Rio Grande, Sandia Pueblo to Isleta Pueblo, CO, NM, TX Ecosystem Restoration Feasibility Study and Environmental Assessment

Appendix B

Climate and Climate Change

U. S. Army Corps of Engineers
Albuquerque District

US Army Corps
of Engineers ®
Albuquerque District

Appendix B – Climate and Climate Change, Sandia to Isleta, Middle Rio Grande Basin, New Mexico

Ariane Pinson, USACE Albuquerque District

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1.1 Guidance

Analysis of climate change impacts to all USACE undertakings is governed by the following policy and guidance:

- USACE Climate Preparedness and Resilience Policy Statement (June 2014).
- Engineering and Construction Bulletin (ECB) 2016-25, Guidance for Incorporating Climate Change Impacts to Inland Hydrology in Civil Works Studies, Designs, and Projects.
- Engineering Technical Letter (ETL) 1100-2-3, Guidance for Detection of Nonstationarities in Annual Maximum Discharges.

1.2 Current Climate in the Middle Rio Grande Basin, New Mexico

The NOAA National Weather Service Cooperative Observer (COOP) station with a relatively complete record is located at Albuquerque International Airport (Station 290234), approximately in the middle of the study area. The period of record for this station is 1897 through present.

The climate at Albuquerque is arid continental with large daily and seasonal temperature differences (Figure 1). Summers tend to be hot and dry; winters tend towards cool and humid. Peak precipitation occurs during the late summer/early fall during the peak of the North American Monsoon (monsoon), with a secondary peak in winter. Spring and fall tends towards warm and dry. At Albuquerque, precipitation averages 9.45” per year. In most months, precipitation is 0.75 in or less, but is higher during the monsoon season: July receives an average of 1.5 in, August 1.58 in, September 1.08 in, and October 1.02 in. Precipitation may fall as snow from October through April, but such snow rarely persists on the ground for more than one day in the study area.

Table 1 Monthly climate normal values for Albuquerque International Airport (1981-2010).

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Mean Max. Temperature (F)	46.8	52.5	60.5	69	78.8	88.3	90.1	87.2	80.7	69	55.8	46.1	68.8
Mean Temperature (F)	36.4	41.4	48.1	56	65.6	74.9	78.3	76.2	69.3	57.5	44.9	36.3	57.2
Mean Min. Temperature (F)	26.1	30.3	35.7	43	52.5	61.6	66.4	65.1	57.9	46.1	34.1	26.5	45.5
Mean Precipitation (in.)	0.38	0.48	0.57	0.61	0.5	0.66	1.5	1.58	1.08	1.02	0.57	0.5	9.45
Heating Degree Days (F)	885	661	524	277	71	4	0	0	26	240	601	890	4180
Cooling Degree Days (F)	0	0	0	7	91	302	411	346	155	10	0	0	1322

Source: Western Regional Climate Center (http://www.wrcc.dri.edu/cgi-bin/cliNORMNCDC2010.pl?nm0234)

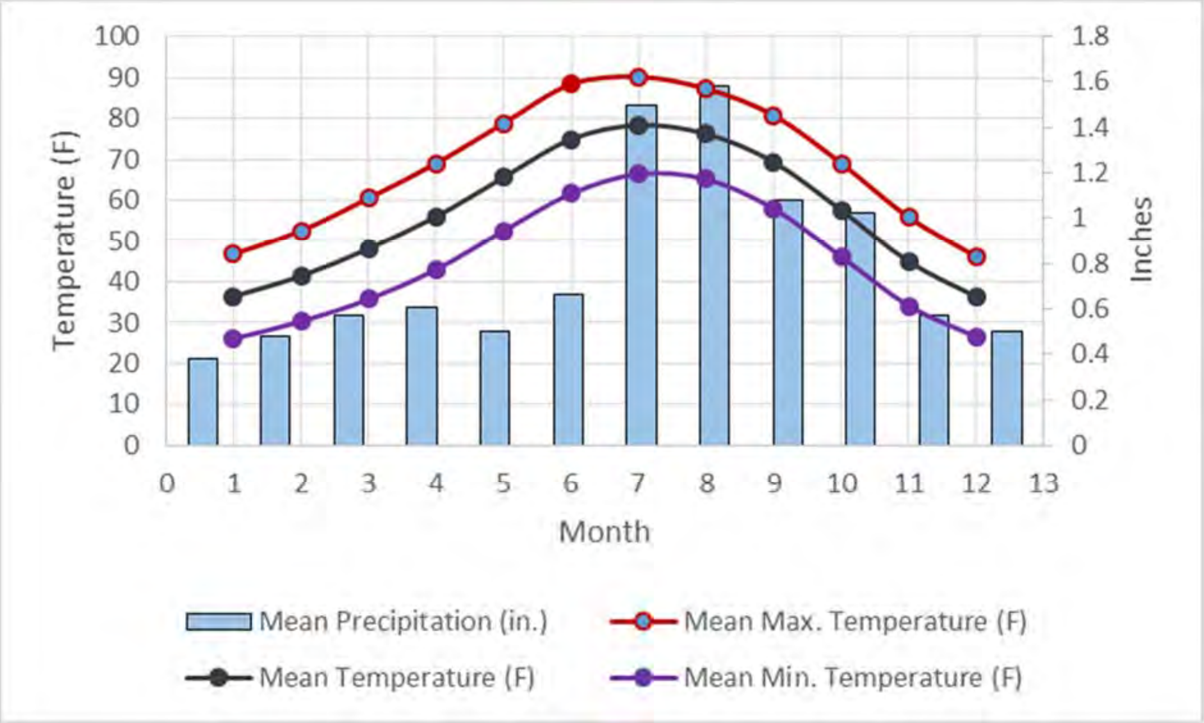


Figure 1 Albuquerque temperature and precipitation, based on monthly climate normal (1981-2010).

Source: Based on data from Table 1.

1.2.1 Effects of Topography on Climate

Topography significantly influences local climate in winter and summer.

- In winter, the dominant pattern is for storms to move into the region from the west or northwest; much of the precipitation falls over the western and central portions of the Jemez Mountains, and the amount declines rapidly moving east of the Sierra de los Valles and down slope to the Rio Grande.

- During the monsoon season, thunderstorm development is encouraged by daytime surface heating over the mountains bordering this basin. Small elevation changes can lead to larger differences in precipitation and other climate variables over short distances (Bowen 1996).

- The Sandia and Manzano Mountains prevent moisture from the Plains from entering the region. The region effectively lies in the rainshadow of the Sandia and Manzano Mountains with respect to moisture transported northwestward from the Gulf of Mexico.

Table 2 Annual maximum series precipitation frequency estimates with 90% confidence intervals (in inches).

Duration	**Annual exceedance probability (1/years)**						
	0.50	**0.10**	**0.4**	**0.2**	**0.1**	**0.05**	**0.02**
	1/2	**1/10**	**1/25**	**1/50**	**1/100**	**1/200**	**1/500**
5-min	**0.205**	**0.357**	**0.439**	**0.5**	**0.567**	**0.635**	**0.725**
	(0.181-0.233)	(0.313-0.403)	(0.383-0.496)	(0.434-0.565)	(0.489-0.640)	(0.542-0.715)	(0.613-0.820)
10-min	**0.312**	**0.543**	**0.669**	**0.762**	**0.863**	**0.966**	**1.1**
	(0.275-0.354)	(0.476-0.613)	(0.584-0.754)	(0.661-0.860)	(0.743-0.975)	(0.825-1.09)	(0.933-1.25)
15-min	**0.387**	**0.674**	**0.829**	**0.945**	**1.07**	**1.2**	**1.37**
	(0.342-0.439)	(0.590-0.760)	(0.723-0.935)	(0.819-1.07)	(0.921-1.21)	(1.02-1.35)	(1.16-1.55)
30-min	**0.52**	**0.907**	**1.12**	**1.27**	**1.44**	**1.61**	**1.84**
	(0.460-0.592)	(0.795-1.02)	(0.974-1.26)	(1.10-1.44)	(1.24-1.63)	(1.38-1.82)	(1.56-2.08)
60-min	**0.644**	**1.12**	**1.38**	**1.57**	**1.78**	**2**	**2.28**
	(0.569-0.732)	(0.984-1.27)	(1.21-1.56)	(1.37-1.78)	(1.54-2.01)	(1.70-2.25)	(1.93-2.58)
2-hr	**0.726**	**1.25**	**1.54**	**1.77**	**2.01**	**2.25**	**2.6**
	(0.642-0.830)	(1.10-1.42)	(1.34-1.74)	(1.53-1.99)	(1.73-2.27)	(1.92-2.54)	(2.19-2.92)
3-hr	**0.761**	**1.29**	**1.59**	**1.81**	**2.06**	**2.31**	**2.66**
	(0.677-0.867)	(1.14-1.46)	(1.39-1.79)	(1.58-2.04)	(1.78-2.32)	(1.98-2.61)	(2.25-3.00)
6-hr	**0.876**	**1.45**	**1.75**	**1.98**	**2.23**	**2.47**	**2.81**
	(0.782-0.994)	(1.29-1.63)	(1.54-1.97)	(1.73-2.22)	(1.94-2.50)	(2.15-2.78)	(2.42-3.17)
12-hr	**0.973**	**1.57**	**1.87**	**2.1**	**2.35**	**2.59**	**2.91**
	(0.878-1.09)	(1.40-1.74)	(1.67-2.07)	(1.86-2.33)	(2.07-2.60)	(2.27-2.87)	(2.52-3.24)
24-hr	**1.1**	**1.75**	**2.08**	**2.34**	**2.6**	**2.86**	**3.21**
	(1.00-1.22)	(1.58-1.92)	(1.88-2.30)	(2.10-2.57)	(2.34-2.86)	(2.56-3.14)	(2.85-3.53)
2-day	**1.18**	**1.85**	**2.2**	**2.46**	**2.74**	**3.01**	**3.37**
	(1.08-1.30)	(1.69-2.03)	(2.00-2.41)	(2.23-2.69)	(2.48-2.99)	(2.70-3.29)	(3.01-3.68)
3-day	**1.27**	**1.97**	**2.34**	**2.62**	**2.9**	**3.18**	**3.55**
	(1.17-1.38)	(1.82-2.15)	(2.15-2.54)	(2.39-2.84)	(2.65-3.15)	(2.89-3.45)	(3.21-3.86)
4-day	**1.35**	**2.1**	**2.48**	**2.77**	**3.07**	**3.35**	**3.73**
	(1.26-1.46)	(1.95-2.26)	(2.30-2.67)	(2.56-2.98)	(2.82-3.30)	(3.08-3.62)	(3.41-4.03)
7-day	**1.55**	**2.38**	**2.8**	**3.1**	**3.41**	**3.71**	**4.09**
	(1.45-1.67)	(2.22-2.57)	(2.60-3.00)	(2.88-3.33)	(3.16-3.67)	(3.42-3.98)	(3.76-4.40)
10-day	**1.72**	**2.65**	**3.12**	**3.47**	**3.83**	**4.17**	**4.61**
	(1.60-1.84)	(2.47-2.83)	(2.90-3.33)	(3.21-3.69)	(3.54-4.07)	(3.84-4.45)	(4.23-4.93)
20-day	**2.18**	**3.31**	**3.84**	**4.22**	**4.6**	**4.95**	**5.39**
	(2.03-2.34)	(3.09-3.54)	(3.58-4.11)	(3.92-4.51)	(4.26-4.91)	(4.58-5.27)	(4.97-5.74)
30-day	**2.61**	**3.9**	**4.48**	**4.89**	**5.3**	**5.67**	**6.11**
	(2.43-2.79)	(3.64-4.16)	(4.18-4.77)	(4.55-5.21)	(4.93-5.64)	(5.26-6.03)	(5.65-6.51)

Duration	**Annual exceedance probability (1/years)**						
	0.50	**0.10**	**0.4**	**0.2**	**0.1**	**0.05**	**0.02**
	1/2	**1/10**	**1/25**	**1/50**	**1/100**	**1/200**	**1/500**
45-day	**3.16**	**4.63**	**5.26**	**5.69**	**6.1**	**6.44**	**6.85**
	(2.97-3.37)	(4.34-4.92)	(4.94-5.59)	(5.34-6.04)	(5.71-6.47)	(6.03-6.84)	(6.40-7.27)
60-day	**3.65**	**5.35**	**6.07**	**6.56**	**7.03**	**7.43**	**7.9**
	(3.42-3.90)	(5.02-5.70)	(5.70-6.47)	(6.15-6.98)	(6.58-7.49)	(6.96-7.92)	(7.39-8.43)

1.3 Climate Drivers in Middle Rio Grande Basin, New Mexico

The climate in the Middle Rio Grande Basin in New Mexico is determined in large part by its location at the boundary between the arid subtropics and the humid mid-latitudes in the interior of the United States (continental, non-coastal location), and its position along the southern margin of the Rocky Mountains.

The Middle Rio Grande Basin, New Mexico is located at 34 to 37°N, right at the boundary of the subtropics and the midlatitudes. It experiences a midlatitude climate in the winter months, characterized by large area storm systems moving along the path of the jet stream. Because the region is in the interior of the North American continent, these storms lose much of their moisture as precipitation over the Sierra Nevada and Rocky Mountains between their origin over the northwest Pacific Ocean and their arrival in New Mexico. Consequently, these storms often bring less precipitation to New Mexico than to areas to the north or west. These storms are typically "rejuvenated" as they encounter sources of moisture east of the Rockies, producing greater precipitation over the plains of eastern New Mexico than in the central part of the state. High snow packs can result in significant spring runoff flows along the Rio Grande mainstem in the study area.

Winter precipitation is highly variable from year-to-year, depending on the sea surface temperatures in the northeastern tropical Pacific. During El Niño years, the eastern tropical Pacific Ocean surface is warm, producing moister air over the ocean that feeds into winter storm systems, producing wet winters and high spring runoff flows in the Southwestern U.S. including New Mexico. Dry winters occur when the eastern tropical Pacific Ocean surface is cool, which reduces evaporation and results in dry air over the ocean. Less moisture is available for storm formation and winter precipitation and spring runoff flows in the Southwestern U.S. are reduced (Sheppard et al. 2002).

With the onset of spring/summer, the storm track moves northward, and the study area is dominated by dry air masses. Pressure differences between midlatitude cyclones (low pressure) and the expanding high pressure zone of descending dry air contributes to the dry, windy conditions typical of April, May and June in the region. In summer, high pressure to the east and low pressure to the west frequently funnels low- and mid-level moisture north from the eastern Pacific and Gulf of Mexico. Over New Mexico, daily heating or the passage of fronts cause this moisture-laden air to rise and produce thunderstorms over the region. These intense, short-lived summer storms are typically limited in area, producing rain in different places on different days. Precipitation intensity of these storms may be quite high, contributing to localized flooding, especially along streams tributary to the Rio Grande. This pattern of summer precipitation is called the "North American Monsoon" (NAM). The Middle Rio Grande Basin of New Mexico is located in the northern part of the NAM area, outside the core monsoon region, and therefore does not receive ample NAM precipitation every year. The NAM may last from mid-July through the end of September. Particularly in the latter half of the NAM, remnant hurricanes may become entrained in monsoonal flow, resulting in a few days of widespread heavy rain across the region that can contribute to widespread flooding (e.g., USACE2014).

Recent overviews of climate change in the Southwestern United States (SWUS) have been provided in (Garfin et al. 2013), (Melillo et al. 2014), and NOAA (2013b). Important syntheses of climate change impacts to New Mexico and Colorado include New Mexico Office of the State Engineer (2006) and Ray et al. (2008).

1.3.1 Recent Temperature Trends

1.3.1.1 Global, National and Western U.S. Temperature Trends

Temperatures in the West have shown a relatively steady rise beginning in the early 20th Century: the consensus view is that recent increases in temperature in the Western U.S. exceed observations in the historic record beginning in the late 19th Century (USGCRP 2009). Across the Mountain 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. Particularly troubling for the region's snowpack and spring runoff have been increases in winter (January, February, March, or JFM) temperatures. The observational record of 1950-1999 shows an 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).

In the Southwestern U.S. as a whole, encompassing New Mexico, Colorado, Arizona, Utah, Nevada, and California, the decade 2001-2010 was the warmest of all decades from 1901-2010, with temperatures increasing approximately 0.9°C±0.3°C (1.6°F) over the period 1901-2010 (Hoerling et al. 2013).

Rates of warming in high elevation areas may be considerably greater than across the Southwest as a whole. In a recent analysis of National Weather Service and SNOTEL site data in the San Juan Mountains, Rangwala and Miller (2010) detect a rate of warming of 1.8°F (1°C) per decade from 1990 to 2005. Lower elevation sites experienced greatest warming during the winter months, warming in winter at an average rate of 2.7°F (1.5°C) per decade. Higher elevation sites experienced their greatest warming during the summer months, with temperatures increasing at a rate of 2.7°F (1.5°C) per decade during this season. The differences in the season of greatest warming are likely due to the reduction in 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.

1.3.2 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 (e.g., Pacific Decadal Oscillation (PDO) vs. ENSO). Because of the high inter-annual, decadal and longer-term variability in precipitation, detecting changes in precipitation has been more challenging than detecting changes in temperature.

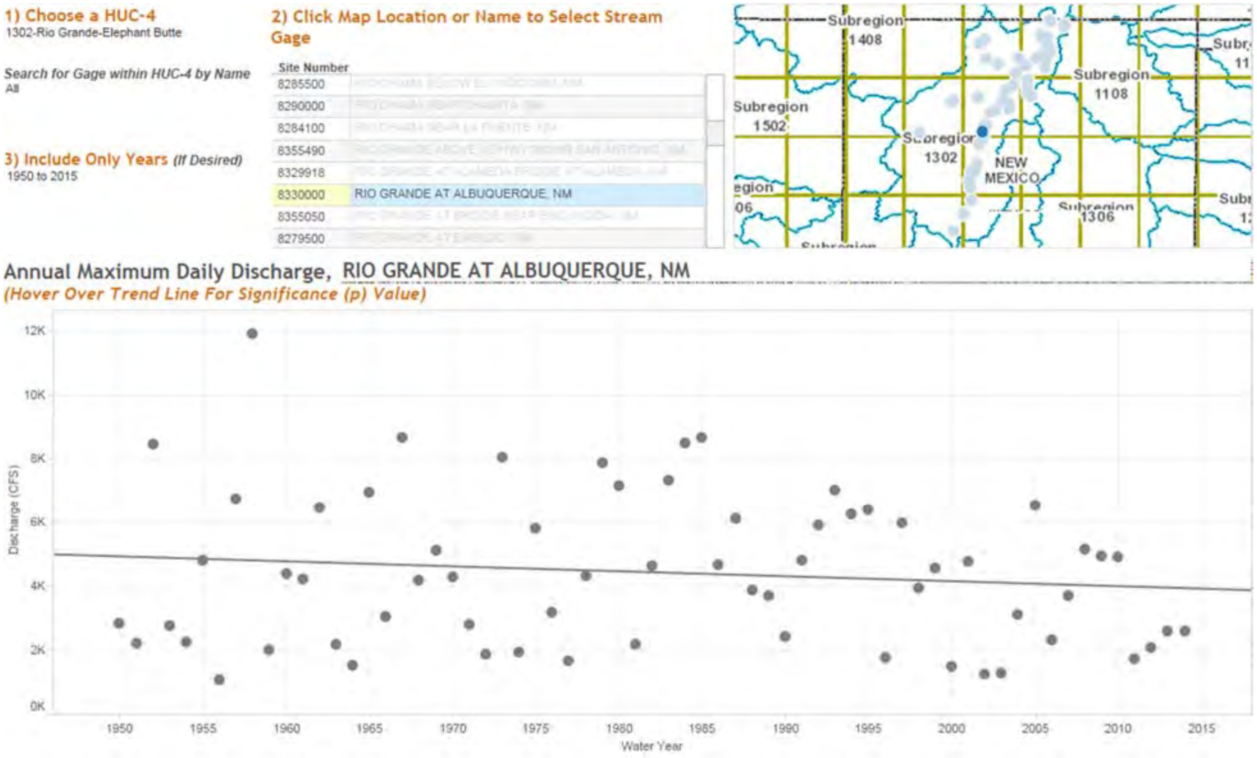
The period of greatest aridity in New Mexico was not the Dust Bowl years of the 1930s but the period 1950-1956 when average annual precipitation remained below the long term average

(Swetnam and Betancourt 1998, Sheppard et al. 2002, Gutzler 2003). Average precipitation years from 1965 through 1975 were followed by the period 1976 through 1997/1998 when warm, wet winters and erratic summer precipitation were the norm (Swetnam and Betancourt 1998, Sheppard et al. 2002, Gutzler 2003). These conditions gave 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, Woodhouse et al. 2010). Since 2001, large portions of the Southwest have experienced drought, with particularly widespread and severe drying in 2002, 2003, 2007, 2009, 2011 and 2012. During these extremes, precipitation across the region averaged 22-25% below the average for the 20th Century (MacDonald 2010), leading to a significant reduction in soil moisture and stream flow. The decade 2001-2010 has had the second-largest area affected by drought (after the period 1951-1960) and the most severe average drought conditions of any decade since 1901 (Hoerling et al. 2013). This drought was ongoing through March 2013 (National Drought Mitigation Center 2013) and is anticipated to persist through winter 2014 (NOAA 2013a).

Despite or because of this variation, no trends have been observed in annual water year precipitation from 1895/96 through 2010/11 for the six-state Southwest (NOAA 2013b). Seasonal time series show no trends for winter, spring and summer, and fall shows a slight upward, but not statistically-significant, trend. In addition, there has been no overall trend in the frequency of extreme precipitation events across the Southwest (NOAA 2011). Throughout the 20th century and into the early 21st century, the number of 1-day-duration and 5-year return interval precipitation events fluctuated, but remained within the range of early 20th century values.

1.3.3 Rio Grande Hydrologic Trends

To better understand current trends in the Middle Rio Grande, the USACE ECB 2014-10 Inland Hydrology tool (https://rsgis-tableau.han.ds.usace.army.mil/t/CCAdaptation/views/ECB2014-10/AboutthisTool?:embed=y&:display_count=no) was accessed 15 March 2016. For the USGS stream gage Rio Grande at Albuquerque (8330000), the tool reported a decreasing trend in annual maximum monthly flows. However this trend is like influenced by flood regulations that cap flood flows to approximately 6,000 cfs in this reach of the Rio Grande (Figure 3).


1) Choose a HUC-4
1302-Rio Grande-Elephant Butte

Search for Gage within HUC-4 by Name
All

3) Include Only Years (If Desired)
1950 to 2015

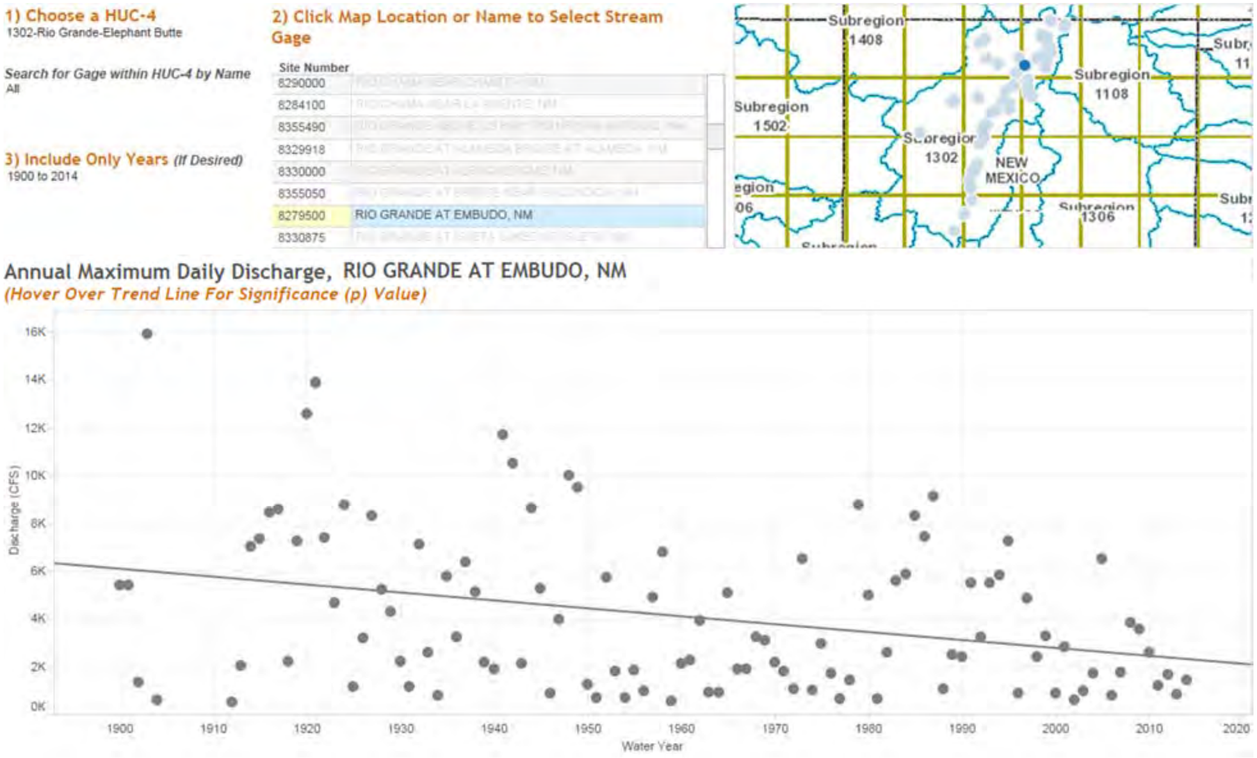
2) Click Map Location or Name to Select Stream Gage

Site Number
8285500
8290000
8284100
8355490
8329918
8330000 RIO GRANDE AT ALBUQUERQUE, NM
8355050
8279500

Annual Maximum Daily Discharge, RIO GRANDE AT ALBUQUERQUE, NM
(Hover Over Trend Line For Significance (p) Value)

Figure 2 Trends in annual maximum daily discharge at the Rio Grande at Albuquerque, NM stream gage.

A similar downward trend is observed upstream at the Rio Grande at Embudo, NM (8729500) gage, which upstream of flood regulation on the Rio Grande mainstem (Figure 4). This suggests that at least a portion of the downward trend at both gages may be due to long-term changes in runoff within the basin.



1) Choose a HUC-4
1302-Rio Grande-Elephant Butte

Search for Gage within HUC-4 by Name
All

3) Include Only Years (If Desired)
1900 to 2014

2) Click Map Location or Name to Select Stream Gage

Site Number	
8290000	[illegible]
8284100	[illegible]
8355490	[illegible]
8329918	[illegible]
8330000	[illegible]
8355050	[illegible]
8279500	RIO GRANDE AT EMBUDO, NM
8330875	[illegible]

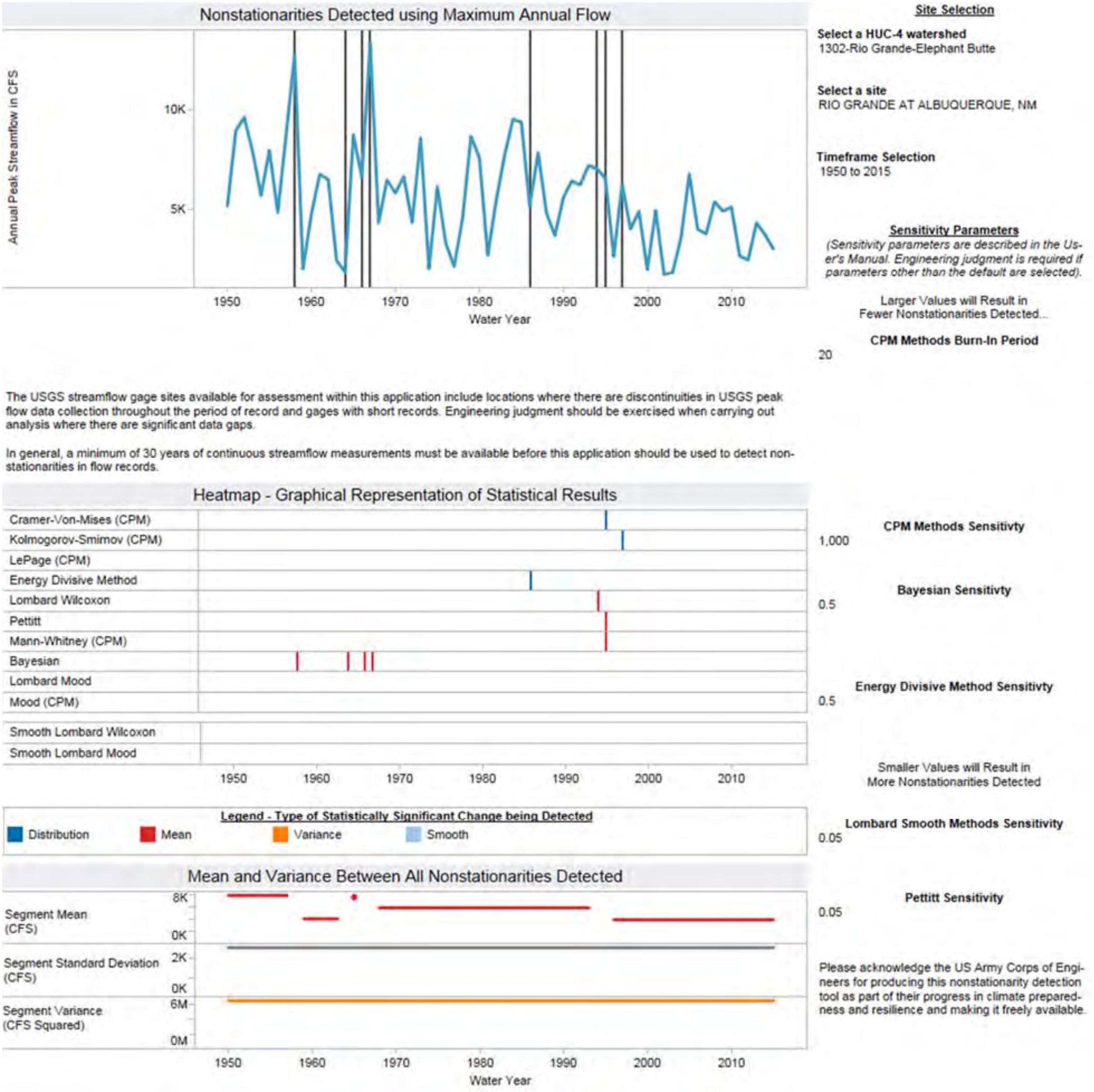
Annual Maximum Daily Discharge, RIO GRANDE AT EMBUDO, NM
(Hover Over Trend Line For Significance (p) Value)

Figure 3 Trends in annual maximum daily discharge at the Rio Grande at Embudo, NM stream gage.

The USACE Nonstationarity Detection Tool (https://maps.crrel.usace.army.mil/apex/f?p=257:1:, accessed 15 March 2016) identifies changes stream flows at a gage that may be due to a range of factors, including changes in technology, stream regulation, the construction of dams, cyclical climate changes, and long term changes in climate due to global warming. The tool is able to detect abrupt and smooth changes in the mean and variance of maximum annual flows, as well as the presence and strength of long-term trends. The year at which a change is detected is called the “change point”. Statistical detection of nonstationarities is influenced by sample size, sample variance, the magnitude of the change, and the location of the change point within the hydrologic time series. Consequently, for the purposes of interpreting the output of this tool, a nonstationarity is identified as a five-year window around a change point or series adjacent change points where multiple different statistical methods identify a nonstationarity.

For the Rio Grande at Albuquerque gage, the only nonstationarity in the annual maximum flow record for 1950-2015 occurs in the mid-1990s (Figure 5). It is represented by a reduction in mean peak flow discharge, but not a detectable change in the variance. This change is not directly related to any changes at this USGS gage.

In comparison, the Rio Grande at Embudo gage for the period 1950-2015 has two clear nonstationarities centered on 1978-80 and again around 1995. These changes are not directly correlated with changes at this USGS gage. These changes in the mean appear to coincide with shifts in the Pacific Decadal Oscillation, from cool to warm circa 1976 and from warm to cool circa 1997. No statistically significant trends in flow were detected for this period.



Site Selection

Select a HUC-4 watershed
1302-Rio Grande-Elephant Butte

Select a site
RIO GRANDE AT ALBUQUERQUE, NM

Timeframe Selection
1950 to 2015

Sensitivity Parameters
(Sensitivity parameters are described in the User's Manual. Engineering judgment is required if parameters other than the default are selected).

Larger Values will Result in Fewer Nonstationarities Detected...

CPM Methods Burn-In Period
20

CPM Methods Sensitivty
1,000

Bayesian Sensitivty
0.5

Energy Divisive Method Sensitivty
0.5

Smaller Values will Result in More Nonstationarities Detected

Lombard Smooth Methods Sensitivity
0.05

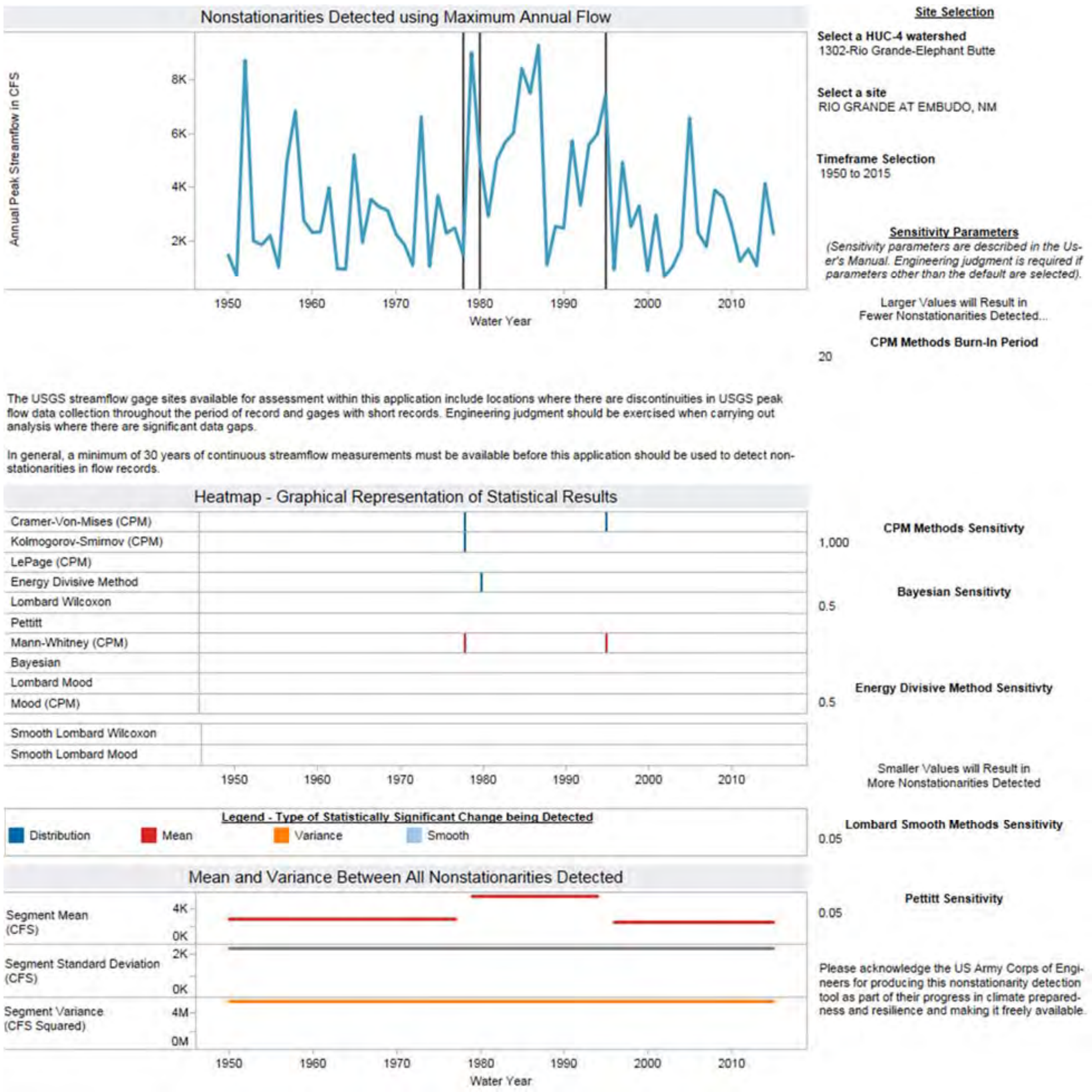
Pettitt Sensitivity
0.05

The USGS streamflow gage sites available for assessment within this application include locations where there are discontinuities in USGS peak flow data collection throughout the period of record and gages with short records. Engineering judgment should be exercised when carrying out analysis where there are significant data gaps.

In general, a minimum of 30 years of continuous streamflow measurements must be available before this application should be used to detect nonstationarities in flow records.

Please acknowledge the US Army Corps of Engineers for producing this nonstationarity detection tool as part of their progress in climate preparedness and resilience and making it freely available.

Figure 4 Nonstationarities in annual maximum flow, Rio Grande at Albuquerque gage.



Site Selection

Select a HUC-4 watershed
1302-Rio Grande-Elephant Butte

Select a site
RIO GRANDE AT EMBUDO, NM

Timeframe Selection
1950 to 2015

Sensitivity Parameters
(Sensitivity parameters are described in the User's Manual. Engineering judgment is required if parameters other than the default are selected).

Larger Values will Result in Fewer Nonstationarities Detected...

CPM Methods Burn-In Period
20

CPM Methods Sensitivty
1,000

Bayesian Sensitivty
0.5

Energy Divisive Method Sensitivty
0.5

Smaller Values will Result in More Nonstationarities Detected

Lombard Smooth Methods Sensitivity
0.05

Pettitt Sensitivity
0.05

The USGS streamflow gage sites available for assessment within this application include locations where there are discontinuities in USGS peak flow data collection throughout the period of record and gages with short records. Engineering judgment should be exercised when carrying out analysis where there are significant data gaps.

In general, a minimum of 30 years of continuous streamflow measurements must be available before this application should be used to detect nonstationarities in flow records.

Please acknowledge the US Army Corps of Engineers for producing this nonstationarity detection tool as part of their progress in climate preparedness and resilience and making it freely available.

Figure 5 Nonstationarities in annaual maximum flow, Rio Grande at Embudo, New Mexico gage.

1.4 Projected Climate Futures

1.4.1 Projected Changes in Temperature, Precipitation

Climate change in the Upper Rio Grande basin was modeled by Reclamation (2011b, a) using the Hybrid Delta-ensemble approach (Brekke et al. 2010) employing output from 16 models from the CMIP3 multi-model dataset. 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 (112 model realizations total). The scenarios chosen are the A2 (high emissions), A1B (business-as-usual emissions) and B1 (low emissions) scenarios. The baseline period is the 1990s. The spatial resolution of the model is 1/8° (about 12 x 12 km).

The basin-average mean-annual temperature is projected to increase by approximately 1.8-3.3°C (5-6°F) during the 21st Century (Reclamation 2011a) relative to the 1990s. Temperature changes are anticipated to be uniform over the basin and to increase steadily through time.

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 period 2010-2039 (Figure 3), 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%.

In the period 2040-2069 (Figure 4), 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).

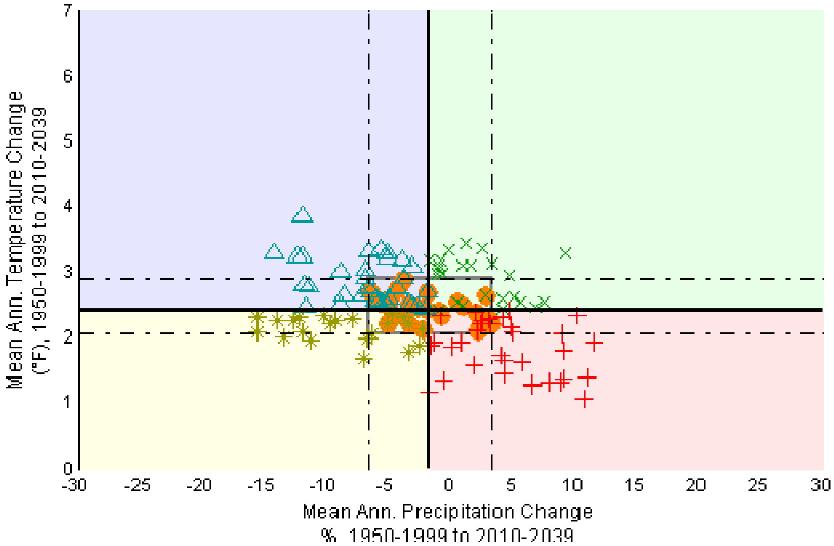


Figure 6: Modeled changes in temperature and precipitation in the period 2010-2039.

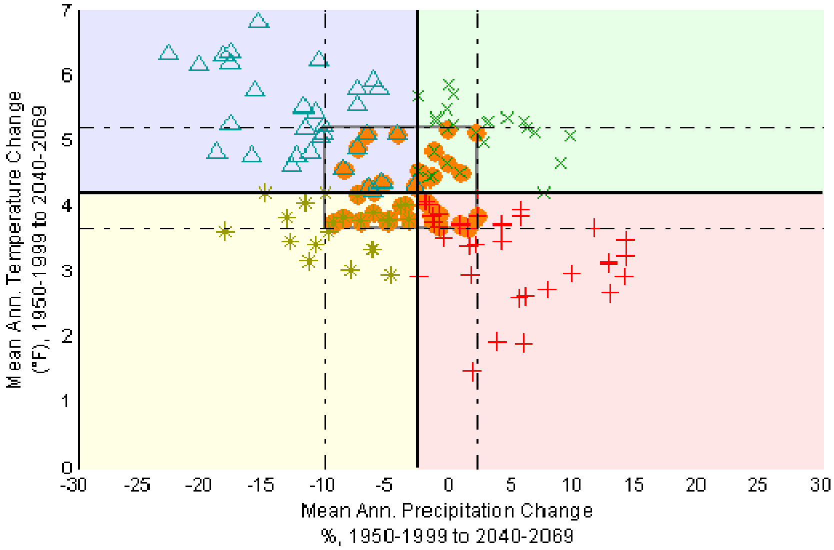


Figure 7: Modeled changes in temperature and precipitation in the period 2040-2069.

1.4.2 Summary of Model Projections for Temperature and Precipitation

Models project substantial warming over the 21st Century of 5-7°F by 2100 as compared to late 20th averages. Modeling using recent RCP scenarios suggests warming may reach as much as 8.5 to 10°F by 2100 under plausible high emissions (large radiative forcing) scenarios, which is slightly higher than earlier estimates. Even with no net changes in precipitation, such warming will exert profound effects on regional hydrology by altering snowpack, spring runoff and evaporation rates.

1.5 Hydrologic Impacts

1.5.1 Projected Hydrologic Changes

Hydrologic changes have been studied primarily at the regional and watershed levels, with most efforts focused on the Colorado and Upper Rio Grande Basins rather than tributary flows. However, there is no reason to expect that the Jemez Mountains will respond differently than the Southern Rocky Mountains as a whole, therefore that tributaries in the watershed should respond substantially differently from the Jemez River, the major drainage in the Jemez Mountains.

1.5.1.1 Projected Changes for the Southwestern U.S.

Reductions in snowpack, declines in snow water equivalence, and advances in snowmelt are all projected to contribute to substantial declines in flows in the Southwest's rivers (Cayan et al. 2013). 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). However, due to earlier spring snowmelt and higher evaporation rates, it is projected that the total basin storage in regional reservoirs could decline by as much as 32% to 40% (Christensen et al. 2004, Leung et al. 2004). Since the headwaters of the Rio Grande are located farther south than those of the Colorado, it is probable that projected declines in flow in the Rio Grande will equal or exceed those for the Colorado River (Cayan et al. 2013).

Reduced total runoff is projected 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 with reduced canopy covers exposing more ground to erosion via rainsplash and other processes. During high-precipitation events, the exposed surfaces may funnel greater share of runoff to streams, contributing higher peak flows than at present.

1.5.1.2 Projected Changes in the Upper Rio Grande

The impacts of climate change on the Rio Grande streamflows are anticipated to be broadly similar. In addition, the freezing altitude is projected to rise and snowpack volume to decrease as temperatures rise. Changes in temperature and precipitation patterns are expected to drive reductions in snowpack (Elias et al. 2015). Higher temperatures will delay the date at which precipitation falls as snow in the fall and cause a 4-6 week earlier shift in the date at which precipitation reverts to rain in the spring. The altitude at which a winter snowpack will develop is anticipated to rise. In the 2005, the RMCO (2005) noted that 10 of the previous 16 years in the Rio Grande Basin had snowpack below the long-term average, a trend that has continued since.

The snow water content of the snowpack has also declined westwide (Mote et al. 2005), and this trend is anticipated to continue. Compared to the water content of the April snowpack for the period 1950-1999, 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 high emissions scenarios (Christensen and Lettenmaier 2007). Similar reductions in snow water equivalence are predicted for all watersheds in the West.

Regional climate models driven by high emissions scenarios indicate that the snowpack may be non-existent south of 36°N (approximately the latitude of the City of Española, New Mexico) by 2100 (Gutzler et al. 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.

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). Whether storm frequency declines as well is not clear. Larger magnitude summer storms may drive bigger magnitude flood events, while concentrating spring runoff earlier in the season may increase the magnitude of spring floods. However, lower overall snowpack volume and SWE, and earlier snowpack melting, are expected to drive down low summer flows (Gleick 2000). The net effect of these changes may be to drive down base flows, while increasing the magnitude of summer flood events. These changes cannot yet be reliably quantified.

1.5.1.3 Upper Rio Grande Impact Assessment

Currently, the most detailed assessment of climate change impacts to New Mexico above Elephant Butte Dam is provided by the Upper Rio Grande Impact Assessment (Reclamation et al. 2013). This study modeled projected flows in the Rio Grande above Elephant Butte Dam for the period 1950-2099 under SRES A2 (high emissions), A1B (moderate emissions) and B1 (low emissions) scenarios using 112 CMIP3 model realizations. The modeled climate outputs were passed to a Variable Infiltration Capacity (VIC) model to generate simulated overland flow that was routed down the Rio Grande and its tributaries using the URGSim model. Modeling assumed no changes to current dam operations, irrigation practices or other socio-economic practices in the future in order to assess the impact of climate change on current river flows.

The models project a decline in average Rio Grande stream flows of approximately one third (Figure 9), along with a reduction of at least one fourth in imported San Juan-Chama Project water. The model simulations consistently project decreasing snowpack, an earlier and smaller spring snowmelt runoff, and an increase in the frequency, intensity and duration of both droughts and floods (Reclamation et al. 2013).

Native inflows to the San Luis Valley in the Upper Rio Grande are anticipated to decline by approximately 33% by the end of the 21st Century compared to today (Reclamation et al. 2013). This would likely reduce consumptive use in the San Luis Valley by about 25%, and result in an approximately 50% decline in downstream water deliveries to New Mexico by the end of the 21st Century (Reclamation et al. 2013).

Simulated flows for the Rio Grande at Otowi show steep declines in peak spring runoff and early summer flows, but little shift in the timing of peak runoff (Reclamation et al. 2013). Annual average flows are projected to decrease 29% on average at Otowi gage (from about 1,400 cfs during the historic period (1950-1999) to about 1,000 cfs by the 2090s) (Reclamation et al. 2013).

At the Central Avenue gage in Albuquerque, flows are anticipated to decrease 36%, from an annual average of approximately 1,100 cfs during the historic period (1950-1999) to less than 700 cfs by the 2090s (Reclamation et al. 2013). May through August flows are likely to be reduced significantly, but there is likely to be little advance in spring runoff timing (Reclamation et al. 2013).

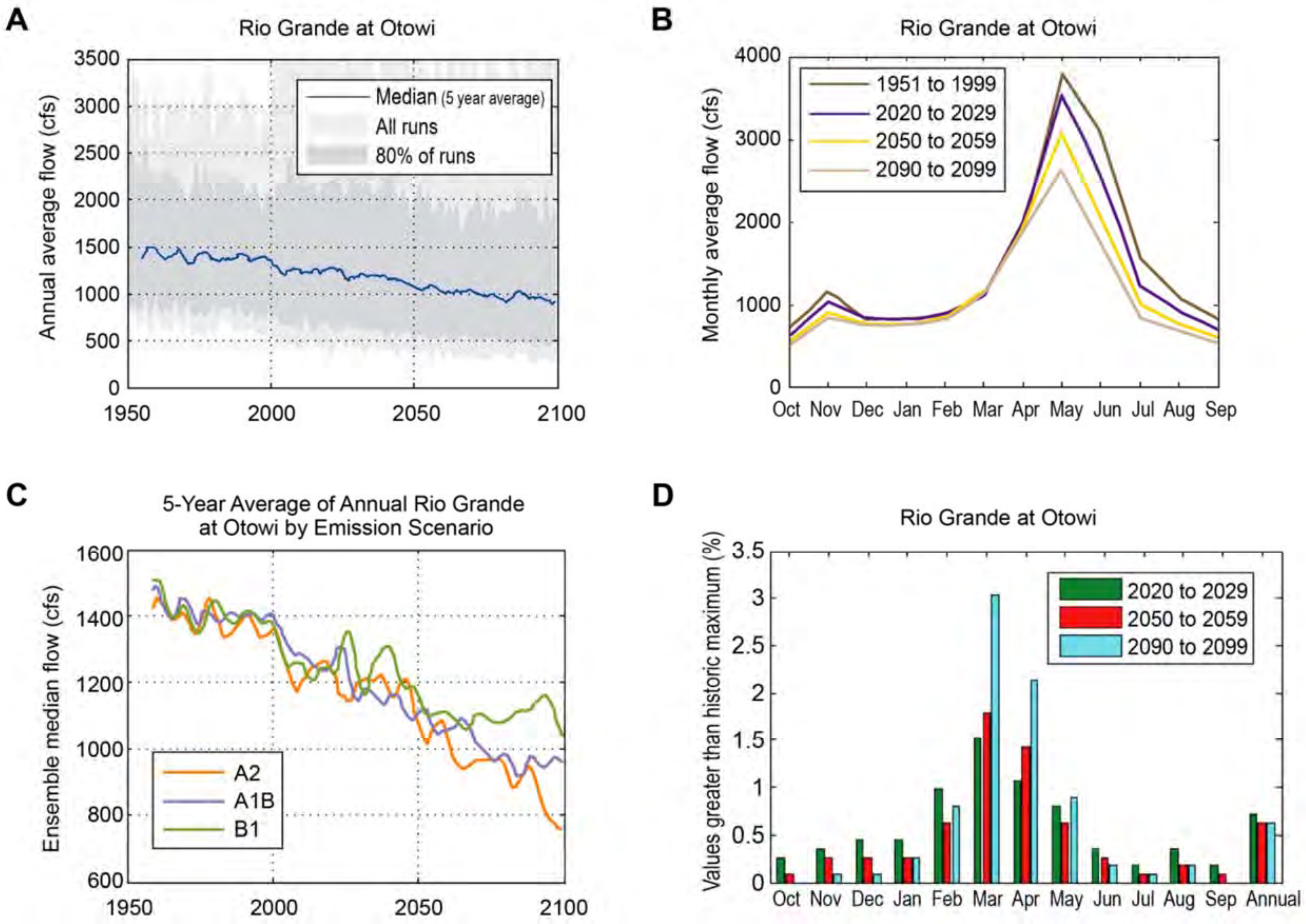


Figure 8 Projected Rio Grande flows at Otowi Gage (Reclamation et al. 2013: Fig. 31).

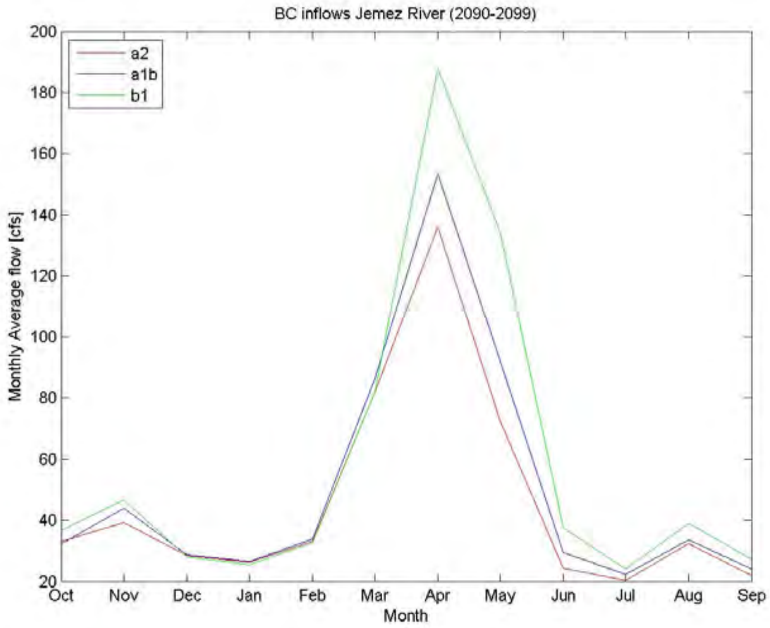


Figure 9 Jemez River monthly average flows in 2090-2099 under different projected emissions scenarios (unpublished data, Reclamation).

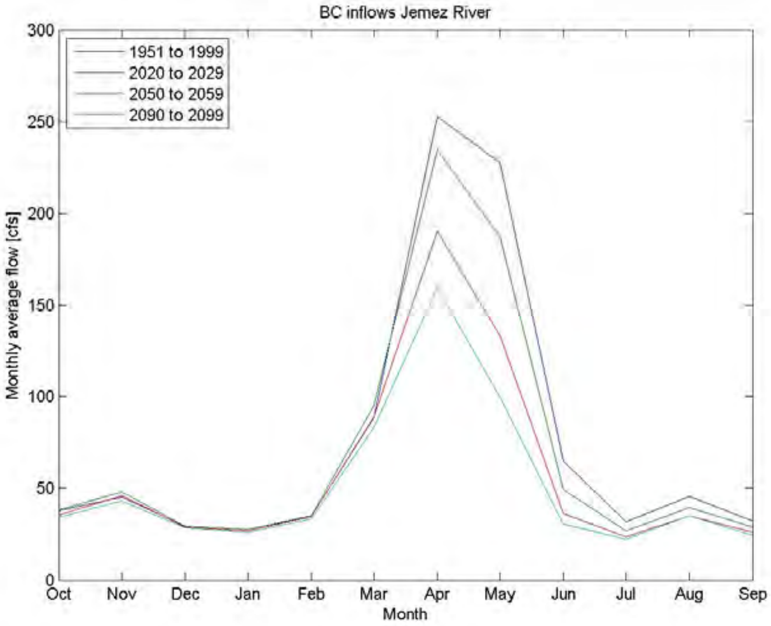


Figure 10 Jemez River monthly average flows, model averages (unpublished data, Reclamation).

Models also show that despite lower average flows, the probability of flows that exceed the historic maximum are likely to increase in frequency over the 21st Century reflecting changes in surface vegetation, hydrologic conditions, and the likelihood that precipitation will concentrate in larger precipitation events with longer dry gaps between these precipitation events that occurred historically (Reclamation et al. 2013). The likelihood of floods larger than historic maximum floods peaks in March and April at 3 and 2%, respectively (Reclamation et al. 2013).

The projected changes for the Jemez River are illustrative of how mountain tributary flows in northern New Mexico may change in the future. Models project declines in Jemez River flows show (Reclamation, unpublished data): for the period 2090-2099, average monthly flows under the SRES B1 scenarios, peak spring flows are likely to be less than 200cfs, declining to under 140 cfs under the SRES A2 (high emissions) scenario.

The evolution of average monthly Jemez River flows for different time periods is shown in Figure 11 (Reclamation, unpublished data). This graphic shows that, compared to historic period flows, future flows in the Jemez River are likely to decline over the 21st Century, with the strongest decline during the spring runoff period resulting from declines in Jemez Mountain snowpack due to warmer winter temperatures, higher rates of snowpack melting and sublimation, and increased evaporation rates.

1.5.1.4 Projected Hydrologic Trends in the Study Area

The ECB 2014-10 tool provides information on projected maximum annual flows based on data downscaled from 93 Coupled Model Intercomparison Programme 5 (CMIP-5) models. Figure 12 shows the range of model projections for annual maximum flow for the period 2000-2099. Collectively, the models show a small, decreasing trend for the Middle Rio Grande (HUC 1302, Rio Grande above Elephant Butte). Looking at the average of the annual maximum monthly flows across all the models, there is a downward trend that is statistically significant (Figure 13). Taken together, these estimates support prior regional and larger-area studies that suggest an overall decrease in spring runoff flooding in the region under a warmer future climate, regardless of whether precipitation increases or decreases.

Finally, the USACE also has developed a tool that examines projected vulnerability of specific USACE business lines to climate change. Using this Watershed Vulnerability Assessment tool (demo version, https://maps.crrel.usace.army.mil/apex/f?p=170:2:13442520479042, accessed 15 March 2016), the future vulnerability of the Middle Rio Grande (HUC 1302) was assessed with respect to flood risk management (Figure 14). The tool shows that this region does not rank as among the most highly vulnerable regions for future flood risk.

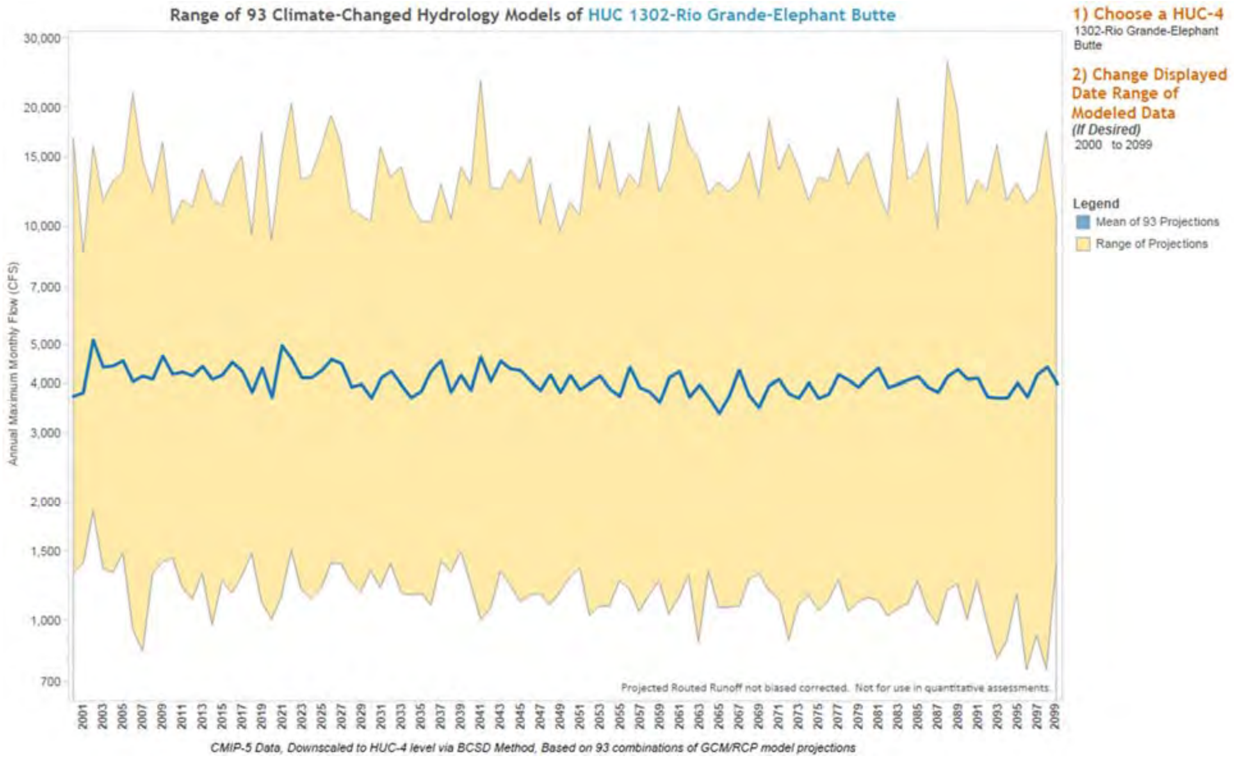


Figure 11 Projected annual maximum monthly stream flow for the Middle Rio Grande (HUC 1302).

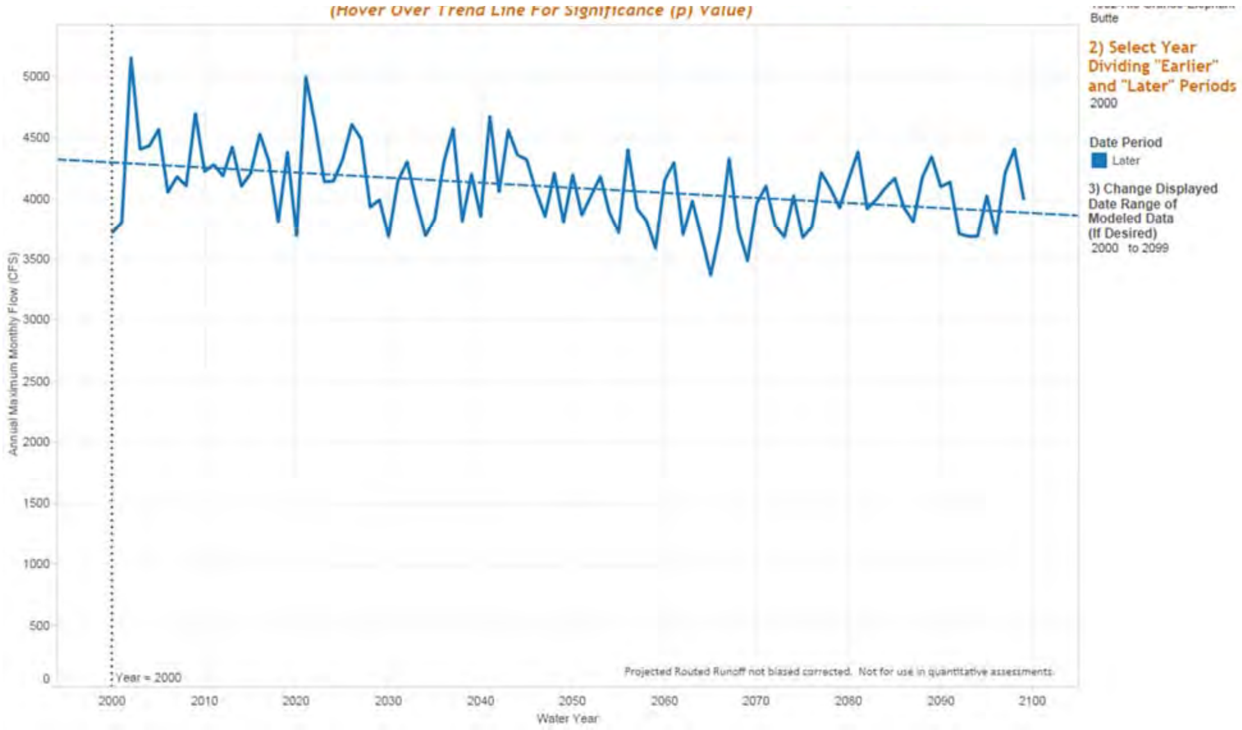
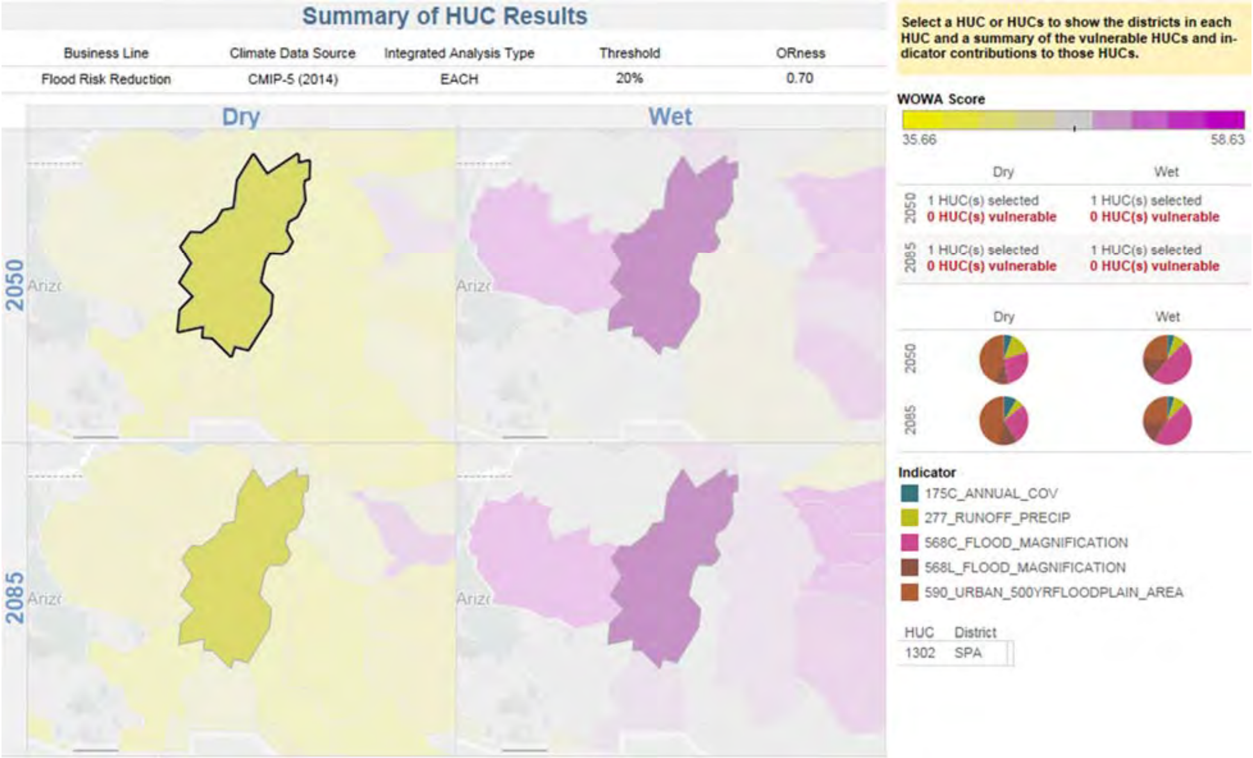


Figure 12 Projected change in mean of the ensemble of annual maximum monthly flows, HUC 1302.



Summary of HUC Results

Business Line	Climate Data Source	Integrated Analysis Type	Threshold	ORness
Flood Risk Reduction	CMIP-5 (2014)	EACH	20%	0.70

Select a HUC or HUCs to show the districts in each HUC and a summary of the vulnerable HUCs and indicator contributions to those HUCs.

	Dry	Wet
2050	1 HUC(s) selected 0 HUC(s) vulnerable	1 HUC(s) selected 0 HUC(s) vulnerable
2085	1 HUC(s) selected 0 HUC(s) vulnerable	1 HUC(s) selected 0 HUC(s) vulnerable

HUC	District
1302	SPA

Figure 13 Future flood risk vulnerability assessment for HUC 1302.

Breaking apart this vulnerability score further, the most significant changes in projected stream flow are seen in the wetter climate models, which show increases in flow variability (annual and monthly coefficients of variation), along with significant increases in runoff as a fraction of precipitation. Significant decreases in runoff in relation to precipitation are seen in the drier climate models.

1.6 Projected Impacts to Riparian and Aquatic Ecosystems

Riparian and aquatic ecosystems along the Rio Grande and tributaries are likely to be affected not only by changes in stream flow that alter water quantity and seasonal water availability, but also by resultant changes in water quality (temperature, nutrients, dissolved oxygen, pollutant concentration), and increases in riparian evaporation affecting riparian plant communities.

Projected impacts to the Middle Rio Grande riparian areas (Friggens et al. 2013) that are likely to be broadly applicable to northern New Mexico riparian areas include:

- Reduced riparian habitat due to decreased stream flows and longer drought.
- Decline in cottonwood gallery forests due to lower flows, more frequent wildfires, disease.

- Loss/reduction of native vegetation and replacement by invasive tree and grass species due to fire and lower water tables, and changes in spring runoff timing/volumes.
- Increasingly arid conditions would favor replacement of grassland and woodland habitats with scrubland, accompanied by reductions in vegetation cover.
- Increased duration of drought, with increases in droughts lasting 5 years or more and increases in drought intensity.

Temperature increases are likely to drive up potential evapotranspiration across the region. However, increases in actual evapotranspiration are likely to be truncated in riparian areas due to lack of available soil moisture. Thus, riparian water consumption among the Rio Grande from Cochiti to Elephant Butte Reservoirs, including the Jemez River Valley, is anticipated to only decline by small amounts as other factors draw down regional water tables and reduce overbanking flows (Reclamation et al. 2013). By century's end, most of the actual water consumption in the riparian zone is anticipated to occur in April and May, when water is most available; however, water is projected to be decreasingly available over the remainder of the growing season (Reclamation et al. 2013). As a result, water stress in the bosque is likely to increase across the 21st Century, particularly in the May-September months (Reclamation et al. 2013). Riparian-dependent species are considered highly vulnerable to such changes.

Federally-listed threatened and endangered species are among the species most vulnerable to climate change in the Middle Rio Grande. The Southwestern Willow Flycatcher (*Empidonax traillii extimus,* flycatcher) is considered the most vulnerable bird species, with the Western Yellow-Billed Cuckoo (*Coccyzus americanus occidentalis,* cuckoo) ranking a close fourth among species studied (Friggens et al. 2013). Both the flycatcher and cuckoo depend on riparian habitat, are sensitive to high temperatures, and vulnerable to changes in phenology that may produce mismatches between food availability and need during nesting or migration (Friggens et al. 2013).

Among the mammals, the recently-listed New Mexico meadow jumping mouse (*Zapus hudsonius luteus*) is considered the most vulnerable species as it is also a riparian obligate species with limited range (Friggens et al. 2013). This species is anticipated to be vulnerable due to (Friggens et al. 2013):

- Loss of habitat and associated dense vegetation structure.
- Limited ability to disperse in the face of habitat change and drought-induced habitat fragmentation.
- Intolerance of heat and desiccation.
- Short lifespan, which might limit its ability to survive and reproduce under protracted drought conditions.

- Disruption of soil temperature cues triggering emergence from hibernation and whether phenological changes in other species will affect the availability of food following hibernation.

Aquatic species are also vulnerable to changes in climate. The Rio Grande cutthroat *(Oncorhynchus clarki virginalis*) (candidate species) trout is a cold-water salmonid endemic to the Rio Grande, Canadian and Pecos river basins currently occupying approximately 12% of its historic range, primarily restricted to isolated stream headwaters (Zeigler et al. 2012). Stream temperature increases, changes to stream flow (including river drying under drought conditions), and changes to water quality due to wildfire and other sources (which becomes increasingly significant as subpopulations become isolated in stream headwaters areas) are anticipated to increase this species' vulnerability to climate change (Zeigler et al. 2012).

The endangered Rio Grande silvery minnow (*Hybognathus amarus*) is also anticipated to be vulnerable to climate change in the Middle Rio Grande from Cochiti Dam to Elephant Butte Reservoir. Advances in the timing of spring runoff may result in flows that are too cold for successful spawning, reductions in spring runoff flows may reduce the frequency of overbanking floods necessary for nursery habitat, and reductions in later summer base flow may result in substantial river drying (M. Porter, personnal communication, USFWS 2007).

Amphibians particularly vulnerable to climate change impacts include the Northern leopard frog (*Lithobates pipiens*), the Western chorus frog (*Pseudacris triseriata*), and the barred tiger salamander (*Ambystoma marvortium)* (Friggens et al. 2013).

1.7 Projected Impacts to Project Features

Table 7 outlines the vulnerability of proposed watershed restoration measures to climate change, summarizes climate change impacts and risks, and suggests possible mitigation actions to reduce the risk of climate change impacts to potential management features.

Table 3 Climate change impacts to project features.

Measure	Vulnerability	Projected Climate Change Impacts and Qualitative Risks
Ecosystem restoration features in the TSP include: • Wetlands • Hi-flow Channels • Willow Swales • Bankline Terracing	• Long term reductions in average and maximum flows resulting in increasing frequency of years with limited spring runoff and poor inundation of riparian ecosystem restoration features.. • Reductions of water availability in the study area resulting in increasing river drying in the study reach impacting fish popualtions.	Projected Climate Change Impacts: • Smaller snowpacks, advances in spring runoff timing may lead to reductions in total runoff volumes, decreases in runoff peak discharges, and decreases in late summer base flow, which may reduce the frequency and extent of overbank flooding and seasonal inundation of ecosystem restoration features (likely). o Altered annual hydrologic cycle will continue to favor establishment of non-native species (e.g., Siberian elm, Russian olive, tamarisk/salt cedar) at the expense of native plans (e.g., cottonwood and willow). o Reduced water availability may also affect wetland species composition. o Increased frequency and duration of river drying in the southern portion of the study area. • Increased temperature and decreased soil moisture/precipitation could lead to increased wildfire hazard in the bosque (likely).

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