of the water flowing year-round in these streams originates as mountain precipitation – the all important winter snow pack and the secondarily important summer rainfall. Snowmelt is 50 to 80% of flow volume in this region (Stewart et al., 2005).

i. Changes to Snowpack

Two variables are of importance with snowpack: how much precipitation falls as snow (snowpack depth), and the amount of water contained in a given volume of snow (snow water equivalence, typically 5 to 20% in freshly fallen snow).

Throughout much of the West, warming winter temperatures have contributed to declines in snowpack in two ways: warmer late fall and early spring temperatures mean that precipitation that formerly fell as snow during these periods now often falls as rain, particularly at lower and in more southerly mountainous regions. Thus the percent of annual mountain precipitation that falls as snow has declined, reducing the amount of water available for runoff in the spring and summer months.

There has also been a long-term decline in the ratio of winter-total snowfall water equivalent (SWE) to winter total precipitation. The most significant reductions have occurred where winter wet-day minimum temperatures averaged for the period 1949-2004 were warmer than -5°C, with the greatest loss between -3°C and 0°C. The changes were most pronounced in spring (Knowles et al., 2006).

In a major review of the data from 1950 to 1997, the Southwestern mountains showed a 60% gain in precipitation (Mote et al., 2005), but this is an artifact of a trend line that begins in the last major Southwestern drought and ends with the last major wet period. A recent study combining observational data and modeled historic snowpack has shown a post-1980 decline in snowpack conditions in the West that has no precedent in twentieth century temporal variability in precipitation, temperature, and estimated SWE. Winter temperatures since 1980 are, on average, higher than any other decade of this century, while the average April 1 SWE and the ration of SWE to precipitation are lower (McCabe and Wolock, 2009).

In a recent study, tree ring records were used to estimate annual SWE since AD 1200 in the Rocky Mountains. Prior to the 1980s, there was a pronounced dipole character to SWE: dry years in the northern Rocky Mountains corresponded to wetter years to the south, and vice-versa. Since 1980, this pattern has broken down, and declines in SWE are evident across the entire cordillera (Pederson et al., 2011). The authors conclude that their data suggest "a fundamental shift from precipitation to temperature as the dominant influence on snowpack in the North American Cordillera."

ii. Advances in Snowmelt

The observational record of 1948-2000 reveals a steady advance in the initiation of snowmelt across the region, with greater advances occurring in the northern Intermountain West (Stewart et al., 2005). The data show earlier snowmelt onsets and advances in the center of mass of the annual hydrograph by one to four weeks. The earlier onset is accompanied by decreased spring and early summer (AMJJ) fractional flows as a greater portion of the runoff occurs earlier in the water year (due to earlier snowmelt and warmer late winter temperatures permitting snow to fall as rain). Importantly, the advance in timing correlates strongly with increases in temperature over this time period, but correlates poorly with long-term changes in the Pacific Ocean sea surface temperatures (SSTs), such as the PDO warm phase from 1976-1999 (it is now in a cool phase since 1999). Model projections suggest continued advances in snowmelt timing, with advances as much as a month or more projected for 2080-2099 relative to baseline data from 1951-1980 (Stewart et al., 2004).

Increased aridity is likely to reduce vegetation cover, leaving soil exposed to aeolian and other erosion processes. In a recent study on the Colorado Plateau, researchers measured dust emissions from different vegetation communities. The communities were selected as analogs for vegetation changes with increasing aridity. The researchers found that increased temperatures due to climate change will increase wind erosion across the Colorado Plateau, leading to much higher dust emissions in areas with low vegetation cover and low rates of biological soil crust (Munson et al., 2011). The dust can move large distances, and can readily be blown onto areas of mountain snow, changing snowfield albedo and thereby helping to accelerate spring snowmelt (Seager and Vecchi, 2010).

iii. Declines in Runoff

The Colorado River has received greater research attention than the Rio Grande, and serves as a proxy for regional stream flows in many analyses. The rivers are similar in that both are "exotic" streams that receive most of their flow from Rocky Mountain runoff rather than runoff from precipitation lower down in the river course. But they differ in a crucial way that suggests projections of future flow based on Colorado River data will underestimate reductions in flows on the Rio Grande. The Colorado River sources runoff from northern Utah and northern and western Wyoming, areas that are likely to see increases in precipitation that partially offsets reduced precipitation in southern Utah and western Colorado. By contrast, the Rio Grande headwaters lie in the San Juan Mountains of southern Colorado, a place that is likely to see overall reductions in precipitation and increases in evaporation due to the northward expansion of the subtropical dry zone. In the 2011 La Niña winter, heavy precipitation in the Northern Rockies coincided with much-reduced precipitation in the Southern Rockies and San Juan Mountains. As a result, the Colorado River is expected to experience an increase in flow relative to last year while flows in the Rio Grande are expected to approach or exceed record lows.

Reductions in snowpack, declines in snow water equivalence, advances in snowmelt, and declines in soil moisture all will contribute to substantial declines in flows in the Southwest's rivers. Studies of the Colorado River show that flow on the Colorado River is likely to be reduced by 10 to 30% (see discussion in Barnett and Pierce, 2009). Since the headwaters of the Rio Grande are located in a region that will

likely see no increases in winter precipitation as well as significant declines in precipitation for the rest of the year (USGCRP, 2009), it is possible that projected declines in flow in the Rio Grande will equal or exceed those for the Colorado River.

Models of future Colorado River flows consistently show reductions in average flow across the 21st century. Coupled ocean-atmosphere global climate models downscaled to the western U.S. were used to drive a Variable Infiltration Capacity (VIC) model to study changes in streamflow as a result of climate change (Christensen et al., 2004; Leung et al., 2004). Modelers drove the model using what is known as the "business as usual" climate scenario (close to the average of the IPCC scenarios). For the Colorado River basin, annual predicted runoff was 14%, 18% and 17% below the historical average for the periods 2010-2039, 2040-2069 and 2070-2098, respectively. However, due to earlier spring snowmelt and higher evaporation rates, it is predicted that the total basin storage in regional reservoirs could decline by as much as 36%, 32% and 40% for these periods, respectively.

A more recent effort used a simple water budget model that calculated the net effects of inflows and outflows on a monthly time step (Barnett and Pierce, 2009). The model incorporates reductions in evaporation from reservoirs as surface area shrinks, as well as changes in river management in response to altered flows. The model shows that, by 2050, if runoff is reduced by 10% and consumption is unchanged, water managers will be unable to deliver all of the promised water 58% of the time. A reduction in runoff of 20% leads to a failure in water delivery approximately 88% of the time if consumption patterns are unchanged. The shortfall ranges from at least 1.2 to 1.9 billion cubic meters per year to approximately 2.2 to 3.4 billion cubic meters per year by 2050 out of a total request of 17.3 billion cubic meters per year. The magnitude of the shortfall is not so great that it could not be compensated for by reductions in demand. Although average flows may decline only a small amount, flow deficits in multi-year drought years have the potential to exceed any in the observational record by as much as 60 to 70% (Cayan et al., 2010).

Reduced runoff and changes in snowpack have a secondary effect on groundwater systems by reducing the amount of water available for recharge. As surface water sources become scarce, groundwater sources may be increasingly relied upon to satisfy water needs. As aquifers are drawn down, the relationship between surface water and ground water may change, reducing surface flow in rivers where groundwater is a significant contributor to surface flow.

Reduced total runoff will likely be accompanied in the future by increases in peak discharge. Precipitation is expected to become more concentrated in time, with fewer but larger storms separated by periods of increased aridity. Aridity will significantly alter vegetation structure, with more xeric vegetation and larger patches of exposed earth. During high-precipitation events, the exposed surfaces may funnel greater share of runoff to streams, contributing higher peak flows than at present.

iv. Other Watershed Changes

In addition to direct effects of warming on the watershed (declines in runoff, snowmelt, snow water equivalence), there are indirect effects on watersheds relating to vegetation response: changes in vegetation composition, water use, pathogens, and wildfire. All these changes may affect that amount of sediment available to be mobilized, particularly during monsoon rains, and also increase the effectiveness of rainsplash in initiating erosion on hillslopes, thereby increasing sediment movement into stream channels.

E. Studies Specific to New Mexico Climate Change and the Rio Grande

The most important recent synthesis of climate change in New Mexico and its hydrologic impact is the report titled *The Impact of Climate Change on New Mexico's Water Supply and Ability to Manage Water Resources* (Watkins, 2006) Observed and predicted impacts of climate change are outlined in a chapter co-authored by David Gutzler (UNM), Gregg Garfin (University of Arizona) and Bernard Zak (Sandia National Laboratories). These authors make the following observations:

- Temperature increases in the Southwest will be greater than the global average due in part to a general tendency for continental interiors to heat more than coastal regions or oceans (IPCC, 2001). Recent warming has been greatest in the northern part of New Mexico in the winter months, consistent with the findings of Dominguez and colleagues (2010). Recent average annual temperatures have been close to 2°F (1°C) above mid-20th century values, with average warming driven in part by winter warming rates nearly double this value.
- Potential changes to New Mexico temperatures based on the SRES A1B scenario were modeled using an ensemble of 18 global climate models downscaled to finer resolution. The models suggest significant increases in temperature in New Mexico by 2100. Statewide, average temperatures are projected to rise more than 3°C (more than 5°F) over the average from 1971 to 2000. This is a change greater than that observed in the instrumental record. Increases in summer temperature are projected to be greater. Similar conclusions were reached by Diffenbaugh and colleagues (Diffenbaugh et al., 2005) using the SRES A2 "high" emissions scenario, which differs from A1B primarily in that emissions rise at a faster rate. For the period 2071-2095, they also project temperature increases of more than 3°C (more than 5°F) relative to 1961-1985 averages, with greater temperature increase to the north (inland). Summer warming is projected to exceed 5°C in northeastern New Mexico. Winter warming in these simulations averages 2° to 4°C, and is projected to be greatest in northwestern New Mexico.

Changes to precipitation have greater uncertainty than for temperature.

- Global climate models driven by the A2 "high emissions" scenario project an annual precipitation decrease by 2100 of 4.8% (29.3 mm) per year, driven mainly by decreases in winter precipitation, but offset slightly by gains in summer precipitation (Watkins, 2006).
- As elsewhere in the West, winter precipitation is expected to increasingly fall as rain rather than snow as warming delays the onset of freezing and advances the start of the growing season (Watkins, 2006). This is expected to be particularly pronounced in the Southwestern states because winter temperatures are already not far below freezing (Felzer and Heard, 1999). Models are split between those showing declines in winter precipitation and those showing small increases. However, temperature-driven increases in evaporation are expected to exceed any increases in precipitation, driving a negative shift in the overall water balance (Nash and Gleick, 1993).
- Models showing reductions in winter precipitation show the mechanism for this is likely to be the northward migration of the winter storm track, particularly in the late winter/early spring. This shift may already be underway, as the data show that the late winter/early spring storm track in the Western states has moved north of the long-term average between 1978 and 1998, contributing to declines in late winter precipitation in New Mexico (McAfee and Russell, 2008). Some models suggest changes in ENSO cycles may also drive declines in winter precipitation. However, there is no model agreement on projected changes to ENSO cycles (Vecchi and Wittenberg, 2010).

Changes in temperature and precipitation patterns are expected to drive changes in snowpack:

- Overall, the freezing altitude is projected to increase and snowpack volume to decrease as temperatures rise. Higher temperatures will delay the date at which precipitation falls as snow and cause a 4-6 week earlier shift in the date at which precipitation falls as rain. The altitude at which a winter snowpack will develop is anticipated to rise. In the 2005, the RMCO noted that 10 of the previous 16 years in the Rio Grande Basin had below-average snowpack (RMCO, 2005), a trend that has continued in recent years.
- The snow water content of the snowpack has also declined (Mote et al., 2005), and this trend is anticipated to continue. Modeling studies of the Colorado River watershed project that the content of water contained in April snowpack will decline by approximately 38% by the end of the 21st century in models driven by the A2 "high emissions" scenario (Christensen and Lettenmaier, 2007). Similar reductions in snow water equivalence are predicted for all watersheds in the West.
- Regional climate models driven by the A2 scenario indicate that the snowpack may be non-existent south of 36°N (south of Santa Fe and the Sangre de Cristo Mountains) by 2100 (Watkins, 2006). The same study showed reductions in snow water equivalence of approximately one-third to one half (approximately 50-200 mm of water) compared to the 1961-1985 average in the San Juan Mountains.

Increases in temperature and increases in evaporation will drive increases in soil moisture deficit.

- In many modeling studies, summer evaporation plateaus – but only because there is no more surface soil moisture to evaporate (Diffenbaugh et al., 2005). Evaporation over reservoirs is expected into increase directly with temperature. Prolonged droughts relative to those of the 20th century are expected (Watkins, 2006).
- Regional models driven by the A2 emissions scenario show a pronounced soil moisture deficit in the spring (March-May) season, particularly in northwest New Mexico where soil moisture is projected to decrease by 5 mm water (20% relative to 1961-1985 simulated baseline). This deficit is driven by earlier spring snow melt accompanied by higher temperatures and greater evaporation (Watkins, 2006).

The future flows in the Rio Grande are expected to decline, as discussed in recent studies.

- Edella Schlager (University of Arizona) and colleagues (Heikkila et al., 2010) studied Costilla Creek, a tributary of the Rio Grande located along the Colorado–New Mexico border, in order to understand how runoff would be affected under the worst-case IPCC SRES A2 scenario. They used a lumped-parameter rainfall-runoff model that included snow storage in the Costilla Creek watershed. Temperature and precipitation data were derived from NRCS-SNOTEL stations and USGS gaging stations. Water demand for agriculture was estimated by ISCCP solar radiation and temperature data. A non-homogeneous hidden Markov model was used to simulate 50 year precipitation levels in the catchment. The results indicate that the region will experience a general warming/drying trend, and that early melting of the snowpack will significantly advance spring runoff.
- Albert Rango (USDA-ARS Jornada Experimental Range) and Jaroslav Martinec estimated snow cover, glacier changes and runoff for rivers in several locations around the world (Rango and Martinec, 2008). They adapted a snowmelt runoff model (SRM) originally designed for seasonal forecasting, and forced it with a 4°C increase in temperature. Their study include sample wet, normal and dry years, and what they called a "normalized year" which was based on the average condition for the period 1957-1994. For the Rio Grande, a greater share of runoff occurred in the winter (October-March) than in the summer (April-September) and the runoff peak was shifted from May to April. Overall runoff also decreased (Table 1).

Table 1: Redistribution of runoff in warmer climates (adapted from Rango and Martinec 2008, Tables 2 and 3).

Base Year	October-March		April-September		Hydrological Year	
	Runoff 106m3	Runoff % of total	Runoff 106m3	Runoff % of total	Runoff 106m3	Runoff % of total
1979 (wet)						
Computed T	91.87	7.6	1120.15	92.4	1212.02	100
Computed T+4°C	146.76	12.3	1046.16	87.7	1192.92	100
1976 (average)						
Computed T	93.22	13.1	616.52	86.9	709.74	100
Computed T+4°C	192.95	28.1	494.80	71.9	687.75	100
1977 (dry)						
Computed T	63.56	24.3	198.17	75.7	261.71	100
Computed T+4°C	77.34	29.2	187.42	71.8	264.76	100
"Normal Year"						
Computed T	74.66	11.7	561.66	88.3	636.32	100
Computed T+4°C	153.06	24.2	479.58	75.8	632.64	100

- In addition to advancing the date of peak spring flood, increases in summer surface temperatures are expected to strengthen convection over the region, producing a more vigorous hydrologic cycle in which storms are more intense (Carnell and Senior, 1998; Hayden, 1999). Whether storm frequency declines as well is not clear. Larger magnitude summer storms are expected to drive bigger magnitude flood events while accelerated spring runoff may drive larger spring floods. In between these events, lower overall snowpacks and earlier melting are expected to drive down low summer flows (Gleick, 2000).

Brian Hurd (NMSU) and Julie Coonrod (UNM) have collaborated on several studies to assess the hydrologic and economic consequences of climate change on the Rio Grande. In a 2008 study (Hurd and Coonrod, 2007, 2008), they use three global climate models driven by the A1B "business as usual" SRES scenario to model hydrology and streamflow changes in 2030 and 2080. The three models are chosen because one represents a slightly "wetter" projection, one a slightly "drier" projection and one a "middle of the road precipitation" projection. Data from climate change is used to drive WATBAL, a conceptual rainfall/runoff model (Yates, 1996), from which they derive streamflow and runoff changes. They then conduct additional modeling to understand the economic implications of the observed hydrologic changes.

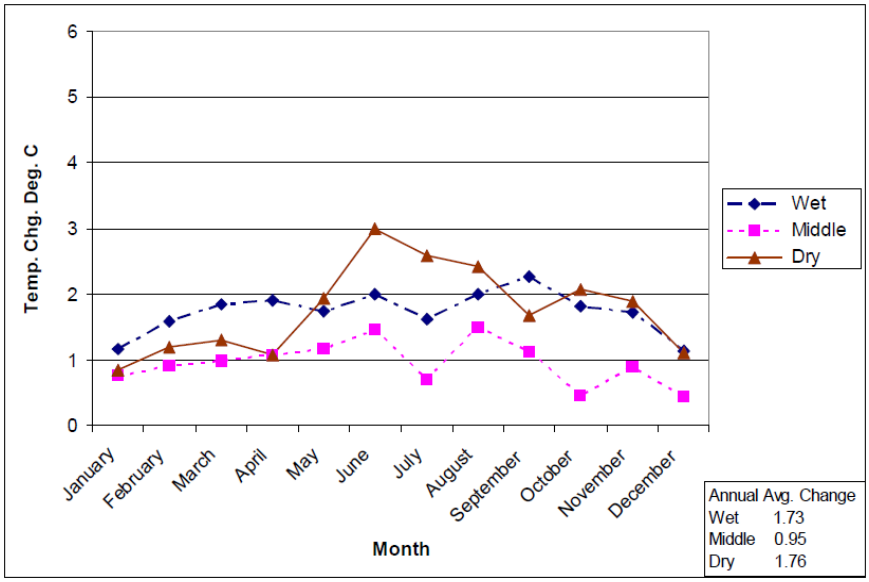


Figure 10: Three scenarios for temperature change projected for the Rio Grande basin in 2030 (source: Hurd and Coonrod, 2007).

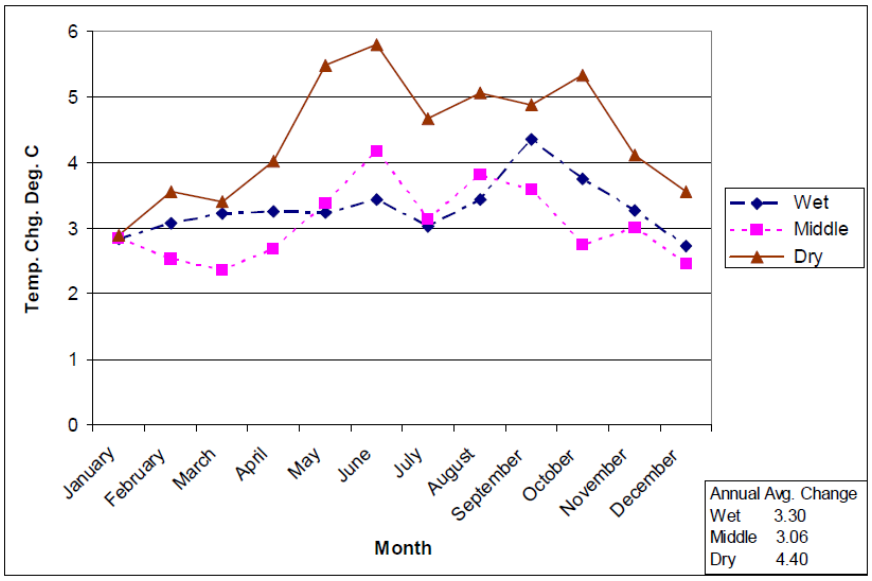


Figure 11: Three scenarios for temperature change projected for the Rio Grande basin in 2080 (source: Hurd and Coonrod, 2007).

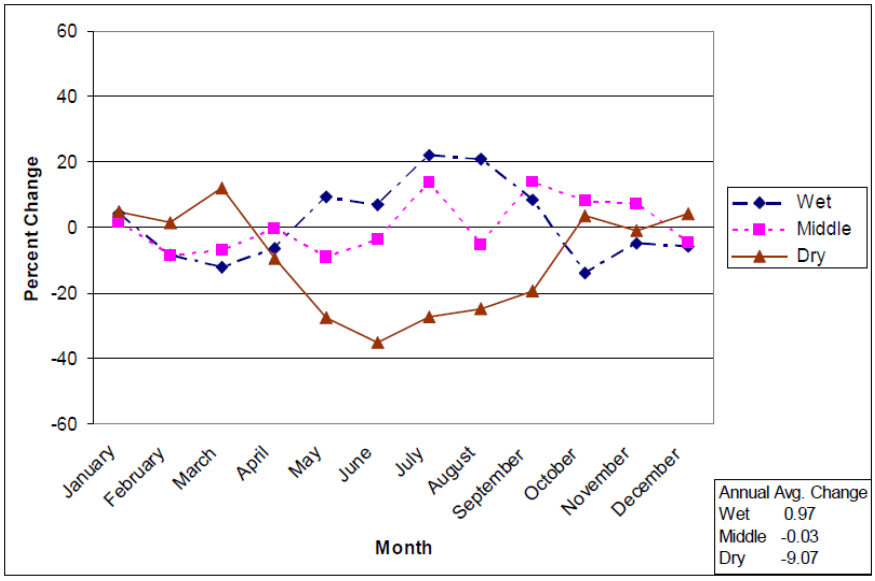


Figure 12: Three scenarios for precipitation change projected for the Rio Grande basin in 2030 (source: Hurd and Coonrod, 2007).

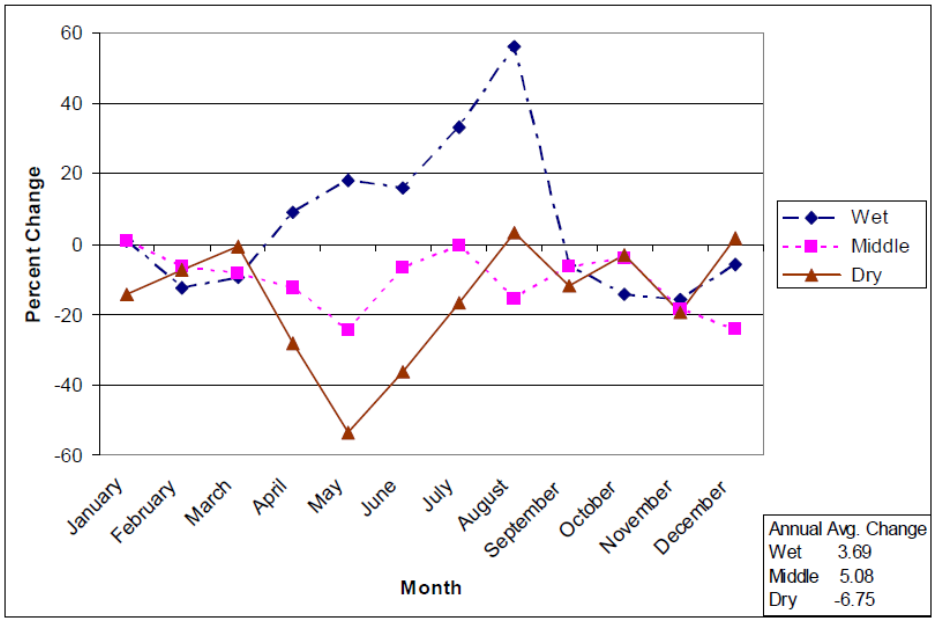


Figure 13: Three scenarios for precipitation change projected for the Rio Grande basin in 2080 (source: Hurd and Coonrod, 2007).

In their models, average annual temperatures increased by 0.95 to 1.76°C by 2030 (Figure 10) and 3.06 to 4.40°C by 2080 (Figure 11). In the wettest model, 2030 precipitation increased by 0.97%, while dry models predicted a precipitation decline of 9.07% (Figure 12). In the 2080 scenario, the wet model showed precipitation gains of 3.69% and the dry model precipitation declines were only 6.75% (Figure 13). The model differences are driven by summer precipitation; all three models predict a drier winter by 2080.

Hurd and Coonrod also detect a change in the average aggregate streamflow compared to the baseline which occurs in their models after 2030, regardless of climate scenario used (Figure 14).

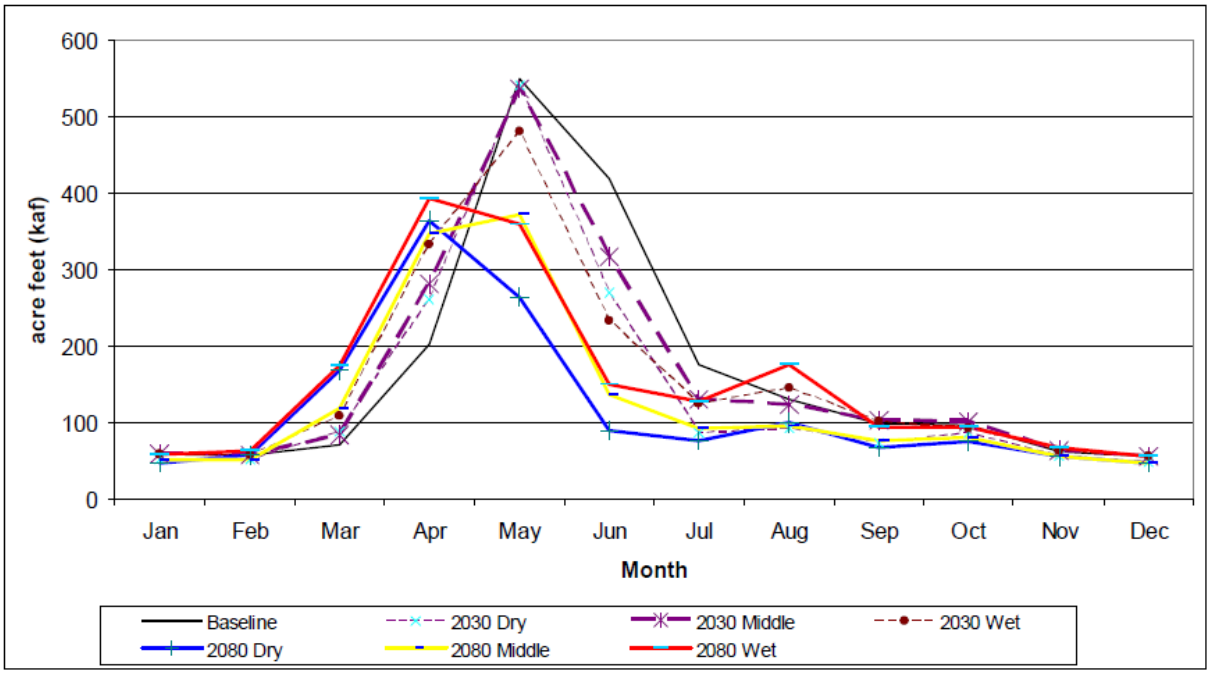


Figure 14: Average aggregate streamflow by month for each climate change scenario (source: Hurd and Coonrod, 2007).

Finally, their modeling shows that cumulated annual basin inflow declines across all scenarios (Figure 15).

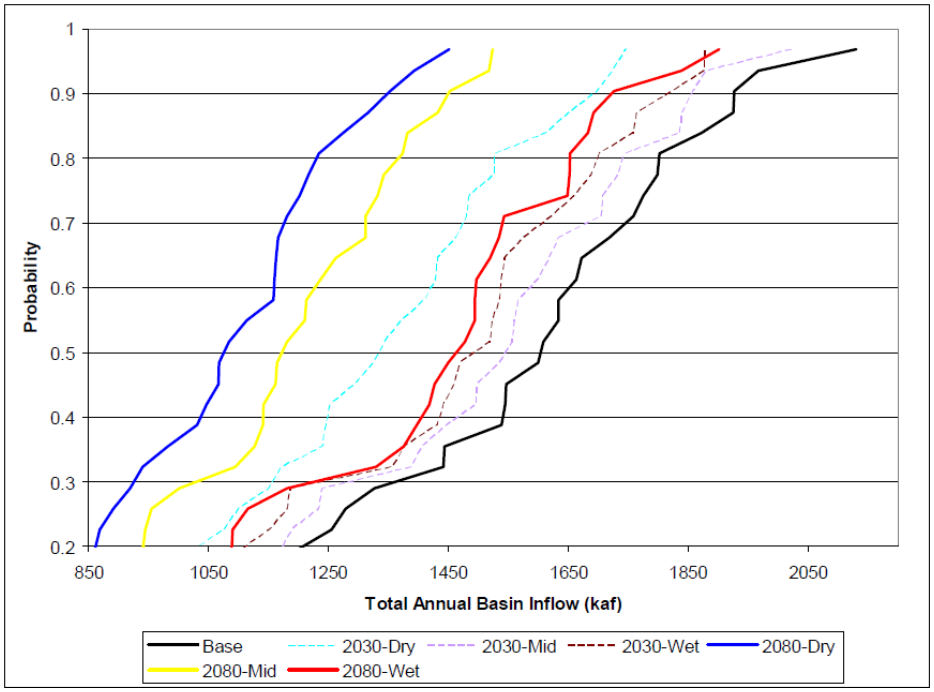


Figure 15: Cumulative distributions of total basin streamflow across the climate change scenarios (source: Hurd and Coonrod, 2007).

Hurd and Coonrod estimate reductions in average annual runoff of -6.3% to -13.7% by 2030 and -8.3% (wet) to -28.7% (dry) by 2080. The economic impacts of these declines, even when coupled with significant population increases, are minimized by the transfer of water rights from agricultural areas to urban users and declines in per capita water use.

The authors point out several important caveats to their studies:

- Dry and baseline scenarios assume no change to the quantity of San Juan-Chama water diverted to the Rio Grande. This may not be realistic under future climate change scenarios, and this would certainly make the projected deficits larger.
- Flooding is not addressed in their economic model, but could have large economic consequences for regions if not addressed.
- Water quality may change, particularly leading to increased salinization and higher pollutant concentrations under low flow conditions.
- Decreased soil moisture will diminish forage production on range lands as well as contribute to larger, more intense forest fires. This will further stress the agricultural sector.
- Hispanic communities in New Mexico will be disproportionately affected by climate change due to declines in acequia water volumes, changes in stream flow, and pressure to sell water rights, all of which stand to reduce and impoverish rural communities.
- Ecological effects of reduced stream flows are also not investigated, but could be significant.

IV. Climate Change and Sediment Contribution to Fluvial Systems

A. Characteristics of the Rio Grande above Cochiti Dam and Lake

The Rio Grande arises in southern Colorado, in the San Juan Mountains near Creede. It flows east to Del Norte, roughly southeast and then south through the San Juan Basin before entering New Mexico near Lobatos. From there it flows across the Taos Plateau, through the Rio Grande Canyon, through the Española Basin, and finally skirts the Pajarito Plateau via White Rock Canyon and enters Cochiti Lake. Upstream of Cochiti Lake, the major tributary is the Rio Chama, which has three reservoirs (El Vado, Heron and Abiquiu Lakes) that trap much of the sediment carried by the Rio Chama.

Sediment loads in the Rio Grande from the Rio Grande Canyon to White Rock Canyon were likely never large (Massong et al., 2007) compared to the discharge of White Rock Canyon. Water exiting the Rio Grande Canyon is relatively clear, having both low suspended sediment and bed load. Bed material is primarily coarse gravel. East side tributaries in the Española Basin contribute mainly cobble, gravel and sand-sized sediment to the Rio Grande, where these tend accumulate in large, coarse-grained alluvial fan complexes. Bank sediment is primarily sand and gravel. On the west side, the river runs along the base of the Pajarito Plateau and other uplands, with coarse colluvial mantles at their base providing little sediment to the river. Above the Rio Chama confluence, the floodplain is narrow and is currently incised. Below the Rio Chama confluence, the floodplain is wider, and is underlain by the coarse alluvial gravels and sands of the Santa Fe Formation. The river channel is slightly sinuous with some migrating meander bends. A mosaic of point bar habitats and islands have formed throughout this reach.

Suspended sediment load in the Rio Grande was measured in 1993-1995 at USGS gages at Del Norte, Trincheras, Conejos and Lobatos in Colorado, and in New Mexico below the Taos Junction Bridge and at Otowi Bridge (Moore and Anderholm, 2002). The Otowi gage is the last gage above Cochiti Lake, providing the primary location for monitoring streamflow into the Lake. The gage at Chamita measures the sediment load in the Rio Chama below Abiquiu Dam, including flows from the key Rio Chama tributaries (Rio del Oso and the Rio Ojo Caliente). Suspended sediment enters the Rio Grande from tributaries during periods of flashy discharge, and tends to be deposited in tributary-mouth alluvial fans. This sediment can be resuspended and transported at a later date by the Rio Grande during periods of increased streamflow. A large share of the sediment load measured at the Otowi gage enters the river from the Rio Chama (Moore and Anderholm, 2002).

In the Rio Grande mainstem, normal high flows occur in May and June, with stream flow at Otowi reaching around 8,000 to 9,000 cfs in 1993-1995. Intra-annual variation in streamflow is high; for instance, during the period 1993-1995, winter streamflow at Otowi was approximately 1,000 cfs. Suspended sediment concentrations in the Rio Grande tend to be positively correlated with streamflow.

Table 2: Estimated daily mean suspended-sediment load and standard error of prediction, water years 1993-95 (Table 5, part., Moore and Anderholm, 2002).

[Station names in table 1.
Sum1 = RGTrinch + Conejos; Sum2 = RGTJB + Chama; Sum3 = RGConvey + RGFldwy; NA, not applicable]

Site identification (table 1)	USGS station number	Water year	Suspended sediments: Estimated daily mean load (tons/day)	Suspended sediments: Standard error of prediction (tons/day)	Suspended sediments: Standard error of prediction (percent)
RGDelN	08220000	1993	152	57.0	37.4
RGDelN	08220000	1994	169	68.7	40.7
RGDelN	08220000	1995	241	103	42.8
RGTrinch	08240000	1993	44	13	29.3
RGTrinch	08240000	1994	41	10	24.8
RGTrinch	08240000	1995	56	16	28.4
Conejos	08249000	1993	73	25	33.8
Conejos	08249000	1994	30	9	30.1
Conejos	08249000	1995	74	20	27.1
Sum1	NA	1993	117	NA	NA
Sum1	NA	1994	71	NA	NA
Sum1	NA	1995	130	NA	NA
RGLob	08251500	1993	111	32	29.0
RGLob	08251500	1994	52	9	16.5
RGLob	08251500	1995	158	58	37.0
RGTJB	08276500	1993	175	54	30.7
RGTJB	08276500	1994	341	93	27.2
RGTJB	08276500	1995	405	138	34.1
Chama	08290000	1993	221	123	55.6
Chama	08290000	1994	1,181	447	37.9
Chama	08290000	1995	1,846	778	42.1
Sum2	NA	1993	396	NA	NA
Sum2	NA	1994	1,523	NA	NA
Sum2	NA	1995	2,251	NA	NA
RGOtowi	08313000	1993	484	147	30.4
RGOtowi	08313000	1994	3,035	822	27.1
RGOtowi	08313000	1995	2,653	703	26.5

B. Stream Response to Climate Change

Stream responses to climate changes in general, and in arid lands in particular, are highly variable, being influenced by changes in precipitation and precipitation-evaporation ratios, and indirectly by changes in infiltration; vegetation cover, soils and land use; stream morphology; ground water levels; and drainage basin characteristics, among other factors.

A significant change in alluvial behavior occurred in the early 1940s across the Southwest. Tributary arroyo systems that had been incising since the late 19th Century began to stabilize their channels (Gellis, 2002; Graf et al., 2010; Leopold, 1976). Deposition within tributary floodplains led to reductions in sediment transport in the Rio Grande and the Colorado River main stems. On the Rio Grande (Gellis, 1992), suspended sediment measurements at Otowi, Rio Puerco near Bernardo, and San Marcial experienced significant declines in suspended sediment concentration between 1948 and 1990, as did the Pecos River near Artesia, the Rio Peñasco at Dayton and the Animas River at Farmington. Likewise, suspended sediment concentrations at Lee's Ferry declined 30%-50% in the years following 1942-1943 (before the closure of the large upstream dams such as Glen Canyon Dam), and year-to-year variation in sedimentation declined (Graf et al., 2010). Discharge likewise declined. The observed changes in

suspended sediment and the aggradation of tributary floodplains coincide with an abrupt decrease in the frequency of large floods along the Rio Grande (Hereford, 1984; Scurlock, 1998).

As early as 1976, Leopold linked the shift to channel aggradation to a global cooling trend beginning about 1940 (Leopold, 1976). The period during which arroyo incision began in the 19th century was "characterized by more frequent heavy rains and a deficiency of light rainfall." Following a notable warming trend in the first part of the 20th century, the mid-twentieth century was characterized by general climate cooling (which many scientists now attribute to high aerosol pollution). This corresponds to renewed floodplain aggradation.

In the Rio Grande system, the period from 1978-1992 saw above average rainfall for the region, while below average precipitation characterizes the period from 1999 to 2002 (Langman and Nolan, 2005) (continuing to present). During the interval 1975-1999, streamflow on the Rio Grande rose, with flow increases primarily in the January, February and March spring runoff season, and in September and October (late monsoon period when moisture is sourced from tropical cyclones). Streamflow has declined since then in the face of drought, particularly during the winter/spring runoff season; slight rises in irrigation season flows reflect releases of stored San Juan-Chama water rather than increases in runoff resulting from monsoonal precipitation.

Streamflow in streams of different size appears to be responsive to different climate factors. Flow in large rivers, especially large exotic streams like the Rio Grande, are most responsive to hydrologic changes at the regional scale, in particular to snowmelt runoff in the late winter and spring. If the current trend towards reduced winter precipitation continues, peak flows in the Rio Grande are expected to decline in size and to occur several weeks earlier in the spring in response to smaller winter snowpacks with lower snow water equivalences, and a greater share of winter precipitation falling as rain. Under situations of declining discharge, the Rio Grande is anticipated to store sediment in its floodplain (Everitt, 1993), at least initially (Hereford, 1984).

Smaller order streams, including most of the tributaries of the Rio Grande above Cochiti Lake, have small catchments that generate only modest spring runoff flows. Instead, flow along these streams peaks in response to local, intense precipitation events that mobilize large volumes of sediment over short time periods (Etheredge et al., 2004; Godfrey et al., 2008). If warming produces a stronger monsoon season, the frequency and intensity of local precipitation events will increase the frequency and size of flashflood events on perennial and ephemeral tributaries of the Rio Grande. Even absent a stronger monsoon, a drier spring would result in sparser vegetation cover and enable significant increases in hillslope erosion, transporting sediment into ephemeral stream channels where flashy discharge can transport it to the stream mouth during summer thunderstorms.

Under a drier winter/average-to-stronger monsoon climate scenario, future sediment transport in the Rio Grande would be affected by two opposed processes. Side streams have the potential to contribute more sediment to stream-mouth alluvial fans while at the same time the mainstem may start to lose its ability to transport that sediment. In the reaches contributing sediment to Cochiti Lake, this contrast may be magnified by the coarse nature of most of the sediment already being transported because it requires comparatively larger discharges to mobilize. Sediment is therefore likely to accumulate in the channel in aggrading reaches of the river and this sediment may only periodically get flushed downstream during exceptionally wet years. Thus, under most climate change scenarios, sediment may not get flushed

downstream to Cochiti Lake in significantly greater quantities, and the overall impact on sedimentation may be limited[8].

A minority of climate models predict reverse conditions: a shift to a more-permanent El Niño-like state will occur, driving up winter precipitation and driving down the summer monsoon since a large snowpack is historically correlated with a weak summer monsoon (Gutzler, 2000). In response, spring runoff would lead to larger spring floods that are better able to flush sediment from mainstem floodplain environments into reservoir systems while simultaneously decreasing sediment contributions from tributary streams (Etheredge et al., 2004).

[8] The expectations for Cochiti Lake may thus be very different from Elephant Butte Reservoir, since fine and abundant sediment is already contributed to the mainstem from the unregulated Rio Puerco and Rio Salado drainages. These rivers have wide, fine-sediment floodplains that could act as significant sediment sources, particularly in response to greater flashy monsoon discharge.

V. Methodology

As detailed in the previous chapters, climate change is anticipated to have profound effects on precipitation, evapotranspiration, soil moisture and runoff, which appears to translate into significantly lower stream flows. It is also anticipated that extreme weather events – big storms – will become larger, meaning that these lower overall flows will be punctuated by peak discharges as large as or larger than at present. Increased aridity is expected to reduce land cover, exposing more bare ground to rainsplash erosion during storm events. Larger storm events should also mobilize larger quantities of alluvial sediment. Together, these translate into a higher stream sediment load and greater deposition in regional reservoirs, such as Cochiti. Estimating how much reservoir sedimentation will change is the goal of the modeling undertaking by this study. This chapter describes the models used to project future climate scenarios, to downscale these to the local region, and to translate these into stream runoff (VIC, URGWOM) and sedimentation values.

A. Modeling Climate Change

Climate change in the study area was modeled using the Hybrid Delta-ensemble (HDe) approach (Brekke et al., 2010). In a hybrid delta model, the difference (delta) between the current and future average for temperature or precipitation in a given month is coupled with (hybridized to) the historical record of daily temperature or precipitation variation to simulate future daily temperature and precipitation. In an HDe model, the climate projections are derived from a suite of models with a range of predictions for future climates based on a range of future greenhouse gas emissions scenarios. The advantage of the ensemble approach is that it reduces the chance that the observed trends will be due to factors other than climate change, such as multi-decadal climate cycles and chance events.

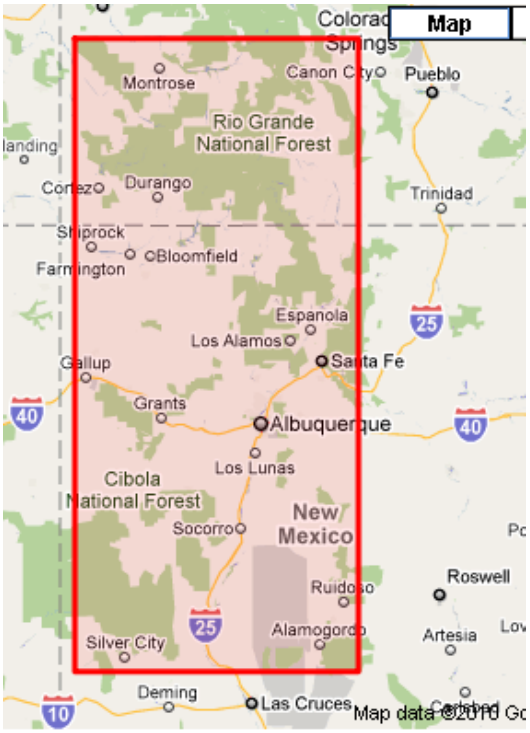


Figure 16: Map showing the region modeled using downscaled and bias-corrected CMIP3 data.

In this study, the HDe uses data developed by the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset. These are bias-corrected and spatially downscaled climate projections derived from CMIP3 data[9], as described by Maurer and colleagues (2007). The outputs are average monthly precipitation and surface air temperature generated from a suite of 16 CMIP3 models forced by 3 IPCC SRES scenarios for future greenhouse gas emissions. The scenarios chosen are the A2 (high emissions), A1B (business-as-usual emissions) and B1 (low emissions) scenarios. Model runs are started from a range of initial conditions reflecting the state of the atmosphere and ocean based on a 20th century controlled simulation representing the initial conditions at the start of the 21st Century. The spatial resolution of the model is 1/8° (about 12 x 12 km).

Since the goal of the climate modeling effort is a daily value for temperature and precipitation to input into the VIC model, the monthly averages for temperature and precipitation are superimposed on a

[9] Data are served at: http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/ , accessed on April 14, 2011.

modern dataset showing the daily variation in these values for a given month. Historical records of daily precipitation and temperature variation in a given month are adjusted to reflect changes in the mean monthly average for these variables in the historical vs. the projected data.

Specifically with respect to this study, the location selected is the Rio Grande basin in New Mexico, and three periods are simulated:

- Historical (1950-1999)
- Near Future (2010-2039)
- Far Future (2040-2069)

The metrics used for this climate change study are the change in period mean annual temperature and precipitation, averaged over the entire region.

The model outputs are classified into 5 categories. The median (50th percentile) temperature and precipitation changes are used to partition the space into four non-overlapping quadrants that bracket the central tendency of the distribution. The 25th and 75th percentiles of temperature and precipitation are used to define a rectangle overlapping the four quadrants that represents the central tendency of the distribution of all model outcomes. The five "categories" thus created are (symbols in figures are shown in the brackets):

- Q1: Wetter, more warming (green Xs)
- Q2: Wetter, less warming (red crosses)
- Q3: Drier, more warming (blue triangles)
- Q4: Drier, less warming (gold asterisks)
- Q5: Middle (orange circles)

All future scenarios for both the 2010-2039 and the 2040-2069 periods showed average temperatures above those of the historical baseline of 1950-1999. In the Near Future (Figure 15), the median warming is projected at 2.5°F (1.4°C), with a range of 1-4°F (0.5-2.25°C). The majority of models predict between 2 and 3°F warming. Precipitation was much more variable, ranging from about -16 to +12% relative to the baseline, with the majority of models predicting a change of between -5% and +4%.

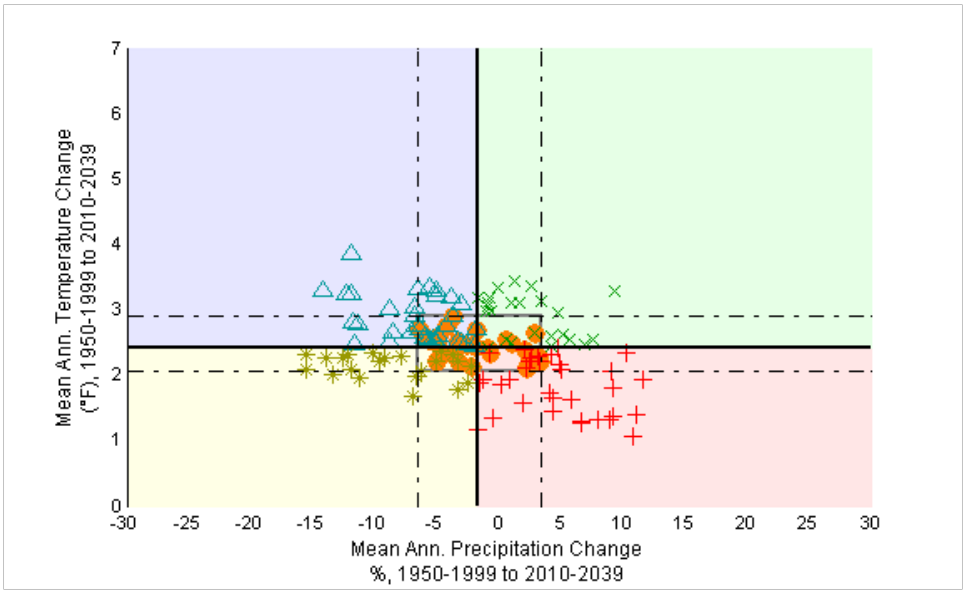


Figure 17: Modeled changes in temperature and precipitation in the Near Future (2010-2039).

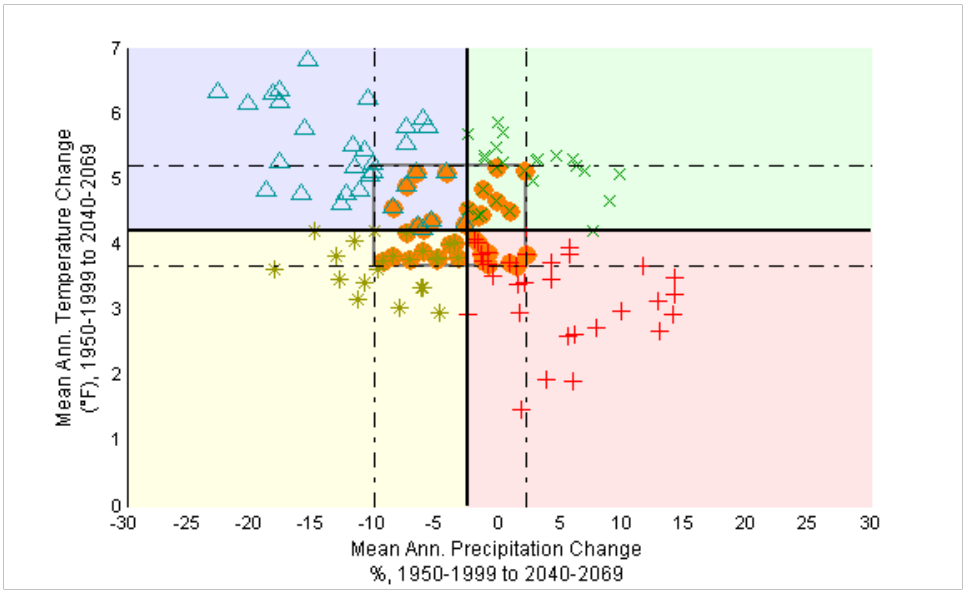


Figure 18: Modeled changes in temperature and precipitation in the Far Future (2040-2069).

In the far future (2040-2069), warming is more pronounced. Median warming is projected to be approximately 4.25°F (2.4°C), ranging from a low of just above 1°F to a high close to 7°F (3.9°C), and with the majority of warming ranging from about 3.75 to 5.25°F. These findings are similar to other studies previously cited which anticipate increases of 2-4°C by 2050 (Barnett and Pierce, 2009) and 4-6°C by 2080 (USGCRP, 2009).

Median precipitation declines by about 2.5% relative to the historic baseline, with 50% of the values ranging between -10% to +2.5%, and the limits of the full dataset ranging from about-22% to +15% relative to the baseline. The projected declines are less than the 10-20% declines projected for the West in 2080-2090 by the US Global Change Research Program (USGCRP, 2009), but in line with the 0-10% declines cited by Barnett and Pierce (2009).

For both temperature and precipitation, the data from the Far Future simulations has greater spread, indicating greater uncertainty, than the data from the Near Future. Finally, the data represent the central tendency for each 30 year period. At least for temperature, the central tendency measure masks the fact that these are points on an increasing trend line: the beginning years of these two-decade long periods may be cooler, and the ending years warmer, than the average for that period.

B. The VIC Model

The Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model (Gao et al., 2009) was developed at the University of Washington by X. Liang, D.P. Lettenmaier and colleagues (Liang et al., 1994). In the Western US, the VIC model has seen widespread use in the study of droughts, changes in snowpack, and impacts on water resources. A VIC model takes as input climate data (usually from a downscaled GCM) and yields the surface runoff, infiltration, and contributions to groundwater of precipitation falling in a subset of a region. The VIC model is typically coupled to a flow routing model to show how downstream river flows are affected by changes in runoff over time[10].

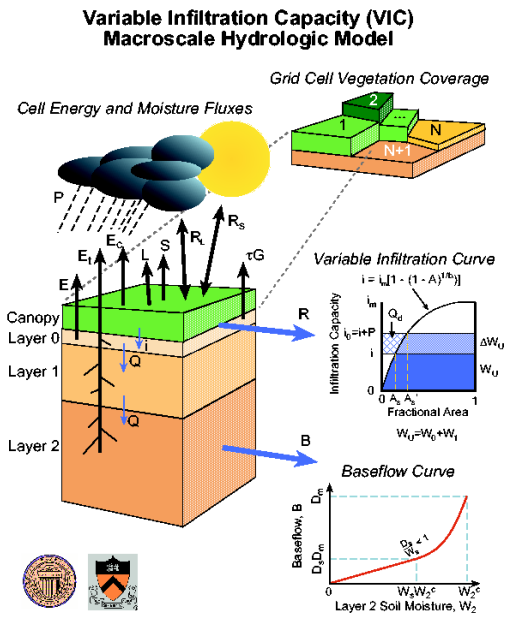


Figure 19: How land cover is modeled in the VIC model (source: Civil Engineering/University of Washington).

The VIC model represents that landscape as an approximately 1km^2 grid of flat uniform cells. Sub-grid heterogeneity – in terms of landform, soils, and land cover – is handled using statistical distributions (e.g., 20% forested, 40% grassland, etc.). Inputs to the model include a daily or sub-daily time series of meteorological drivers such as precipitation, air temperature, minimum temperature, maximum temperature, shortwave and longwave insolation, air pressure, density, vapor pressure, and wind speed. Model outputs are surface and subsurface runoff via the local channel network.

An important caveat to the VIC model is that it is run on a cell-by-cell basis. The entire simulation is run for each grid cell separately, one cell at a time. Inputs and outputs for each cell are stored in files specific to that cell, and that file includes a record of surface and subsurface runoff in the local channel network for each cell. Water is assumed to enter a cell solely from the atmosphere; surface and subsurface runoff crossing cell boundaries outside of the local channel network are assumed to be small, and are not simulated by the model. In addition, once the water reaches the channel network, it is assumed to stay in that channel and does not flow back into the soil.

[10] Description of VIC model in this section from the University of Washington, Variable Infiltration Capacity (VIC) Macroscale Hydrologic Model, VIC Model Overview webpage, http://www.hydro.washington.edu/Lettenmaier/Models/VIC/Overview/ModelOverview.shtml, accessed April 13, 2011.

In the VIC model, land cover is simulated by dividing the cell into an arbitrary number of "tiles" that correspond to the fraction of that grid cell in a given land cover type (Figure 19). Spatial distributions of land cover are not modeled, but rather all patches of a single land cover type are lumped into a single tile within a grid cell. A weighting algorithm is used to average fluxes and storage across all land cover types within a grid cell to determine model outputs for each time step.

Soils are modeled in layers. The total number of layers is arbitrary, but usually three layers are used. Infiltration in the upper layers is controlled by model parameterization. Water loss from surface layers can occur through gravity-driven flow to lower layers, or through evapotranspiration. Drainage from the bottom layer is modeled by ARNO baseflow formulation.

In the VIC model, snow exists in several forms, including ground snow pack, snow in the vegetation canopy and snow on top of lake ice. Snow is modeled in two layers, with energy balance at the pack surface solved separately from the subsurface. Spatial variation in snow coverage and blowing snow sublimation can also be handled by the model.

In addition to meteorological variables mentioned above, VIC is able to handle spatial and vertical variability in precipitation arising from storm fronts and topography (Figure 20). To address the spatial variation in precipitation relating to the passage of storm fronts and local convective activity, the cell can be divided into two time-varying parts: a wet fraction (where precipitation is falling) and dry fraction. Fluxes from the wet and dry fractions are weighted by area and averaged to give the flux from a specific grid cell.

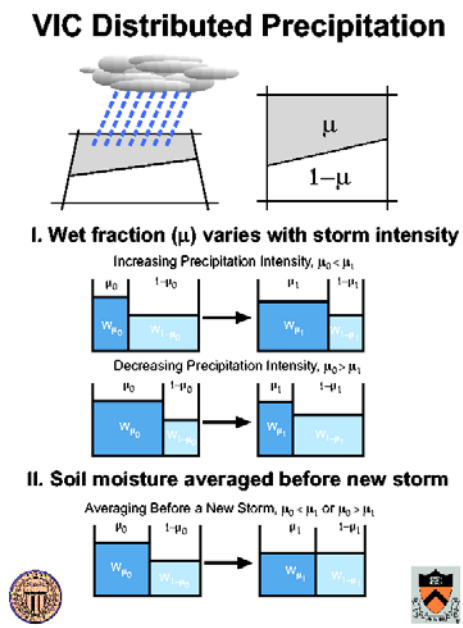


Figure 20: Distributed precipitation in VIC (source: Civil Engineering/University of Washington).

Elevation bands are used to model topographic influences on precipitation quantity and type (Figure 21). Each cell is divided into a series of steps ("elevation bands"), and for each step, meteorological forcings are adjusted for relief relative to the average elevation of the grid cell. As with land cover, "elevation bands" do not reflect topographic reality, but rather lump the total area within the cell at a given elevation into a single elevation unit. The band-specific values for some variables (such as snowpack) can be written separately in the output files, but most output data are weighted by area fraction and averaged to produce a single grid-cell output value for that cell. VIC can also model frozen soil, permafrost, frost, excess soil ice, and ground subsidence when ice melts.

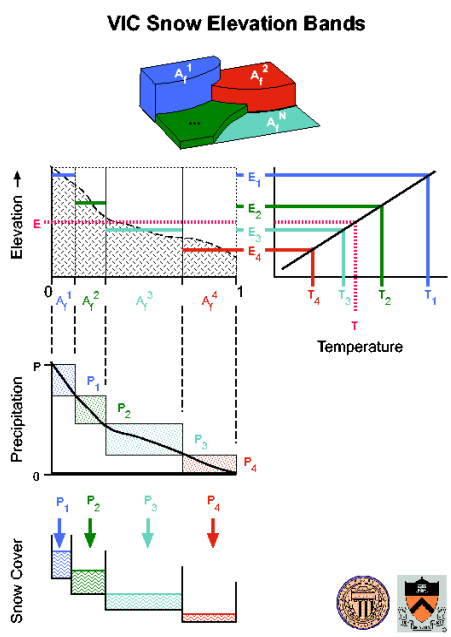


Figure 21: Snow elevation bands in VIC (source: Civil Engineering/University of Washington).

In the VIC model, lakes and wetlands occupy a single tile within a grid cell (Figure 22). This allows wetland area to change dynamically, as a fraction of the tile area, in response to fluctuations in lake level. Multiple lakes/wetlands within a grid cell are treated as a single tile. Lakes and wetlands are not currently linked to the channel network. Inflows into the lake/wetland are derived from the surrounding upland tiles within the same grid cell. Lake outflows (channel and subsurface) are connected to the channel network.

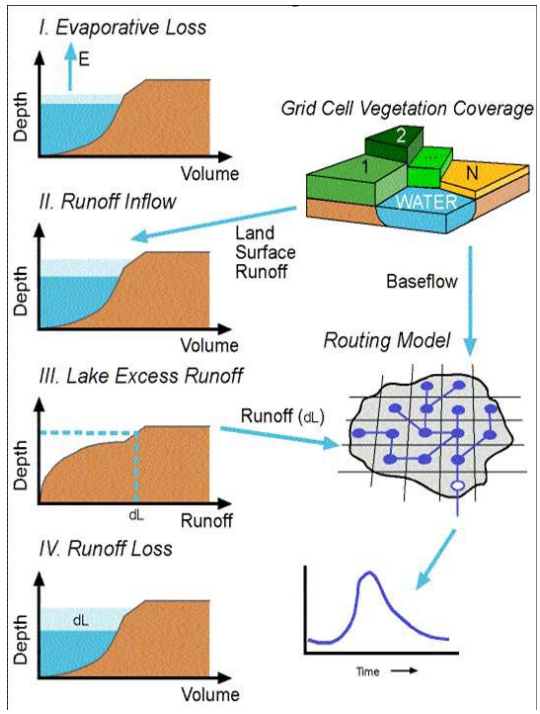


Figure 22: Lakes and Wetlands in VIC (source: Civil Engineering/University of Washington).

Finally, stream flow routing is modeled separately from the simulation of the land surface. Each grid cell is treated as a node in stream channel network, and flow is routed from cell to cell based on a unit hydrograph that accounts for the travel time of water from its origin to the channel network. Linearized St. Venant's equations are used route flow through the channel network.

i. Validation and Application of the VIC Model

A number of studies, primarily by VIC developers in collaboration with researchers, have been published assessing the success of the VIC model in retrodicting (modeling past) flow using historical climate data. These studies show both linear biases in some model outputs and suggest potential biases resulting from problematic model inputs.

In recent study, Wenger and colleagues (Wenger et al., 2010a) validated VIC model predictions of Rocky Mountain snowmelt-driven stream flows by using the model to retrodict historic flow patterns. Their study area is the Shoshone National Forest within the Missouri River basin. The authors input meteorological forcing data produced using a combination of both low elevation station observations and statistically derived estimates of high elevation temperature and precipitation. Model outputs were assigned to every stream segment in the basin with watersheds < 2500 km^2. Monthly discharges from the VIC model were compared to USGS stream gage data from 8 streams characterized by minimal upstream anthropogenic flow modifications.

The data showed that the VIC model is consistently biased with respect to the timing of the snowmelt peak, with all sites retrodicted to begin about a month prior to the observed date. This was consistent with a previous study that showed a linear bias to peak spring flows, with the center of flow of rain-dominated sites predicted too late while snowmelt sites were predicted too early. Wegener and colleagues argue that "the error is a result of either inaccurate snowmelt or soil modeling/calibration" [p. 5]. A post-hoc linear bias correction could be used to bring the data into alignment with the historic data, but the authors argue a preferable solution would be to fix the error in the model. Although model output did not exactly match the historical data, there were no other consistent patterns of bias in the VIC model outputs.

In an expanded test using data from 55 USGS gaging stations in the Pacific Northwest, Wenger and colleagues (Wenger et al., 2010b) found good to acceptable fits for 42 (77%) of sites. Center of flow mass was underpredicted by a median of 12 days, a bias that was also found to be linear and correctable. There was a detectable bias to earlier flows for snowmelt sites and later flows for winter rain sites, both of

which could plausibly be explained by model underpredictions of winter snowfall: if winter rain is underestimated then the center of flow mass will be overestimated; however, if winter snow is underestimated, the snowpack will be predicted to melt earlier and the center of flow mass will be underestimated. The authors site several possible reasons for this error, including biases in the meteorological data input to the model and improper model calibration.

Probabilities and frequencies of high winter flows were well-predicted, with higher-frequency events better predicted than low. Predictions of summer high flow events were poor and much larger in the model than in the observational data. For mean annual flow, data predictions were accurate and slightly negatively biased; for low summer flows, the predictions were accurate but slightly positively biased. The low-flow bias is amenable to reduction by simple linear transformation. Low summer flows were "poorly predicted with a strong negative bias", but the pattern of interannual flow variability was well-captured by the model. The model did a poor job of estimating the number of days in each water year that discrete high flow pulses occurred (high pulse count), exhibiting high error and high bias, and a general over-prediction of events. Overall, sites with higher mean annual flows were better predicted than sites with lower mean annual flows. Predictions were also worse for sites with strong groundwater influence.

Snow simulations from VIC in the western U.S. are reported as "generally quite good" by Mote and colleagues (2005). VIC has also been successfully used in streamflow forecasting applications (e.g., Christensen and Lettenmaier, 2007; Christensen et al., 2004; Nijssen et al., 2001) and for producing climate change scenarios (e.g., Snover et al., 2003).

C. Upper Rio Grande Water Operations Model (URGWOM)

The Upper Rio Grande Water Operations Model (URGWOM (USACE, 2012)) is used to simulate water delivery through projects in the Rio Grande Basin in New Mexico, from the Colorado State Line to El Paso, Texas. The model is primarily designed to complete accounting calculations for tracking the delivery of water allocated to specific users, given changes in river flow and facility operations. The model uses coded rule sets to set dam releases, diversions, and other demands. The model takes into account flood wave travel times; reservoir operation and seepage; conveyance losses to deep percolation, evaporation, and transpiration; surface water-ground water interaction; and irrigation return flows. URGWOM can be coupled with other models for use in simulating water supply, rainfall/runoff, climate change impacts, hydraulic changes and changes to groundwater. URGWOM was developed using the RiverWare software development platform.

URGWOM is composed of four modules:

- Planning Model: The planning Model is used to simulate the impacts of proposed actions on the overall water budget, including short-term and long-term water deliveries to users, river flows, interstate Compact deliveries, and Compact status. Multiple model runs can be used to compare the effects of proposed changes in water operations with standard operations. In addition, the module can be coupled with historical hydrology or simulated hydrology data to investigate the impact of climate change on river flows. Inputs include long-term forecast and up-to-current conditions. Outputs include long-term daily hydrographs, storages, and system conditions.
- Forecast Model: The Forecast Model is used to process data provided by the Natural Resources Conservation Service (NRCS) and the National Weather Service (NWS). Model outputs include forecasts of runoff that serve as inputs to the Water Operations Model. Inputs include up-to current volumes, historic year hydrograph shapes, and forecasted (March-July) flows. Outputs include contractor losses and storages, total losses and computed inflow, local inflows, and reservoir reports.
- Water Operations Model: The Water Operations Model is used to complete the daily timestep rule-based simulations used to forecast operations, deliveries, and resulting flows through the end of the calendar year. The model is run on the first day of each month from February through May, taking as input the runoff data provided by the Forecast Model. Inputs include past days' inflows, initial storages, and forecasted daily inflows. Outputs include forecasted reservoir outflows and resulting stream flows, and total and contractor storages.
- Accounting Model: The Accounting Model maintains year-to-date records of water storage and deliveries to water users. This model takes as inputs actual operations, rather than rules. Input data include contractor and total outflows, storage (elevation), weather data, stream gages, and forecasted diversions, wastewater, and other flows.

URGWOM is a collaborative product of the Corps, Bureau of Reclamation, U.S. Fish and Wildlife Service, U.S. Geological Survey, Bureau of Indian Affairs, and the International Boundary and Water Commission. Additional participants in URGWOM development include the New Mexico Interstate Stream Commission, the University of New Mexico, and the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado at Boulder. Cooperating agencies are provided opportunities to be involved with URGWOM development through participation on the Steering Committee and currently include the City of Santa Fe, Paseo del Norte Watershed Council, Ohkay Owingeh Pueblo, Colorado Division of Water Resources, New Mexico Department of Agriculture, Desert Research Institute, Caballo Soil and Water Conservation District, and Rio Grande Restoration, Inc.

For this climate change study the Water Operations Model was used to complete daily timestep rule-based simulations to forecast operations, deliveries, sediment inflow and resulting flows for 31 years of inflows (1975-2005). The period of record used in this study was from January 1, 1975 to December 31, 2005; this time is the period when operation of Cochiti Lake started. The period of record used in the study was also chosen because it is a complete data set that the Corps has available to run the URGWOM.

D. Calculating Reservoir Sedimentation Rates

The sedimentation rate in Cochiti Lake below the elevation of the permanent pool is estimated from historical data of suspended sediment and bedload passing the USGS Gage at Otowi Bridge, located below the Rio Grande-Rio Chama confluence and well-upstream of the pool at Cochiti Dam and Lake. The baseline period is 1986 to 1998.

Suspended sediment transport equations were derived from a double mass curve of discharge against sediment (tons/day) averaged across monthly and seasonal totals (Kolk, 2002). Cross section lines approximately 6000 feet upstream of the head of the lake were used to develop the hydrologic data need to model the bed load based on sediment transport equations (Box 1). The HEC-RAS model was used to quantify energy slope, top width, average velocity and hydraulic depth. Sediment transport was modeled using the Meyer-Peter & Muller transport equation. Suspended sediment distribution is approximately 35% clay, 10% silt, and 45% sand. Comparison with sediment data from below Cochiti Dam suggests the dam has an 87% trap efficiency.

Sedimentation rates across the baseline period were not constant. From October 1981 to October 1986, 2925 acre-feet was lost from storage due to sedimentation below the permanent pool. From October 1986 to June 1991, 3427 acre-feet of storage was lost, while from June 1991 through June 1998, 7487 acre-feet of storage was lost. An iterative series of model runs and regression curves for periods across the year (October to February, March to May, June, July to September) were used to calibrate the Meyer-Peter & Muller transport equations so they more accurately fit the historic period data. When plotted as sediment rating curves of suspended sediment vs. discharge, the data for each monthly group has a great deal of spread, and r^2 values for the regression lines tended to be low (r^2, ranging from less than 0.1 to ~0.3, with one value as high as 0.6035). The calibrated Meyer-Peter and Muller equations estimated 3402 acre-feet of volume lost to storage due to sedimentation while in the period 1991-1998, the model estimated the volume of storage loss due to sedimentation at 7541 acre-feet. The percent errors in the modeled results are considered within acceptable limits.

Box 1. Equations for Calculating the total Sediment Load Accumulating below the Elevation of the Permanent Pool at Cochiti Lake.

Source: Kolk, 2002.

Total Load = Suspended sediment load (empirical) + bed load (theoretical)
Q= discharge
SSL = suspended sediment load
Cfs = cubic feet per second
BL = bedload

Suspended Sediment Rating Curves for Oct. to Feb.

Q<750 cfs SSL = $Q^{1.5380}$ (1.63650×10^{-2})
750-1450 cfs SSL = $Q^{1.8313}$ (2.66584×10^{-3})
Q>1450 cfs SSL = $Q^{2.7851}$ (1.92675×10^{-6})

Suspended Sediment Rating Curves for Mar. to May

Q<4300 cfs SSL = $Q^{2.3473}$ (7.64562×10^{-5})
Q>4300 cfs SSL = $Q^{-0.52498}$ (2.5211166×10^{6})

Suspended Sediment Rating Curves for June

Q<2250 cfs SSL = $Q^{1.702}$ (3.81873×10^{-3})
2250-6600 cfs SSL = $Q^{2.1004}$ (2.13550×10^{-4})
Q>6600 cfs SSL = $Q^{8.4898}$ (1.71218×10^{-28})

Suspended Sediment Rating Curves for Jul. to Sep.

Q<1750 cfs SSL = $Q^{1.0471}$ (1.17897)
Q>1750 cfs SSL = $Q^{2.2395}$ (1.64755×10^{-4})

Bed Load Rating Curves

Q<4500 cfs BL = 0
4500-7500 cfs BL = (1.27234)Q-5819.11
Q>7500 cfs BL = (2.03126)Q-11330.98

Volume Lost

$$= \frac{\text{(trap efficiency)*(total load)*2000*(1-(sed. above permanent pool))}}{\text{(Unit weight)*43560}}$$

Trap efficiency = 0.87

Percent Sedimentation Above the Permanent Pool

$=([(\text{WSE-(perm. pool elev.)/(perm. pool elev.-invert)})]/0.08934)^{0.574}$

Unit weight = 70.76 lbs./ft^3

E. Combining Models to Simulate Future Runoff and River Flows in the Rio Grande

Future sedimentation at Cochiti Lake was determined by inputting the climate change data into the VIC model. The VIC model is based on pre-development or natural conditions. For this study, the historical inflows were multiplied by the monthly flow ratios computed from the VIC model at forecast inflow points used in the URGWOM to simulate the different future climate conditions. The resultant climate adjusted inflows were then a suitable dataset for usage in the URGWOM to arrive at hydrologic impacts due to climate change. The seasonal discharge was input to the sediment transport equations to determine sedimentation rates.

VI. Results

A. Results: Changes in Runoff

Projected changes in annual runoff were modeled by the Bureau of Reclamation (Brekke et al., 2011). The model results are similar to those predicted by other modeling efforts, and to trends that are emerging in the current observational data: wetter northern climates will drive increases in runoff while progressively drier southern climates will drive down runoff. The effects are more pronounced in the Rio Grande Basin than in the Colorado River Basin because of the Colorado's larger catchment that includes parts of the Northern Rockies. Runoff declines are more pronounced and more widespread in the Far Future (2040-2069) than in the Near Future (2010-2039) (Figures 23 and 24).

In the Rio Grande Basin, runoff declines are projected to be 10 to ≥20% in the Upper Rio Grande by the 2020s, and increasing to ≥20% by the 2050s. Declines are also evident in the Colorado River Basin, but are offset by increases in some parts of the catchment.

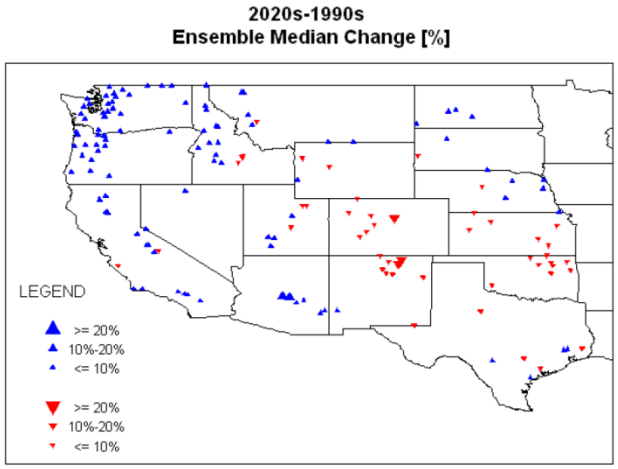


Figure 23: Ensemble median percentage change in annual runoff for 2020-2029 compared to 1990-1999 (source: Brekke et al., 2011).

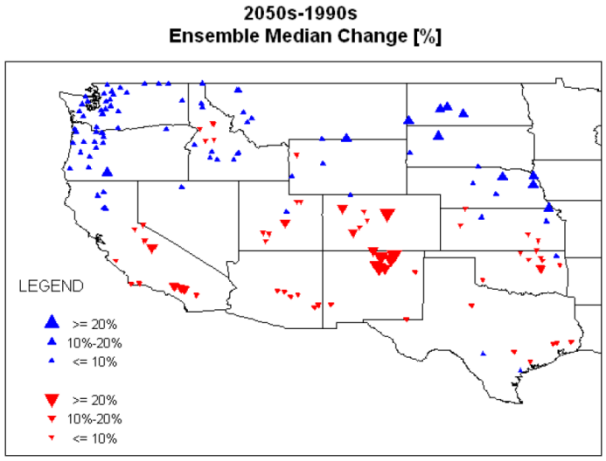


Figure 24: Ensemble median percentage change in annual runoff for 2050-2059 compared to 1990-1999 (source: Brekke et al., 2011).

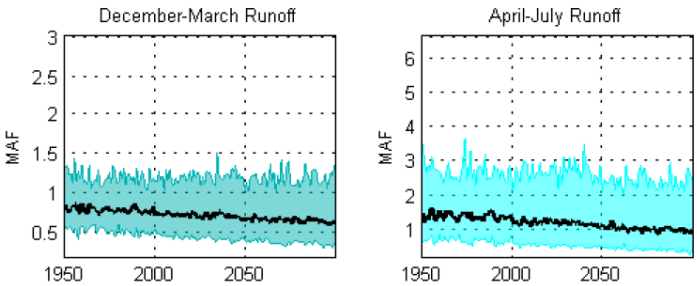


Figure 25: Projected changes in seasonal runoff, Rio Grande Basin (source: Brekke et al., 2011).

Models also project that changes in runoff will occur both during the winter and spring/early summer, with spring/early summer runoff declining faster over time. This reflects the overall decline in snowpack and advancement of spring runoff anticipated by other modeling efforts (see Chapter III).

Changes at the USGS gages at Otowi (above Cochiti) and Lobatos (at the Colorado-New Mexico border) were also modeled.

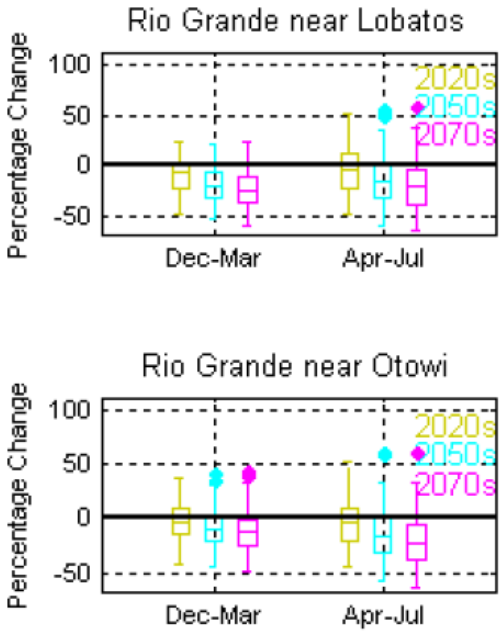


Figure 26: Projected percentage change in stream flow at the USGS gages at Lobatos and Otowi (source: Brekke et al., 2011).

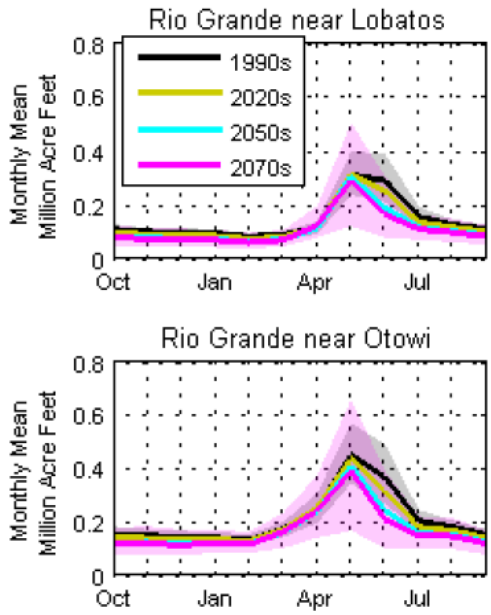


Figure 27: Projected changes in flow at Lobatos and Otowi (source: Brekke et al., 2011).

Average projected declines in flow by 2070 at both Lobatos and Otowi are approximately 25% compared to the average for 1990-1999, but the range is broad, with some models projecting gains in runoff. These projections are larger, but agree in direction, with those of other projects in the Southwest reviewed in Chapter III. For instance, Rango and Martinec projected runoff declines in excess of 12% with a 4°C increase in temperature while Hurd and Coonrod project runoff declines of as much as 1/3 by 2080[11]. These findings are also in line with projected declines in flow along the Colorado River of 10-30% by 2050[12]. Advances in spring runoff are also evident in the modeled hydrographs for Otowi and Lobatos gages.

[11] Rango and Martinec, 2008, *op cit;* Hurd and Coonrod, 2007, *op cit.*
[12] Barnett and Pierce, 2010, *op cit.;* Leung et al., 2004, *op cit.;* Christiansen et al., 2004, *op cit.*

B. Results: Changes in Inflow and Sedimentation at Cochiti

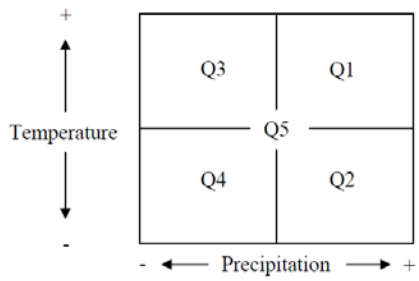


Figure 28: Quadrant designations for modeled combinations of temperature and precipitation.

Inflow and sedimentation were modeled based on five climate scenarios (Figure 28). The model results concentrated in a spread diagonally across these scenarios along the Q3-Q5-Q2 axis, so the results discussion focuses on this axis. To review, the Q2 scenario is the wettest future: limited rises in temperature are accompanied by small increases in precipitation. Lower temperature rises limit evaporative demand, resulting in net gains in soil moisture and water balance. The Q3 scenario is the driest future, in which the highest temperature increases coincide with significant declines in precipitation. The combination drives high rates of evaporation and declines in runoff. Q5 is the median scenario, capturing the central tendency of the models. Although this spread is treated "equally likely" in this modeling viewpoint, temperature rises consonant with the Q3 & Q 1 scenarios are considered likely by most researchers (see review in Chapter III).

Because of the way the models were constructed, the graphics in this section show model projections relative to the historic baseline period of 1975-2005.

i. Near Future (2010-2039)

For the Near Future (2010-2039) scenario, projections were developed for the average hydrograph, average monthly inflow, cumulative sediment storage, and relative sediment accumulation at Cochiti Lake.

The average hydrograph (Figure 29) shows the historic period (1975-2005) baseline in blue. Relative to this baseline, the "optimal" Q2 scenario, in which less warming is accompanied by increases in precipitation, shows greater inflow at Cochiti in all seasons of the year. The only exception is July, where inflow is equal to the baseline condition. The median (Q5), and the warmer, wetter scenario (Q1) are similar to the historic baseline from January through May, but declines relative to that baseline beginning in June. The overall volume of water in the Q5 and Q1 hydrographs is less than the historic baseline and a slightly greater share of that volume is projected to occur in earlier part of the year.

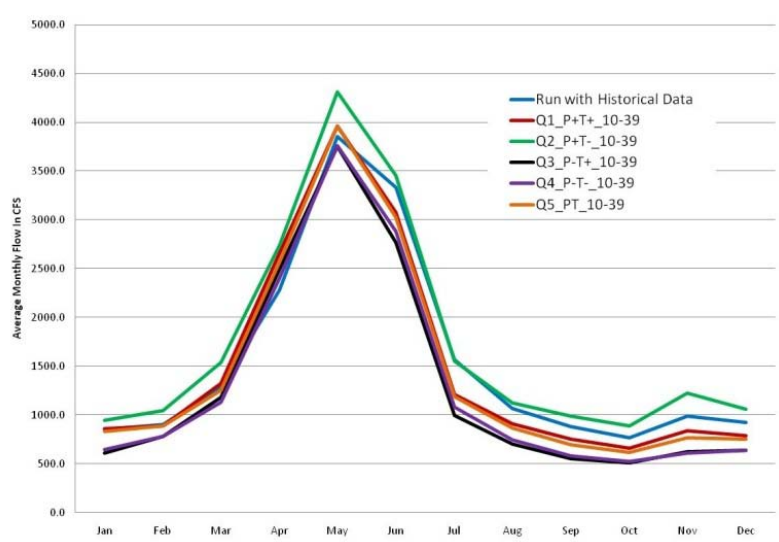


Figure 29: Projected change in inflow hydrograph at Cochiti Lake (2010-2039).

These trends are more pronounced in the warmer, drier (Q3) and less warmer, drier (Q4) scenarios. January-March inflows at Cochiti are projected to be below the baseline in every month of the year except April. In April, reflecting earlier peak spring runoff, both scenarios are slightly above the historic period baseline, and in June, they are

significantly below. Again, this is reflecting a shift towards a greater share of runoff happening earlier in the year under warmer climates.

The same trends are visible in the graph of average monthly inflows (Figure 30), in which all scenarios show greater inflow to Cochiti during April, and all but the wettest scenario show reduced inflows to Cochiti in June, compared to the historic baseline. This pattern continues into the July-December period, where all but the optimal, wettest "Q2" scenario show drier late summer, fall, and early winter conditions compared to the historic baseline.

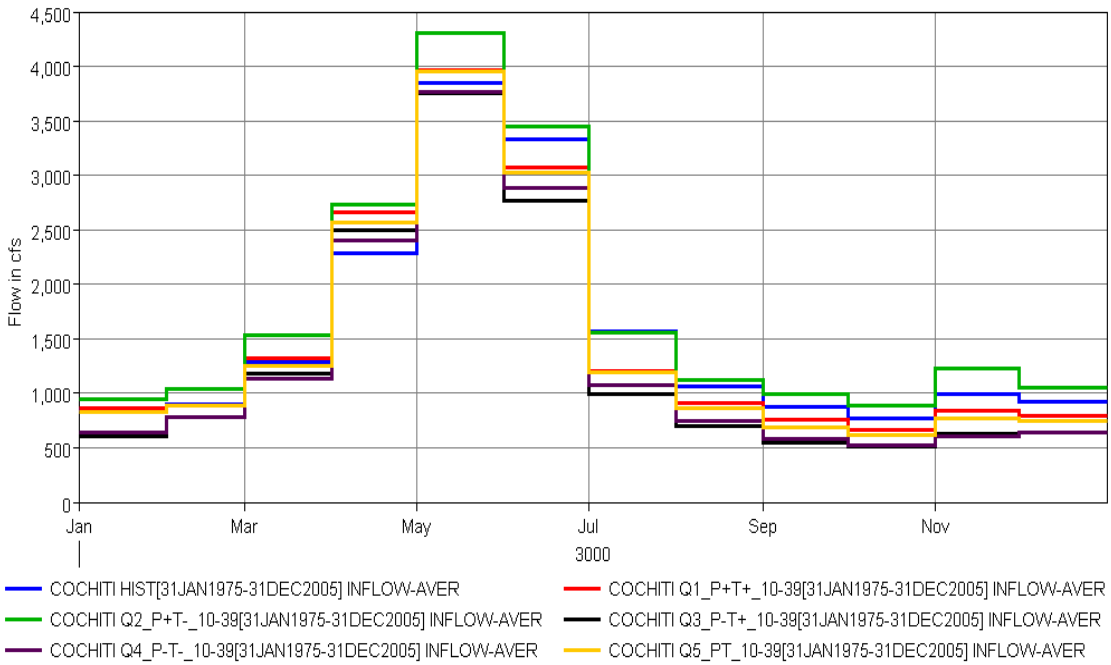


Figure 30: Projected changes to monthly inflow at Cochiti Lake (2010-2039).

Changes in storage at Cochiti Lake correlate with changes in precipitation levels (Figure 31). The wettest (Q2) scenario projects an increase in storage at Cochiti Lake. The median and Q1 scenarios show storage levels comparable to the baseline, while the driest scenarios (Q3, Q4) anticipate storage declines relative to the baseline.

Projected sediment accumulation (Figure 32) for the different Near Future scenarios is shown against the historic period data for 1975-2005 as a means of highlighting how sediment accumulation would have been different had future climates already been in place. With the exception of the wettest, Q2 scenario, the remaining four scenarios predict significant declines in sediment accumulation over time at Cochiti, with the amount of sediment influx declining with aridity (both precipitation decrease as well as temperature increases that are likely to increase evapotranspiration rates). For the three driest scenarios and the median climate scenario, sedimentation rates are lower than historic (the lines diverge over time). Not surprisingly, the sedimentation rate of the wet (Q2) scenario is greater than historically.

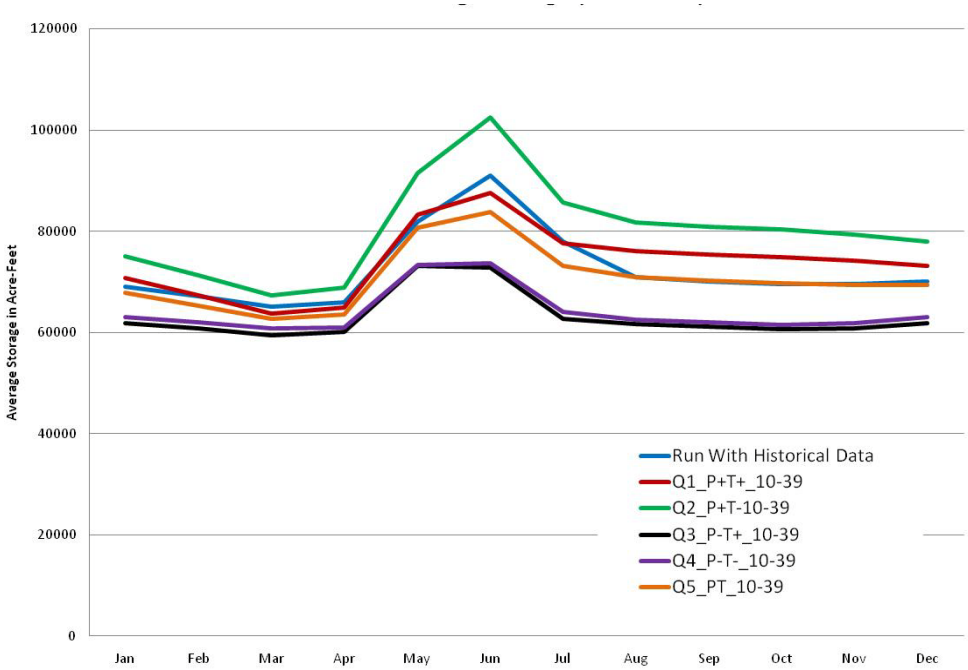


Figure 31: Projected changes in Cochiti Lake average storage (2010-2039).

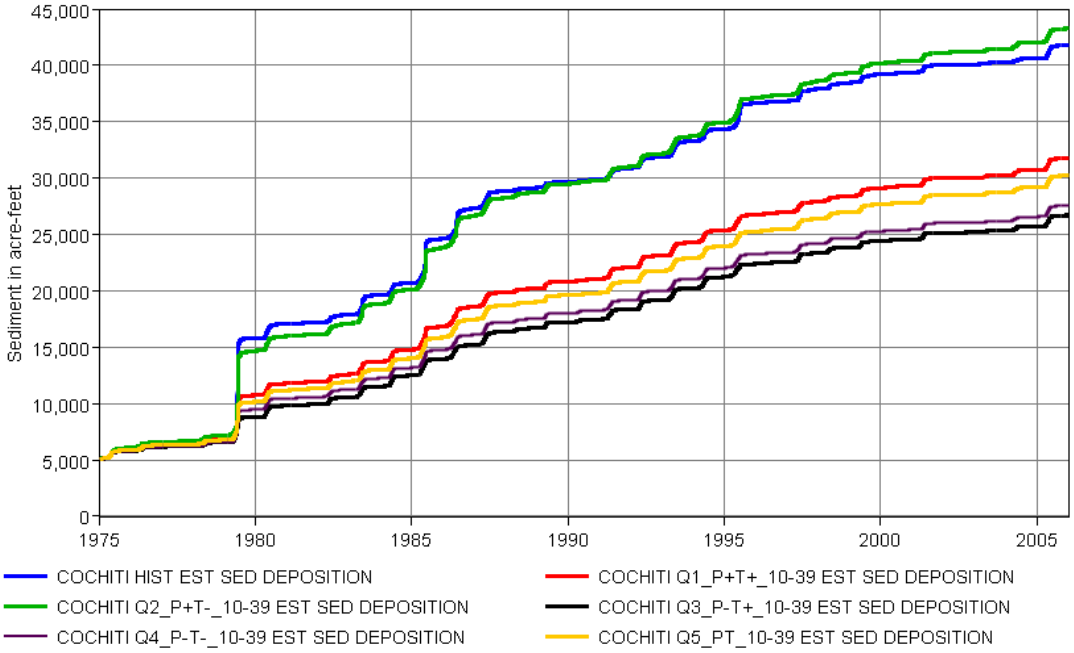


Figure 32: Projected changes in accumulated sediment deposition at Cochiti Lake (2010-2039).

i. Far Future (2040-2069)

The model projections for the Far Future are similar to, but more pronounced than, the results for the Near Future. The projected shift in the hydrograph is evident in all five scenarios (Figure 33), which show declines in June and July inflow to Cochiti and gains in April inflow relative to the historic period (1975-2005) baseline. As expected, the optimal, wettest "Q2" scenario shows total water volume comparable to the historic period, and shows January to May inflow values in excess of the historic period average.

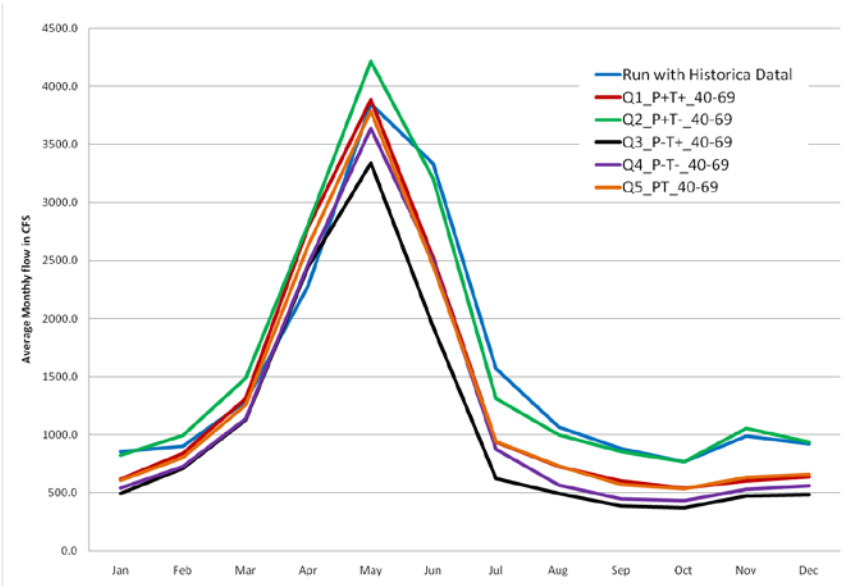


Figure 33: Projected change in inflow hydrograph at Cochiti Lake (2040-2069).

In the remaining four scenarios, including the median, June through February inflows are below the historic period average, then gradually increase until the inflows exceed the historic baseline in April. In all but the wettest of these four scenarios, the May inflow to Cochiti is below the historic period average. These patterns are in line with climate model projections for reductions in winter precipitation due a poleward expansion of the subtropical zone that reduces the penetration of winter storm systems into the Rio Grande watershed.

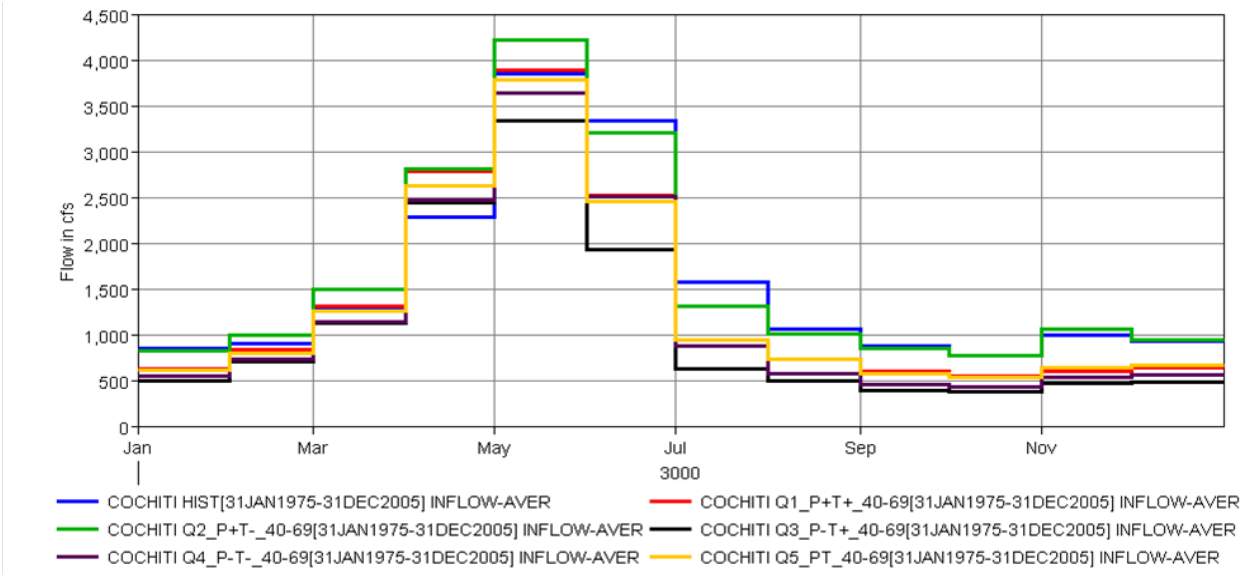


Figure 34: Projected changes to monthly inflow at Cochiti Lake (2040-2069).

The shifts in the hydrograph towards lower total inflows, and a greater share of these inflows occurring earlier in the year, are also evident in the graph of Cochiti Lake average monthly inflow (Figure 34). All five scenarios show increased April inflow relative to the historical baseline, as well as decreases in June, late summer and fall inflows. Only the wettest scenario (Q2) shows inflows comparable to the baseline during the fall and winter.

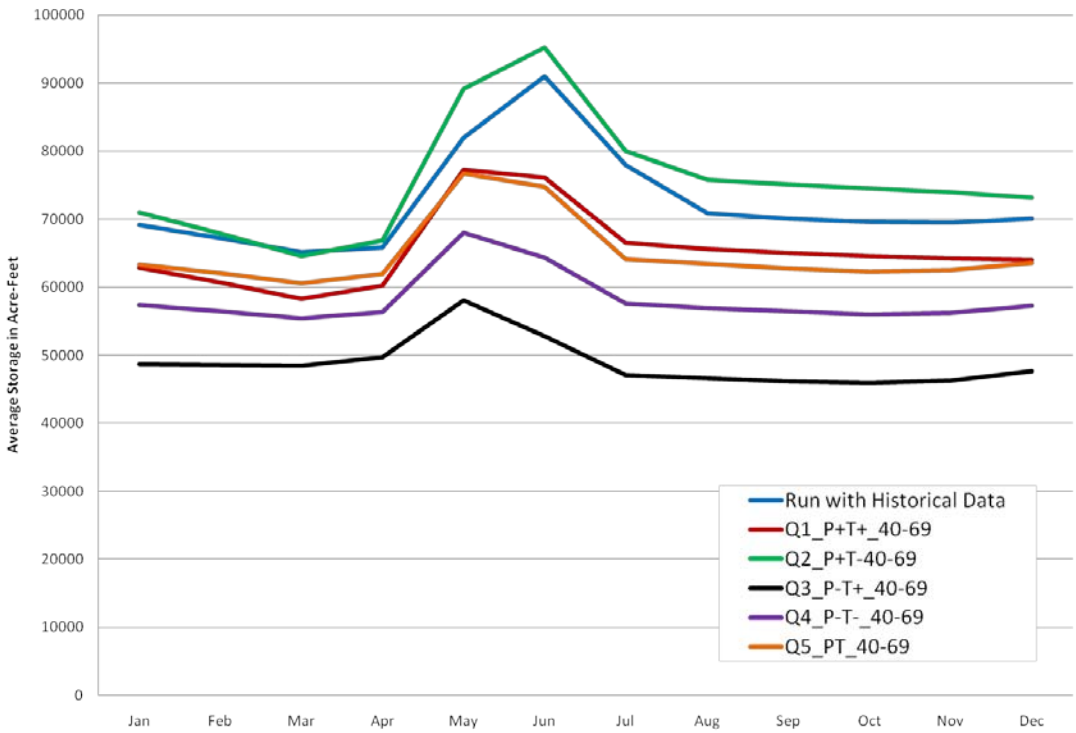


Figure 35: Projected changes to Cochiti Lake average storage (2040-2069).

Changes in water storage at Cochiti Lake in the Far Future, for all but the wettest scenario, are lower than the historic baseline (Figure 35). Wet climate projections indicate water storage levels at the reservoir comparable to the historic period.

Projected sediment accumulation for the different Far Future scenarios is shown against the historic period data for 1975-2005 as a means of highlighting how sediment accumulation would have been different had future climates already been in place (Figure 36). All five scenarios show net declines in sediment deposition, and show both declines in the accumulated sediment and in the relative rate of sediment accumulation over time. As with the Near Future, sedimentation rates and sediment volumes decline with greater aridity. The greatest difference is between the warmer, drier future scenario (Q3) and the baseline: sediment accumulation is less, and occurs at a rate that declines over time, for scenariosQ1, and Q3-5. The wet climate scenario (Q2) also shows a slight trend towards declining rates of sediment accumulation over time.

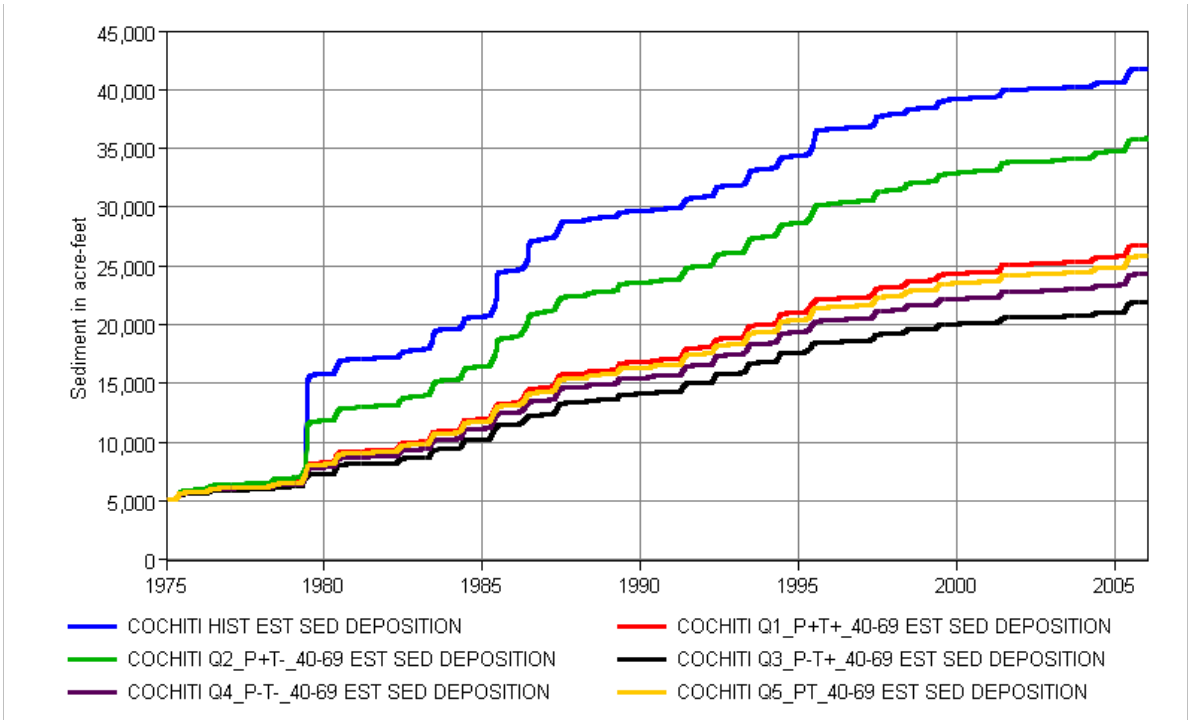


Figure 36: Projected changes in accumulated sediment deposition at Cochiti Lake (2040-2069).

C. Limitations of Approach

In these models, the comparisons are relative to each other and sediment equations could be updated. The last time the Corps did a sediment survey at Cochiti was in 1998. Since Cochiti is not a water supply reservoir it is not possible to compare impacts at the reservoir but it might be possible to compare how the reservoir elevation changes over time to maintain the recreation pool and how inflow is impacted.

Cochiti is operated to pass flow. Therefore, it is not possible to study changes in discharge intensity with the predicted concentration of precipitation into fewer, larger events. If the event is large, the Corps would be in flood control operations and basing flow levels from Cochiti on downstream conditions. This would represent no change from how the dam is currently operated.

Since historical data was used, the approach may not adequately capture shifts in the hydrograph to earlier spring runoff with lower peak flows. The peaks in the runs occur at the same time as the historical flows. However, by looking at the monthly values, it is possible to get a sense of how the hydrograph might shift under different climate scenarios.

Future efforts would benefit from a refinement of the approach used in the sediment transport equations, especially encompassing drought years. The current equations were formulated based on data from what are now acknowledged to have been a series of wet years from 1986-1998. Therefore, they many not adequately capture how sedimentation changes with drought (especially if these changes are non-linear due to effects such as changes in vegetation cover in the catchment). In future studies, it might be very useful to use two sediment transport equations: one representing sedimentation during “wet” years and the other covering sedimentation during “dry years”. In addition, the Corps’ Cochiti Baseline Study (in progress) might provide a new set of equations since the study will develop a sediment transport model.

The existing stream flow data are not adjusted for the presence of San Juan-Chama diversion water. Future iterations of this project would benefit from data input that corrects for this water. It would also be interesting to rerun the models with the daily data provided by the VIC model.

Elevation-area-capacity tables were not available that reflected change over time for the period used as the baseline in this study at Cochiti.

Finally, this study focused on long-term changes to average sedimentation rates in the reservoir. However, sedimentation is responsive to a wide range of non-climate variables at a range of temporal and spatial scales that were not considered in this study.

D. Lessons Learned

In completing this study, important lessons were learned. These lessons can be grouped into categories of local knowledge, education, and non-climate watershed changes.

i. Local Knowledge

Local knowledge, by which is meant knowledge specific to the District and the study area, is a critical component to project execution. Knowledge of local climate, climate trends, hydrology and fluvial geomorphology are essential to make sense of model results. Particularly in the mountain West, topography strongly impacts regional air flows, temperature gradients, and precipitation gradients in ways not captured by large-scale climate models. On the ground climate and climate change may be starkly different between two points within 15 miles of each other. These factors are not readily generalized across large areas. Understanding how to make use of regional climate model projections in the context of locally highly-variable landscape responses is an important, but unexplored area of District need.

River basin conditions, including sediment supply and grain size, soil and sediment type, slope, vegetation cover (type, density, health), groundwater withdrawal, headwater latitude and altitude, and other factors interact with climate change in ways that affect how much a given river's flow will be impacted by a given change in climate. For instance, above Cochiti Dam much of the bedload is clastic and may have a reduced likelihood of transport as the competence and capacity of the Rio Grande declines under a changing climate. However, undammed tributaries such as the Rio Puerco and Rio Salado flow through thick, fine-grained alluvium that may be more readily entrained under future climate conditions, potentially increasing sediment supply to downstream reservoirs such as the Bureau of Reclamation's Elephant Butte Dam and Lake. Reach-specific stream characteristics and how these are likely to interact with climate change are not factors readily generalized, and such basin-specific knowledge is important to interpreting model projections of future hydrologic states.

Human changes to the landscape complicate the hydrologic response. Changes in climate (such as drought or precipitation concentration into fewer, larger storms) may contribute to increased tributary sediment yield, but the abundance of dams, stilling basins, recreational ponds, and stock ponds along almost every water course on almost every Western tributary means that a significant share of any increase in sediment yield may be captured in these upstream basins. Local knowledge is important to understanding how human alterations to hydrologic systems might mitigate (or enhance) erosion, sediment transport and flooding in response to local hydroclimate changes.

ii. Education

Like all disciplines, a great deal of knowledge is required to understand climate change and its impacts on the landscape. Climate change is complex and its effects nuanced, and for many areas comprehensive syntheses of trends and models do not currently exist. National- and global-scale syntheses are an inadequate substitute because they mask locally-important temporal and spatial variation in climate change and its impacts. In addition, climate change science is rapidly evolving, and there is increasing recognition of the importance of global teleconnections in structuring local climates. Consequently, while the broad patterns of climate change are easy to grasp, actionable knowledge is significantly harder to obtain, and that knowledge is not easily obtainable under the current project-oriented structure of the Corps. The level of interest in and knowledge about climate change among staff at all levels is highly variable. A variety of levels of knowledge and commitment to the problem mean on-going educational efforts are essential for staff, sponsors, partners, and stakeholders.

While collaboration with Federal, State and local agencies, non-profits, academics, and stakeholders provides access to knowledgeable individuals, expertise needs to be available within the District to be able to evaluate the information produced by others. Data obtained from collaborators cannot be assumed to be error- or bias-free, but must be evaluated by people familiar with the likely range of values. For instance, in this project, anomalous values from the daily timestep climate simulation were recognized by the hydrologic engineer prior to routing the data through the URGWOM model. Although this problem prevented more fine-scaled modeling of sediment yield, it took a local hydrologic engineer familiar with the Rio Grande to identify the problem.

iii. Non-Climate Watershed Changes

Climate change is only one kind of watershed change that can affect stream flow in a basin. A variety of natural and human changes can affect the way water moves through the watershed in ways that can affect sediment transport in a river system.

Local landscape-ecosystem interactions may be important drivers of local and regional responses to changes in climate. For instance, increasing aridity in the Southwest is expected to increase conifer mortality through direct water stress directly, increased susceptibility to infestation (e.g., bark beetles), changes to browsing species composition, and by the increasing size, intensity and frequency of wildfire. Changes to logging and grazing patterns have effects on both wildfire occurrence and landscape susceptibility erosion. Capturing these in sediment yield models is vital, and yet for many watersheds, quantifying these relationships is a major unmet need. Due to lack of information, it was not possible to control for ecological changes in the watershed that affect the baseline date used to estimate sediment transport rates in this study. It was, therefore, also not possible to model the effects of future changes.

However, these changes can be significant, as has been evident in the 18 months following the Las Conchas fire in the Jemez Mountains adjacent to Cochiti Lake. The geometry of the landscape around Cochiti Lake makes it uniquely susceptible to receiving sediment transported via post-wildfire erosion from adjacent mountain slopes. Cochiti Lake is located on the Rio Grande at the mouth of White Rock Canyon, a steep walled notch between the Jemez Mountains (volcanic field) to the west and the much-lower Caja del Rio (volcanic field) to the east. While the Caja del Rio is not forested, the Jemez mountains are heavily forested, ranging from pinyon-juniper woodlands in the foothills, to Ponderosa pine forest at mid-elation, and dense mixed-conifer forest to mountain summits above 11,000 feet asl. The Jemez Mountains are a large, volcanic caldera that last formed during eruptions 1.62 million and 1.25 million years ago (Goff, 2009), producing a steep-sided ring of mountain peaks around a central valley containing multiple resurgent domes. Ejecta from the last two major caldera-forming eruptions has

accumulated around the perimeter of the volcano, creating flanking plateaus of lithified volcanic ash and basalt flows. Hundreds of millennia of fluvial erosion have notched this plateau into a series of short, narrow, steep-sided watersheds extending from the eastern caldera rim, down the caldera side and cutting down through the volcanic plateaus to the river at an elevation close to 5600 ft asl. Soils are generally weakly developed. The west side of Cochiti Lake, the west bank of the Rio Grande, and the Rio Grande's major tributary, the Rio Chama, abut the Jemez Mountains and received runoff flow over a linear distance of approximately 70 miles.

Figure 37 High intensity burn, Santa Clara Canyon

Figure 38 View west along south side of the bunkhouse, Dixon Conference Center, Cochiti Canyon, after the Las Conchas fire and before the flood of 22 August 2011

Figure 39 South side of the bunkhouse, Dixon Conference Center, Cochiti Canyon, following the Las Conchas fire and the flood of 22 August 2011. The grey line is the high water mark.

Figure 40 Cochiti Canyon, post-fire, post-flood

The Jemez Mountains, like many high elevation areas of New Mexico, promote and receive the majority of their annual precipitation during the summer monsoon season in the form of locally-intense thunderstorms. Typically, heavy rain falls on the trees or on the heavy duff of needles, infiltrates into the soil, and eventually finds its way to the Rio Grande.

However, in areas that are moderately to severely burned by wildfire, the vegetation is completely burned away, the needle duff burned to ashes, and soil organic matter volatilized (Figure 37). There are no longer any plants to bind the sediment to the steep hillslopes, and there are neither roots nor soil organic matter to cohere the dirt. Without the intervening canopy and duff, rainsplash is able to dislodge sediment particles from the surface and transport them downhill into tributary washes.

Five large wildfires have burned the eastern Jemez Mountains in recent decades, and have been accompanied by higher precipitation/run-off ratios and greater sediment transport to the Rio Grande:

- La Mesa Fire of June 1977, which burned approximately 15,270 acres (62.5 km²) of land primarily in Bandelier NM and Los Alamos National Laboratory. This fire burned the headwaters area of the Rio de los Frijoles, the main watershed at Bandelier National Monument (McCord, 1996), with approximately 21% of the burn area identified as “high severity” (Haire and McGarigal, 2009).
- The Dome Fire of April 1996 burned 16,516 acres (66.8 km²) in Capulin Canyon and the Dome Wilderness on the eastern flanks of the Jemez Mountains. Approximately 24% of the burn area was identified as “high severity” (Haire and McGarigal, 2009).
- The Oso Complex Fire started in June 1998 and burned 5,185 acres (21 km²) of land in the eastern Jemez Mountains, including more than 1,200 acres (4.9 km²) of Santa Clara Pueblo land. Of this, 55% of the burn was categorized as “high severity” (Haire and McGarigal, 2009).
- The Cerro Grande Fire of May and June 2000 burned 48,000 acre (190 km²) on the plateau on which Los Alamos National Lab sits and on the steep eastern flanks of the Jemez Mountains to the west. Approximately 24% of the burn could be categorized as “high severity” (Haire and McGarigal, 2009).
- Las Conchas Fire of July 2011, which burned 156,293 acres (630 km^2), intensely burning most of the eastern flank of the Jemez mountains from the headwaters of the major stream entering the Rio Grande just below Cochiti Dam north to Santa Clara Creek above the upstream end of White Rock Canyon. Approximately 18% of the burn area overall can be considered “high severity” burn (U.S. Department of Agriculture Forest Service, 2011).

Hydrologic consequences for the Jemez Mountain tributaries feeding into the Rio Grande at and above CDL include dramatically altered hydrologic response to precipitation events. In Santa Clara Canyon in the late summer following the Las Conchas Fire, small precipitation events were capable of initiating larger-than-historical floods and modeling showed that the potential magnitude of flood discharge is 4-8 times larger under post-fire conditions than previously (USACE, 2011). Large floods (>2,000 cfs at the confluence of Santa Clara and Sawyer Creeks) that formerly were the 4% chance (25-yr) flood are now rated as the 50% chance (2-yr) flood event.

Similar increases in peak flows have been recorded for the other major fires in the area, all of which affected watersheds tributary to Cochiti Lake or the Rio Grande above Cochiti Lake. After the La Mesa fire, the Rito de los Frijoles peak flood in 1978 was 3,030 ft^3/s, as compared to 19 ft^3/s in the 6 year period from 1964-1969 (Veenhuis and Bowman, 2002). There were 29 peak flow events from 1977-1979 that exceeded the pre-fire peak flow, 17 of which exceeded 100 ft^3/s. In the second year, peak flows were 10 to 15 times the pre-fire peak flows, and during the third year peak flows were 3-5 times the pre-fire peak flows. After 1979, the canopy had still not recovered, and peak flows remained above the pre-fire mean 22 years after the fire. The median suspended-sediment concentration in samples collected after the

fire was 1,340 mg/L (vs. 16 mg/L prior). In the period 1993-1995, about 20 tons/year of suspended sediment were transported past the Frijoles Canyon gaging station; in the first year after the fire about 4,400 tons of suspended sediment were transported past this gaging station, an increase of approximately 220 times.

In Capulin Canyon, hit hard by the Dome fire, the peak flow in the first year was 3,630 ft^3/s, decreasing to less than 400 ft^3/s, and less than 160 ft^3/s by 1998, an order of magnitude greater than the pre-fire median annual peak flow (Veenhuis and Bowman, 2002). Like the Rio de los Frijoles drainage, the maximum peak flows and maximum suspended sediment loads were highest in the first 3 years following the fire.

The practical difference in pre-fire and post-fire peak flows is evident in Figure 38 and Figure 39. Figure 38 shows the south side of the historic bunkhouse at the Dixon Conference Center in Cochiti Canyon immediately after the Las Conchas fire. The channel of the stream draining the canyon is visible in the foreground. One of the places most severely burned during the Las Conchas fire was Cochiti Canyon, from about the Dixon Conference Center upstream to the headwaters. The fire missed the bunkhouse, although it destroyed the main building at the conference center. Two rainfall events occurred in Cochiti Canyon, one on August 21, 2011 measuring 1.6 inches of rainfall and one on August 22, 2011 measuring 1.5 inches. The latter produced a devastating flash flood in Cochiti Canyon with an estimated peak flow of 23,000 cfs that moved boulders approximately 8’ in diameter (Figure 40) and produced the wreckage visible in Figure 39. In addition, the flood destroyed a large 4-car-garage-size outbuilding located at the photo point in Figure 39, and several houses and farm outbuildings just downstream of Dixon Conference Center. The flood sent nearly 100 tons of woody debris down Cochiti Canyon and into Cochiti Lake via a short segment of the Rio Grande.

The significance of these fire data are:

- Post-fire sediment delivery from these small canyons draining directly into Cochiti Lake or into the Rio Grande directly above are large enough to show up as detectable sediment pulses (steps) in the historical baseline of sediment yield at Cochiti Lake used in this study (e.g., 1979, 1996). Whereas changes in sedimentation due to long-term changes in temperature, precipitation, and evaporation in the larger catchment are expected to be approximately linear and evidence a declining rate over time in model results, sediment delivery from fire scars occurs as step-wise increases in sediment contribution to the reservoir in the first few years post-fire. The frequency and magnitude of these sediment pulses is an important contributor to sedimentation in the lake.

- Fire frequency, size, and intensity are anticipated to increase across the Southwest in response to climate change over the coming decades. By using the historical flow as the baseline and adding changes in temperature and precipitation to it, the model used in this study assumed that the pattern (frequency) of other causes of sediment contribution would remain unchanged – the number and magnitude of step increases/decade are assumed to be constant. This may not be true under future climate scenarios, and this may be further exacerbated by factors such as forest loss due to drought, disease, pests and other causes in the catchment that alter the canopy structure.

A more integrated watershed model that captures landscapes away from the immediate proximity to stream channels is needed to more effectively account for watershed changes that affect stream flow and ground water recharge. Collaborative efforts with other land management and research institutions would be needed to achieve such a model.

VII. Conclusions

This study assesses the impacts of projected climate changes on sedimentation and water storage at Cochiti Dam and Lake. The broad-brush approach to modeling the climate change yielded a wide range of predicted future conditions under the assumption that all five projected scenarios were equally-likely.

However, recent trends in temperature suggest that not all future climate scenarios are equally-probable for New Mexico. Models predicting less warming (Q2 and Q4) anticipate Near Future warming of ~1-2.5°F (0.5-1.4°C) above mid-20th century averages (1950 to 1999). Instrumental data show that the average temperature in the period 2003-2007 in the Colorado River Basin was 2.2°F higher than the 20th Century average (Saunders et al., 2008), and as of 2006 New Mexico had already warmed nearly 2°F (1.1°C) (Gutzler, 2007; Watkins, 2006). Given the continued rise in global carbon emissions, average temperatures for 2010-2039 are likely to be higher than 2.5°F above the mid-20th Century average.

Taken together, the observational data suggest that models predicting slower rates of warming significantly underestimate the true warming rate, and that the "more warming" scenarios (Q1, Q3) and the median (Q5) probably more accurately reflect the range of plausible projections of future climate in New Mexico. Therefore, the discussion that follows focuses on the consequences for rates of inflow and sedimentation at Cochiti Lake under these three scenarios.

A. How is projected climate change expected to affect watershed sediment yield?

Under all three scenarios, projected changes in climate are expected to result in a decrease in sediment contribution to Cochiti Reservoir. The major tributary above Cochiti is the Rio Chama. Reservoirs on this river retain a large amount of sediment behind them, restricting the amount of additional sediment that this large tributary might contribute to the Rio Grande under different climate change scenarios. Sediment contributions from high, flashy flows along tributaries during the summer monsoon might increase. However, given the gravel-dominant nature of the bed and bank materials across much of the reach from the Rio Grande Canyon to Cochiti, it is not clear that the projected lower mainstem flows would be effective at transporting these materials to the reservoir. Therefore it is logical that the model projections are for less sediment accumulation in the reservoir and a gradually declining rate of sediment contribution relative to the historic baseline data.

Although reservoir sedimentation rates are likely to decline, sediment yield from tributary arroyos is expected to continue and to possibly increase as climate warms. Increasing sediment storage in the mainstem channel may contribute to increasing rates of aggradation in the Rio Grande that, in turn, may reduce the size of flow needed to produce overbanking floods. This has important implications for Corps flood control structure design and placement, and represents an area where further research is urgently needed.

B. How would changes in sediment yield affect the rate of reservoir sedimentation and associated loss of storage capacity?

Under all three scenarios, the rate of sediment accumulation behind Cochiti Dam is expected to decline, resulting in a finding of no adverse effect on the lifetime of the project, and possibly leading to an increase in its potential lifetime. This finding is in line with other studies of reservoir sedimentation in the West that have concluded limited effects on reservoir lifetime from changes in reservoir sedimentation in the Southwest (Graf et al., 2010).

C. How might these latter effects interact with hydrologic impacts to ultimately affect water delivery reliability?

Because the Cochiti Dam and Lake project is a pass-through, flood control project, climate change is unlikely to affect dam operations. The reductions in stream flow projected by the climate scenarios may:

- May reduce total water available for irrigation and municipal drinking water, setting in motion conflicts over water rights and water rights acquisition.
- May affect ground water recharge, reducing ground water contributions to the river in ground water contributing reaches. This effect may be exacerbated by increased ground water pumping as users attempt to meet needs no longer met by surface water rights.
- Reduce the water available overall for conservation and recreational purposes.
- Reduce peak flows, resulting in reductions in the size and frequency of overbanking flows, to the detriment of endangered species, their critical habitat, and constructed restoration features within the riparian zone. Increased river drying during summer and fall months will also be deleterious to species and habitats.
- Increase the concentration of pollutants in the water because the ability of the river to dilute the pollutant sources may decrease with decreases in flow.
- May require a re-thinking of the concept of “stationarity”, that historic flows provide a reference point for allocating water rights and uses in legal, environmental, and other water rights settings.

Although many of these impacts are outside the Corps’ authority, additional effort is needed to identify areas where Corps action could make a difference to the Rio Grande and its many dependent communities.

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