Appendix C10
Climate Change Effects on Water Demand and Losses

Appendix C10—Climate Change Effects on Water Demand and Losses

1.0 Introduction

The purpose of the Colorado River Basin Water Supply and Demand Study (Study) is to conduct a comprehensive study to define current and future imbalances in water supply and demand in the Colorado River Basin (Basin) and the adjacent areas of the seven Basin Colorado River States (Basin States)[1] that receive Colorado River water over the next 50 years, and to develop and analyze adaptation and mitigation strategies to resolve those imbalances. One of the potential influences that is explored is impact to water supply and demand related to changes in climate and meteorological inputs to the Basin. This appendix compares the approaches to and results of adjusting demands and losses to reflect projected changes in future climate. The potential effects of climate change on future water supply are described in *Technical Report B – Water Supply Assessment* (Reclamation, 2012).

2.0 Background

This section summarizes relevant previous work that evaluated the effect of climate change on potential evapotranspiration (PET), compares methods for estimating PET, and describes how results may differ among the methods examined.

As summarized in Bormann (2011), approaches used to compute PET include those based on aerodynamic concepts, temperature-based approaches, radiation-based approaches, and combination equations, including resistance-type approaches. In general, the methods can be divided into empirical and physically based methods. Empirical methods (for example, Blaney-Criddle method [Stephens and Stewart, circa 1960]) relate complex evaporation and transpiration processes into an equation based on crop type and temperature. Physically based methods (for example, Penman-Monteith method [Monteith, 1965]) calculate PET based on a more explicit physical process, but are data-intensive as well as data-sensitive. PET estimates can vary widely among the various methods, but the Penman-Monteith method has been shown to estimate actual PET most accurately from lysimeter and field studies (American Society of Civil Engineers [ASCE], 2005; Jensen et al., 1990; and Hill et al., 1983).

Researchers suggest that different PET methods produce different results under similar climate changes assumptions (McKenney and Rosenberg, 1993; Kingston et al., 2009; Bormann, 2011). For example, Kingston et al. (2009) investigated the global response of six different PET methods: 1) Penman-Monteith, 2) Hamon, 3) Hargreaves, 4) Priestley-Taylor, 5) Blaney-Criddle, and 6) Jensen-Haise, to a 2-degree Celsius rise in global mean temperature. They observed that all PET methods applied in the study indicate increases in PET due to assumed climate warming; however, the methods' resultant estimates of PET change varied by more than 100 percent.

[1] Arizona, California, Colorado, New Mexico, Nevada, Utah, and Wyoming.

Another study by Yates and Strzepek (1994) compared results of different PET methods for four river basins: the Blue Nile River basin of Africa; the Vistula River basin in Poland; the East River, a tributary of the Colorado River in the United States; and the Mulberry River, a tributary of the Arkansas River in the United States. PET methods evaluated included physically based (Penman-Monteith, Priestly-Taylor) and empirical (Hargreaves, Thonthwaite, Blaney-Criddle) methods. On average, these methods resulted in about a 3 to 8 percent increase in PET per degree Celsius warming. The authors found that the Penman-based methods are on average the least sensitive to warming, but have the greatest amount of variability. In contrast, they observe a range of variability, but with less climate sensitivity in the empirical methods (Hargreaves, Thonthwaite, and Blaney-Criddle). Although different results are found under the same climate scenarios for a given basin, the authors argue that it is difficult to draw definitive conclusions between the empirical and physical methods because different climatological regions show different trends.

2.1 PET Methods Used Historically in Reclamation Colorado River Studies

Reclamation has historically used an empirically based approach, the Blaney-Criddle or modified Blaney-Criddle method, for calculating consumptive uses and losses in the Basin.

In 2010, Reclamation's Technical Services Center (TSC) applied the modified Blaney-Criddle method, coupled with the Soil Conservation Service effective precipitation method, to examine potential change in agricultural demand caused by changes in temperature and precipitation. A report on this work is included in *Technical Report C - Water Demand Assessment*, appendix C4 (Reclamation, 2011). The TSC considered incremental increases in temperature and precipitation to gauge the sensitivity of each state’s agricultural areas to possible climate change. The TSC found that agricultural demands increased by approximately 5 percent for each degree Fahrenheit (approximately 0.5 degree Celsius) increase in temperature, and by approximately 1 percent for each 5 percent reduction in precipitation.

To estimate streamflow changes under future projected climate, Reclamation uses the Variable Infiltration Capacity (VIC) hydrologic model to calculate runoff in the Basin. The VIC model incorporates the Penman-Monteith method for estimating potential and actual evapotranspiration in runoff calculations. The VIC hydrologic modeling was used to support the water supply analysis for the Study (see *Technical Report B - Water Supply Assessment* [Reclamation, 2012]).

3.0 Selection of PET Method for Application to Basin Demands

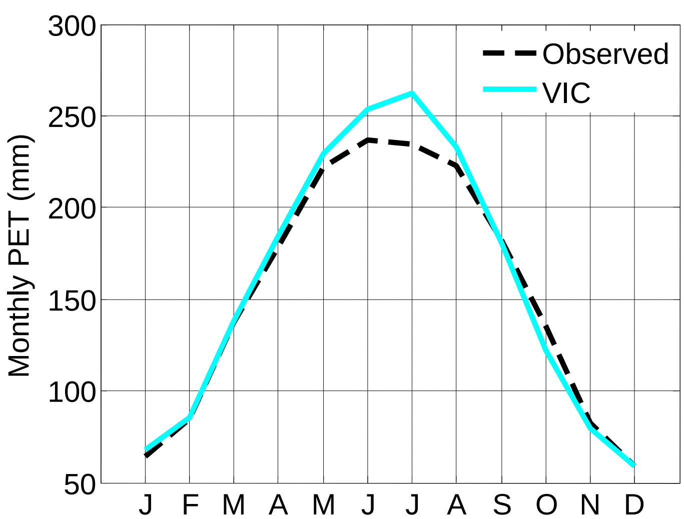
This section summarizes the process used to select an appropriate PET method for application to Basin demands in the Study. Parameter and demand estimates were provided by the Basin States and were generally derived from the states’ planning processes, or in some cases, planning of individual water agencies, such as the Southern Nevada Water Authority and Metropolitan Water District of Southern California. The Basin States have developed their demands through 2060 without consideration of future climate change. This appendix presents an approach to scale these demands for future climate realizations that are developed as a part of the Study.

This section first provides a comparison of VIC-simulated PET to observed PET at selected locations, then compares the PET sensitivity to warming considering Penman-Monteith methods (embedded in VIC and in an external program) and three other PET methods (Blaney-Criddle, Hargreaves, and Priestley-Taylor, and last describes the selected method for incorporating the effects of climate change on agricultural demand, outdoor urban demand, phreatophyte use, and reservoir evaporation.

3.1 Evaluations of VIC-simulated PET to Observed PET

To compare VIC-simulated PET with measured station data, historical observed meteorology for one location was simulated using the VIC model. Figure C10-1 compares PET measured at the California Irrigation Management Information System (CIMIS) station and VIC-simulated PET under historical observed meteorology (Maurer et al. 2002). CIMIS PET data are taken from a station at Calipatria/Mulberry (CIMIS station #41) in the Imperial Valley, California (black color curve in figure C10-1). VIC-simulated PET value is taken from the nearest VIC grid cell (blue color curve in figure C10-1). The PET values have been averaged for the period 1984–1999, which represents the historical overlapping period.

FIGURE C10-1
Comparison of Observed PET and Simulated PET for the Calipatria/Mulberry Station (CIMIS station #41) in California's Imperial Valley



The results indicate a reasonable comparison for most of the year, but an overestimation by the VIC model in the summer months. However, the comparison may have some discrepancies due to the following: (1) the CIMIS PET calculation is based on the CIMIS Penman-Monteith equation, which is a modified version, but the PET implementation in VIC is based on Penman-Monteith; (2) the CIMIS PET data represent the PET for a specific location, but VIC values are representative for a grid cell with an area of approximately 144 square kilometers, such that site-specific conditions are averaged; and (3) there could be potential differences between the historical meteorology data applied in the VIC simulations and the measured meteorology at the CIMIS station. Detailed validation or recalibration for site-specific conditions has not been conducted in the Study.

3.2 Comparison of VIC-simulated PET Changes under Climate Warming to Other Methods

To investigate difference in PET change due to PET calculation methodology, PET was calculated using five different methods for a 1-degree Celsius increase in daily average warming. VIC-simulated PET was compared to four other PET calculation methods implemented in an external program, REF-ET (Reference Evapotranspiration Calculator, Version – Windows 3.1, July 2011, available at http://www.kimberly.uidaho.edu/ref-et/.) The REF-ET program is considered one of the most robust applications for PET estimation. For the purpose of comparison, the reference crop was fixed to short grass for all applicable methods. The five PET methods are presented in tables C10-1 and C10-2. Table C10-1 provides the method, reference, and type, ranging from temperature-based to energy and aerodynamic processes. Table C10-2 shows the general data requirements for the selected PET methods.

TABLE C10-1
Approaches Used for Estimation of PET Sensitivity

PET Method	Reference	Method Type
VIC-ET Penman-Monteith	Penman-Monteith Implemented in VIC (Allen et al., 1998; Liang et al., 1996 and 1994)	Combinations of energy and aerodynamic process
REF-ET Penman-Monteith	FAO56 Penman-Monteith for 0.12 m grass ETo with rs = 70 s/m (Allen et al., 1998)[1]	Energy-based
REF-ET Blaney-Criddle	FAO-ID-24 Blaney-Criddle (Doorenbos and Pruitt, 1977)	Temperature-based
REF-ET Hargreaves	1985 Hargreaves (Hargreaves and Samani, 1985)	Temperature-based
REF ET Priestley-Taylor	Priestley-Taylor (Priestley and Taylor, 1972)	Radiation-based

[1] In 2005, ASCE and the Irrigation Association formally adopted a new standard for reference PET estimation based on a parameterization of the Penman-Monteith equation (ASCE, 2005), called the ASCE Standardized Penman-Monteith equation. ASCE Penman-Monteith Standardized Form is identical to the FAO56 Penman-Montieth for a grass reference.

TABLE C10-2
Data Requirements for the Selected Formulae for PET, Modified from McKenney and Rosenberg (1993)

PET Method	Temperature	Solar Radiation/Net Radiation	Humidity	Wind Speed	Latitude/ day-length	Plant Physiological Characteristics
VIC-ET Penman-Monteith	X	X	X	X		X
REF-ET Penman-Monteith	X	X	X	X		X
REF-ET Blaney-Criddle	X				X	
REF-ET Hargreaves	X		X		X	
REF ET Priestley-Taylor	X	X				

Tables C10-3 and C10-4 show the results comparing the temperature sensitivity of PET using PET computed from VIC and PET computed using the four different methods noted in table C10-1 and implemented in REF-ET under a 1-degree Celsius warming in daily average temperature. The locations included in tables C10-3 and C10-4 represent selected VIC model grid cells for each state planning area within the Study Area.

Figures C10-2 and C10-3 show the selected VIC grid locations for each of the planning areas. The agricultural grid cells were selected based on the following: density of agricultural lands, location of long-term evapotranspiration measurement stations, and location outside of federally managed lands (figure C10-2). For municipal and industrial (M&I) demands, the grid cells were selected to be near the city with highest population or approximately in the center of urban clusters (figure C10-3).

FIGURE C10-2
Selected VIC Grid Cells for Agricultural Regions for Each of the Planning Areas (dotted area represents irrigated land)

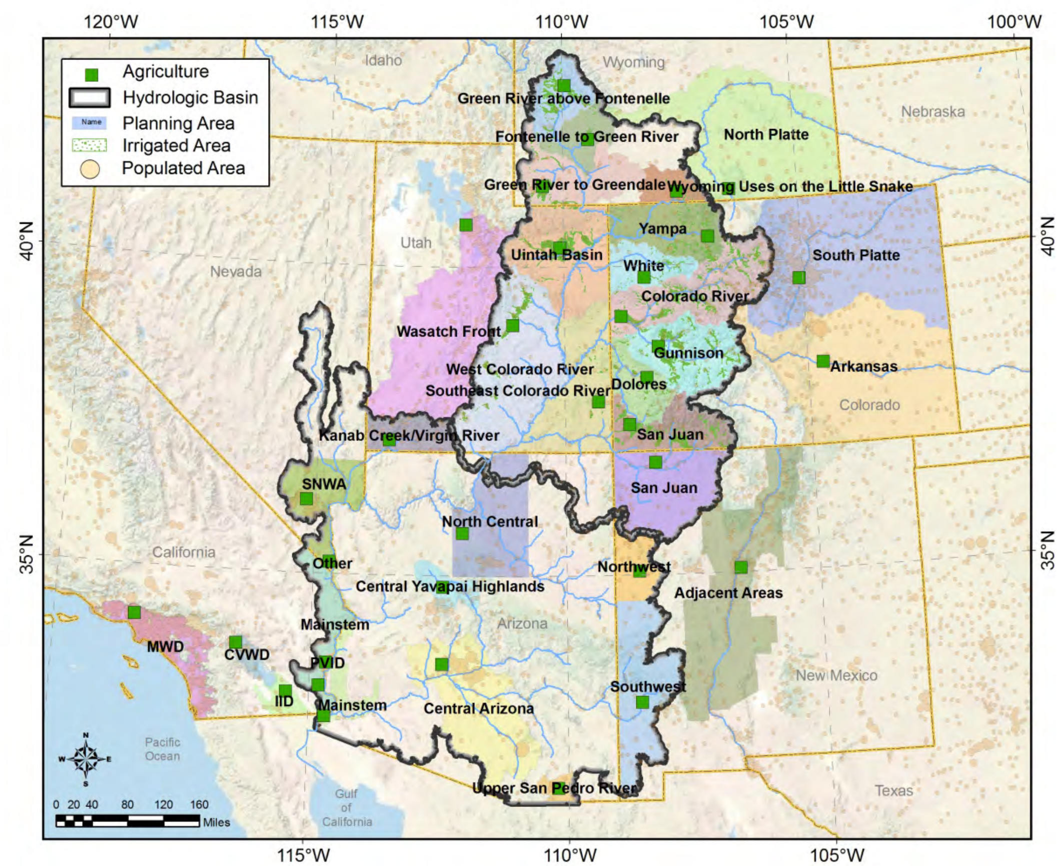
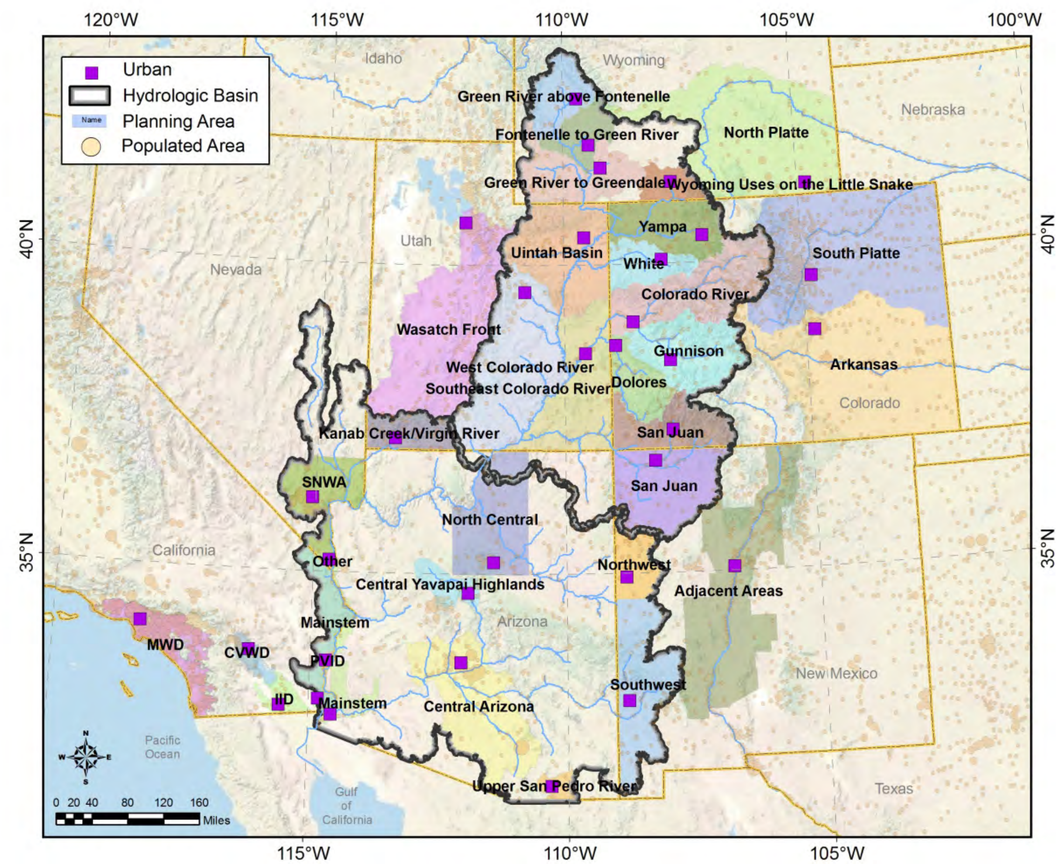


FIGURE C10-3
Selected VIC Grid Cells for Urban Regions for Each of the Planning Areas (circles represent population centers)



Temperature sensitivity of PET (change in PET per degree of warming), presented in tables C10-3 and C10-4, was computed over the period 1950–1999. Daily gridded meteorological observations of maximum daily temperature, minimum temperature, and wind speed were obtained from the Surface Water Modeling Group at the University of Washington (http://www.hydro.washington.edu; Maurer et al., 2002). In the REF-ET program, maximum, minimum and average daily temperatures, average daily wind speed, net radiation, relative humidity, and vapor pressure were supplied as input. Net radiation, relative humidity, and vapor pressure are estimated in VIC based on daily maximum temperature, minimum temperature, and temperature range based on empirical relationships (Maurer et al., 2002).

REF-ET computes average daily dew point and daily solar radiation using empirical equations. Standard values for grass height and surface resistances are used in the REF-ET (grass reference height is 0.12 meter [m] and grass surface resistance for the above grass height is 70 seconds per meter [s/m]).

As can be seen in tables C10-3 and C10-4, there is considerable spatial variation in PET sensitivity across the Study Area. The average PET sensitivity computed from the locations considered for agricultural locations are 2.2, 2.5, 5.7, 3.3, and 2.0 percent using the methods VIC-ET Penman-Monteith, REF-ET Penman-Monteith, REF-ET Blaney-Criddle, REF-ET Hargreaves, and REF ET Priestley-Taylor, respectively. The values computed by these methods for the locations considered for urban regions are 2.2, 2.4, 5.4, 3.2, and 1.7 percent, respectively. The VIC-simulated PET suggests a lower sensitivity than that reported under the Blaney-Criddle estimates (Reclamation, 2011) (see also tables C10-3 and C10-4). However, the VIC- simulated PET compares reasonably well to PET simulated under the REF-ET program using the Penman-Monteith method. At high elevations (generally above 1,800 m), the VIC-simulated PET shows lesser sensitivity (figure C10-4) than other methods. Specifically, the PET sensitivity computed using the VIC model shows slightly higher sensitivity at the lower elevations (arid locations), but lower sensitivity at the higher elevations (energy-limited locations) compared to the REF-ET implemented Penman-Monteith application. Because both models use the standard Penman-Monteith equation, it appears that the differences in PET sensitivity are due to parameterization of meteorological inputs.

TABLE C10-3
PET Sensitivity due to 1-degree Celsius warming computed using VIC and four different PET methods implemented in the REF-ET program for the locations considered to adjust agricultural demands.

					PET Sensitivity (%)				
State	**Planning Area**	**Latitude**	**Longitude[1]**	**Elevation (m)**	**VIC PM**	**REF-ET PM**	**REF-ET BC**	**REF-ET Harg**	**REF ET Prs-Tylr**
CO	Colorado River-Cisco UT	39.1875	-108.8125	1451	2.2	2.4	5.6	3.3	2.0
CO	Dolores River-Cisco	38.1875	-108.3125	2117	2.0	3.0	6.8	3.7	2.9
CO	San Juan-Bluff	37.4375	-108.6875	1988	1.9	2.9	6.0	3.4	2.8
CO	White River-Watson	39.8125	-108.3125	2051	2.0	3.3	7.7	3.9	3.4
CO	Yampa Maybell	40.4375	-106.9375	2145	1.8	3.8	8.8	4.1	4.5
CO	Gunnison River-Grand Junction	38.6875	-108.0625	1576	2.2	2.3	5.5	3.3	2.2
CO	South Platte	39.6875	-105.0625	1655	2.6	2.7	5.5	3.3	2.0
CO	Arkansas	38.3125	-104.6875	1505	2.8	2.5	5.1	3.2	1.5
NM	San Juan	36.8125	-108.1875	1736	2.2	2.3	5.3	3.3	1.7
NM	Adjacent Areas	35.0625	-106.5625	1633	2.5	2.2	4.6	3.0	1.3
NM	Southwest	32.9375	-108.5625	1455	2.4	2.2	4.6	3.1	1.4
NM	Northwest	35.0625	-108.5625	2157	2.2	2.6	6.1	3.6	2.2
UT	Southeast Colorado River	37.8125	-109.3125	2064	1.9	3.0	6.5	3.6	2.9
UT	West Colorado River	39.0625	-111.0625	1801	2.4	2.5	5.9	3.4	1.8
UT	Kanab Creek-Virgin River	37.1875	-113.5625	1185	2.0	1.9	4.4	2.9	1.2
UT	Uintah Basin	40.3125	-110.0625	1636	2.4	2.4	6.3	3.5	1.7
UT	Wasatch Front	40.6875	-112.0625	1398	2.0	2.5	5.4	3.2	2.1

TABLE C10-3 (CONTINUED)
PET Sensitivity due to 1-degree Celsius warming computed using VIC and four different PET methods implemented in the REF-ET program for the locations considered to adjust agricultural demands.

State	Planning Area	Latitude	Longitude[1]	Elevation (m)	PET Sensitivity (%)				
					VIC PM	REF-ET PM	REF-ET BC	REF-ET Harg	REF ET Prs-Tylr
WY	Green River to Greendale	41.3125	-110.4375	2125	2.3	3.2	7.8	3.9	3.0
WY	Wyoming Uses on the Little Snake	41.1875	-107.5625	2104	2.3	3.3	8.1	3.9	3.0
WY	Green River above Fontenelle	42.9375	-109.9375	2255	2.6	3.7	10.8	4.4	3.8
WY	Fontenelle to Green River	42.0625	-109.4375	2013	2.7	3.0	8.7	4.0	2.4
WY	North Platte	41.1875	-106.4375	2535	1.7	4.3	10.3	4.4	5.1
AZ	Central Arizona	33.5625	-112.4375	372	2.0	1.6	3.4	2.5	0.7
AZ	Mainstem	32.6875	-114.6875	45	2.1	1.6	3.2	2.5	0.6
AZ	Central Yavapai Highlands	34.8125	-112.4375	1410	2.1	2.1	4.8	3.1	1.5
AZ	Upper San Pedro River	31.5625	-110.1875	1291	2.2	1.8	3.9	2.8	1.1
AZ	North Central	35.6875	-112.0625	1921	1.8	2.6	5.6	3.3	2.4
CA	IID	33.0625	-115.4375	-32	2.0	1.6	3.0	2.4	0.6
CA	CVWD	33.8125	-116.4375	149	2.1	1.6	3.2	2.5	0.6
CA	MWD	34.1875	-118.4375	241	2.8	2.2	3.9	2.8	1.0
CA	Mainstem	33.1875	-114.8125	270	2.0	1.6	3.3	2.5	0.6
CA	PVID	33.5625	-114.6875	90	2.0	1.5	3.2	2.4	0.6
NV	SNWA	36.1875	-115.1875	655	2.1	1.7	3.7	2.6	0.7
NV	Other	35.1875	-114.6875	744	2.1	1.7	3.7	2.6	0.7
				Average	2.2	2.5	5.6	3.2	1.9
				Max	2.8	4.3	10.8	4.4	5.1
				Min	1.7	1.5	3.0	2.4	0.6

[1] Longitude values are negative west of the prime meridian.
PM – Penman-Monteith
BC – Blaney-Criddle
Harg – Hargreaves
Prs-Tylr – Priestley-Taylor

TABLE C10-4
PET sensitivity due to 1-degree Celsius Warming Computed using VIC and four different PET methods implemented in the REF-ET Program for the locations considered to adjust urban demands.

State	Planning Area	Latitude	Longitude[1]	Elevation (m)	PET Sensitivity (%)				
					VIC PM	REF-ET PM	REF-ET BC	REF-ET Harg	REF ET Prs-Tylr
CO	Colorado River-Cisco UT	39.0625	-108.5625	1449	2.2	2.2	5.2	3.1	1.6
CO	Dolores River-Cisco	38.6875	-108.9375	1760	2.1	2.5	5.8	3.4	2.1
CO	San Juan-Bluff	37.3125	-107.8125	2303	1.5	3.3	7.2	3.8	3.4
CO	White River-Watson	40.0625	-107.9375	2025	2.0	3.2	7.3	3.8	3.2
CO	Yampa Maybell	40.4375	-107.0625	2121	1.7	3.6	8.3	4.0	3.9
CO	Gunnison River-Grand Junction	38.4375	-107.8125	1898	2.2	2.6	6.1	3.5	2.2
CO	South Platte	39.6875	-104.8125	1692	2.6	2.7	5.6	3.3	1.9
CO	Arkansas	38.8125	-104.8125	1879	2.9	2.8	5.9	3.5	2.0
NM	San Juan	36.8125	-108.1875	1736	2.2	2.3	5.3	3.3	1.7
NM	Adjacent Areas	35.0625	-106.6875	1532	2.5	2.2	4.5	3.0	1.2
NM	Southwest	32.9375	-108.8125	1856	2.5	2.4	5.4	3.4	1.7
NM	Northwest	34.9375	-108.8125	2138	2.3	2.6	6.1	3.5	2.2
UT	Southeast Colorado River	38.5625	-109.5625	1385	2.1	2.1	5.0	3.1	1.4
UT	West Colorado River	39.5625	-110.8125	1717	2.2	2.5	5.7	3.3	2.0
UT	Kanab Creek-Virgin River	37.1875	-113.4375	1074	2.0	1.9	4.3	2.9	1.1
UT	Uintah Basin	40.4375	-109.5625	1703	2.4	2.6	6.7	3.6	2.0
UT	Wasatch Front	40.6875	-112.0625	1398	2.0	2.5	5.4	3.2	2.1
WY	Green River to Greendale	41.5625	-109.1875	1996	2.4	2.9	7.2	3.7	2.5
WY	Wyoming Uses on the Little Snake	41.3125	-107.6875	2026	2.5	3.0	7.7	3.8	2.7
WY	Green River above Fontenelle	42.6875	-109.6875	2165	2.6	3.5	10.1	4.3	3.3
WY	Fontenelle to Green River	41.9375	-109.4375	2049	2.6	3.0	8.3	4.0	2.4

TABLE C10-4 (CONTINUED)
PET sensitivity due to 1-degree Celsius Warming Computed using VIC and four different PET methods implemented in the REF-ET Program for the locations considered to adjust urban demands.

State	Planning Area	Latitude	Longitude[1]	Elevation (m)	PET Sensitivity (%)				
					VIC PM	REF-ET PM	REF-ET BC	REF-ET Harg	REF ET Prs-Tylr
WY	North Platte	41.1875	-104.8125	1879	2.9	2.9	6.6	3.6	2.1
AZ	Central Arizona	33.5625	-112.0625	415	2.1	1.6	3.4	2.5	0.8
AZ	Mainstem	32.6875	-114.5625	55	2.0	1.6	3.2	2.4	0.6
AZ	Central Yavapai Highlands	34.6875	-111.9375	1048	2.0	1.8	4.1	2.8	1.1
AZ	Upper San Pedro River	31.5625	-110.3125	1435	2.2	1.9	4.2	2.9	1.2
AZ	North Central	35.1875	-111.4375	1966	2.0	2.6	6.2	3.5	2.3
CA	IID	32.8125	-115.5625	-17	2.1	1.7	3.2	2.5	0.6
CA	CVWD	33.6875	-116.1875	-2	2.1	1.6	3.1	2.4	0.5
CA	MWD	34.0625	-118.3125	100	2.9	2.4	3.9	2.8	1.1
CA	Mainstem	32.9375	-114.8125	244	2.1	1.6	3.3	2.5	0.6
CA	PVID	33.5625	-114.6875	90	2.0	1.5	3.2	2.4	0.6
NV	SNWA	36.1875	-115.0625	566	2.1	1.7	3.6	2.6	0.6
NV	Other	35.1875	-114.6875	744	2.1	1.7	3.7	2.6	0.7
				Average	2.2	2.4	5.4	3.2	1.7
				Max	2.9	3.6	10.1	4.3	3.9
				Min	1.5	1.5	3.1	2.4	0.5

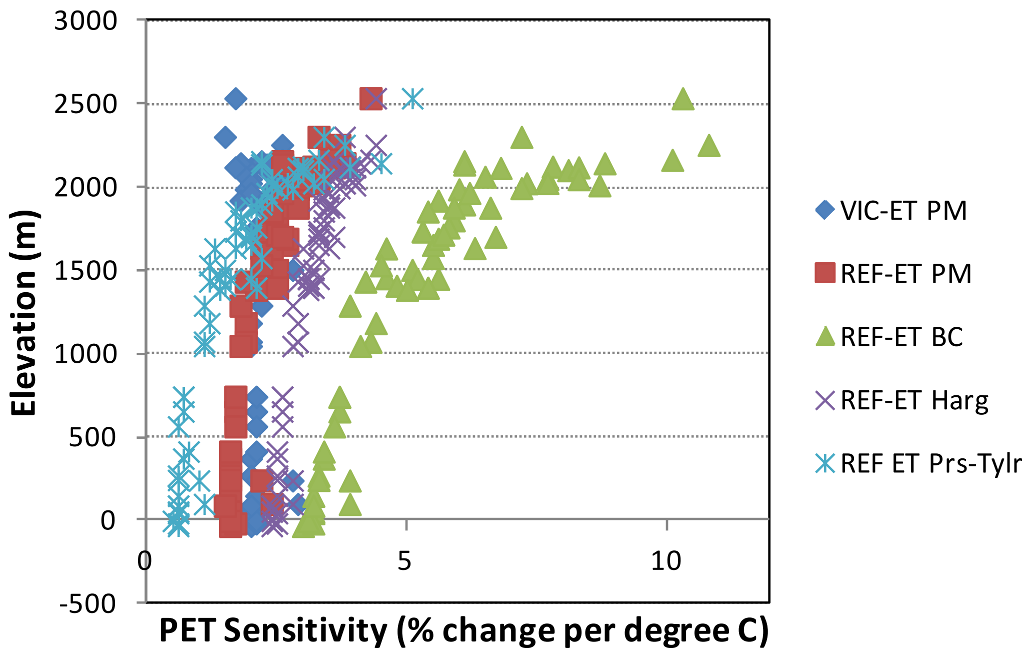
[1] Longitude values are negative west of the prime meridian.
PM – Penman-Monteith
BC – Blaney-Criddle
Harg – Hargreaves
Prs-Tylr – Priestley-Taylor

The Blaney-Criddle method produced the highest PET sensitivity to climate warming (greatest increase in PET per degree of warming) compared to the other methods. The Penman-Monteith method is a physically based method and is more likely to capture the dynamic responses of PET under meteorological changes. It was found that the Penman-Monteith method produced changes in PET of approximately 2 to 3 percent per degree Celsius warming. This sensitivity was greater than that estimated under the Priestly-Taylor method and less than that under the Hargreaves method, but results were generally within 1 percentage point of these two methods. Conversely, the Blaney-Criddle method, when simulated under identical meteorological conditions, suggests a change of almost double that in the other methods.

3.3 Selection of PET Method for Estimating Change in Demand

Based on these analyses and in order to be consistent between the calculations used to estimate supply changes under future climate conditions, the Penman-Monteith method, as implemented in the VIC model, was proposed for estimating potential change in demands due to climate change. However, because VIC Penman-Monteith appears to underestimate the response of warming to PET change at high elevations (approximately above 1,800 m), the REF-ET Penman-Monteith sensitivity factors were used to adjust demands for these areas.

FIGURE C10-4
PET change in response to a change in temperature as predicted by Penman-Monteith method implemented in VIC and four different PET methods implemented in the REF-ET program for computing PET. PET changes computed over the grid locations presented in tables C10-3 and C10-4 are plotted against corresponding average location elevations. Different methods are represented by different symbols in the plot.



4.0 Method of Incorporating Effects of Climate Change on Demands, Phreatophyte Losses, and Reservoir Evaporation

In order to incorporate the effects of climate change on demands included in the Study, a method has been developed to adjust the agricultural and outdoor M&I demands. As discussed previously, the water demands for each of the scenarios have been developed without consideration of future climate change. The method applied in the Study consists of indexing the agricultural and outdoor M&I demands to changes in PET associated with the particular climate projection included in the Downscaled GCM Projected water supply scenario. No direct changes are made to the demand scenarios; however, these demands are indexed by each future climate realization based on projections of PET and precipitation (P) (as described below). This methodology is applied for all agricultural and outdoor M&I demands in the Study Area. A similar method is applied for phreatophyte losses and reservoir evaporation. The climatic factors are computed for two representative VIC grid coordinates for each planning area, as shown in figures C10-2 and C10-3; one grid cell is used to adjust agricultural demands and the second grid cell is used to adjust outdoor M&I demands. The climatic factor used to adjust the agricultural demand is also used to adjust phreatophyte losses in the Lower Basin. In addition, a set of VIC grid cells are identified where climatic factors are estimated to adjust reservoir evaporation rates in response to potential climate change. The climatic factors are computed for the period 1985–2060; however, the factors for the period 2010–2060 are used to modify the demand scenarios.

4.1 Method to Compute Climate Indexing Factor to Adjust Agricultural, Outdoor Urban Demands and Phreatophyte Losses

The method consists of the following steps:

1. Extract the monthly PET and P for each VIC simulation as driven by the downscaled climate model simulations.
2. Adjust the VIC-simulated PET for grid cells above 1,800 m based on the simulated REF-ET Penman-Monteith values.
3. Compute PET minus P for each month. If PET is greater than P, then this value is an indicator of the irrigation demand. If this value is less than zero, set the (PET - P) equal to zero for that month.
4. Compute the annual sum of the monthly (PET- P) values.
5. For each year for the period 1985–2060, annual (PET- P) (averaged over 31-year moving window centered over the year in calculation) are divided by the (PET - P) annual value averaged over the 1971–2000 historical climatological period.
6. This value represents the factor applied to the no-climate change agricultural, outdoor urban demands, and phreatophyte losses to calculate the climate change agricultural and outdoor M&I demands, as well as phreatophyte losses.
7. Steps 1–5 are repeated for each of the selected VIC grid cells. Note that step 2 is only performed for the VIC grid cells located at high elevation (approximately above 1,800 m).

4.2 Method to Compute Climate Indexing Factor to Adjust Reservoir Evaporation

The climate indexing factor to adjust reservoir evaporation loss is calculated with the same methods described to compute the climate indexing factor to adjust agricultural, outdoor M&I demands and phreatophyte losses. However, in this case, the following three changes are considered.

1. PET is considered from VIC-simulated open water surface (evaporation only).
2. No adjustments are made to the VIC-simulated open water surface evaporation for high elevations because it is not known whether the VIC high-elevation underestimation is also present in the calculation of open water surface evaporation.

3. The net evaporation term (PET-P) was not set to equal to zero, if (PET-P) <0 to reflect the potential for precipitation to produce negative net evaporation in some months/years.

VIC grid coordinates, depicted in figure C10-5, were selected for the reservoirs considered in the Colorado River Simulation System (CRSS) to compute climate indexing factors to adjust reservoirs evaporation losses.

FIGURE C10-5
Selected VIC Grid Cells to Adjust Reservoirs Evaporation Losses

4.3 Summary Results of VIC Model Methods

Figure C10-6 illustrates the (PET - P) factor over the Study period 1985–2060. PET is simulated here by the VIC hydrologic model (using PET from short grass surface) as driven by downscaled climate model forcings at a representative location in the Imperial Valley. For each year for the period 1985–2060, annual (PET- P) (averaged over the 31-year moving window centered over the year in calculation) is divided by the (PET- P) value averaged over the period 1971–2000. Thinner curves represent the (PET- P) fractions simulated by VIC as driven by 112 downscaled climate projections. Thicker curves represent the 10th, 50th, and 90th percentiles computed from 112 simulations. VIC-simulated PET and downscaled P values are taken from a VIC grid cell near the CIMIS station at Calipatria/Mulberry (CIMIS station #41) in the Imperial Valley. Results exhibit considerable variability in the projections. The median of the projections indicates an increase in annual PET of about 2.5 percent in 2035 and almost 4.5 percent by 2060.

FIGURE C10-6
Climate indexing factor for agricultural demands in the Imperial Valley based on 112 climate projections (thick red lines represent the 10th, 50th, and 90th percentile of the projections).

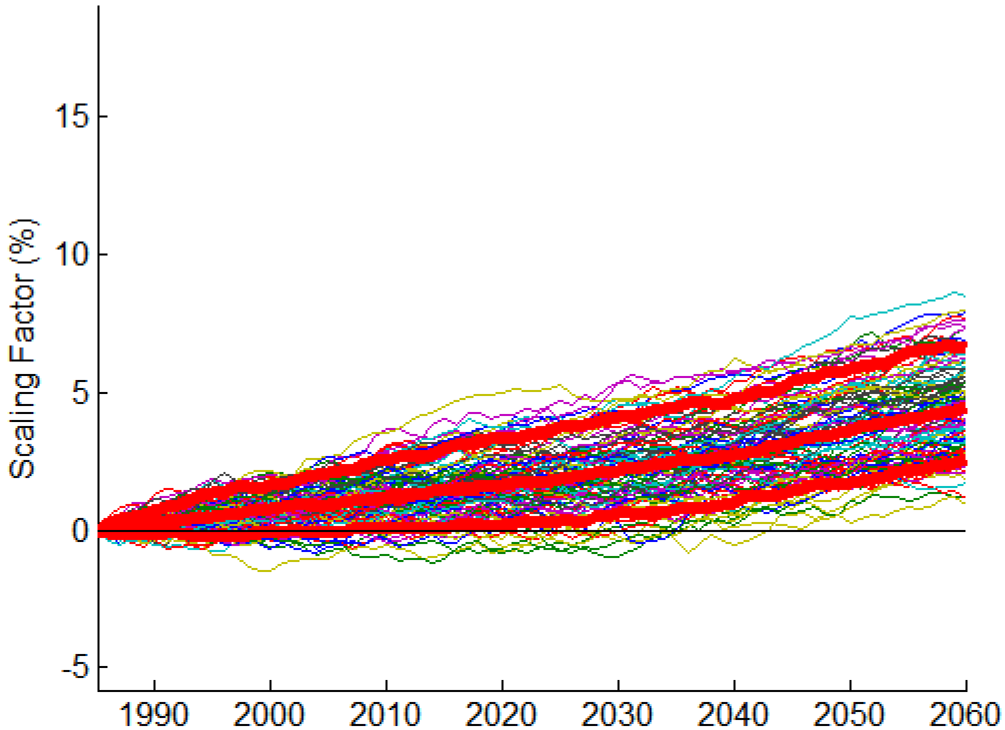


Figure C10-7 shows the (PET - P) factor over the period 1985–2060 to adjust outdoor demands. This factor is computed for a location in central Arizona. The median of the projections indicates an increase in demands of about 3.8 percent in 2035 and almost 6.8 percent by 2060.

FIGURE C10-7
Climate indexing factor for a representative location in central Arizona to adjust outdoor urban demands based on 112 climate projections (thick red lines represent the 10th, 50th, and 90th percentile of the projections).

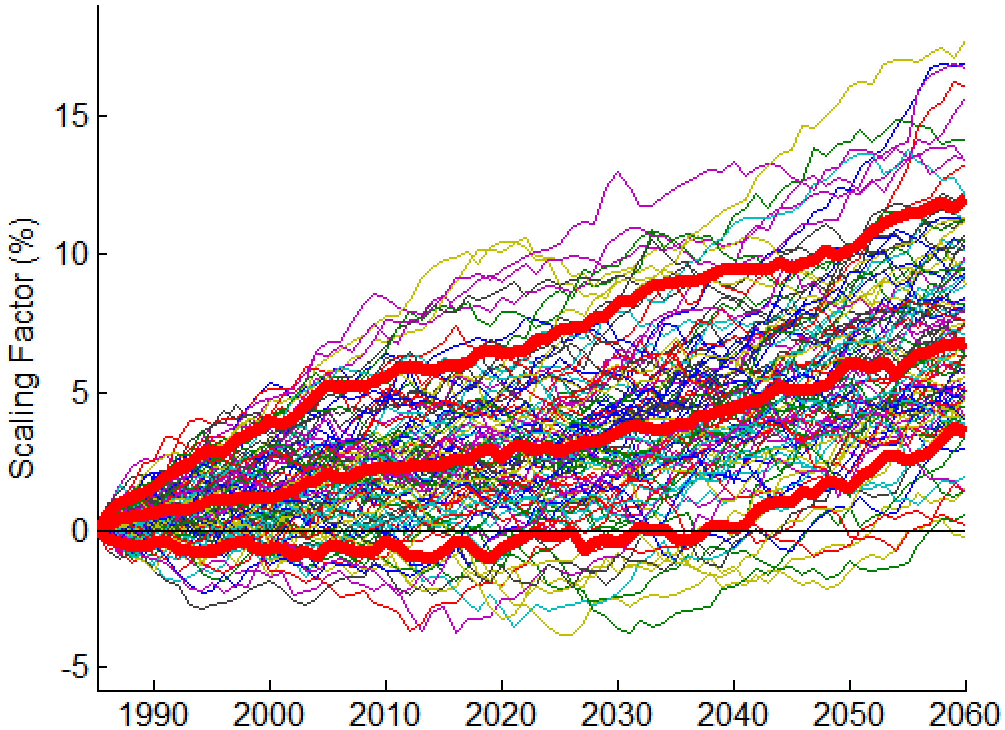


Figure C10-8 shows the (PET - P) fraction for the period 1985–2060 for a grid cell near Lake Mead, displaying a representative fraction used to adjust reservoir evaporation. PET is simulated by the VIC hydrologic model (using PET from open water surface) as driven by the 112 downscaled climate projections. For each year for the period 1985–2060, annual (PET- P) (averaged over the 31-year moving window centered over the year in calculation) is divided by the (PET- P) value averaged over the period 1971–2000. Thinner curves represent the (PET - P) fractions simulated by VIC as driven by 112 downscaled climate model projections. Thicker curves represent the 10th, 50th, and 90th percentiles computed from 112 simulations. The median of the projections indicates an increase in net evaporation loss of about 1 percent in 2035 and almost 3 percent by 2060.

FIGURE C10-8
Climate indexing factor used to adjust reservoir evaporation in Lake Mead based on 112 climate projections (thick red lines represent the 10th, 50th, and 90th percentile of the projections).

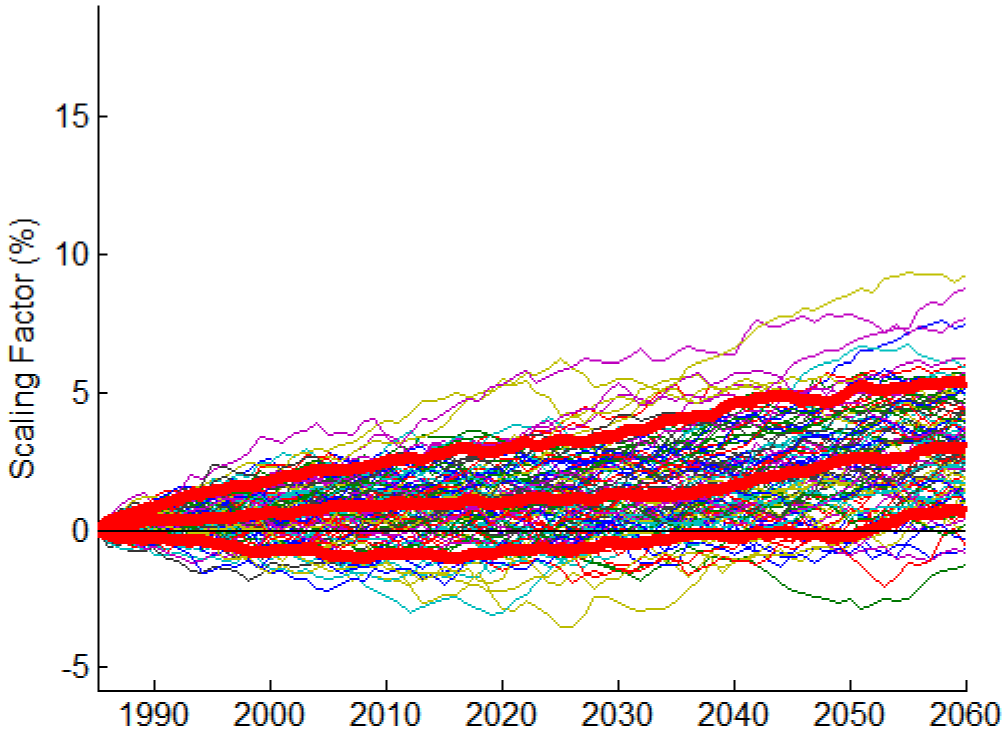
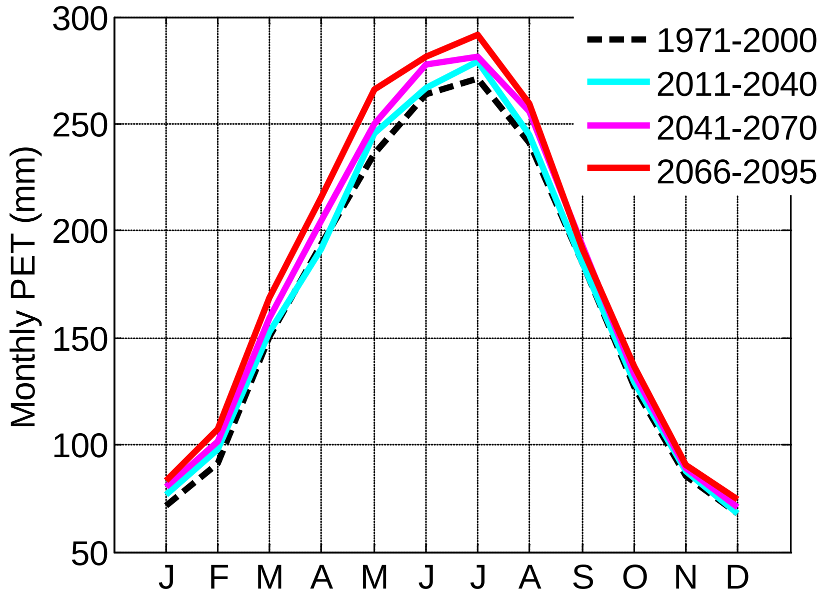


Figure C10-9 presents the monthly shifts in PET under various future climate periods. The downscaled climate model projection is taken from a representative downscaled climate model forcing (from sresa2.cccma_cgcm3_1.4). VIC-simulated PET values are taken from a VIC grid cell near the CIMIS station at Calipatria/Mulberry (CIMIS station #41) in the Imperial Valley. The results show an increase in PET under each projected future climate with respect to the model-simulated historical period. The figure also shows a marked increase in PET for January through August. Very little increase is projected during September through December.

FIGURE C10-9
Monthly changes in simulated PET under three future conditions compared to historical climate. Climate indexing factor for agricultural demands in the Imperial Valley based on 112 climate projections (thick red lines represent the 10th, 50th, and 90th percentile of the projections).



Figures C10-10 and C10-11 present the mean percent change in the climate indexing factor to adjust agricultural and outdoor M&I demands, respectively. There are some spatial variations in the climate indexing factor throughout the planning areas. The variability is controlled by projected changes in meteorological variables across the planning areas. The mean of the projections indicates an increase of almost 6.5 percent, with an increase ranging between almost 3 percent and about 10 percent by 2060 for agricultural demands. For outdoor M&I demands, the mean of the projections indicates an increase of about 6.4 percent, with an increase ranging between almost 3.2 percent and 12 percent by 2060. Consideration of precipitation in the scaling factor calculations contributes to changes in the scaling factor. For some planning areas, precipitation changes reduce the net evapotranspiration demand due to projected wetter conditions during the irrigation season, while projected reduced precipitation during the irrigation season exacerbates the increases in PET.

FIGURE C10-10
Mean projected percent change in climate indexing factor by 2060 to adjust agricultural demands. Values are averaged from 112 climate simulations (red portion of the bar shows the demand change contribution from warming; the blue portion shows the contribution due to precipitation change; and the dashed bar reflects the net change).

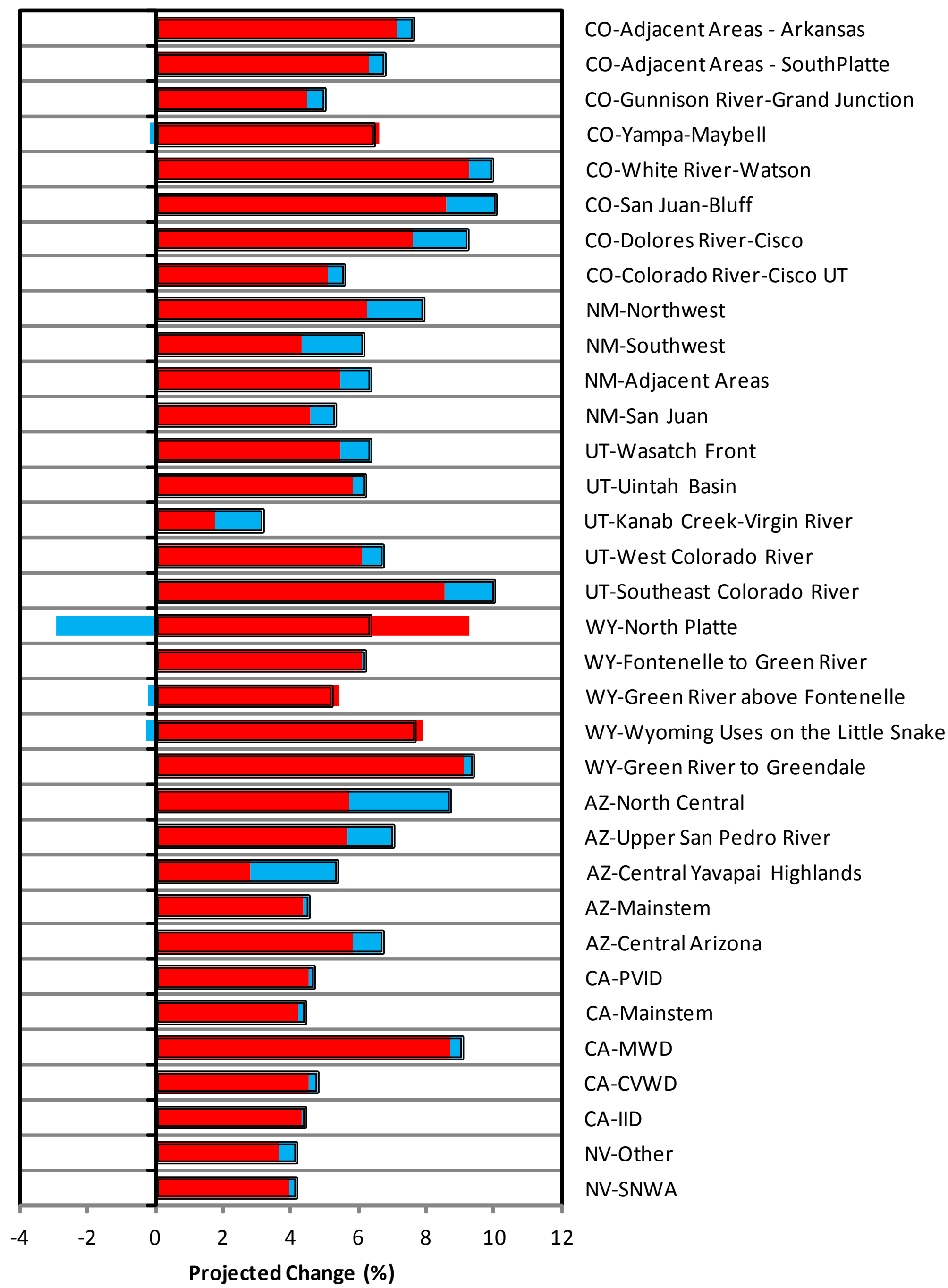
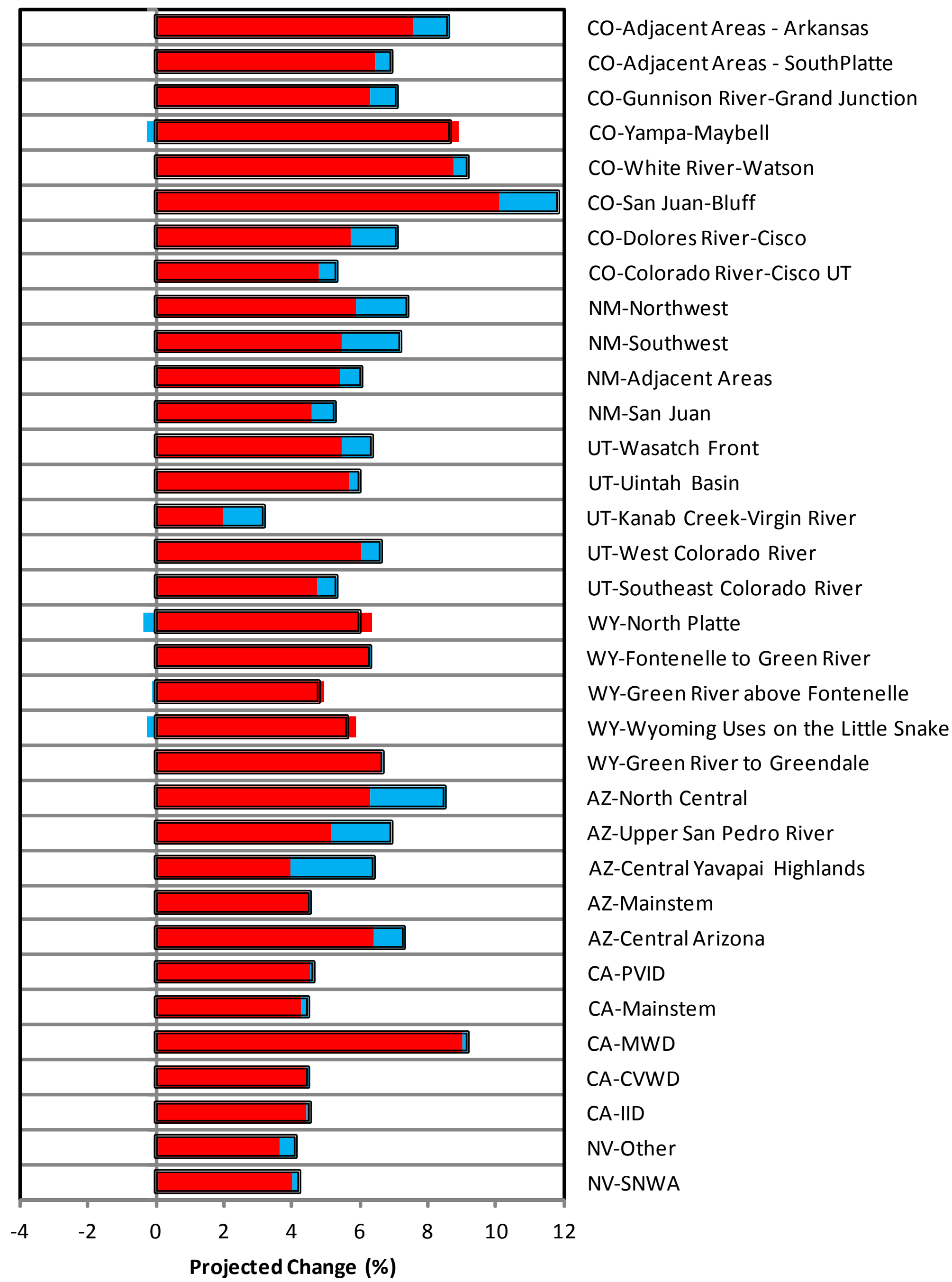


FIGURE C10-11
Mean projected percent change in climate indexing factor by 2060 to adjust outdoor M&I demands. Values are averaged from 112 climate simulations (red portion of the bar shows the demand change contribution from warming; the blue portion shows the contribution due to precipitation change; and the dashed bar reflects the net change).



Figures C10-12 and C10-13 present the spatial distributions of the mean percent change in the climate indexing factor to adjust agricultural and outdoor M&I demands over the planning areas, respectively. The size of the circle reflects the relative projected change in demand.

FIGURE C10-12
Spatial distribution of mean projected percent change in climate indexing factor by 2060 to adjust agricultural demands. Values are averaged from 112 climate simulations.

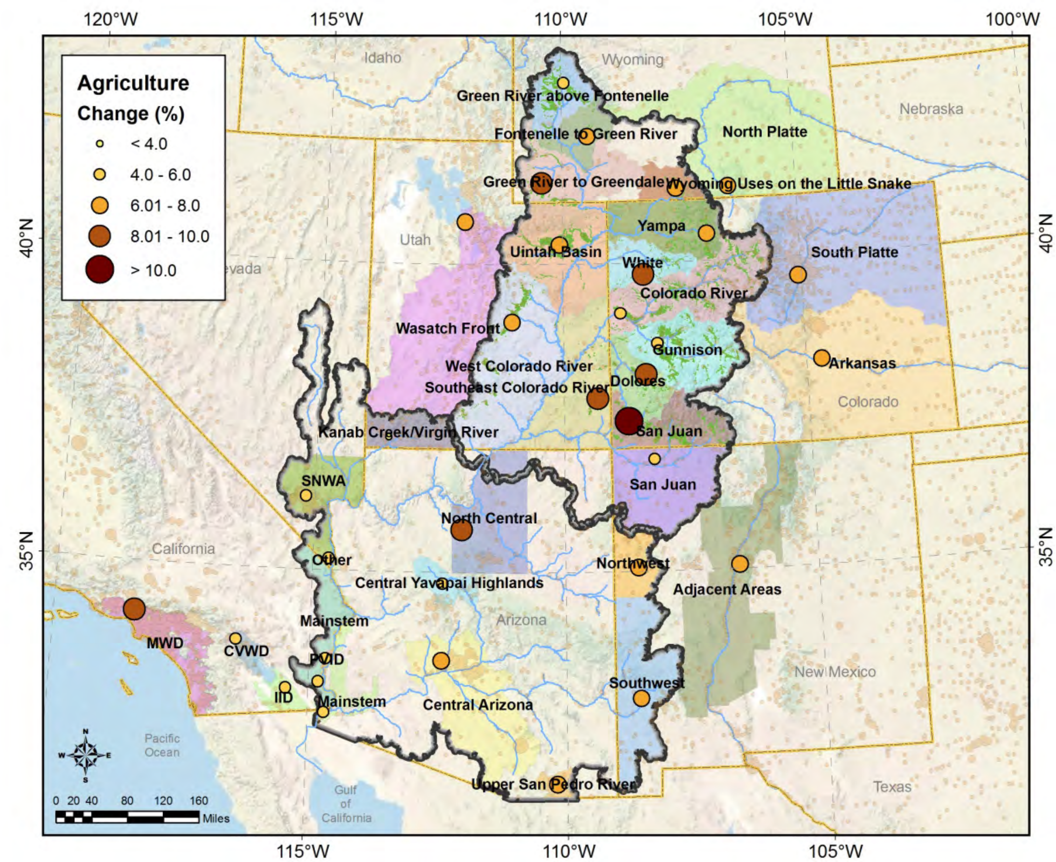


FIGURE C10-13
Spatial distribution of mean projected percent change in climate indexing factor by 2060 to adjust outdoor M&I demands. Values are averaged from 112 climate simulations.

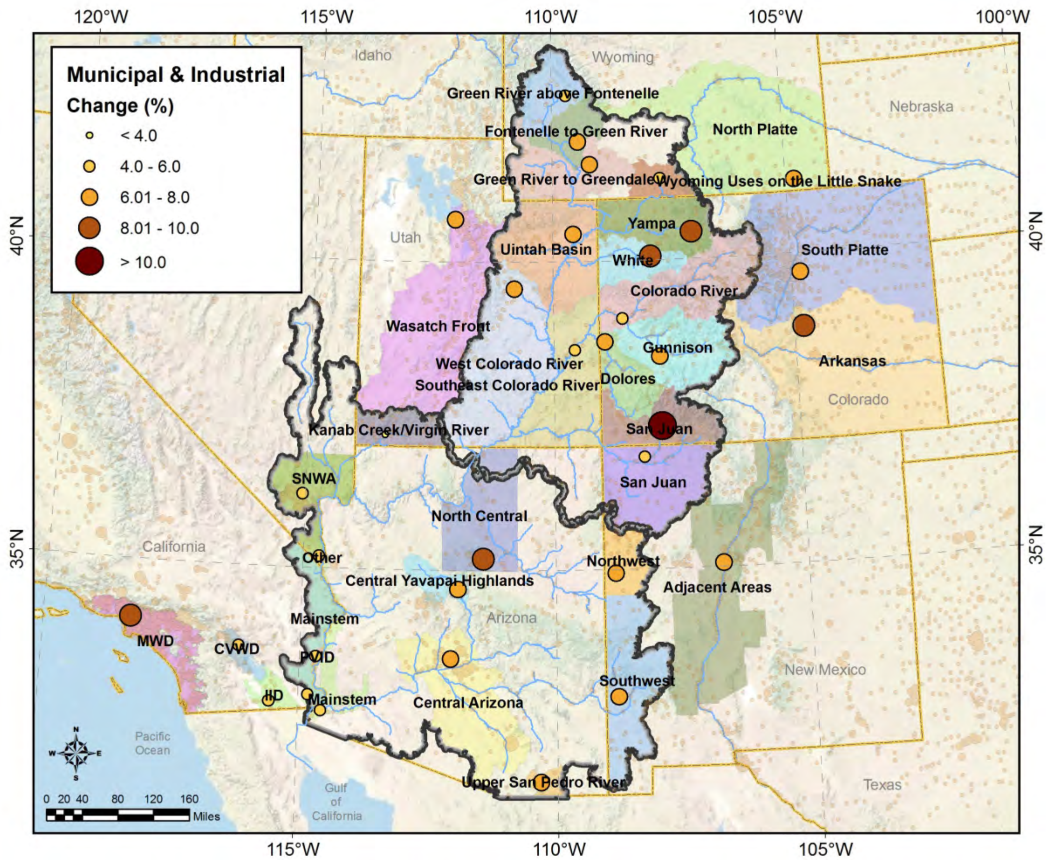
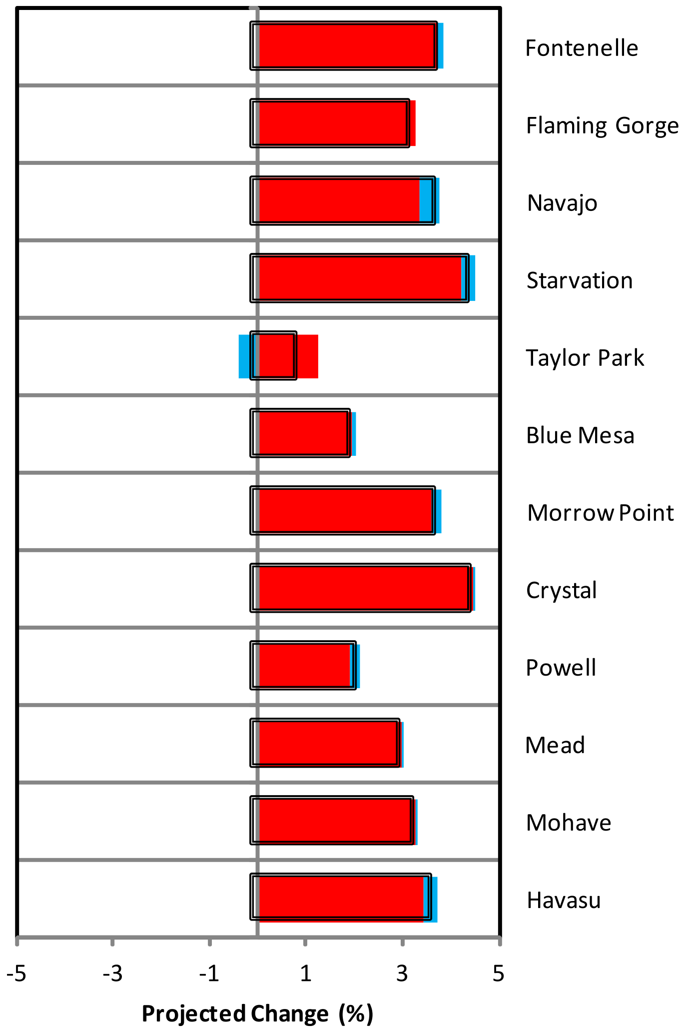


Figure C10-14 represents the mean percent change in climate indexing factor to adjust reservoir evaporation losses by 2060. The mean increase is projected to vary between about 1 percent to 4.5 percent, with an average of a little over 3 percent.

FIGURE C10-14
Mean projected percent change in climate indexing factor by 2060 to adjust reservoir evaporation loss. Values are averaged from 112 climate simulations (red portion of the bar shows the demand change contribution from warming; the blue portion shows the contribution due to precipitation change; and the dashed bar reflects the net change).



5.0 Summary and Limitations

Comparisons of VIC-simulated PET with station measurements of PET indicate general agreement, but discrepancies during summer months are likely due to scale and local meteorology differences. Warming exhibits an increase in PET and VIC-simulated PET shows increases on the order of 2 percent per degree Celsius of warming. The VIC simulations appear to underestimate PET changes at higher elevations (greater than about 1,800 m) compared to the Penman-Monteith method implemented in the REF-ET program. The Blaney-Criddle method shows sensitivity almost double that of the sensitivities suggested by the Penman-Monteith, Hargreaves, and Priestley-Taylor methods, leading to the preference for application of the Penman-Monteith in the Study. Given that VIC Penman-Monteith underestimates the response of warming to PET change at high elevations (approximately above 1,800 m), the ratios of REF-ET Penman-Monteith sensitivity divided by the VIC Penman-Monteith sensitivity are applied to adjust the annual projected change in PET as driven by the downscaled climate model simulations at high elevations.

PET estimated by the Penman-Monteith method embedded in VIC was used to construct the climate indexing factor. One of the future water supply scenarios is developed using the VIC simulations as driven by the same downscaled climate projections. These future water supply and water demand scenarios will be used in the CRSS to indicate the ability of the Colorado River to meet the needs of Basin resources under multiple future conditions. Overall, the approach described in this appendix provides an internally consistent methodology for including the potential effects of climate change on agricultural, outdoor urban demands, phreatophyte losses, and reservoir evaporation rates.

5.1 Limitations

The Penman-Monteith method is a function of climatic variables, including temperature, solar radiation, relative humidity, wind speed, and vegetation physiological characteristics. Due to unavailability of downscaled climate information for use in VIC for relative humidity, solar radiation, and wind speed, humidity and downward solar and longwave radiation were estimated using the algorithms of Kimball et al. (1997) and Thornton and Running (1999), which are based on the daily temperature range and daily average temperature, respectively. The Penman-Monteith method is sensitive to radiation inputs; however, due to the lack of observed data, particularly at the high elevation, no attempt was made to adjust the results for changes in radiation. Wind speed for the future climate was produced using resampling of the historical wind speed data taken from Maurer et al. (2002). Researchers have found that higher carbon dioxide concentrations cause partial stomatal closure in some crops, which decreases transpiration (for example, Ramirez and Finnerty, 1996). The PET implementation in the VIC model does not include any direct effect of ambient carbon dioxide concentrations and may overstate the changes in PET due to this limitation.

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