SECTION 1 - OBJECTIVES

The Central Valley Project Integrated Resource Plan (CVP IRP) provides an assessment of impacts of future climatic and socioeconomic uncertainties on the Central Valley Project Divisions and explores various portfolios of systemwide and local adaptation strategies addressing the numerous water resources management challenges confronting the Central Valley Project (CVP) in the twenty-first century, including water supply reliability, infrastructure and operations, socioeconomic and environmental conditions, and changing climate. Building upon and expanding previous studies performed under the CVP Yield Feasibility Investigation Program, the CVP IRP has the following four principal objectives:

- Perform a scenario-based CVP Division–specific supply and demand analysis incorporating the potential impacts of climate and socioeconomic changes and other factors through the year 2100.
- Assess the potential impacts of CVP Division-specific supply-demand imbalances on CVP infrastructure and operations.
- Identify and analyze portfolios of potential water management actions to address CVP Division-specific supply-demand imbalances.
- Perform analyses to determine the effectiveness and tradeoffs among these potential water management portfolios.

The CVP IRP technical approach was developed to assess the effectiveness of a range of water management actions (including systemwide actions such as new surface storage, conveyance, and local actions such as additional water use efficiency and recycled water use) to increase supply and reduce unmet demands for each CVP Division. Tradeoff analyses were performed to assess the effectiveness of potential water management actions covering a broad range of agricultural and municipal water supply and demand, water quality and water temperature, economics, hydropower, and greenhouse gas (GHG) emission objectives, and to provide a basis to better understand the benefits and limitations of these potential management actions.

The CVP IRP has also developed a suite of decision support tools to analyze a wide range of potential water management actions. This suite of models can also be used to facilitate current and future collaborative planning activities with other federal agencies, State of California (State) agencies, and CVP stakeholders including the Sacramento-San Joaquin Basins Study and other Bureau of Reclamation (Reclamation) and California Department of Water Resources (DWR) planning studies.

Figures are used throughout this report to illustrate analyses and results. Table 1-1 defines the many acronyms and abbreviations found on those figures.

Table 1-1. Figure Acronym and Abbreviation List

Acronym and Abbreviation List	Definition
°C	degrees Centigrade
AG	agriculture
Ag	agriculture
Avg	average
BCDC	San Francisco Bay Conservation and Development Commission
C	degrees Centigrade
C.S.D.	Community Services District
CCWD	Contra Costa Water District
cm	centimeter
CO_2	carbon dioxide
CT	Current Trends
CVP	Central Valley Project
deg C	degrees Centigrade
deg F	degrees Fahrenheit
DRMS	Delta Risk Management Strategy
EC	electrical conductivity
EG	Expansive Growth
GCM	Global Climate Model
GHG	greenhouse gas
GW	groundwater
GWh/year	gigawatt hours per year
I.D.	Irrigation District
IPCC	Intergovernmental Panel on Climate
IRP	Integrated Resource Plan
ISB	Independent Science Board
km	kilometer
kPa	kilopascals
LAWS	Land Atmosphere Water Simulator
m	meter
M&I	municipal and industrial
max	maximum
min	minimum
MJ/m2	mega-joules per square meter
mm	millimeter
mtCO_2e/year	metric tons of CO_2 equivalents
noCC	no climate change
NODOS	North-of-Delta Offstream Storage
OCAP	Operations Criteria and Plan
P50[a]	50th percentile of precipitation
PA	Planning Area
ppm	parts per million
Q1	drier, less warming

Acronym and Abbreviation List	Definition
Q2	drier, more warming
Q3	wetter, more warming
Q4	wetter, less warming
Q5	ensemble median
Rs	solar radiation
SA	Service Area
Sac HR	Sacramento River Hydrologic Region
SBA	South Bay Aqueduct
SG	Slow Growth
SJ HR	San Joaquin River Hydrologic Region
SW	surface water
SWP	State Water Project
T50[b]	50th percentile of temperature
TAF	thousand acre-feet
taf/mo	thousand acre-feet per month
TAF/year	thousand acre-feet per year
Tdew	dew point temperature
TL HR	Tulare Lake Hydrologic Region
Tmax	maximum temperature
Tmin	minimum temperature
UMHOS/CM	micromhos per centimeter
USACE	U.S. Army Corps of Engineers
VPD	vapor pressure deficit
W.D.	Water District
W.S.A.	Water Service Area
WA	Water Agency
WEAP	Water Evaluation and Planning
WY	water year

[a] See Figure 3-4: Where P = precipitation and the numeral = percentile
[b] See Figure 3-4: Where T = temperature and the numeral = percentile

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SECTION 2 - OVERVIEW OF ANALYTICAL APPROACH

The CVP IRP employed a scenario-based analytical approach that evaluated the effectiveness of potential water management actions under a range of potential future uncertainties. An analytical framework was developed to evaluate the combined effects of climate change and socioeconomics on water supplies, and urban and agricultural demands in the Sacramento, San Joaquin, and Tulare Lake Basins. This basin-scale information was used to assess impacts within CVP Divisions and to evaluate impacts on the coordinated operations of the CVP–State Water Project (SWP) system under current regulatory requirements. The analytical framework is depicted on Figure 2-1 and includes the following components:

- Critical uncertainties and scenario development
- Agricultural water demand and productivity
- Hydrology and systems analysis
- Performance assessment tools
- Performance metrics
- Baseline condition analysis
- Analysis of portfolios of potential water management actions

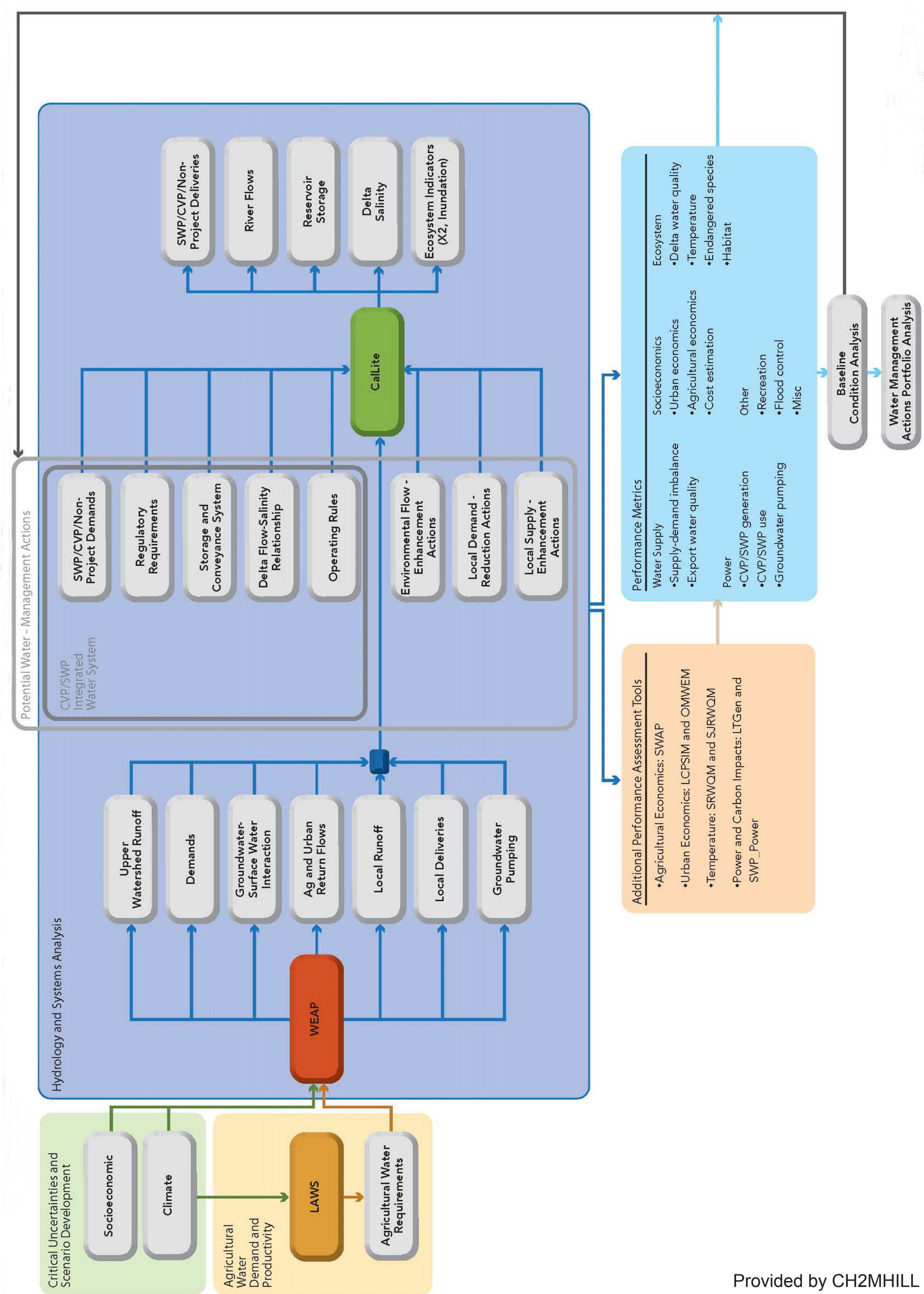
These components were integrated to allow comprehensive analysis of potential water management actions affecting successful adaptation strategies. The analysis accounts for critical uncertainties in socioeconomic and climate conditions by using a suite of scenarios developed to reflect a range of possible futures. In the CVP IRP analytical framework, the effects of climatic uncertainties on supply and demand were consistently evaluated. Climate impacts on supply were simulated through the use of hydrologic models. The hydrology and systems analysis uses the Water Evaluation and Planning model of the Central Valley (WEAP-CV) and CalLite models in an integrated manner. The WEAP-CV model was used to generate surface water and groundwater flows, and local area demands, which were used as inputs for the CVP IRP CalLite model. CalLite was then used to simulate CVP and SWP facilities, operations, and allocation decisions. The CVP IRP CalLite model was also used to simulate changes to the system resulting from potential local and systemwide water management actions under the suite of future scenarios. To provide consistent evaluation of agricultural and outdoor urban water requirements, the Land Atmosphere Water Simulator (LAWS) model was used to assess how climate change affects the water requirements and yields of major agricultural crops grown in the CVP Service Area. This approach allowed potential climate changes to have consistent effects on both water supply and agricultural demands.

The results of the hydrology and systems analysis were then used to provide inputs for additional performance assessment tools that evaluate how potential water management actions affect agricultural and urban water management economics, water quality and temperature, power generation and use, and GHG emissions.

In this study, the hydrology and systems analysis, and other performance assessment tools were first used to perform a multi-resource Baseline condition analysis. The Baseline condition analysis generated performance metrics for a wide range of factors. The results of the Baseline condition analysis were used to help identify portfolios of water management actions to be analyzed by the CVP IRP modeling tools. These portfolios were designed to reflect various potential water management strategies consisting of groups of water management actions.

The following discussions provide additional detail on each component of the CVP IRP analytical approach.

Figure 2-1. Analysis Framework



Provided by CH2MHILL

SECTION 3 - CRITICAL UNCERTAINTIES AND SCENARIO DEVELOPMENT

To account for a range of uncertainty in future conditions, a suite of scenarios was developed for the CVP IRP to reflect the following conditions:

- Three future socioeconomic conditions
- Six future climate conditions, including one reflecting historical conditions without climate changes and five reflecting climate change conditions

These three socioeconomic futures and six climate futures were combined to form the suite of eighteen future scenarios. Each scenario was analyzed for the period from October 2011 to September 2099 using a transient approach in which the climate and socioeconomic factors gradually change as the simulation moves through time. The following sections describe how the socioeconomic and climate futures were developed.

3.1 Socioeconomic Futures

The CVP IRP used the following three socioeconomic future scenarios developed by the California Water Plan Update 2009 (CWP) (DWR, 2009a):

- Current Trends (CT), which assumed that recent trends will to continue into the future
- Slow Growth (SG), which assumed that future development is less resource-intensive than under recent conditions
- Expansive Growth (EG), which assumed that future development is more resource-intensive than under recent conditions

For each scenario, the CWP quantified population projected in 10-year increments from 2010 through 2050. The CWP used these population estimates to develop WEAP-CV inputs relating to urban and agricultural land use. For the 2010–2050 period, CWP data were used directly by the CVP IRP. Through consultation with DWR CWP staff, the CWP population estimates and the WEAP-CV urban and agricultural inputs were extended in 10-year increments through 2100 for the CVP IRP.

3.1.1 Population Projections

Population projections were developed using a methodology consistent with the CWP. Projections for each California county were developed by using data from the California Department of Finance (DOF) and the Public Policy Institute of California (PPIC) (DOF, 2007 and Johnson, 2008, respectively).

The DOF developed a single population projection through 2050 for each county; these projections were used by DWR to develop its Current Trends scenario. The PPIC developed three projections for each county through 2100 that reflect low, medium, and high rates of population growth.

Table 3-1 shows the data sources used to estimate county populations during the 2010–2050 and 2050–2100 periods. For the 2010–2050 period, the CWP used DOF data to develop estimates for the Current Trends scenario and used PPIC data to develop estimates for the Slow Growth scenario and the Expansive Growth scenario. For the 2050–2100 period, the CVP IRP approach continued using PPIC data to develop estimates for the Slow Growth scenario and Expansive Growth scenario. However, DOF data were available through only 2050, so the Current Trends scenario projections for the 2050–2100 period were developed using PPIC data and adjusted to make the projections consistent with the DOF projections for the 2010–2050 period.

DWR used the county estimates to develop population estimates for each Hydrologic Region and Planning Area during the 2010–2050 period. For the 2050–2100 period, the CVP IRP used a similar method to develop estimates of population for each Hydrologic Region and Planning Area.

Table 3-1. Population Data Sources Used to Estimate County Populations for Each Scenario

Scenario	2010–2050	2050–2100
Current Trends	DOF	PPIC[a]
Slow Growth	PPIC	PPIC
Expansive Growth	PPIC	PPIC

[b] See Figure 3-4: Where T = temperature and the numeral = percentile

The resulting statewide population projections for each scenario are provided on Figure 3-1. Figure 3-2 shows the population of each Central Valley Hydrologic Region (Sacramento, San Joaquin, and Tulare Lake) in each scenario in 2005 (base), 2050, and 2100 projections.

3.1.2 Irrigated Land Area Projections

After the population projections were developed, the socioeconomic scenarios were used to project irrigated land areas in each county. For each scenario in the CWP, DWR developed assumptions about the relationships between population growth, and urban and agricultural land use. This approach was used to extend projected irrigated land areas beyond 2050 for use in the CVP IRP. Figure 3-3 shows the total irrigated land area in each Central Valley Hydrologic Region for each scenario in 2005 (base), 2050, and 2100.

3.1.3 Urban Demographic Projections

The population projections were also used to develop residential, commercial, and industrial demographic factors in each Planning Area. Figures 3-4 through 3-7 show the projected numbers of single-family homes, multi-family homes, commercial employment, and industrial employment in each Central Valley Hydrologic Region for each scenario in 2005 (base), 2050, and 2100.

3.2 Climate Futures

The CVP IRP study used six climate future projections: one reflecting the historical hydrology without climate change, and five statistically representative (termed ensemble-informed) climate change projections that are similar to the approach used for the Bay Delta Conservation Plan (BDCP)[2]. Each climate change future was characterized by changes in climate, hydrology, and sea level rise. The following sections describe how ensemble-informed climate hydrology and sea level rise inputs were developed for each climate future.

3.2.1 Ensemble-Informed Climate Scenarios

Five climate sequences were developed using statistical techniques similar to those used to develop climate scenarios for the BDCP. These techniques employed the full range of the 112 (see Figure 3-8) bias-corrected spatially downscaled climate projections (Maurer et al., 2007) to develop the five statistically relevant climate scenarios employed in this study. These five sequences were developed using a multi-model hybrid delta ensemble approach in which the ensemble of future climate change projections was broken into regions representing future climate uncertainties ranging from (Q1) drier, less warming; (Q2) drier, more warming; (Q3) wetter, more warming; and (Q4) wetter, less warming scenarios than captured by the ensemble median (Q5). These regions are labeled Q1 through Q4 on Figure 3-8. The ensemble "consensus" region (Q5) samples from inner quartiles (25th to 75th percentile) of the ensemble represented the central tendency of projected climate changes. In each of the five regions, a subset of climate change projections, consisting of those bounded by the region were identified. For Q5, all of the projections in the bounded region were included. For the Q1 through Q4 regions, the subset consisted of the 10 nearest neighbors to the 10–90 percentile points (see Figure 3-8). This approach was employed to sample the range of climate

2 http://baydeltaconservationplan.com

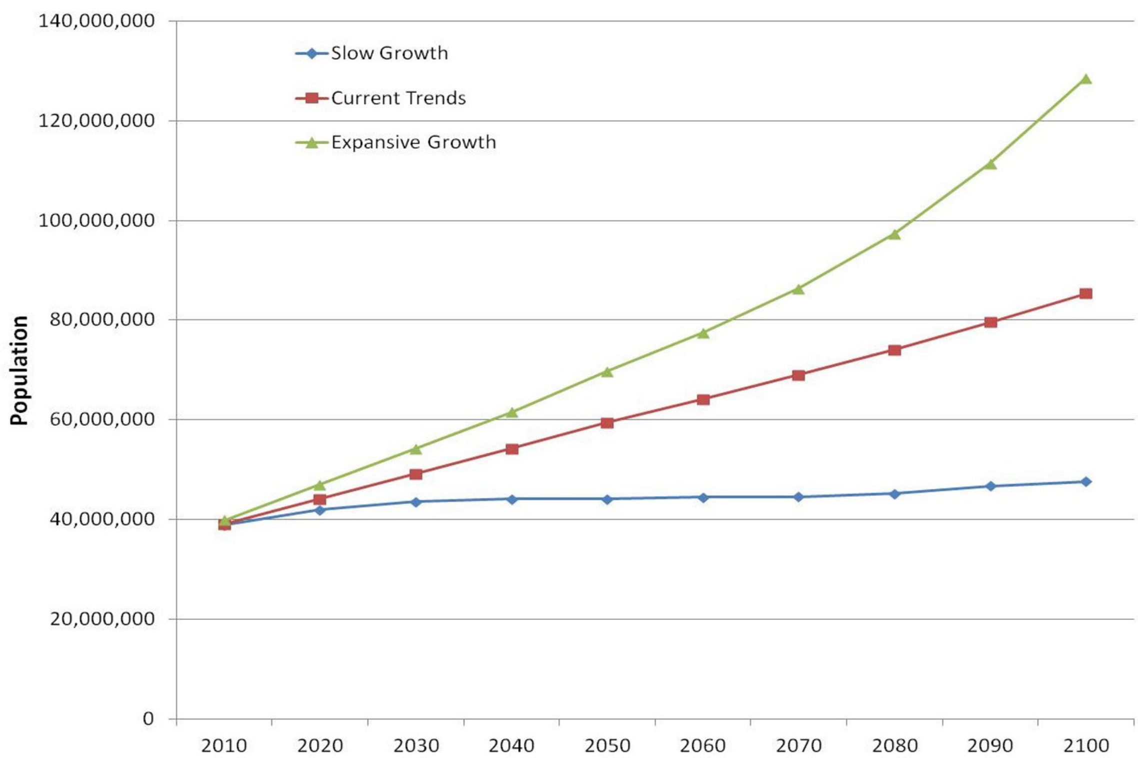


Figure 3-1. Statewide Population Projections under Each Scenario

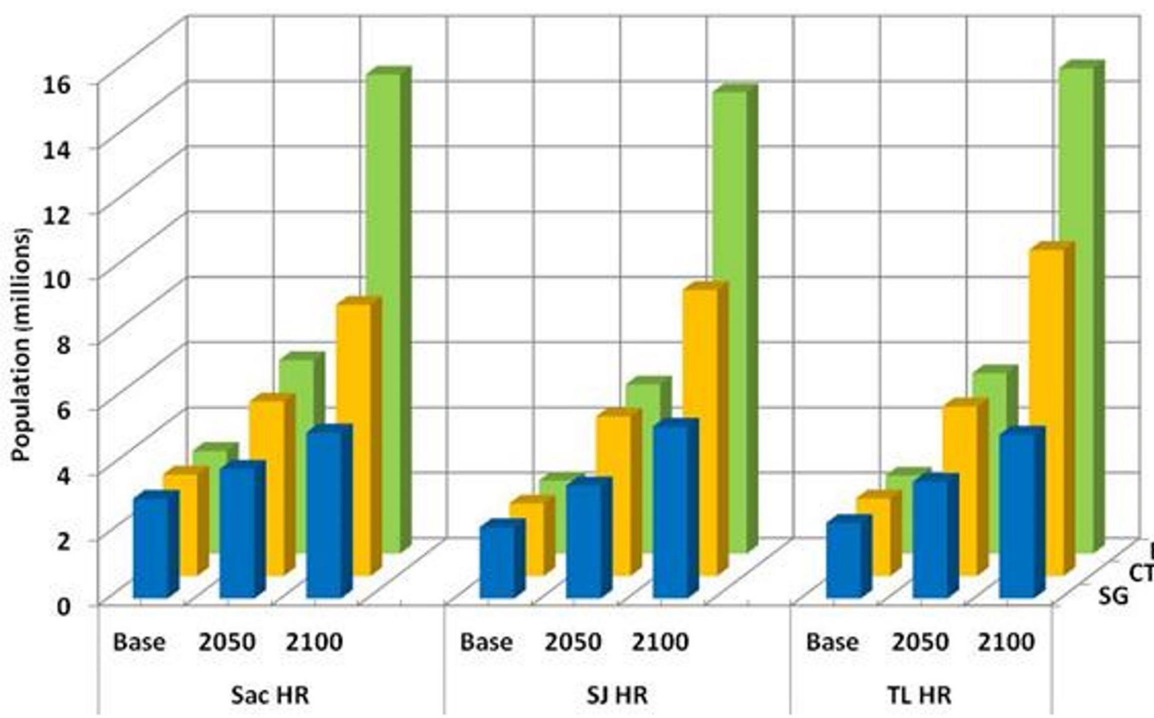


Figure 3-2. Valley Population Projections by Hydrologic Region under Each Scenario

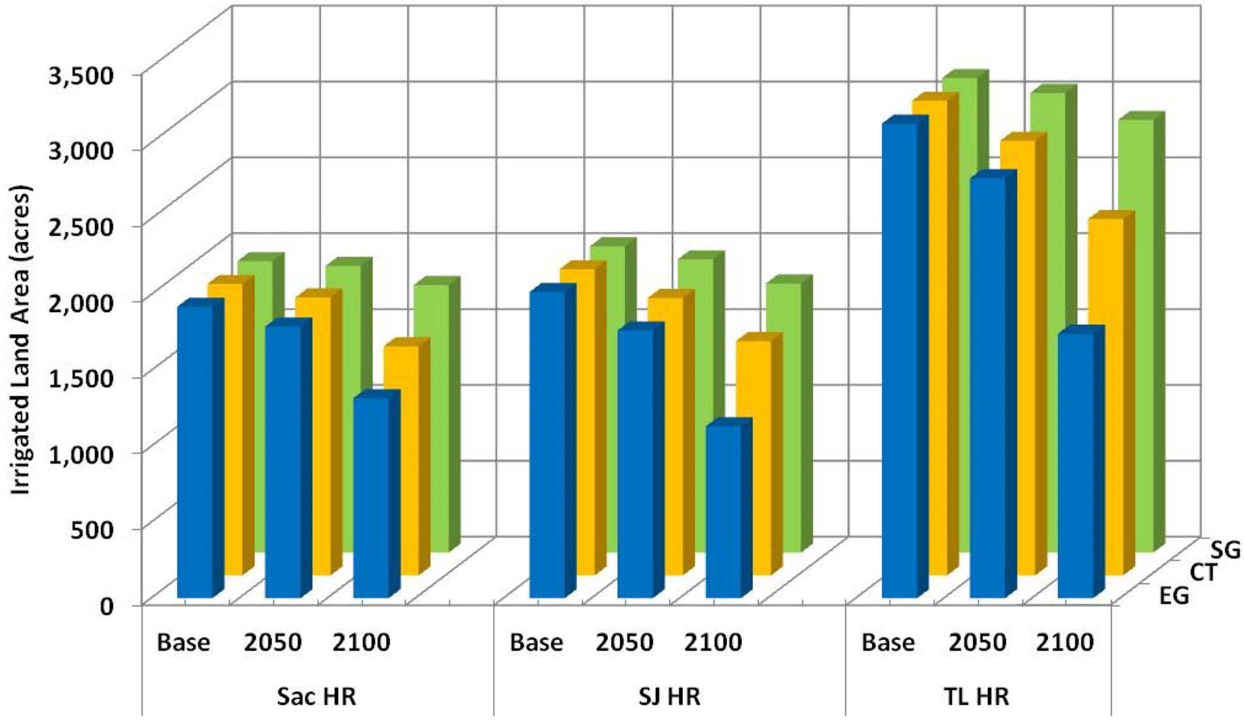


Figure 3-3. Irrigated Land Area Projections by Hydrologic Region under Each Scenario

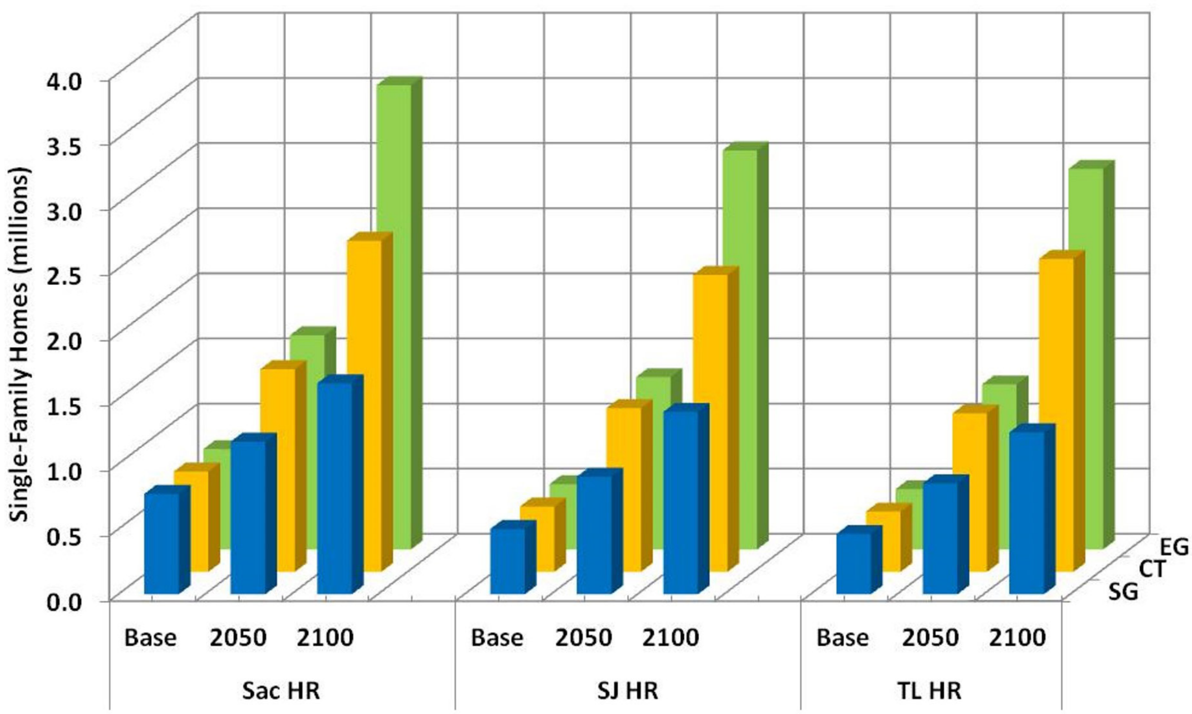


Figure 3-4. Single-Family Home Projections by Hydrologic Region under Each Scenario

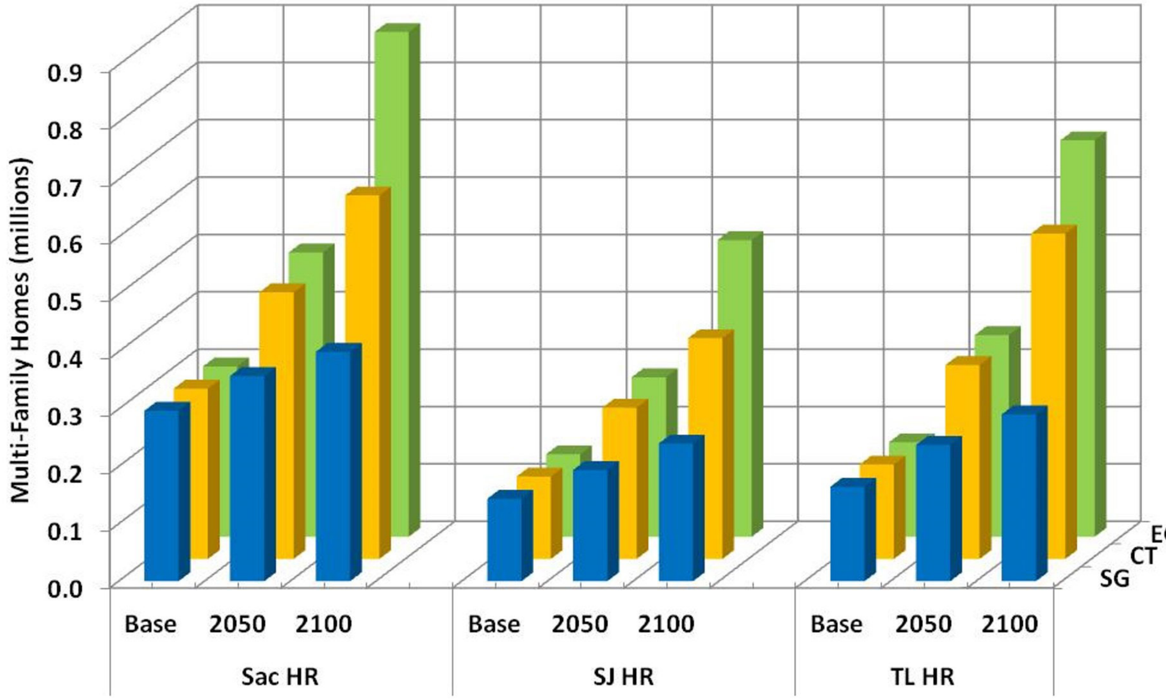


Figure 3-5. Multi-Family Home Projections by Hydrologic Region under Each Scenario

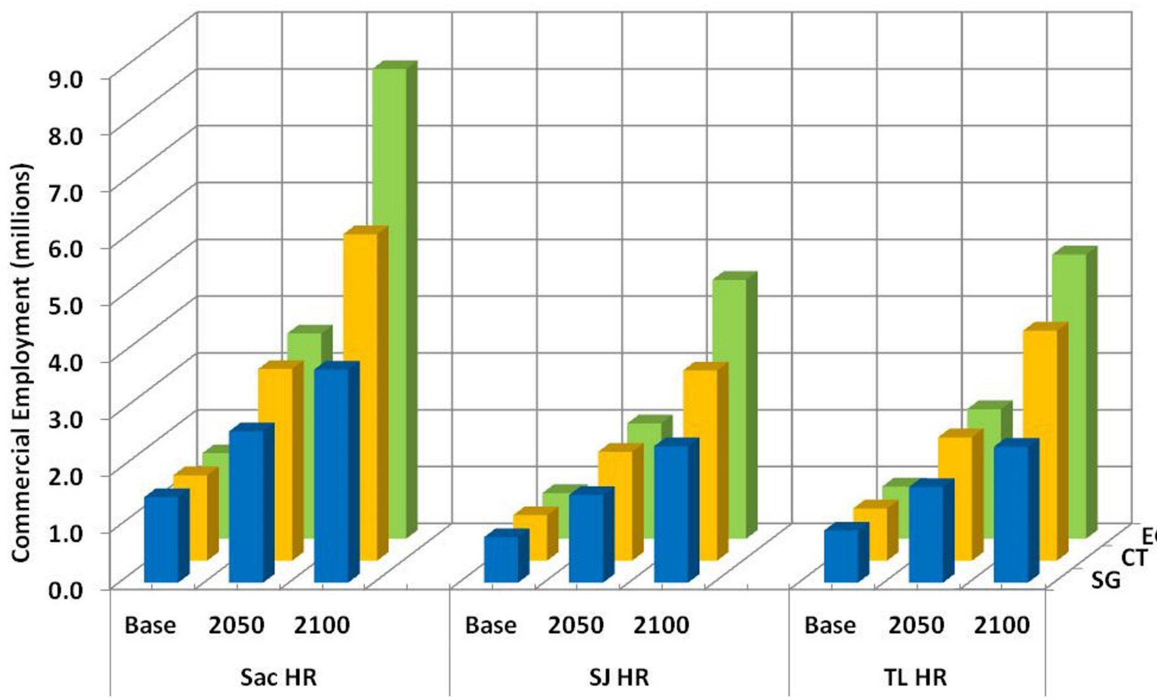


Figure 3-6. Commercial Employment Projections by Hydrologic Region under Each Scenario

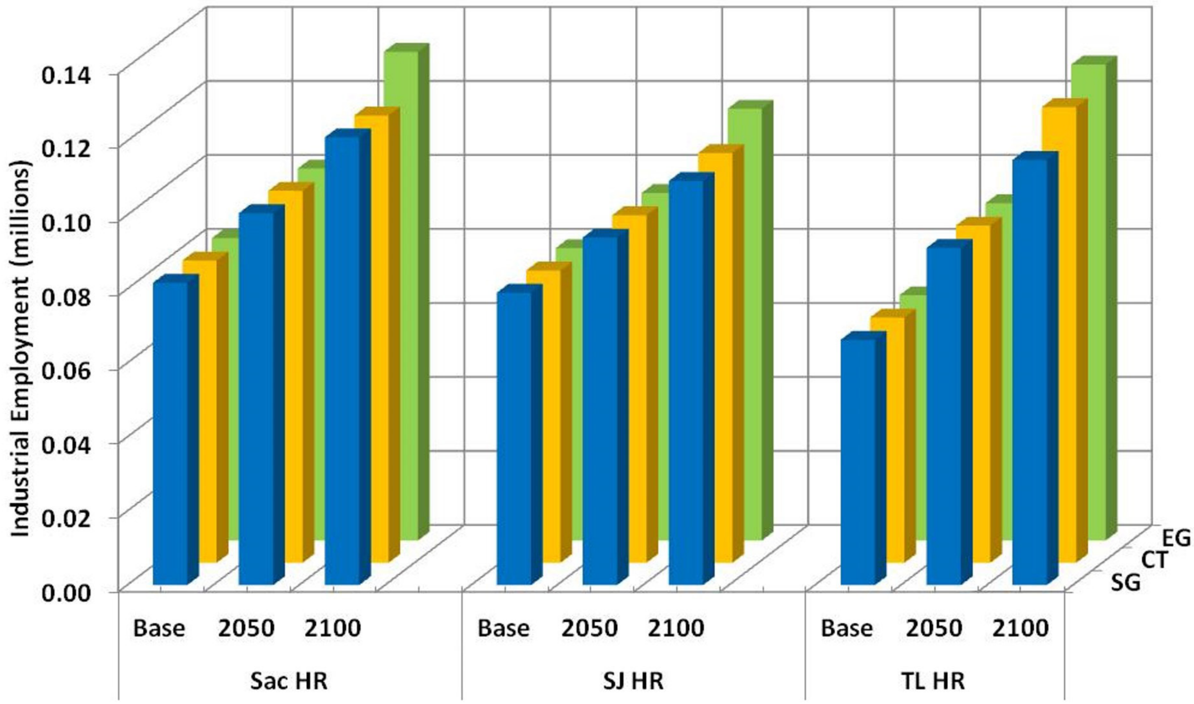
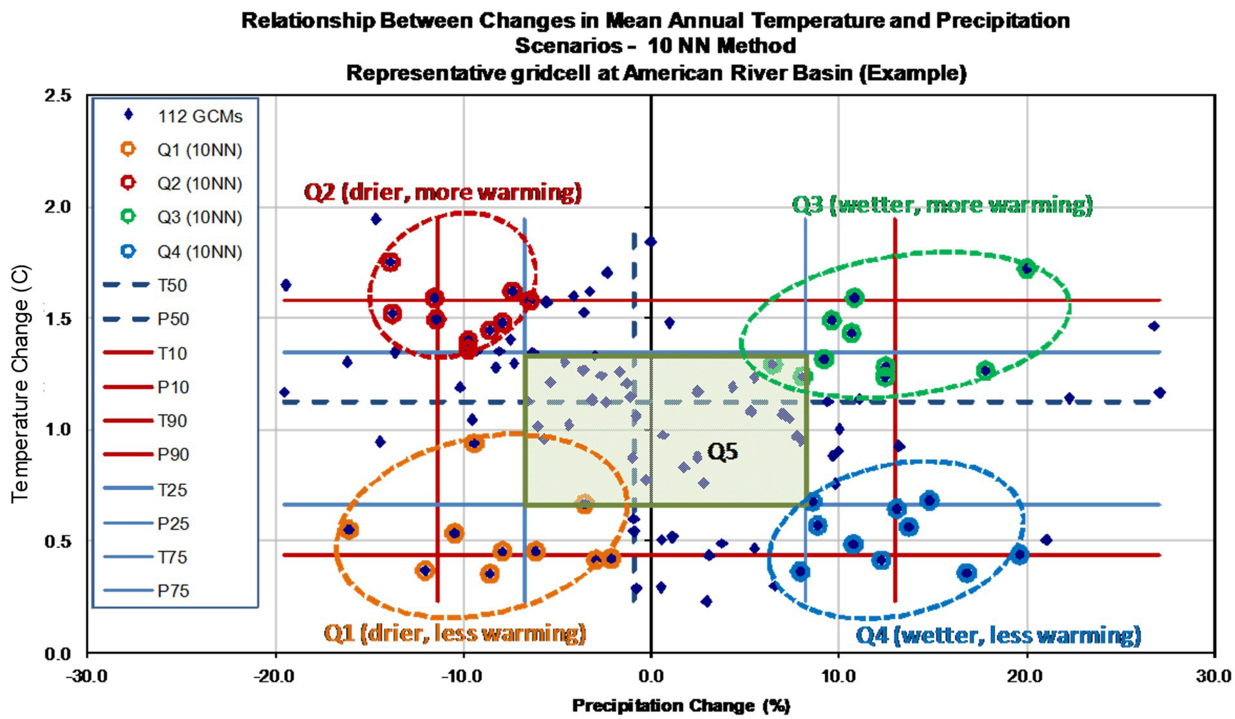


Figure 3-7. Industrial Employment Projections by Hydrologic Regions under Each Scenario



Note: Example of downscaled climate projections and sub-ensembles used for deriving climate scenarios (Q1–Q5) at grid cell in American River Basin at 2025. The Q5 scenario is bounded by the 25th and 75th percentile joint temperature-precipitation change. Scenarios Q1–Q4 were selected to reflect the results of the 10 projections nearest each of 10th and 90th joint temperature-precipitation change percentiles in each of the quadrants.

Figure 3-8. Downscaled Climate Projections Used by the CVP IRP projection uncertainty present in the complete ensemble of the 112 projections, but to allow a smaller representative set of scenarios to be included in the analysis.

To develop the transient climate change scenarios for each of the five regions, a historical cumulative distribution function (CDF) was developed using a 30-year period centered around 1985 (1971–2000) from gridded temperature and precipitation data (Hamlet and Lettenmaier, 2005). In addition, three future CDFs were developed using 30-year periods centered around 2025 (2011–2040), 2055 (2041–2070), and 2084 (2070–2099) from the projected climate data. A “quantile mapping” was developed for each of these periods to redevelop a monthly time series of temperature and precipitation reflecting the observed natural variability sequence (1915–2003) and the projected climate change. The method applies the change for any particular year by interpolating from the two CDFs that bracket the simulation year. This process adjusted the historical observed climate records by the climate shifts projected to occur in the future. An automated process was used to identify ensemble members and generate the five transient projection sequences at locations within the Central Valley watershed.

Figure 3-9 shows the climate grid locations where the transient climate projections were developed and used in the WEAP-CV hydrologic modeling, and LAWS crop evapotranspiration (ET) and yield modeling.

Figure 3-10 shows temperature and precipitation for transient climate scenarios Q1 through Q5 for a representative grid cell in the American River Basin. The plot also contains observed historical temperature and precipitation for comparison. Figure 3-11 shows the transient climate departure with warming gradually increasing over time. All projections were consistent in the direction of the temperature change, but varied in terms of climate sensitivity. It is interesting to note that trends in the precipitation projections were less apparent because of naturally occurring decadal and multi-decadal precipitation variations. By construction, the transient climate scenarios method preserved the historical inter-annual sequences, but included changes in the variability as suggested from the climate projections.

An analysis of the effects of potential future climate changes on agricultural water demands and productivity requires more information than just projections of future temperature and precipitation conditions. Crop growth, yield, and ET are also sensitive to other meteorological conditions including solar radiation (Rs), atmospheric humidity, wind speed, and carbon dioxide (CO_2). The climate projections described above did not include projections for these meteorological conditions. Consequently, several estimation methods using the Q1 through Q5 temperature and precipitation projections were employed to obtain values for these meteorological conditions corresponding to the future climate projections.

To represent a reasonable range of spatial variability in these meteorological conditions, four locations were selected to characterize representative conditions in the Central Valley. These locations are shown in bright red on Figure 3-9. They were selected to include existing California Irrigation Management Information System (CIMIS) stations located at Gerber, Davis, Firebaugh, and Shafter. These CIMIS stations were chosen because at these locations long-term observations of daily maximum and minimum temperature (Tmax and Tmin, respectively), Rs, dew point temperature (Tdew), relative humidity, and wind speed were available. All of the historical data from the stations were also carefully checked for erroneous values prior to preparing the subsequent projections. Missing data values were estimated using methods developed by Annandale et al. (2002).

Rs is one of the primary factors affecting crop ET. It can be estimated from the Tmax and Tmin using the clear sky radiation, which only depends on latitude, day of the year, and a site-specific parameter (B). The CIMIS station historical records where used to calibrate B parameters, and the climate projections of Tmax and Tmin were then used to compute Rs based on the Thornton and Running (1999) method for each of the Q1–Q5 climate projections.

The average Tmax, Tmin, and Rs results in the Baseline; and each of the Q1–Q5 climate projections during the early (2020), mid- (2050), and late (2080) twenty-first century are presented on Figures 3-12 through 3-14.

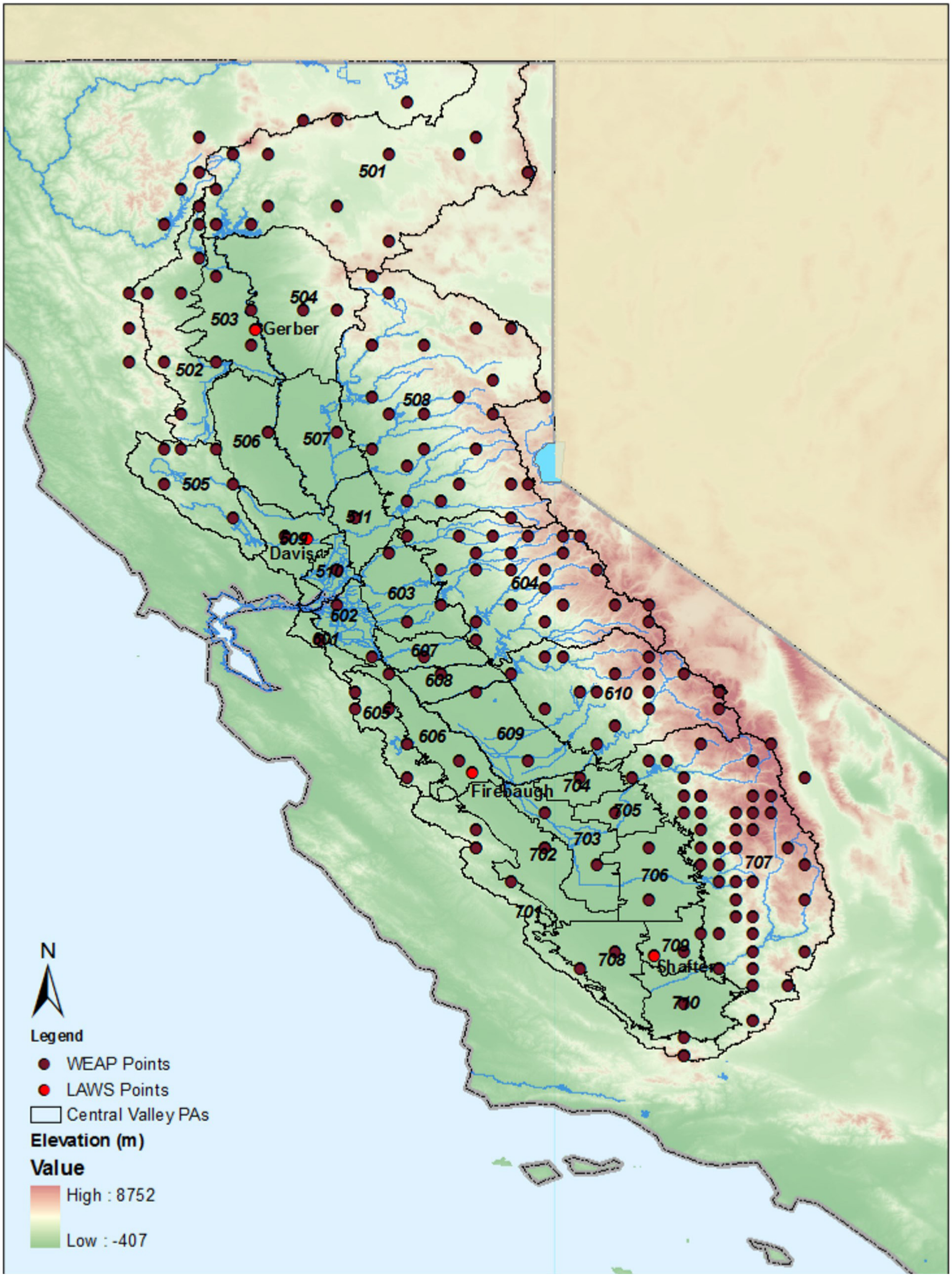
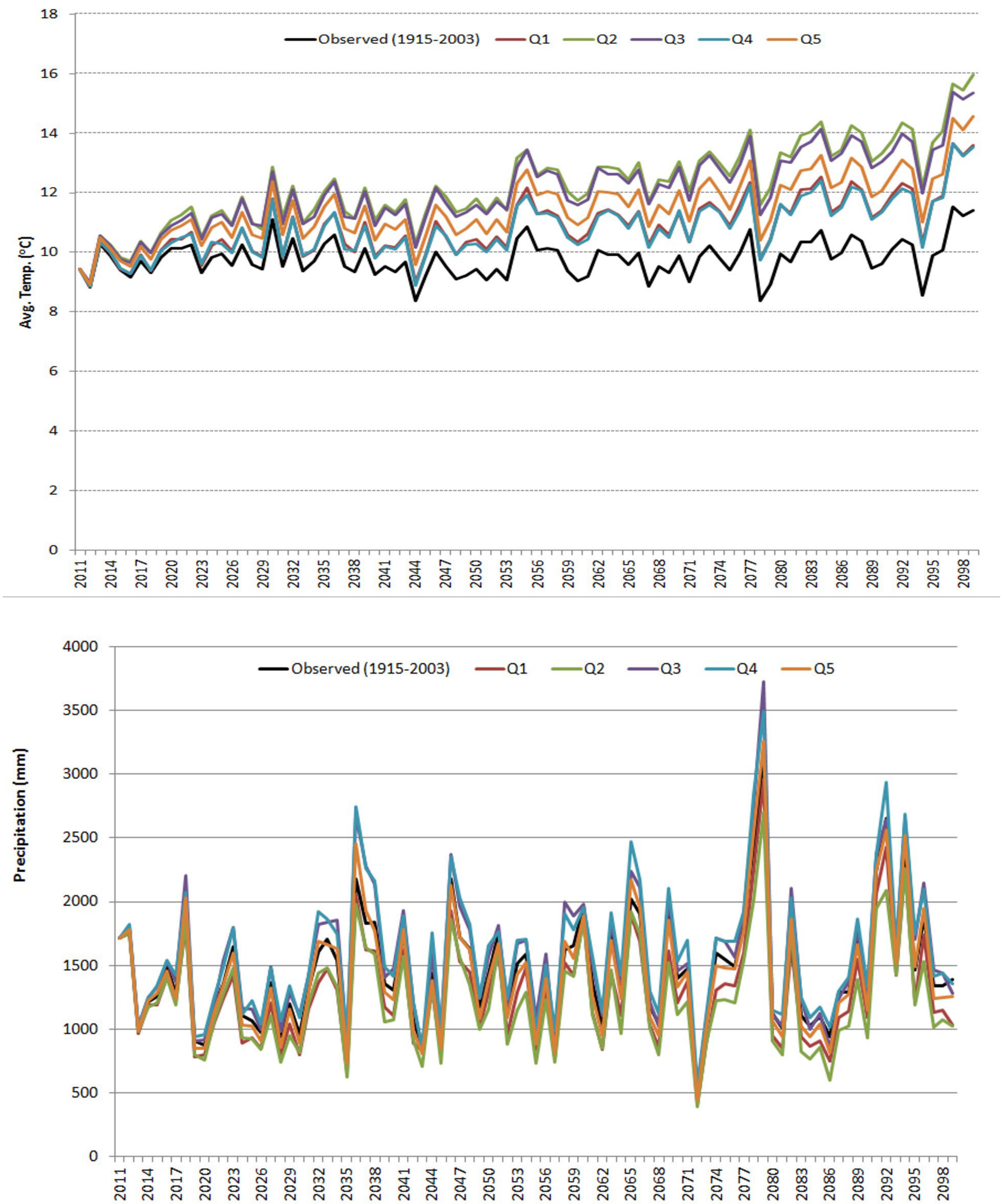


Figure 3-9. Locations of Climate Input Projections in the Sacramento River, San Joaquin River, and Tulare Lake Hydrologic Regions under Each Scenario



Note: Transient ensemble-informed climate scenarios for a representative grid cell in the American River Basin (Example). Average annual temperature is shown in the top plot and annual precipitation in the bottom plot. Colored lines represent transient climate scenarios Q1 through Q5. The black line represents annual average temperature and precipitation computed from historical observed data (Hamlet and Lettenmaier, 2005).

Figure 3-10. Temperature (top) and Precipitation (bottom) Projections under Each Climate Scenario

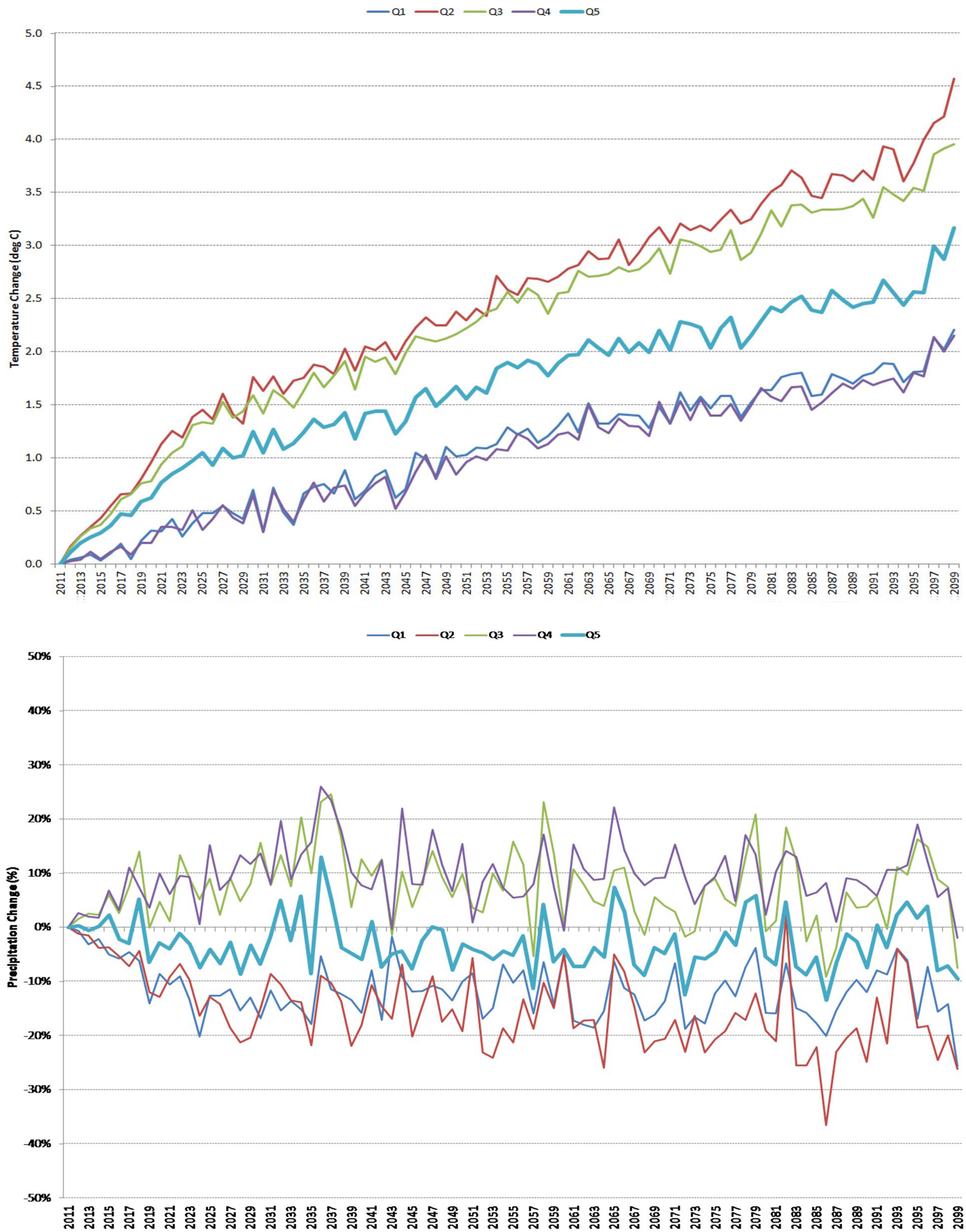


Figure 3-11. Change in Temperature (top) and Precipitation (bottom) Projections in the Sacramento River, San Joaquin River, and Tulare Lake Hydrologic Regions under Each Scenario

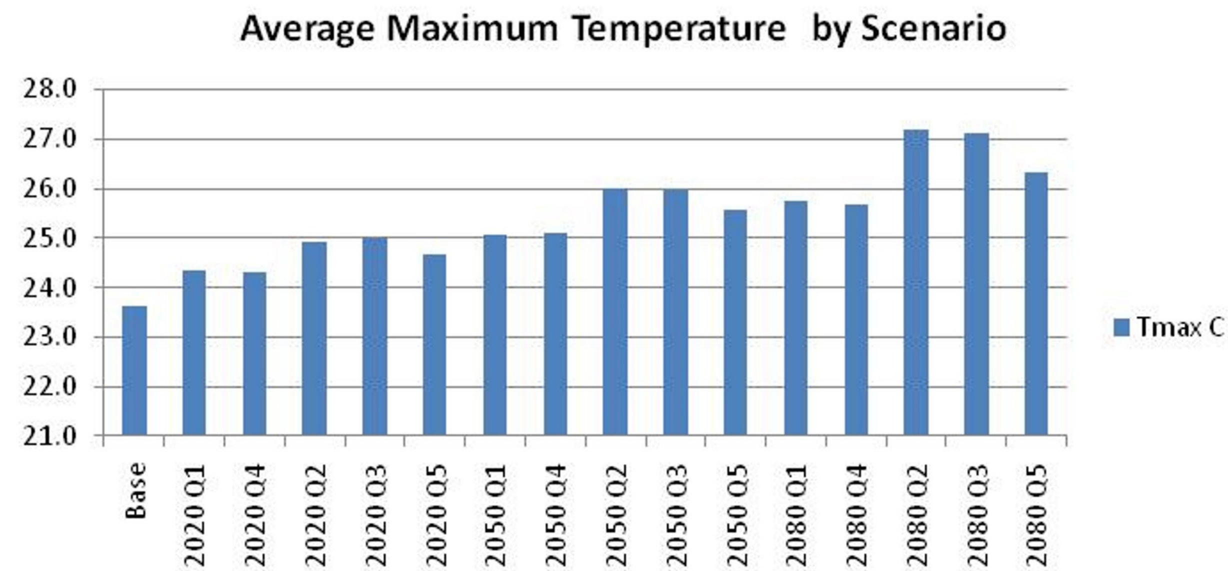


Figure 3-12. Projected Average Daily Maximum Temperatures in °C for Each Climate Scenario

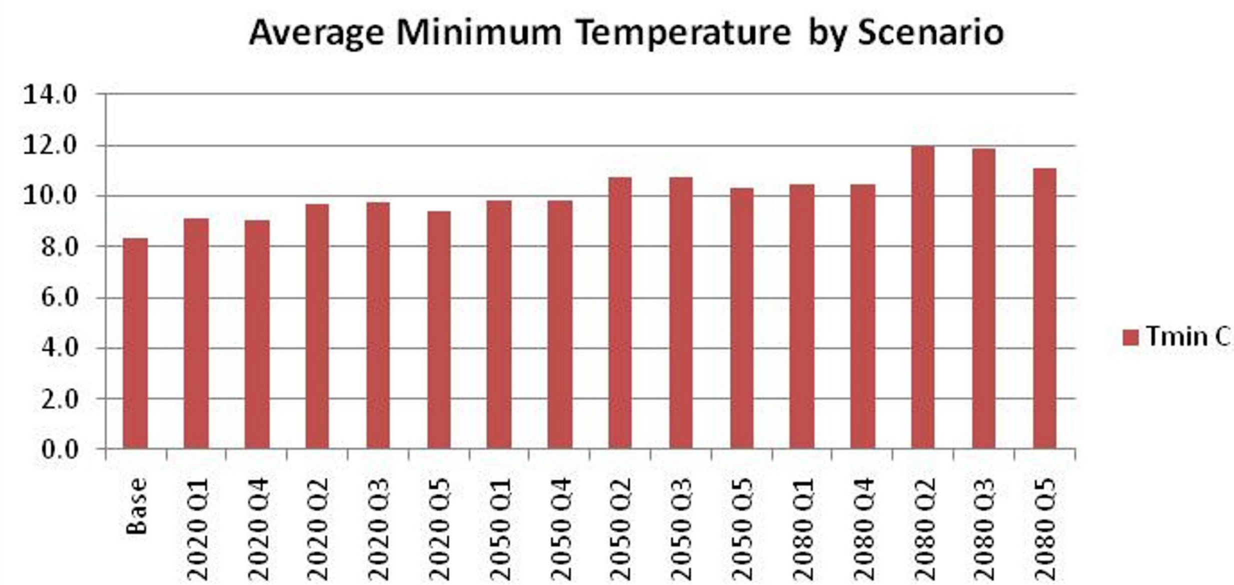


Figure 3-13. Projected Average Daily Minimum Temperatures in °C for Each Climate Scenario during the Early (2020), Mid- (2055), and Late (2084) Twenty-First Century

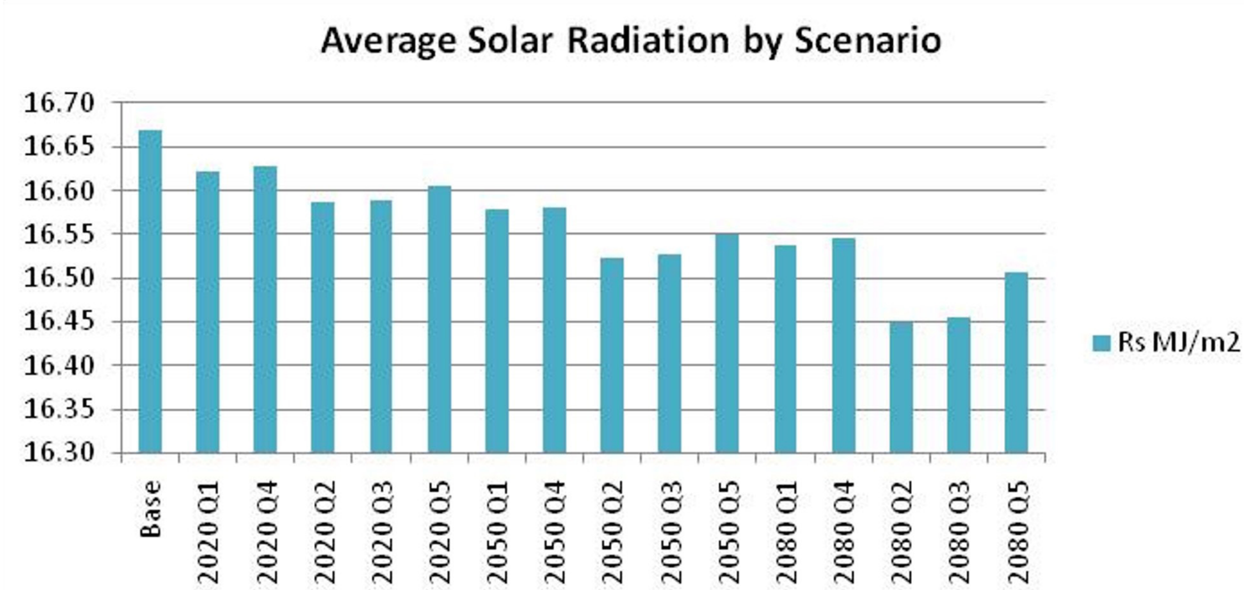


Figure 3-14. Projected Average Solar Radiation in MJ/m2 for Each Climate Scenario during the Early (2020), Mid-(2050), and Late (2080) Twenty-First Century

Atmospheric humidity also has a significant effect on crop ET. As the air becomes drier, ET generally increases. Tdew is an indicator of the moisture content of the air. As the atmospheric humidity increases, Tdew also increases. The daily Tmin is a good indicator of Tdew. Cloudiness and high humidity reduce the amount of heat loss from the surface to the atmosphere, which is generally reflected in higher Tmin values. To estimate projected changes in atmospheric humidity, the CIMIS station records were analyzed to determine the monthly average differences between the observed Tmin and Tdew values. This difference is referred to as the dew point depression. To estimate projected changes in Tdew, these monthly average observed dew point depression values were subtracted for the projected Tmin values. The averaged results for each scenario are presented on Figure 3-15.

The effects of atmospheric humidity are reflected in ET calculations by the difference between the saturated vapor pressure in the moist plant leaves and the typically drier surrounding atmosphere. This difference is referred to as the vapor pressure deficit (VPD). As the VPD increases, crop ET generally increases. Because the saturation vapor pressure is a function of temperature, projections of VPD can be computed from the projections of daily Tmax, Tmin, and Tdew using the results described above. Figure 3-16 shows the projected average VPD results associated with each climate scenario.

CO_2 has also been observed to exert a strong effect on crop ET. As CO_2 concentrations increase, many crops have been observed to exhibit reductions in ET. Consequently, the Q1 through Q5 climate projections were analyzed to determine the frequency in which different CO_2 emission scenarios were present in each of these ensembles. Because the CO_2 concentrations associated with each ensemble member are known, a weighted average CO_2 concentration could be computed for each of the five climate projections on a decadal basis throughout the twenty-first century. These results are presented on Figure 3-17.

3.2.2 Sea Level Changes

The CALFED Science Program (Healey, 2007), National Research Council (National Research Council, 2012), and others have made assessments of the range of potential future sea level rise throughout the twenty-first century. These studies indicate that as sea level rise progresses during the century, the hydrodynamics of the San Francisco Bay–Sacramento–San Joaquin Delta estuary will change, causing the salinity of water in the Delta estuary to increase. This increasing salinity will most likely have significant impacts on water management throughout the Central Valley and other regions of the State.

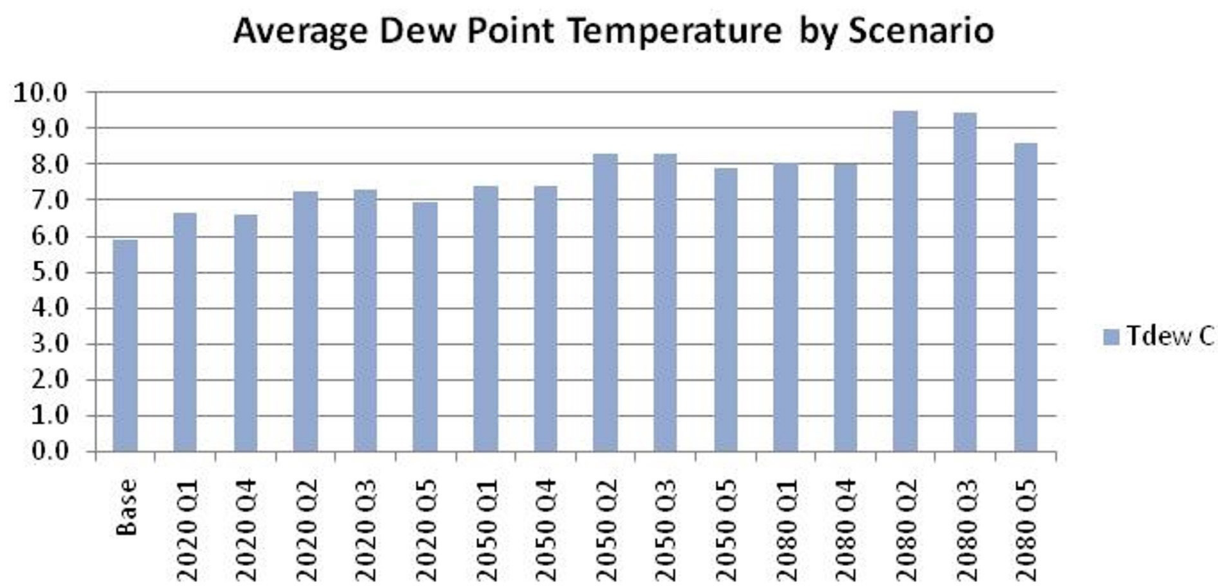


Figure 3-15. Projected Average Daily Dew Point Temperatures in °C for Each Climate Scenario during the Early (2020), Mid- (2050), and Late (2080) Twenty-First Century

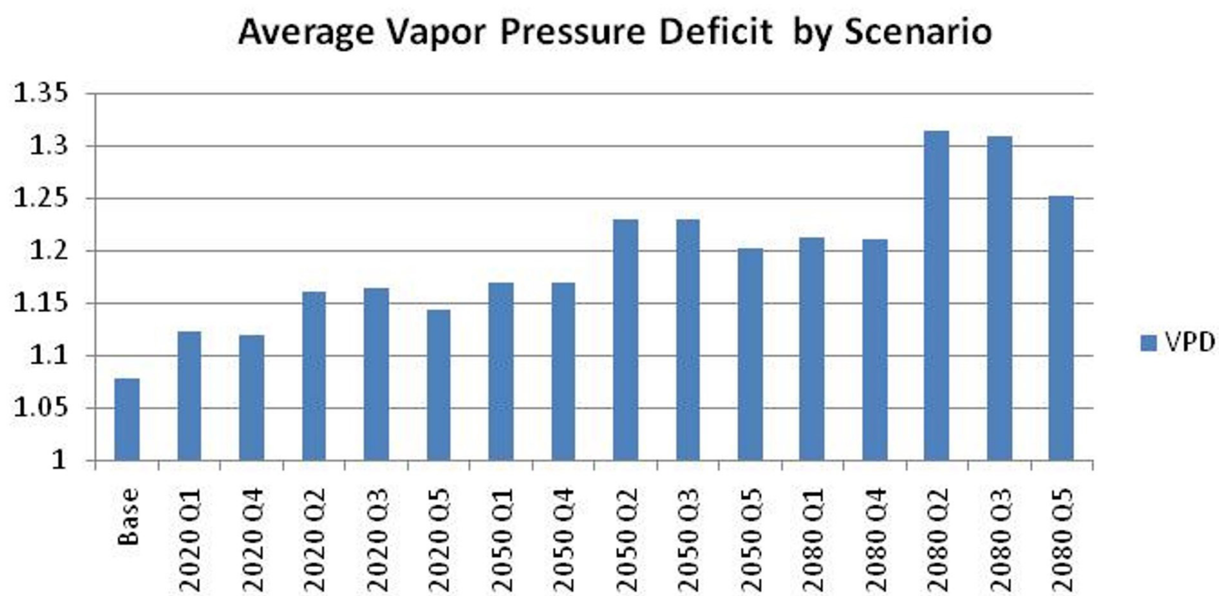


Figure 3-16. Projected Average Daily Vapor Pressure Deficits in kPa for Each Climate Scenario during the Early (2020), Mid- (2050), and Late (2080) Twenty-First Century

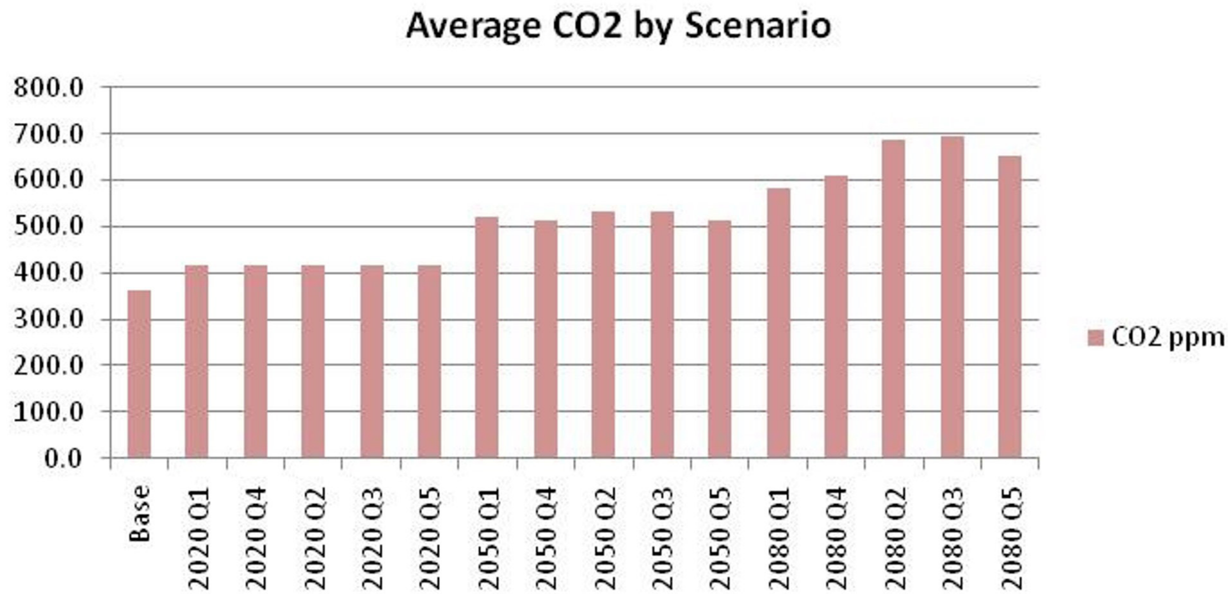
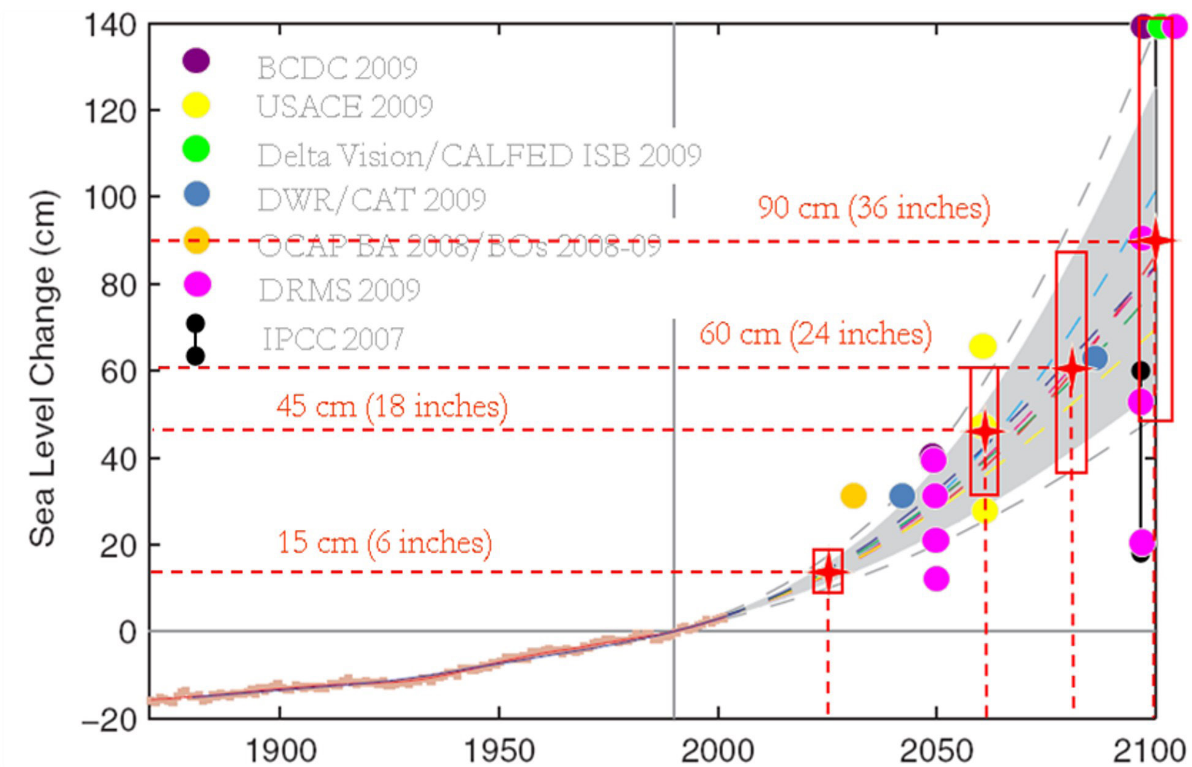


Figure 3-17. Projected Average Daily Average Carbon Dioxide Concentrations (ppm of CO2 by Volume of Air) for Each Climate Scenario during the Early (2020), Mid- (2050), and Late (2080) Twenty-First Century



Note: Complete reference information for citations on this figure is provided in Section 9, References, Table 9-1.

Figure 3-18. Range of Future Mean Sea Level Based on Global Mean Temperature Projections and Sea Level Rise Values

Figure 3-18 shows various projected ranges of potential sea level change in the Bay-Delta through the year 2100. Most State and federal planning processes in the Central Valley (such as the BDCP) have considered sea level rise through mid-century. In these studies, sea level rises from 60 to 90 centimeters (cm) (2 to 3 feet) have been simulated using existing hydrodynamic models. Under current conditions, sea level rise much greater than these levels would most likely inundate many of the Delta islands and would likely cause large-scale levee failures that cannot be simulated without making broad policy assumptions related to levee hardening and land use throughout the Bay Delta.

As part of the CVP IRP transient climate change analysis approach, sea level rise was assumed to gradually increase in the CVP IRP CalLite simulations from 2011 to 2099 on the basis of global temperature as reflected in the range of projections. Figure 3-19 shows the projected sea level rise used for each CVP IRP climate scenario. The highest sea level rises occurred in the two warmest climate scenarios (Q2 and Q3, which have almost the same rates of rise), and other differences among scenarios corresponding to the amount of warming projected in each climate scenario. In the CVP IRP CalLite simulations, an artificial neural network (ANN) model reflecting a no-sea level rise condition was used to determine salinity requirements and conditions in the Delta. This ANN was adjusted to reflect changes in Delta conditions due to sea level rise. For the CVP IRP study, sea level was projected to gradually rise up to a maximum of between 105 and 120 cm across the five scenarios. To adjust the inputs and outputs of the no-sea level rise ANN, relationships between flow and salinity were developed and incorporated into the CVP IRP CalLite model to simulate the effects of the projected sea level rise on the Bay-Delta system. These relationships were developed using results derived from UNTRIM model simulations (MacWilliams et al., 2008) and through calibration based on a CALSIM II simulation performed for the CVP IRP that incorporated sea level rise. In each of the scenarios, sea level rise was assumed to change the elevation and flow-salinity dynamics of the Delta, but the basic configuration of the Delta (levees and islands) was assumed to be unchanged because of difficulty in making defensible assumptions of Bay and Delta community adaptation measures.

3.3 Agricultural Water Demand and Productivity

In the previous sections, the approaches used to develop the projections for climate change on water supply and demand were described. The projections were developed to provide a consistent assessment of how climate change affects both water supply, and agricultural and outdoor urban water demands. The LAWS model (Tansey et al., 2011) was used to compute crop water requirements, growth, and yield on the basis of Q1–Q5 climate projections. To accomplish this objective, the LAWS model was modified to include the biophysical processes that are needed to simulate the major effects of climate on crop ET, growth, and yield. Crop growth and yield modeling are considered important because climate effects on crop yields have important implications for agricultural productivity and economics.

Prior to employing the projected climate changes in the LAWS model, it was calibrated using the historically observed climate data from the Gerber, Davis, Firebaugh, and Shafter CIMIS stations for 20 major crops grown in the Central Valley. The California Crop and Soil Evapotranspiration study (Irrigation Training and Research Center, 2003) was used to provide historical period data on crop ET and growing seasons at the four CIMIS calibration locations. Historical crop yield data were obtained from the Statewide Agricultural Production (SWAP) model (Howitt et al., 2012). Initial estimates of crop parameters were obtained from the literature sources and adjusted to match the reported ET and yield data.

The calibrated LAWS model was used to simulate the effects of climate changes associated with the previously described Q1 through Q5 climate projections. These LAWS simulations produced the corresponding projected crop ET and yield data sets for major crops grown in the Central Valley. These data sets were used in the subsequent WEAP-CV and SWAP modeling. Using these projected crop ET data sets in the WEAP-CV hydrology simulations provided consistent climate-based projections of both water supply and demands in the Central Valley. By including the effects of projected climate

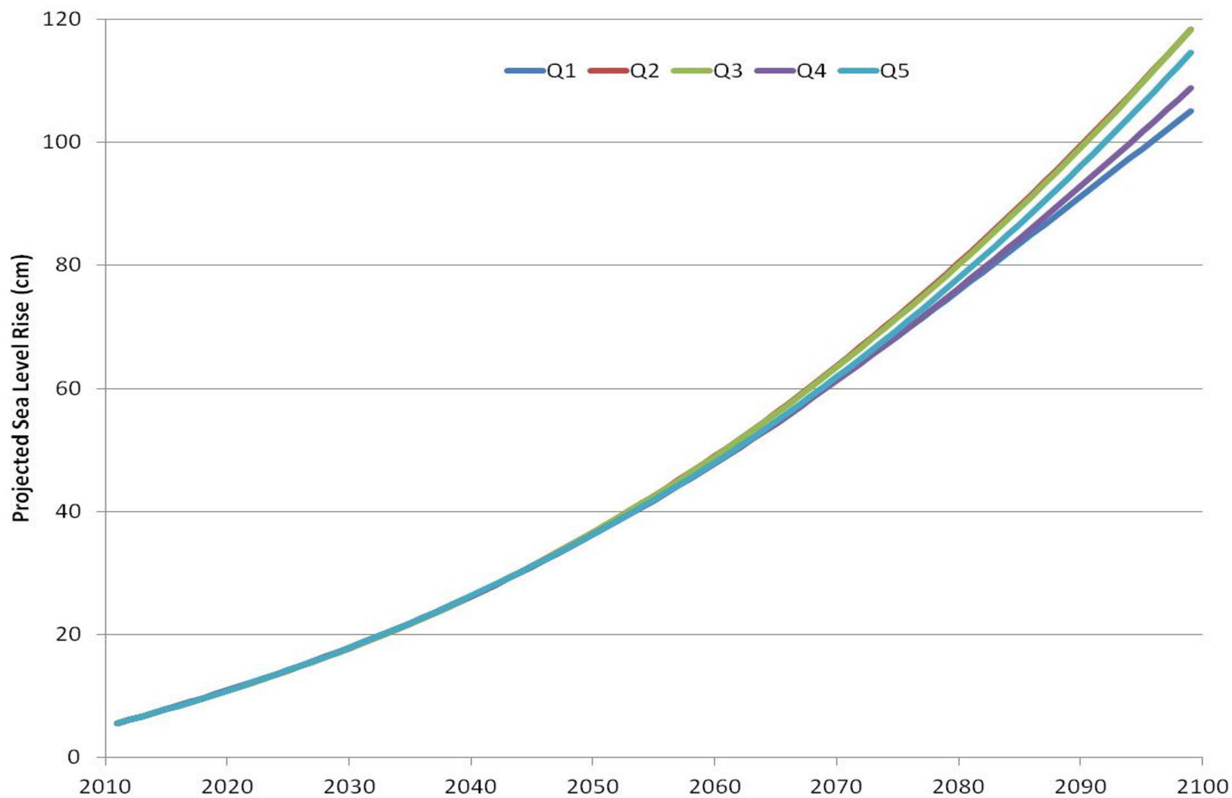


Figure 3-19. Projected Sea Level Rise Values in Each CVP IRP Scenario

changes on both water and demands, an improved representation of climate effects on the CVP-SWP water system operations was achieved.

These improvements in supply and demand consistency also benefitted the agricultural economic evaluations using the SWAP model. The SWAP model was calibrated on the basis of 15 years of observed farmers' decisions about cropping patterns; and it used water supply and demands over time, along with consideration of the costs and revenues associated with these production systems, to determine an optimal land and water resource allocation that maximizes economic benefits. Using both the projected ET and major crop yield data in the SWAP model provided improved consistency among the projected economic changes for each of the Q1 through Q5 climate projections.

SECTION 4 - HYDROLOGY AND SYSTEMS ANALYSIS

4.1 Geographic Representation of the CVP Service Area

The CVP IRP technical analysis was designed to report modeling results for each CVP Division. Much of this supply and demand information was derived from WEAP-CV model results, which are on the CWP's Planning Area spatial scale. Therefore, the hydrology and systems analysis tools were developed to translate the Planning Area–scale data to corresponding data for each of the following nine CVP Divisions:

- Trinity River Division
- Shasta Division
- Sacramento River Division
- American River Division
- Delta Division
- West San Joaquin Division
- Friant Division
- East Side Division
- San Felipe Division

The geographic extent of each Division is defined by the boundaries of the CVP water districts that divert water from rivers with facilities within that Division (see Figure 4-1). Similarly, the demand for each Division is equal to the sum of the demands of all of the CVP districts within the Division.

4.1.1 California Water Plan Geographic Regions

The CWP develops and uses data at the spatial scales of Hydrologic Regions and Planning Areas. California is divided into 10 Hydrologic Regions, each of which is divided into a number of Planning Areas. The CWP has used the WEAP-CV model to develop estimates of hydrology and demand at the Planning Area–scale in the Sacramento River, San Joaquin River, and Delta Hydrologic Regions. In this study, some of these Planning Areas were subdivided into even smaller geographic units for the purpose of improved model simulations.

The Planning Area and Hydrologic Regions modeled in the CVP IRP study are shown on Figure 4-2. These Planning Areas provide coverage for the entire CVP Service Area with the exception of the San Felipe Division. Therefore, hydrology and demand data for the San Felipe Division were developed outside of the WEAP-CV model, as described in the following discussion.

4.2 Simulation of the CVP-SWP Integrated Water System

This section describes how simulations were performed using the CVP IRP models for the projected baseline socioeconomic–climate scenarios and for each potential water management action portfolio. All simulations were performed over the period from October 2011 to September 2099 using a transient approach in which the climate and socioeconomic factors gradually change as the simulation progresses through time.

4.2.1 Approach

The simulation of the CVP IRP scenarios to analyze potential water management actions was performed using a newly developed version of DWR's original CalLite model (Islam et al., 2011) and the CWP's WEAP-CV Planning Area model of the Sacramento and San Joaquin Valleys. For the CVP IRP, both of these models were extended to include the Tulare Lake Basin. The CVP IRP CalLite model was also enhanced to simulate sea level rise and updated to include recent regulatory decisions affecting CVP-SWP operations. These new CVP IRP versions of the CalLite and WEAP-CV models were then applied in an integrated manner to perform the simulations described here. First, the CVP IRP WEAP-CV model was used to develop climate-based watershed runoff for the main watersheds of the Central Valley and climate-based demand estimates for the Delta, Sacramento River, San Joaquin River, and Tulare Lake Hydrologic Regions. The WEAP-CV model was used to simulate precipitation runoff directly from

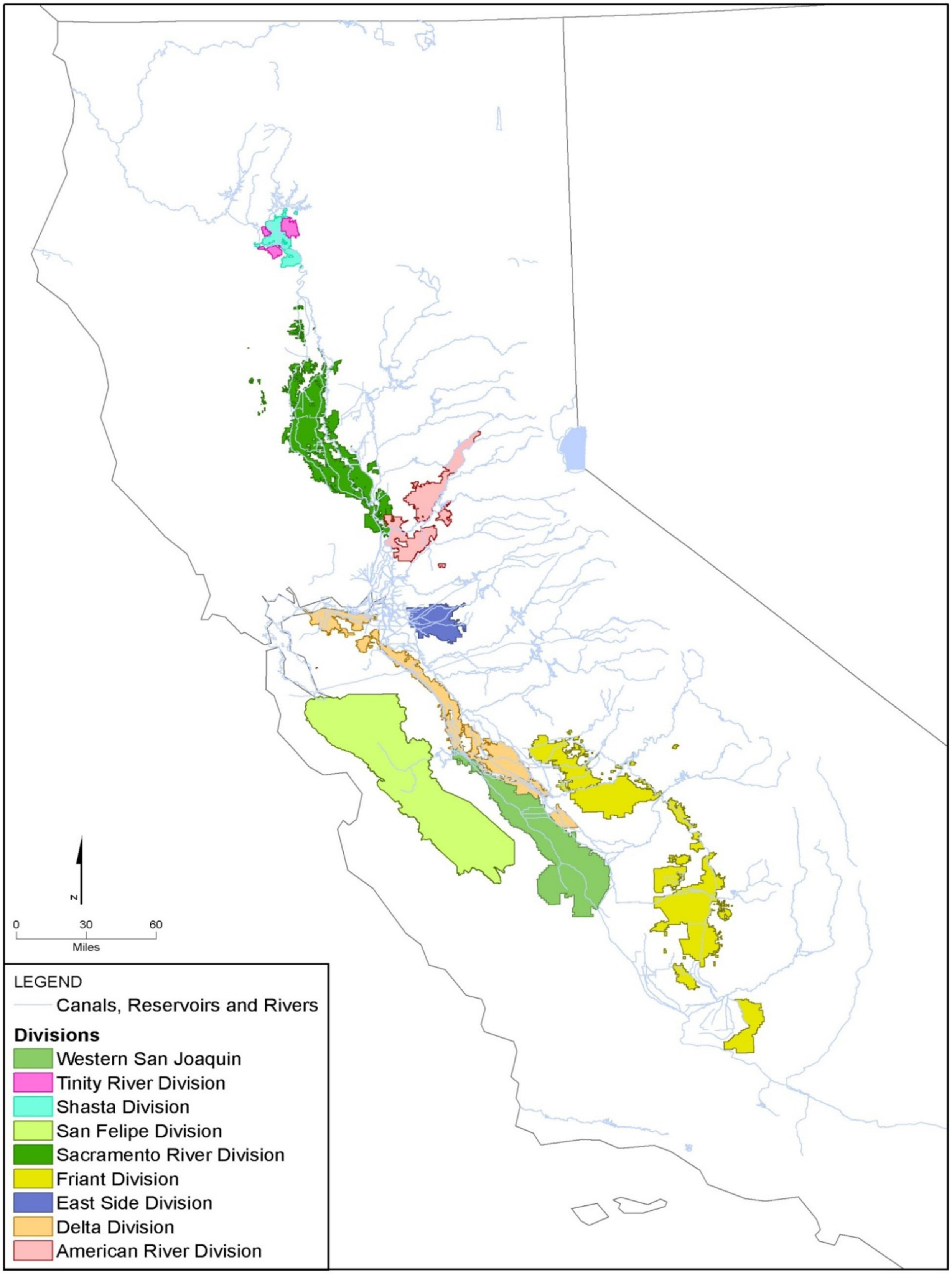


Figure 4-1. Map of CVP Divisions

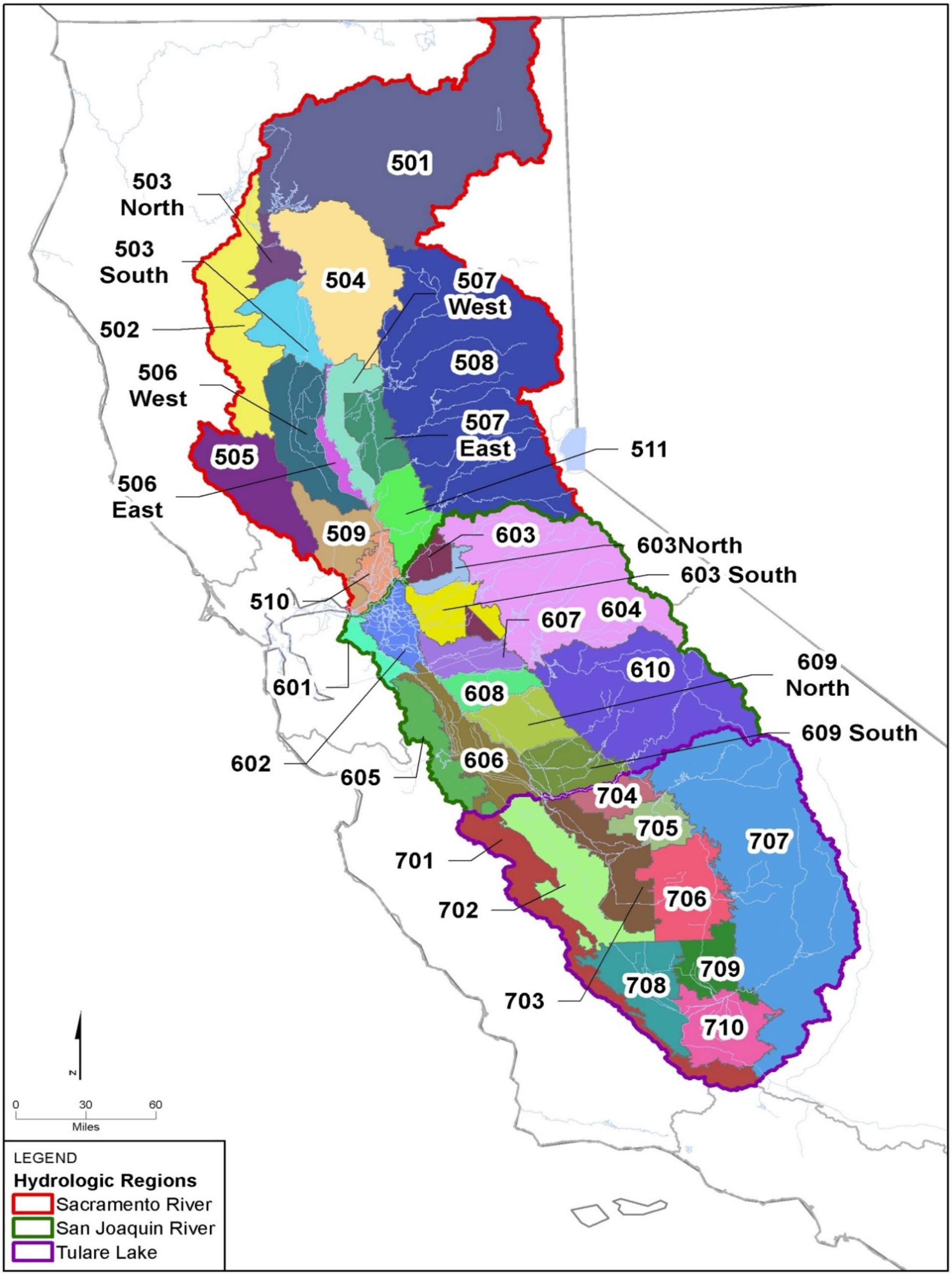


Figure 4-2. Planning Areas in the Sacramento River, San Joaquin River, and Tulare Lake Hydrologic Regions

the climate projections in these watersheds and water demands in each of Central Valley Planning Areas in the Central Valley

The CVP IRP CalLite model simulated water conditions in the CVP and SWP systems, with explicit representations of Bay-Delta regulatory requirements, and the CVP and SWP storage operations and allocation decisions. CVP IRP CalLite simulated CVP and SWP operations in the Sacramento Valley, San Joaquin River system, Tulare Lake Region, the Bay-Delta, and the South-of–Delta export areas.

Figure 4-3 provides a generic representation of a reservoir and river system simulated by the CVP IRP WEAP-CV/CalLite integrated models. The figure depicts hydrology, demand, and operational components included in the simulation, and indicates which model provided the data for each component of the analysis. Table 4-1 lists the components simulated by each model. The WEAP-CV model produced the hydrology and demand components, and the CalLite model produced outputs relating to system operations, and local and systemwide management actions.

Because the CVP IRP WEAP-CV model did not cover the San Felipe Division, the WEAP-CV components shown in Table 4-1 were developed separately for the San Felipe Division and included as inputs into the CVP IRP CalLite simulations. Local inflow and precipitation, agricultural and urban water use, demand, return flows, local deliveries, and groundwater pumping for the San Felipe Division were estimated using county-scale information for San Benito and Santa Clara Counties developed by DWR’s CWP (DWR, 2009a).

The CVP IRP CalLite model simulated SWP, CVP, and non-project deliveries to the San Felipe Division along with local supply-enhancement and demand-reduction actions. Therefore, local water management actions in the San Felipe Division were evaluated despite the absence of a CVP IRP WEAP-CV model of the region.

The CVP IRP WEAP-CV model was used to simulate each of the 18 socioeconomic-climate scenarios for the period between October 2011 and September 2099. Each scenario was analyzed in this period using a transient approach in which the climate and socioeconomic factors gradually change as the simulation progresses through time. The climate-based supply and demand factors produced by WEAP-CV were used as inputs to the CalLite model to perform simulations under different socioeconomic and climatic conditions.

The CVP IRP CalLite model simulated water conditions in the CVP and SWP systems with explicit representations of Delta regulatory requirements with coordinated CVP-SWP reservoir operation criteria and allocation decisions for the Sacramento Valley, San Joaquin River, the Delta, Tulare Lake, and other the South-of–Delta export areas.

The CVP IRP CalLite model was also used to perform simulations of a variety of potential local and systemwide water management actions using the transient approach for each of the 18 socioeconomic-climate scenarios. For each scenario, CVP IRP CalLite computed a supply-demand balance within each CVP Division, and produced CVP Division and systemwide outputs relating to flow, storage, deliveries, and a variety of other performance metrics.

4.2.2 WEAP-CV/CalLite Interaction

The following sections describe the CVP IRP WEAP-CV/CalLite interaction required to perform CVP IRP CalLite simulations using the WEAP-CV output data, and how CVP IRP CalLite used WEAP-CV and CalLite outputs to compute water balances for each CVP Division.

4.2.2.1 Agricultural and Urban Demands

The WEAP-CV model was used to simulate agricultural and urban demands in each Planning Area. The WEAP-CV simulation did not distinguish among CVP, SWP, and non-project demands. To use these data in a CVP IRP CalLite simulation, the demand data produced by WEAP-CV were disaggregated into different contract types and then mapped to the appropriate CVP Divisions. As an example of how CVP contractor districts relate geographically to Planning Areas, Figure 4 4 depicts the CVP contractors surrounding Planning Area 503 North. The figure shows how each Planning Area can contain multiple CVP contractors and a CVP contractor can overlap multiple Planning Areas. A mapping

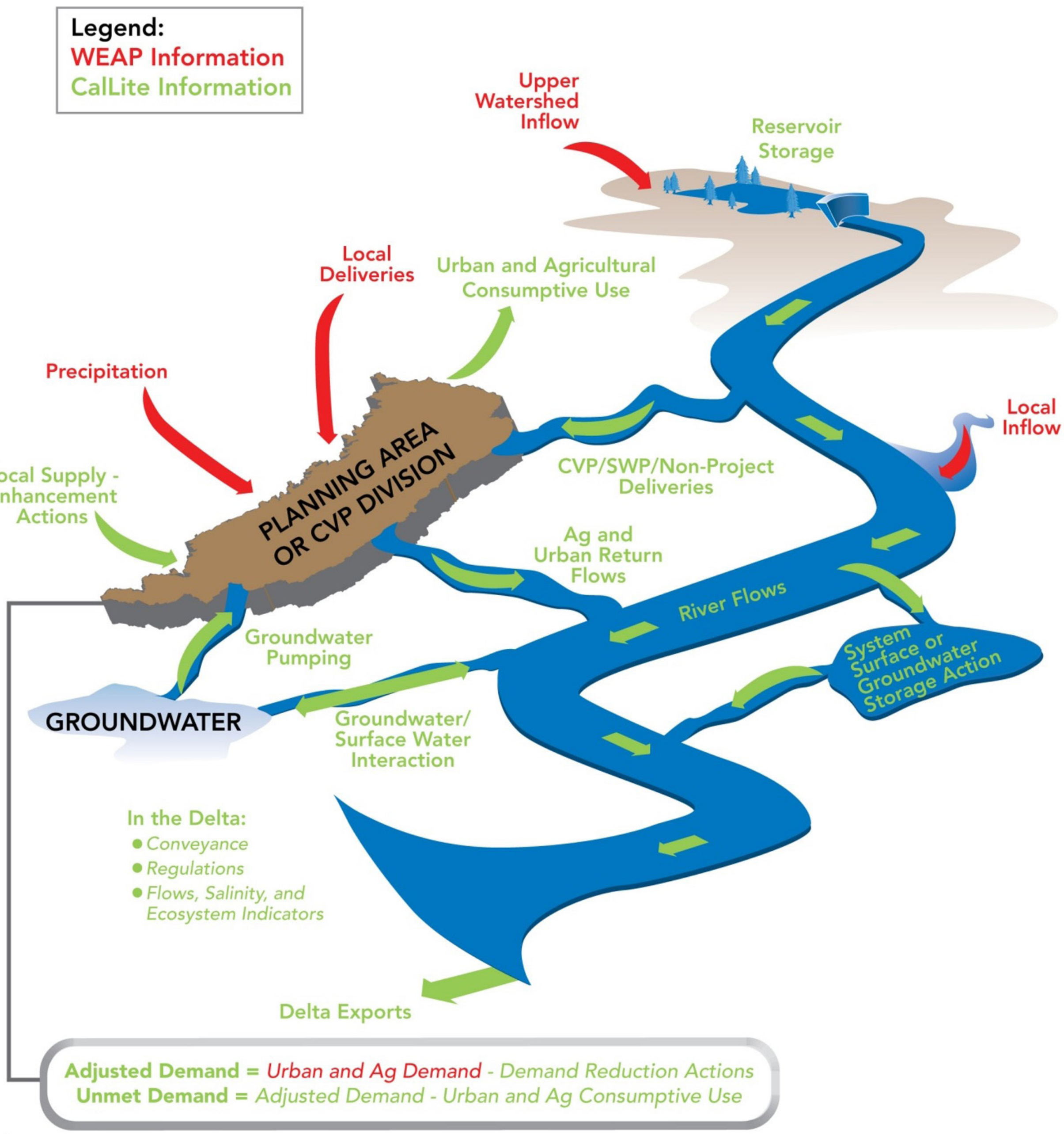


Figure 4-3. Hydrology and Demand Components

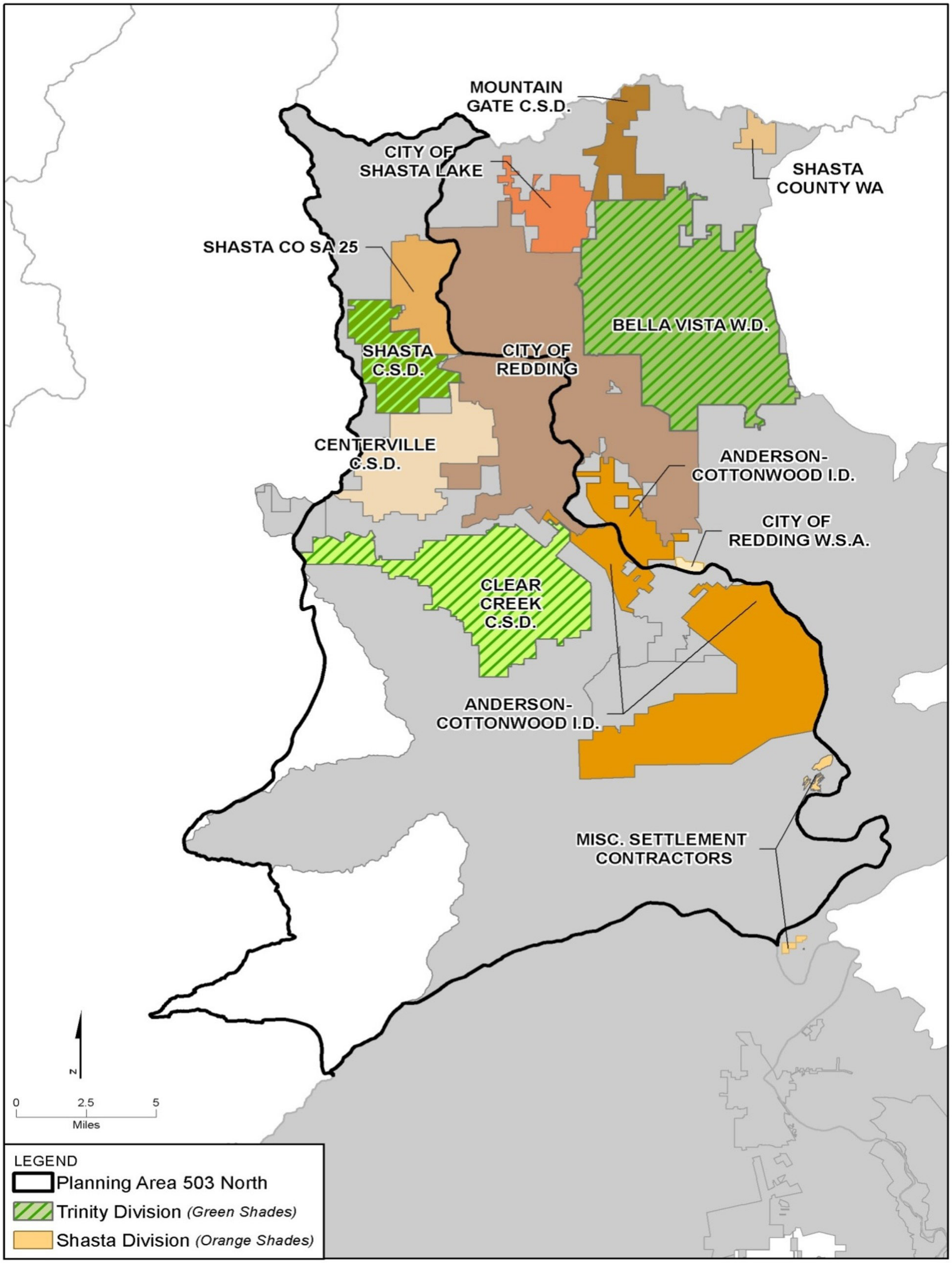


Figure 4-4. CVP Contractor Districts in Planning Area 503 North

Table 4-1. CVP IRP Simulation Components Produced by Each Model

WEAP-CV	CalLite
Upper watershed inflow	SWP, CVP, and non-project deliveries
Local inflow	River flows
Precipitation	Reservoir storage
Urban and agricultural water demand	Agricultural and urban return flows
Local deliveries	Groundwater pumping
	Local supply-enhancement actions
	Local demand-reduction actions
	Systemwide management actions
	Adjusted demand
	Unmet demand
	Delta conveyance, regulations, and exports
	Delta flow, salinity, and ecosystem indicators
	Groundwater/surface water interaction

exercise was performed using Geographic Information System (GIS) to convert the WEAP-CV Planning Area scale data to CVP Divisions.

Therefore, conversion of WEAP-CV demand data for use in CVP IRP CalLite involved the following steps:

- Disaggregation of Planning Area data to CalLite nodes by contract type
- Mapping of CalLite node contract type data to CVP Divisions

The disaggregation of demand within each Planning Area was performed by using Microsoft Excel pre-processing spreadsheets that define the percent breakdown of demand types for each land use type in each Planning Area. The breakdown of demand type was developed using data developed for DWR and Reclamation's joint CALSIM III model development effort. A lookup table was used to define the percent of land use for each water demand type in each Planning Area. The following demand types were used:

- CVP: agricultural, municipal and industrial (M&I), Settlement Contractors, Exchange Contractors, and refuges
- SWP: agricultural, M&I, Feather River Service Area
- Non-project: agricultural and M&I

The pre-processing spreadsheets used this information to compute the demand for each demand type at each CVP IRP CalLite node under each scenario.

The demand breakdown at each CalLite node was also used to map the CalLite node scale demand and delivery data to each CVP Division. This was accomplished by identifying the relevant CVP Division of each contractor in each CalLite node and cross-referencing the contract type demand delivery data to the appropriate Division. The total delivery to each CVP Division was then computed as the total for all relevant nodes.

4.2.2.2 Surface Water and Groundwater Hydrology and Return Flows

The CVP IRP CalLite and WEAP-CV models were enhanced to allow hydrologic and return flow information developed in WEAP-CV to be used as inputs to the CalLite model. The following steps were used to enhance the models:

- The CalLite network was overlain on a map with the Planning Areas, Hydrologic Regions, and the WEAP-CV network.
- The overlay was examined to identify the most appropriate linkage points for integrating rim station and valley floor hydrology, return flows (non-irrigated and irrigated), and surface/groundwater interactions in CalLite and WEAP-CV.

- A data-transfer routine was developed to convert WEAP-CV data to CalLite inputs at each linkage point.

The following sections describe how inputs were developed at each CalLite node for upper watershed inflows, return flows, groundwater/surface water interactions, and valley floor diversion nodes.

4.2.2.3 Upper Watershed Hydrology

The WEAP-CV model was applied to develop upper watershed runoff values under each scenario. However, a comparison of the WEAP-CV-simulated historical period streamflows with the observed streamflows revealed some remaining biases in the modeled flows. As an example, Figure 4-5 shows the difference in monthly values between the WEAP-CV-simulated and observed streamflows into Shasta Lake. These biases result from several factors, including spatial and temporal errors in climate forcings, unresolved surface water and groundwater interactions, and other complexities normally inherent in hydrologic model calibration. To address these issues, bias corrections of the WEAP-CV streamflows were performed for all of the watershed inflows into the CVP IRP CalLite model to better reflect the statistics of the observed streamflows for the historical simulation period. The resulting bias-corrected historical inflow factors were used in the CVP IRP CalLite model to exactly match the annual and monthly averages of the observed historical upper watershed flows. These bias-correction adjustments factors were also used to adjust the upper watershed inflows in the projected future socioeconomic-climate scenario simulations.

4.2.2.4 Valley Floor Hydrology

Valley floor hydrology inputs in CVP IRP CalLite were developed using the "Flow to GW No Irrigation" and the "Flow to River No Irrigation" outputs from WEAP-CV. A GIS mapping process was applied to identify the percentage of the flow coming from each WEAP-CV Planning Area that would run off to each CalLite node and groundwater aquifer. These outputs were mapped to the corresponding CalLite groundwater aquifer nodes and used directly in the CalLite model.

The irrigation return flow components were dynamically simulated in WEAP-CV and vary for each scenario. Therefore, the irrigation return flows were computed dynamically in CVP IRP CalLite using functions derived from WEAP-CV results for each Planning Area.

4.2.2.5 Return Flows and Groundwater-Surface Water Interaction

Return flows and groundwater/surface water interactions were also determined dynamically in CalLite using equations derived from WEAP-CV results to determine the return flow quantities and groundwater/surface water flows resulting from the CalLite deliveries and groundwater storage values in each month. A GIS mapping process was applied to identify the appropriate return flow destinations (such as, river locations and groundwater aquifers) for each CVP IRP CalLite node. A similar mapping exercise was used to determine the appropriate surface water locations for groundwater-surface water interactions to be implemented for each groundwater aquifer.

4.2.3 Computing a Water Balance for a CVP Division

The water balance for each CVP Division was computed in the CVP IRP CalLite model for the 18 socioeconomic scenarios using the CalLite node-scale demand, and hydrology information and the results of the CalLite simulations. The supply and demand components used in the water balance were identified by focusing on the inputs and outputs to the local demand nodes shown on Figure 4-3. Those components used to compute supply and demand are listed in Table 4-2. The difference between the sum of the supplies and the sum of the demands equals the unmet demand computed by CalLite. Post-processing routines in CalLite were developed to produce supply and demand information for each CVP Division.

4.3 Application of Additional Performance Assessment Tools

In addition to using metrics available from CVP IRP CalLite, the effects of future socioeconomic and climatic uncertainties on each portfolio of water management actions were evaluated for water quality and temperature, agricultural and urban economics, hydropower, and GHGs impacts to better understand the benefits and limitations of potential actions. The following tools were

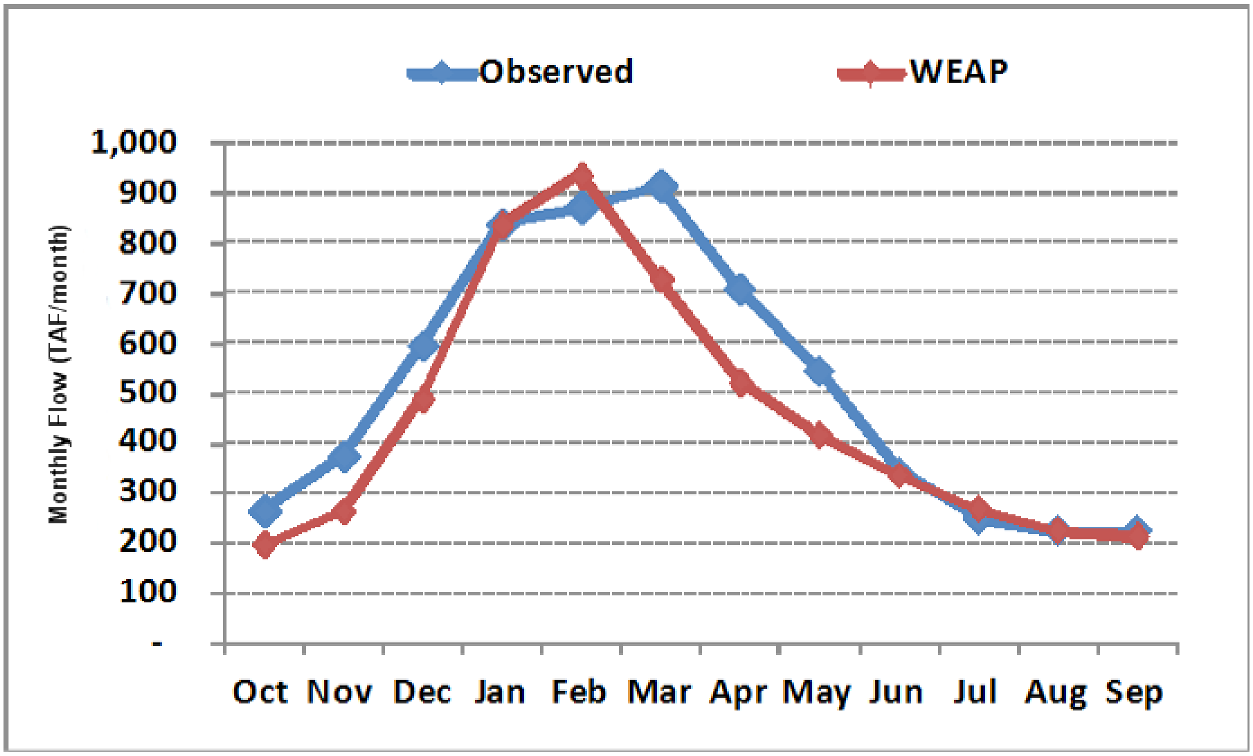


Figure 4-5. Example Comparison of Average Monthly Observed and Non-Bias Corrected Simulated Inflow into Lake Shasta on the Sacramento River

Table 4-2. Components of Supply and Demand Used to Compute Water Balance for CVP Divisions

Supply	Demand
SWP, CVP, and non-project deliveries	Urban and agricultural demands
Local inflow and precipitation	Local demand-reduction actions
Local deliveries	
Groundwater pumping	
Local supply-enhancement actions	

used to perform the analysis and generate reporting metric results for the factors for tradeoff analyses among the portfolios of actions. The following briefly describes how these performance assessments tools were employed:

- Urban economics: the Least-Cost Planning Simulation Model (LCPSIM) provided economic results for the South San Francisco Bay Area region. In addition, the Other Municipal Water Economics Model (OMWEM) was used to perform economic analysis of other urban regions in the remainder of the CVP IRP Service Area.
- Water quality costs: the South Bay Water Quality Model (SBWQM) provided water quality cost results for the South San Francisco Bay Area region.
- Agricultural economics: The SWAP model was used to perform economic analysis in agricultural regions in the Central Valley.
- Water temperature: The Sacramento River Water Quality Model (SRWQM) and San Joaquin River Water Quality Model (SJRWQM) were used to perform temperature analysis on rivers in the Sacramento and San Joaquin Valleys.
- Hydropower and GHGs: LTGen and SWP_Power were used to perform power generation and use analysis for the CVP and SWP systems. These models were enhanced to estimate the GHG emissions changes related to CVP and SWP power and pumping facilities.

Each of these tools was used to simulate three selected socioeconomic-climate scenarios for the Baseline and with each portfolio of water management actions. The following scenarios were selected to reflect the median, upper, and lower range of potential future impacts to reflect a reasonable range of uncertainties:

- Current Trends growth with median future temperature and precipitation change (CT-Q5)
- Expansive Growth with higher temperature and lower precipitation changes (EG-Q2)
- Slow Growth with lower temperature and higher precipitation changes (SG-Q4)

In the following section, a brief overview of these performance assessment tools is presented.

4.3.1 Economic Models

4.3.1.1 Least-Cost Planning Simulation Model (LCPSIM)

LCPSIM is an annual time-step urban water service system reliability management model (DWR, 2009b). Its objective is to estimate the least-cost water supply management strategy for an area, given the mix of available supplies. The model uses a shortage loss function derived from contingent valuation studies and water agency shortage allocation strategies. It accounts for the ability of shortage management (contingency) measures, including water transfers, to reduce regional costs and losses associated with shortage events. It also considers long-term regional demand-reduction and supply-augmentation measures in conjunction with regional carryover storage opportunities that can reduce the frequency, magnitude, and duration of those shortage events.

A shortage event, or foregone use, is the most direct consequence of water supply unreliability. Foregone use occurs when, for example, residential users or businesses have established a lifestyle or a level of economic production based on expected availability of water that is not met in a particular year or sequence of years.

Assuming that long-term supply augmentation measures are adopted in order of their cost, with lowest-cost measures adopted first, LCPSIM finds the water management strategy that minimizes the sum of the total annual cost of the adopted long-term measures and the total expected annual shortage costs and losses remaining after their adoption. The value of the availability of a supply from a proposed project can be determined from the change it produces in this least-cost mix of supply measures and shortages.

The LCPSIM, San Francisco Bay – South model was updated for the CVP IRP for three development scenarios at the 2025, 2055, and 2084 levels of development. Model refinements primarily involved updating model parameters with available population and water portfolio information from Reclamation and DWR's CWP (2009a). Parameters pertinent to the level of development (LOD) not available from the CWP

(DWR, 2009a) were estimated using the existing 2025 and 2055 models. Model preparation also included necessary adjustments to the model analysis period to accommodate CalLite model outputs.

4.3.1.2 Other Municipal Water Economics Model (OMWEM)

Several relatively small M&I water providers were not covered by LCPSIM. A set of individual spreadsheet models, collectively called OMWEM, was used to estimate economic benefits of changes in SWP or CVP supplies for potentially effected M&I water providers outside the San Francisco Bay – South region. The model includes CVP M&I supplies north of the Delta, SWP and CVP supplies to the Central Valley and the Central Coast, SWP supplies or supply exchanges to the desert regions east of the South Coast Hydrologic Region, and American River contractors. The model estimates the economic value of M&I supply changes in these areas as the change in cost of shortages and alternative supplies (such as groundwater pumping or transfers).

Data available from 2010 Urban Water Management Plans were used to estimate 2025 water demand and supplies for an average condition and a dry condition, and to identify additional water supply options and their costs. Water demand estimates for 2055 and 2084, at the three development scenarios, were based on population projections developed by the CVP IRP. For each LOD and develop-ment scenario, OMWEM used project water supplies to match supply to demand. If supply was insufficient to meet demand in years categorized as below normal water supply or drier, the model calculated the cost of additional water supplies.

4.3.1.3 South Bay Water Quality Model (SBWQM)

SBWQM was used by the CVP IRP to perform M&I salinity assessment for the portion of the Bay Area region from Contra Costa County in the north to Santa Clara County in the south. The model was originally developed and used for the economic evaluation of a proposed expansion of Los Vaqueros Reservoir (Reclamation, 2006). It uses estimated relationships between salinity, and damages to residential appliances and fixtures to estimate the benefits from changes in salinity. Specific model outputs compare change in average salinity and change in annual salinity costs.

The model inputs included project water supply and chloride concentrations in milligrams per liter from CalLite. Separate calculations were provided for the Contra Costa Water District (CCWD) and agencies that use the South Bay Aqueduct (SBA). For CCWD, water quality estimates were based on diversion volume and water quality at Old River and Rock Slough. For the other areas, water quality was based on diversion volume and salinity at H. O. Banks Pumping Plant (Banks PP). Changes in water quality at the City of Antioch’s diversion were used to estimate additional cost of treatment or replacement supply.

The SBWQM was updated for three development scenarios at three levels of development, 2025, 2055, and 2084. Model preparation involved updating available population and water portfolio information from Reclamation and DWR’s CWP (2009a).

4.3.1.4 Statewide Agricultural Production Model (SWAP)

The SWAP model is a regional model of irrigated agricultural production and economics that simulates the decisions of agricultural producers (farmers) in California (Howitt et al., 2012). Its data coverage is most detailed in the Central Valley, but it also includes production regions in the Central Coast, South Coast, and desert areas. The model assumes that farmers maximize profit subject to resource, technical, and market constraints. Farmers sell and buy in competitive markets, and no one farmer can affect or control the price of any commodity. The model selects those crops, water supplies, and other inputs that maximize profit subject to constraints on water and land, and subject to economic conditions regarding prices, yields, and costs.

SWAP incorporates project water supplies (SWP and CVP), other local water supplies, and groundwater. As conditions change within a SWAP region (for example, the quantity of available project water supply increases or the cost of groundwater pumping increases), the model optimizes production by adjusting the crop types and acreages, water sources and quantities used, and other inputs. It also fallows land when that appears to be the most cost-effective response to resource conditions.

The SWAP model covers 27 agricultural subregions in the Central Valley that were analyzed for the CVP IRP study. The SWAP model was used to compare the short- or long-run response of agriculture to potential changes in SWP and CVP irrigation water delivery, other surface water or groundwater conditions, or other economic values or restrictions. Results from the CalLite model were used as inputs into SWAP through a standardized data linkage tool. Groundwater analysis was used to develop assumptions, estimates, and, if appropriate, restrictions on pumping rates and pumping lifts for use in the SWAP model. Model output includes intensive and extensive margin production response by agriculture, input use per acre, and aggregate input use, respectively.

4.3.2 Water Temperature Models

SRWQM and SJRWQM were developed by Reclamation and others to simulate water temperature in the major CVP reservoirs and rivers in the Sacramento River and San Joaquin River systems. These models were developed using integrated HEC-5 and HEC-5Q models. SRWQM simulated mean daily reservoir and river temperatures at Shasta, Trinity, Lewiston, Whiskeytown, and Keswick Reservoirs and the Trinity River; Clear Creek; the upper Sacramento River from Shasta to Knights Landing; and Stony Creek by using the flow and meteorological parameters on a 6-hour time step. SJRWQM simulated mean daily reservoir and river temperatures in the San Joaquin River Basin stretching from the rim reservoirs (New Melones, New Don Pedro, McClure, and Millerton) to Vernalis by using flow and meteorological parameters on a 6-hour time step. More detailed descriptions of the SRWQM and SJRWQM are available in two reports by Resource Management Associates, Inc. (2003 and 2007).

4.3.3 Hydropower and Greenhouse Gas Models

The hydropower analysis used several spreadsheet post-processors that evaluated the power impacts of flow scenarios from CALSIM II operations studies on a monthly time step. The following post-processor tools were used in the CVP IRP analysis:

- LTGen: analyzes hydropower generation and usage at CVP facilities
- SWP_Power: analyzes hydropower generation and usage at SWP facilities

For power generation facilities, the tools estimated average annual energy generation as well as average annual peaking power capacity. For pumping facilities, the tools estimated average annual energy requirements. The tools also checked to determine whether off-peak energy use targets were being met. Transmission losses were estimated for both pumping and generation facilities.

For the CVP IRP, LTGen and SWP_Power were enhanced to estimate GHG emissions in the SWP system (due to greater energy use than energy generation) or potential GHG offsets in the CVP system (due to greater energy generation than use) that are related to energy generation and use at the major project facilities so that a “relative” GHG footprint could be evaluated for each new water management scenario.

4.4 Reporting of Modeling Results

4.4.1 Performance Metrics

Performance metrics provide a common technical basis for comparing water management actions. They can be used to identify the impacts of the water management actions in an incremental fashion to identify the benefits and tradeoffs among actions. For the CVP IRP, tradeoff analyses were performed among the different actions using performance metrics related to water supply, water quality (salinity and temperature), hydropower, GHGs, socioeconomics, and ecological resources. These metrics were quantified using the outputs of the CVP IRP modeling tools for the Baseline and selected portfolios of water management actions as described in the following sections.

4.4.2 Decision Support and Analysis Tool

A CVP IRP Decision Support and Analysis Tool (DSAT) consisting of a geodatabase and GIS viewer was also developed to display performance metrics results for each CVP Division. A convenient graphical user interface provides users with the capability to spatially display CVP Division information, scenarios, and strategies using predefined queries and simple reporting capabilities. These capabilities include queries to view spatially referenced documents. Figure 4-6 shows an example screen from the CVP IRP DSAT that demonstrates the types of displays that can be shown. The current version of the DSAT displays current and future water supply and demand affecting water management in each CVP Division.

Figure 4-6. Example Decision Support and Analysis Tool Screen

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