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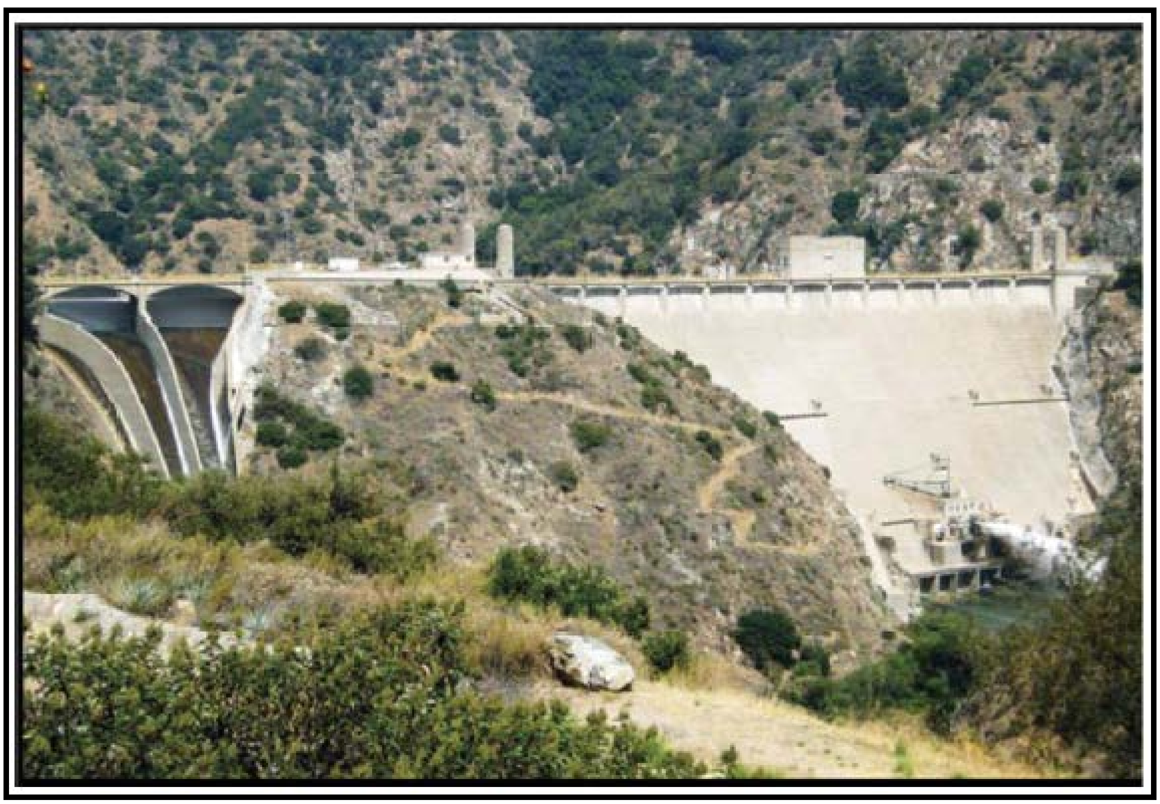
Los Angeles Basin Stormwater Conservation Study

Task 3.1 Development of Climate-Adjusted Hydrologic Model Inputs



U.S. Department of the Interior
Technical Service Center
Bureau of Reclamation

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Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

Cover Photo: Morris Dam across the San Gabriel River, California.

Los Angeles Basin Stormwater Conservation Study

Task 3.1. Development of Climate-Adjusted Hydrologic Model Inputs

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Acronyms and Abbreviations

°C	degrees Celsius
BCCA	Bias-Correction Constructed Analogue
BCSD	Bias-Correction and Spatial Disaggregation
CDF	Cumulative Distribution Function
CMIP3	Coupled Model Intercomparison Project, Phase 3
CMIP5	Coupled Model Intercomparison Project, Phase 5
GCM	Global Climate Model
GEV-1 distribution	Type 1 Generalized Extreme Value Distribution, also commonly referred to as Gumbel Extreme Value Distribution
IPCC	Intergovernmental Panel on Climate Change
LA Basin Study	Los Angeles Basin Stormwater Conservation Study
LACDPW	Los Angeles County Department of Public Works
LACFCD	Los Angeles County Flood Control District
NLDAS	National Land Data Assimilation System
NOAA	National Oceanic and Atmospheric Administration
RCP	Representative Concentration Pathway
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
TSC	Technical Service Center
VIC	Variable Infiltration Capacity
WMMS	Watershed Management Modeling System

Glossary

Bias-correction: Process by which to account for global climate model biases toward being too wet, too dry, too warm, or too cool relative to the historical baseline.

Cool season: The period from September through April; for any given year, the cool season extends from September 1 of the previous year through April 30 of the current year.

Climate scenario: Climate scenarios are created by grouping together climate projections with similar attributes (e.g. temperature and precipitation).

Cumulative distribution function (CDF): Cumulative distribution function or distribution function is a function that gives the probability that a random variable is less than or equal to a specified value of the independent variable of the function.

Emissions pathway: A representation of a potential future release of greenhouse gases and other pollutants in the atmosphere, both natural and anthropogenic, used as input to a climate model.

Future period: The 89-year period defined from January 1, 2011 to December 31, 2099.

Julian day: Continuous count of the days in a year. January 1 is Day 1 in the Julian calendar and December 31 is Day 365 in a non-leap year (Day 366 in a leap-year).

Periodicity of wet/dry spells: The intervals between wet and dry periods.

Projection: Climate conditions and meteorological parameters (e.g. temperature and precipitation) corresponding to a given global climate model simulation of future climate conditions under a given emissions scenario or representative concentration pathway and given initial conditions.

Projection membership diagram: Plot illustrating the magnitude change in temperature (displayed on the ordinate or vertical axis) and percent change of precipitation (displayed on the abscissa or horizontal axis) between simulated historical and projected future climate conditions for individual climate projections. Projection membership diagrams are used to visualize and interpret climate projections and to define climate scenarios.

Representative concentration pathways (RCPs): Four scenarios of time-dependent greenhouse gas and air pollutant emissions trajectories used as input into the CMIP5 climate models. RCP2.6 (“high mitigation” pathway) represents a scenario where the radiative forcing peaks before year 2100 and then declines. RCP8.5 (“business-as-usual” pathway) represents a scenario where the radiative forcing continues to rise after year 2100. RCP4.5 and RCP6.0 are emissions pathways that fall within the bounds of RCP2.6 and RCP8.5 and were not included in this study.

Simulated historical conditions: Simulation of 20th century climate change conditions. Simulated historical climate conditions consist of global climate model simulations informed by estimated historical forcing parameters, including historical land cover distribution and atmospheric composition.

Executive Summary

Water resource managers are currently being faced with the challenge of developing sustainable methods for adaptation and mitigation to climate change.

To address the challenges involved in changing climates in the Los Angeles Basin, Los Angeles County Flood Control District (LACFCD) is partnering with the U.S. Department of the Interior, Bureau of Reclamation's (Reclamation) Southern California Area Office in the WaterSMART (Sustain and Manage America's Resources for Tomorrow) Basin Studies program to conduct the Los Angeles Basin Stormwater Conservation Study (LA Basin Study). The LA Basin Study is studying long-term flood control and water conservation impacts from projected population and climate conditions. Upon completion, the LA Basin Study will inform potential changes to operating stormwater capture systems, modifying existing facilities, and developing new facilities that could help address future flood control and water supply conditions.

Literature Synthesis

A large volume of research and publications have focused on precipitation and temperature trends for California and are referenced in a literature synthesis completed by Reclamation (2011 Lit). Overall results from this literature synthesis for the Los Angeles basin area suggest:

- Increases in temperatures
- Increases in evaporation rates
- Decreases in annual precipitation
- Increases in extreme precipitation events

LA Basin Study Task 3.1

Reclamation's Technical Service Center (TSC) performed Task 3.1 of the LA Basin Study—to develop and evaluate projected future climate conditions related to precipitation frequency over the Los Angeles Basin. The subtasks were to:

- Consider existing projections of climate change in the LA Basin Study area

- Determine appropriate climate scenarios for use in developing precipitation and potential evaporation input datasets to support subsequent hydrologic modeling

- Prepare data (hourly precipitation and potential evaporation) for input into the LACFCD's Watershed Management Modeling System (WMMS)

- Determine storm event frequency for planning purposes

The data, methods, and results from Task 3.1 are documented in this report. Results from these four subtasks were then transmitted to LACFCD, who used these results as input in their WWMMS as part of Task 3.2 of the LA Basin Study. LACFCD is preparing a companion report with the results from the hydrologic modeling.

Consider Existing Projections

Three sets of downscaled climate change projections were evaluated:

- **CMIP3-BCSD:** The climate change projections from the World Climate Research Programme's Coupled Model Intercomparison Project, Phase 3 (CMIP3), released in 2006. The projections were downscaled using the Bias-Correction and Spatial Disaggregation (BCSD) process. We used 112 projections from this set.

- **CMIP5-BCSD:** The climate change projections from the World Climate Research Programme's Coupled Model Intercomparison Project, Phase 5 (CMIP5), released in 2013. The projections were downscaled using the BCSD process. We used 100 projections from this set.

- **CMIP5-BCCA:** Selected projections from CMIP5 that represent a range of potential climate futures. These projections were downscaled using the Bias-Correction Constructed Analogue (BCCA) process. We used 37 projections from this set.

Determine Appropriate Climate Scenarios

Bias-Correction and Spatial Disaggregation Projections and Scenarios

We grouped projections from the BCSD-CMIP3 and BCSD-CMIP5 sets, based on changes in precipitation and temperature to inform five climate scenarios:

- **Hot-wet:** Q1—Enhanced precipitation magnitude with hotter temperature

- **Hot-dry:** Q2—Diminished precipitation magnitude with hotter temperature

- **Warm-dry:** Q3—Diminished precipitation magnitude with warmer temperature

- **Warm-wet:** Q4—Enhanced precipitation magnitude with warmer temperature

- **Central:** Q5—The central tendency scenario lies within the middle area of the graphs

The projected temperature change for all climate change scenarios is positive, hence the designation of "warm" and "hot." Ten climate scenarios (i.e., five from CMIP3-BCSD and five from CMIP5-BCSD) were analyzed.

Bias-Correction Constructed Analogue Projections

As the CMIP5-BCCA projections were available at a daily time-step, we were able to directly use these climate projections instead of categorizing these projections by climate scenario. This method captures the time evolution of climate state sequences as projected by the Global Climate Models (GCMs).

To capture the variability in future climate conditions, we evaluated a range of projections representing the high and low emissions trajectories (referred to as Representative Concentration Pathways [RCP], in CMIP5):

- **"Business-as-usual" pathway:** RCP8.5, the high emissions trajectory (a total of 21 projections)

- **"High mitigation" pathway:** RCP2.6, the low emissions trajectory (a total of 16 projections)

Thus, there were a total of 37 CMIP5-BCCA projections, and each projection was analyzed independently.

Prepare Data for Input into the Hydrology Model: Hourly Projections of Precipitation and Potential Evaporation

Continuous hourly precipitation and potential evaporation time-series for the period 2011 through 2099 were conditioned on the five CMIP3-BCSD scenarios, five CMIP5-BCSD scenarios, and 37 CMIP5-BCCA projections. In total, we developed 47 time-series of precipitation and potential evaporation for input into the WMMS for subsequent hydrologic analysis. By analyzing all 47 time-series, the range of uncertainty and variability for the future climate is expected to be broadly characterized.

Bias-Correction and Spatial Disaggregation Projections

Precipitation

We developed hourly continuous time-series of precipitation for the five CMIP3-BCSD and five CMIP5-BCSD climate scenarios by applying percentile-specific changes between cumulative distribution functions (CDF) of simulated historical precipitation and cumulative distribution functions of projected future precipitation to the historical observations at the daily time-scale. Hourly disaggregation of the daily projections was subsequently completed using patterns from the historical record (1986 through 1999) precipitation archive.

Potential Evaporation

To create the hourly potential evaporation dataset, we first derived adjustment factors using simulated historical and projected evaporation magnitudes, and then the adjustment factors were applied to the historical evaporation archive. The two models used to derive the simulated historical and projected evaporation magnitudes were:

- CMIP3-BCSD scenarios, the Variable Infiltration Capacity (VIC) model (Reclamation 2011 [TM])

- CMIP5-BCSD scenarios, the Hargreaves-Samani model (Hargreaves and Samani 1982)

Bias-Correction Constructed Analogue Projections

Precipitation

To create the hourly continuous precipitation time-series for the 37 CMIP5-BCCA projections, a local bias-correction using the historical precipitation observations and a subsequent disaggregation of daily to sub-daily measurements was completed.

Potential Evaporation

To create the hourly potential evaporation dataset, we first derived adjustment factors using simulated historical and projected evaporation magnitudes, and then we applied the adjustment factors to the historical evaporation archive. The model used to derive the simulated historical and projected evaporation magnitudes was:

- CMIP5-BCCA projections, the Hargreaves-Samani model (Hargreaves and Samani 1982)

Determine Storm Event Frequency

We examined the potential intensity and frequency of storm events. This is in contrast to the annual amount of precipitation and associated trends. Even though the annual amount of precipitation may change in a future climate, the more important factor for decision-makers is the magnitude and intensity of that precipitation. Projected changes in precipitation frequency, magnitude, volume, and periodicity of wet/dry spells will likely have implications on infrastructure performance in the Los Angeles Basin.

To determine storm event frequency, we calculated storm events for five CMIP3-BCSD scenarios, five CMIP5-BCSD scenarios, and 37 CMIP5-BCCA projections at several recurrence intervals (5-year, 10-year, 25-year, 50-year, 100-year, and 200-year) at the 24-hour duration. The storm events were calculated at each precipitation gage within the study area. As the current standard for infrastructure design in the LA Basin is the 24-hour, 1-in-50 year storm event

(Los Angeles County Department of Public Works [LACDPW] 2006), this report focuses on that event. Difference maps showing the change in precipitation depths (i.e., the intensity of the precipitation) of the 24-hour, 1-in-50-year precipitation events between the current climate and the potential future climate regimes were developed.

Overall, the BCCA projections show a decrease of precipitation intensity in the future, whereas the BCSD projections show a more neutral to slight increase in precipitation intensity in the future. Note that, this change analysis is specific to the 24-hour, 1-in-50 year storm frequency event for the Los Angeles basin, and climate literature thus far points to an increase in extreme events under a changing climate. This conclusion in literature is quite broad and is not tied to any specific storm event frequency and duration. Furthermore, refinements to current knowledge are expected as climate science continues to evolve.

1. Introduction

The Los Angeles County Flood Control District (LACFCD) provides flood protection, water conservation, recreation, and aesthetic enhancement within an area encompassing approximately 3,000 square miles. LACFCD is partnering with the U.S. Department of the Interior, Bureau of Reclamation's (Reclamation) Southern California Area Office in the WaterSMART (Sustain and Manage America's Resources for Tomorrow) Basin Studies Program to study long-term flood control and water conservation impacts from projected population and climate conditions. The Los Angeles Basin Stormwater Conservation Study (LA Basin Study) will recommend potential changes to operating stormwater capture systems, modifying existing facilities, and developing new facilities that could help resolve future flood control and water supply issues.

1.1 Study Purpose and Objectives

Reclamation's Technical Service Center (TSC) performed Task 3.1 of the LA Basin Study to develop and evaluate projected future climate conditions related to precipitation frequency over the LA Basin. The subtasks were to:

a. Consider existing projections of climate change in the LA Basin Study area

b. Determine appropriate climate scenarios for use in developing precipitation and potential evaporation input datasets to support subsequent hydrologic modeling

c. Prepare data (hourly precipitation and potential evaporation) for input into the LACFCD's Watershed Management Modeling System (WMMS)

d. Determine storm event frequency for planning purposes

The data, methods, and results from Task 3.1 are documented in this report. Results from these four subtasks were then transmitted to LACFCD, who used these results in their WMMS as part of Task 3.2 of the LA Basin Study. LACFCD is preparing a companion report with the results from the hydrologic modeling.

1.2 Description of LA Basin Study Area

The LA Basin Study encompasses several watersheds, including: the Los Angeles River, San Gabriel River, Ballona Creek, South Santa Monica Bay, North Santa Monica Bay, and Dominguez Channel/Los Angeles Harbor. Task 3.1 incorporates all six of the above watersheds, including areas outside of Los Angeles County, for a total study area of approximately 1,900 square miles (Figure 1).

1.3 Potential Future Climate Change Impacts

1.3.1 Literature Review

The Literature Synthesis on Climate Change Implications for Water and Environmental Resources summarizes current climate change research and potential impacts for water resource managers. This synthesis summarizes information regarding the potential changes in future climate for Reclamation's Lower Colorado region, which includes this study area. Findings pertinent to this LA Basin Study (Reclamation 2011 [Lit]), including conclusions drawn from the graphics in Appendix B of the synthesis, include:

- **Increases in temperatures.** Studies consistently show that the temperature for the study region will continue to increase. Increases in both minimum and maximum temperatures may be expected, with increases in extreme warm temperatures and decreases in extreme cool temperatures. For the Los Angeles area, a mean temperature increase of 1 to 3 degrees Celsius (°C) may be expected by 2050.

- **Increases in rates of evaporation.** Due to the warming, higher evaporation rates are also expected.

- **Decreases in annual precipitation.** Studies suggest that the storm track in the Pacific Ocean may shift northward resulting in less frequent precipitation events along the coast of southern California. Changes in mean annual precipitation indicate a mean drying (i.e., less precipitation) of 2 to 5 percent since the mid-20th century with little additional change by mid-21st century. Additional drying (mean reduction of 2 to 5 percent) could occur along the coastal areas of California.

- **Increases in extreme precipitation events.** Overall, precipitation may be less frequent but more intense. In other words, the contribution to annual precipitation by extreme precipitation events may increase. The heavy rainfall events may be interspersed with longer, relatively dry periods. The higher evaporation rates associated with the positive temperature trends may decrease soil moisture resulting in reduced storm runoff. Note that, the literature does not associate a specific return period to extreme precipitation events but rather discusses extreme precipitation events in general terms.

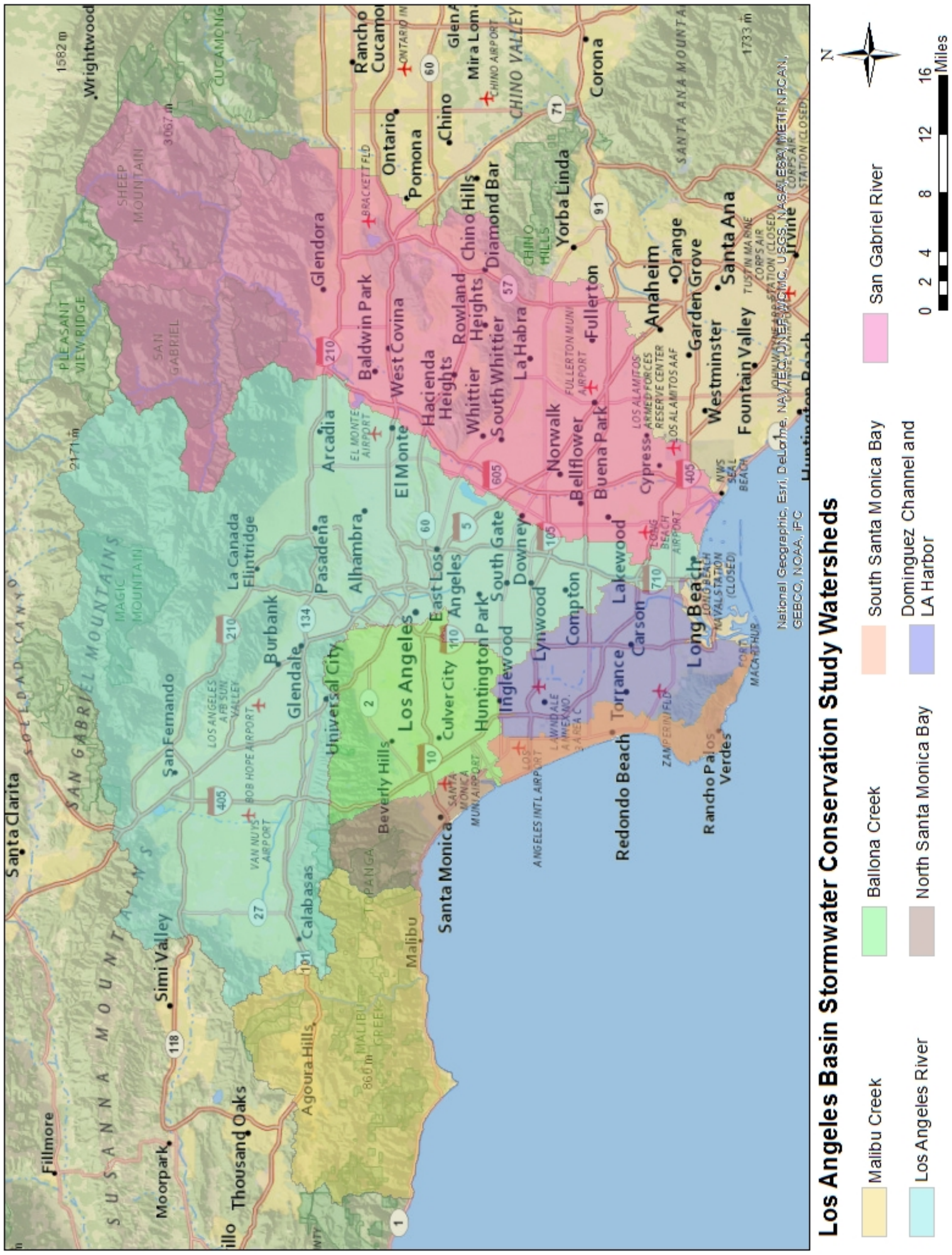

Figure 1. Map of the basin study area.

1.3.2 LA Basin Study Task 3.1

As discussed in the previous section, the Literature Synthesis provides an overall view of potential climate change impacts (Reclamation 2011 [Lit]). However, to effectively assess runoff and stormwater capture in the future for the LA Basin Study area, we developed a wide range of projections as input into the WMMS model to account for the variability in projected precipitation change. See Chapter 2 for a discussion of the methodology used in this analysis, including examining the existing projections of climate change in the LA Basin Study area, determining the appropriate climate scenarios for use, and preparing continuous hourly projected precipitation and potential evaporation.

According to the Literature Synthesis, annual amounts of precipitation may change under a future climate. However, a more important factor for decision-makers is the magnitude of that precipitation. Projected changes in precipitation frequency, magnitude, as well as changes in the periodicity of wet/dry spells (i.e., the intervals between wet and dry periods) may have implications for infrastructure design. For example, even if the amount of mean annual precipitation remains the same in the future, the volume of runoff may be altered due to changes in soil moisture, evaporation, and the magnitude of individual events. Thus, the total amount of annual precipitation may be a lesser indicator of potential runoff than changes in storm frequency. This study focuses on developing precipitation inputs by analyzing the 24-hour, 1-in-50 year precipitation event, which is used as a reference storm for water management and design in the Los Angeles County Department of Public Works (LACDPW) Hydrology Manual (LACDPW 2006). See Chapter 3 for a discussion of storm event frequency. See Appendix C for the tables of storm event frequency and associated precipitation intensity for each of the 134 precipitation gages in the LA Basin study area.

Note that while the Literature Synthesis' reference period is 1950 through 1979, this study uses 1986 through 1999 as the historical reference period. Thus, the results from the Literature Synthesis provide only a general overview and are not used directly in this study.

2. Development of Climate-Adjusted Hydrologic Model Inputs

Chapter 2.0 details the methods that were used to create hourly precipitation and potential evaporation inputs to WMMS based on the CMIP3-BCSD, CMIP5-BCSD, and CMIP5-BCCA[1] precipitation and temperature projections:

- Section 2.1 describes the historical data used in the analysis.
- Section 2.2 describes the global climate models and future projections.
- Section 2.3 describes the selection of the spatial and temporal subsets of the projections.
- Section 2.4 describes the methods used to create the hourly precipitation and potential evaporation inputs from the CMIP3-BCSD and CMIP5-BCSD projections, including selection of five climate scenarios which represent the range of projected future climate conditions.
- Section 2.5 describes the methods used to create hourly precipitation and evaporation inputs from the CMIP5-BCCA projections.

2.1 Historical Data

2.1.1 Historical Precipitation Data

Historical observed hourly precipitation data were obtained from precipitation gages operated by the Los Angeles County Department of Public Works (LACDPW). LACDPW has maintained digital records of precipitation observations from the network of precipitation gages located throughout the study area since January 1986. For this study, gage records were screened to identify gages that were in mostly continuous operation from January 1, 1986 through December 31, 1999. A total of 134 precipitation gages were identified for use in this analysis (Figure 2).

[1] CMIP3: Coupled Model Intercomparison Project, Phase 3
CMIP5: Coupled Model Intercomparison Project, Phase 5
BCSD: Bias-Correction and Spatial Disaggregation
BCCA: Bias-Correction Constructed Analogue

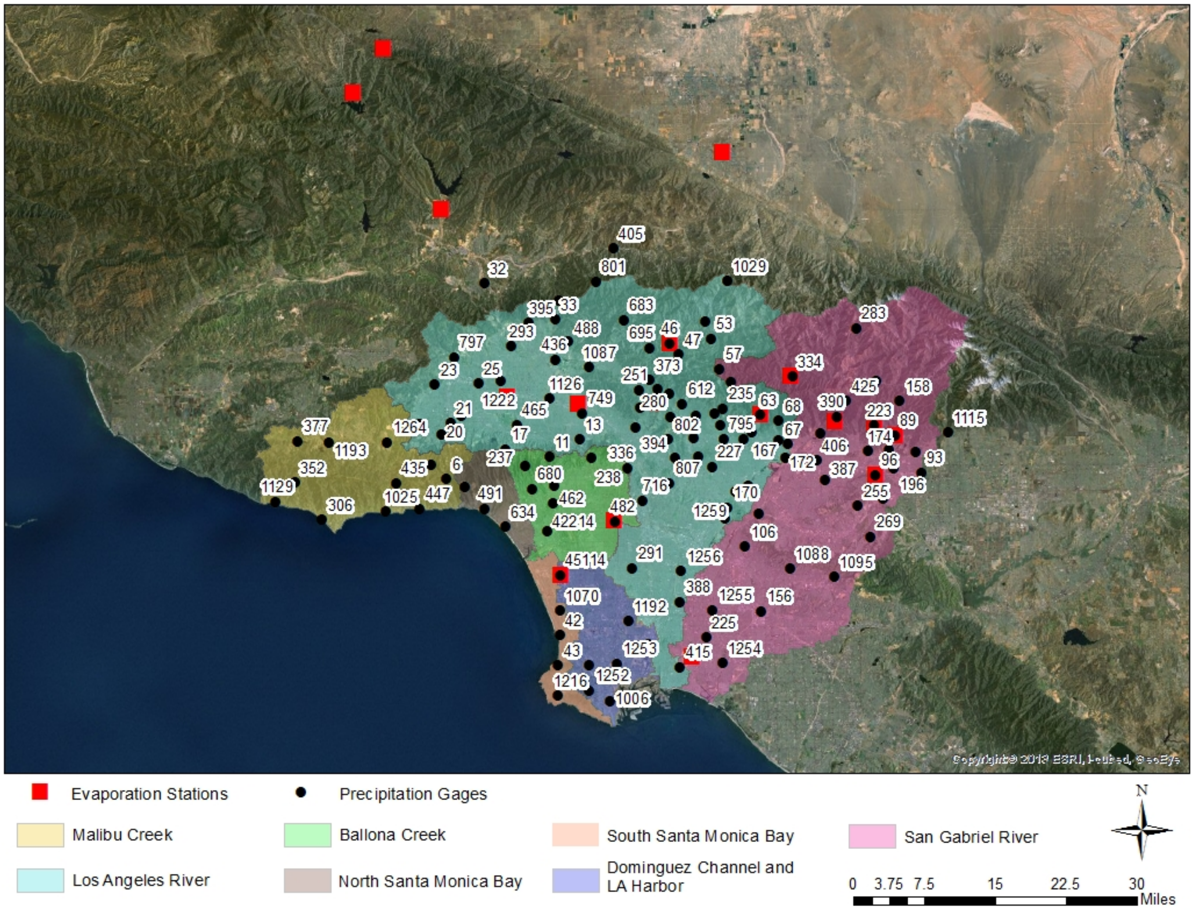

Figure 2. Map of LACDPW precipitation gages and evaporation stations used in this study.

2.1.2 Historical Potential Evaporation Data

Historical potential evaporation data included pan evaporation measurements from 17 evaporation stations operated by LACDPW in the study area, along with computed historical pan evaporation calculated from hydrometeorological data (Tetra Tech 2010). For this study, LACFCD provided hourly potential evaporation records for these 17 evaporation sites across the study area (Figure 2).

2.2 Future Climate Projections

2.2.1 Global Climate Models (GCM)

Projections of future precipitation and temperatures are developed by simulating global climate conditions from the late 19th century (from about 1860) through the end of the 21st century using GCMs. These models include coupled atmosphere and ocean general circulation models (Reclamation 2011 [TM]). Because it is difficult to project future emissions and anthropogenic factors that influence

climate, scientists use various assumptions to produce a range of possible future conditions. Specifically, GCMs simulate the potential global climate response to several greenhouse gas emissions trajectories (Reclamation 2011 [TM]).
Two sets of climate change projections were evaluated:

- **CMIP3:** The climate change projections from the World Climate Research Programme's Coupled Model Intercomparison Project, Phase 3 (CMIP3) released in 2006.

- **CMIP5:** The climate change projections from the World Climate Research Programme's Coupled Model Intercomparison Project, Phase 5 (CMIP5) released in 2013.

For the period 1860 through 1999, GCMs were constrained by estimated historical atmospheric composition, including historical atmospheric concentrations of greenhouse gases and aerosols that affect the atmospheric radiation and energy budgets.

For the period 2000 through 2099, GCMs use various trajectories of future atmospheric conditions. CMIP3 and CMIP5 used different approaches for estimating these emissions trajectories.

CMIP3 Emissions Trajectories

CMIP3 used three potential future greenhouse gas emissions, as shown in Figure 3:

- “High” emissions scenario: A2.
- “Medium” emissions scenario: A1B.
- “Low” emissions scenario: B1.

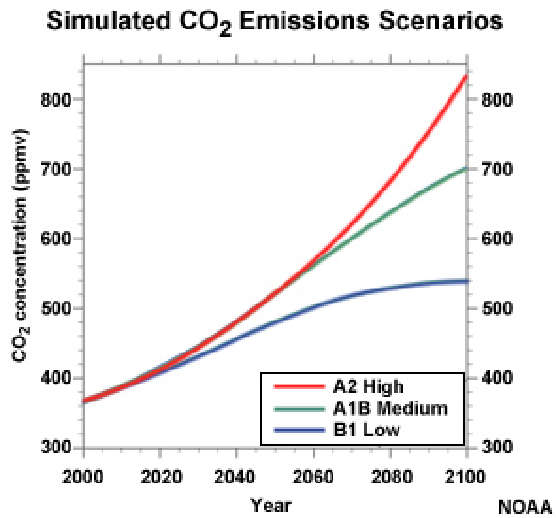

Figure 3. Simulated carbon dioxide emissions scenarios used in CMIP3 projections (based on Intergovernmental Panel on Climate Change [IPCC 2007]).

CMIP5 Emissions Trajectories

CMIP5 used four representative concentration pathways (RCP) (Reclamation 2013). The RCPs are defined by their total radiative forcing pathway and level by 2100 (Figure 4):

- **"Business-as-usual" pathway:** RCP8.5. The radiative forcing continues to rise after year 2100. This is considered the high emissions pathway.

- **"Middle" pathways:** RCP4.5 and RCP6.0. These pathways lie between the RCP8.5 and RCP2.6 and are not included in this study.

- **"High mitigation" pathway:** RCP2.6. The radiative forcing peaks before year 2050 and then declines. This is considered the low emissions pathway.

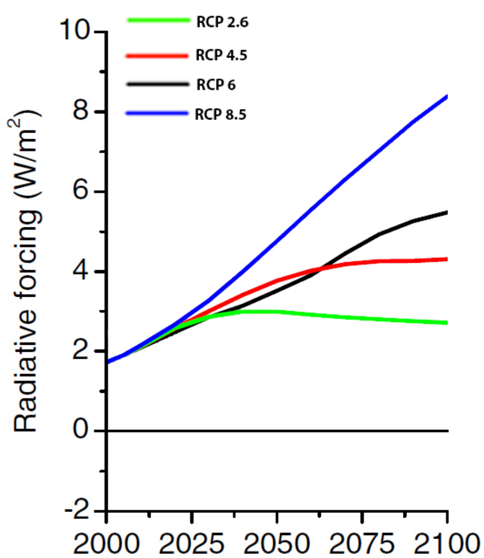

Figure 4. Radiative forcing of the RCPs (emission scenarios used by CMIP5 projections, based on van Vuuren et al [2011]).

2.2.2 Downscaled Projections

The spatial and temporal (i.e., timescale) resolutions of GCM output are generally too coarse to use these model outputs as inputs for hydrologic models. Horizontal resolution of GCMs typically range from approximately 1.0° to 2.5° latitude by 1.0° to 2.5° longitude (approximately 100 to 250 kilometers [km] [approximately 62 to 155 miles] north-south by 100 to 250 km [approximately 62 to 155 miles] east-west). GCM output is typically archived at a monthly timescale. The spatial resolution of the GCMs used in CMIP5 is slightly finer on average than those used in CMIP3.

A single grid cell within a GCM is approximately the size of the LA Basin study domain. Thus, we need to translate GCM output to a locally relevant resolution (i.e., "spatially downscaled"). We also need the GCM output to be finely resolved in time (i.e., temporally disaggregated). Thus, GCM output is spatially downscaled and temporally disaggregated prior to use in hydrology and water resources applications.

Bias-correction is a process to account for global climate model biases toward being wet, dry, warm, or cool relative to the historical baseline. For this study, we evaluated three sets of downscaled GCM climate change projections for precipitation and temperature: two sets of projections that used the bias-correction and spatial disaggregation (BCSD) algorithm for downscaling and one set that used the bias-correction constructed analogue (BCCA) downscaling algorithm (Figure 5).

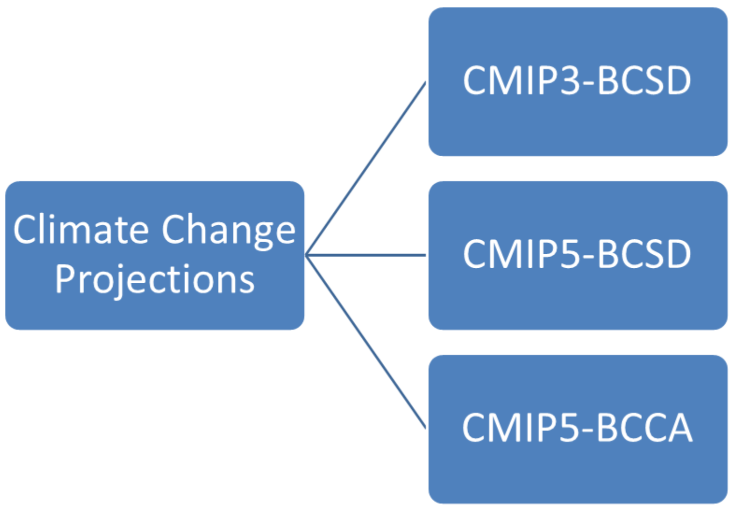

Figure 5. Sets of downscaled projections used.

Bias-Correction and Spatial Disaggregation—CMIP3-BCSD and CMIP5-BCSD Projections

Two of the projection sets (CMIP3 and CMIP5) used BCSD to downscale the GCM projections. The GCM projections of monthly precipitation and temperature were bias-corrected at a coarse scale (2.0° by 2.0°) based on a dataset of gridded historical observations. The bias-corrected projections were then spatially disaggregated over the continental U.S. to the uniform National Land Data Assimilation System (NLDAS) grid at the resolution of 1/8° latitude by 1/8° longitude using the BCSD statistical downscaling method (Wood et al. 2002).

Monthly precipitation and temperature projections were developed for the period 1950 through 2099; data for the historical period 1950 through 1999 correspond to output from GCM simulations of 20th century climate whereas projections for the period 2000 through 2099 correspond to output from GCM projections of potential 21st century climate conditions (see Reclamation 2011 [TM] and Reclamation 2013 for details).

- **CMIP3-BCSD projections.** All 112 CMIP3-BSCD projections of precipitation and temperature were considered in this study. 16 modeling agencies (e.g., Max Planck Institute for Meteorology in Germany and Bjerknes Centre for Climate Research in Norway) developed the GCMs using three greenhouse gas emissions (See Section 2.2.1).

- **CMIP5-BCSD projections.** Of the 234 CMIP5-BCSD projections of precipitation and temperature, only 100 were processed at the time of this study. The 100 CMIP5-BCSD projections that were included in this analysis captured projections from the climate modeling agencies that contributed to the experiment. The CMIP5 projection archive represents 29 modeling agencies that developed GCMs using four emission pathways (See Section 2.2.1).

Bias-Correction Constructed Analogue—CMIP5-BCCA Projections

The BCSD climate projections are produced on a monthly time-step and therefore do not address potential changes in daily temperature range or potential changes in daily precipitation conditions. To address this, the BCCA algorithm (developed at Scripps Institution of Oceanography, U.S. Geological Survey, and Santa Clara University) was leveraged. The technique operates on daily GCM output—producing daily projections of minimum temperature, maximum temperature, and precipitation at the same spatial resolution as BCSD information (Reclamation 2012).

In the BCCA downscaling method (Hidalgo et al. 2008), coarse scale GCM projections of daily precipitation and temperature were bias-corrected based on a dataset of gridded historical observations, similar to the bias-correction step in the BCSD method. The coarse resolution bias-corrected projections were then linearly combined to a coarse resolution historical analogue. The coarse resolution bias-corrected projections were downscaled by applying the same linear function to a corresponding fine resolution (1/8° by 1/8°) historical analogue. This resolution is equivalent to the resolution of the BCSD projections and also uses the NLDAS grid.

2.3 Spatial and Temporal Subsets of Climate Projections

2.3.1 Spatial Subsets

To correspond with the study area, gridded daily precipitation and temperature were obtained for the period 1950 through 2099 for all simulations in the three downscaled sets of projections (i.e., CMIP3-BCSD, CMIP5-BCSD, and CMIP5-BCCA) (Reclamation 2013). All projections are available on the uniform NLDAS 1/8° x 1/8° grid, and data from only those grid cells that overlap the study area were considered in the analysis. As shown in Figure 6, 52 such grid cells cover the study area.

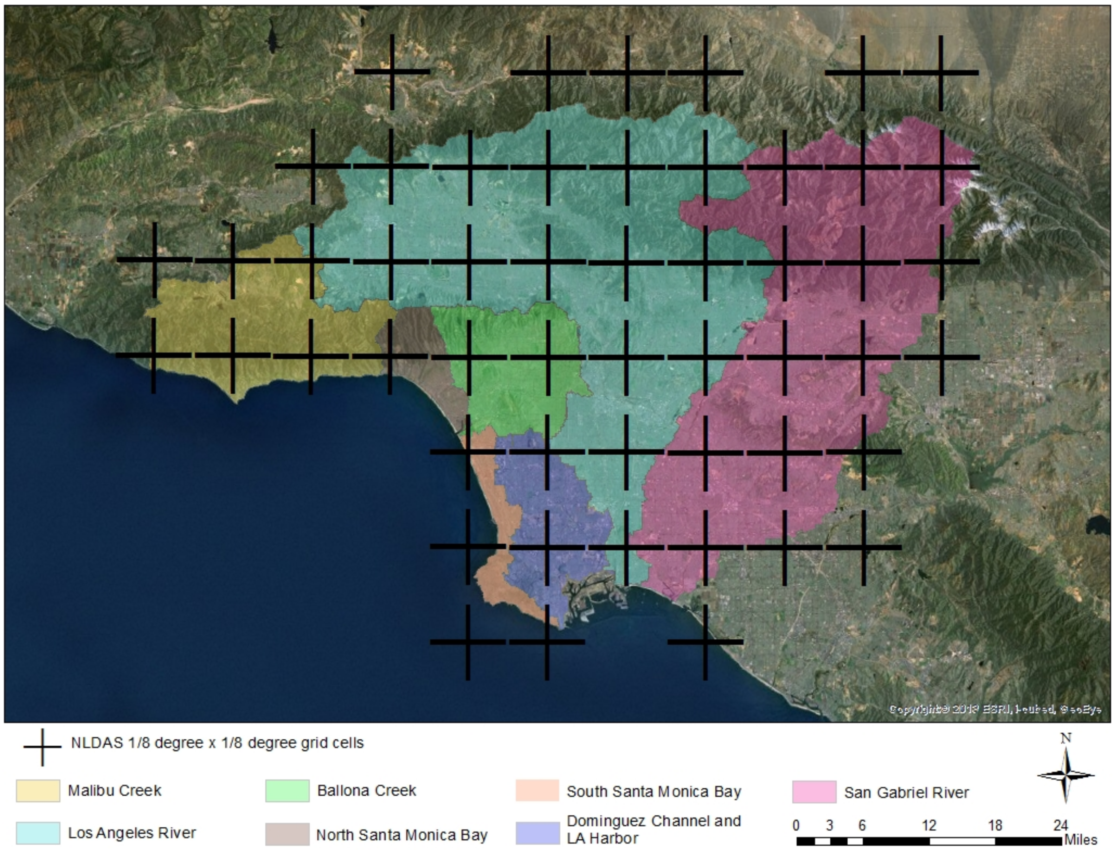

Figure 6. Map showing the NLDAS grid cells that correspond with the study area (crosses represent the center points of each grid cell).

2.3.2 Temporal Subsets

The three downscaled sets of projections (i.e., CMIP3-BCSD, CMIP5-BCSD, and CMIP5-BCCA) were available for the period 1950 through 2099 (Reclamation 2013). For this study, we used two subset periods: a historical reference period and a future period. The historical reference period was restricted to the 14-year time period 1986 through 1999. The year 1986 was selected for consistency with the start date of the LACDPW's digital record of precipitation, temperature, and potential evaporation. The year 1999 corresponds to the end date of the GCMs' historical simulations. The future period is the 89-year period 2011 through 2099. For consistency with the length of the historical period (14 years) and to ensure sample size consistency in the subsequent analysis, the future period was divided into six shorter time periods (future periods 1 through 6), where the first five periods were 14 years long and the last period was 19 years long (Table 1).

Table 1. Years and Duration Associated with the Simulated Historical Period

Future Period	Start year	End year	Duration
Historical reference period	1986	1999	14 years
Future period 1	2011	2024	13 years
Future period 2	2025	2038	14 years
Future period 3	2039	2052	14 years
Future period 4	2053	2066	14 years
Future period 5	2067	2080	14 years
Future period 6	2081	2099	19 years

2.4 CMIP3-BCSD and CMIP5-BCSD Climate Scenarios

Five climate scenarios were developed from the 112 CMIP3-BCSD projections, and five additional climate scenarios were developed from the 100 CMIP5-BCSD projections. Hourly time series of projected precipitation and potential evaporation were then developed for each of the climate scenarios.

- Section 2.4.1 summarizes the methods used to develop the climate scenarios from the CMIP3-BCSD and CMIP5-BCSD projections.
- Section 2.4.2 summarizes the methods used to develop hourly time series of projected future precipitation.
- Section 2.4.3 summarizes the methods used to develop hourly time series of projected future potential evaporation.

2.4.1 CMIP3-BCSD and CMIP5-BCSD Projection Selection

To reduce the number of climate projections considered in subsequent analyses, we grouped the projections into five climate scenarios that adequately represented the wide range of potential future conditions. Five climate scenarios were developed from the 112 CMIP3-BCSD projections, and five additional climate scenarios were developed from the 100 CMIP5-BCSD projections. Each climate scenario consists of ten individual climate projections selected from the CMIP3-BCSD projections and the CMIP5-BCSD projections. To determine which climate projections belonged to each climate scenario, we developed projection membership diagrams (see Appendix A for CMIP3-BCSD and Appendix B for CMIP5-BCSD). Projection membership diagrams group the CMIP3-BSCD and the CMIP5-BCSD projections based on their potential future changes in precipitation and temperature from the simulated historical period.

Change in Precipitation for Projection Membership Diagrams

To define the change in precipitation for the projection membership diagrams, frequency analysis was selected because it is possible that seasonal total precipitation may increase in a future climate while sub-seasonal (e.g., daily or monthly) precipitation values may decrease (i.e., there may be long duration drizzle accumulation without extreme storm runoff events). The change in precipitation was defined as the percent change in depth between the 1-in-50-year precipitation event in the historical reference period and in a selected future period. The pertinent variables to determine the percent change in precipitation were:

- **The 24-hour, 1-in-50-year precipitation event:** (i.e., the return period used extensively in the LACDPW's Hydrology Manual [2006]). For each future period, the 24-hour, 1-in-50-year precipitation depth was calculated using the L-moments regional frequency method (Hosking and Wallace 1997). Regional frequency statistics allow for space-for-time substitution, (i.e., data from sites within a statistically and climatologically homogeneous region can be pooled together, and the parameters to describe the regional probability distribution represent all sites within the region). The sites for this particular analysis corresponded to the 52 grid cells that comprised the study area. It was assumed that the study domain was a statistically and climatologically homogeneous region.

- **The cool season**: (i.e., September through April). The largest storm events occur in the cool (winter) season in this area. The cool season extends from one calendar year into the next, so in keeping with the nomenclature of Table 1, a cool season was denoted as September through December of the previous year (e.g., for the cool season for 1986, we used September through December 1985) and January through April of the present year (e.g,. for 1986 we used January through April 1986). From the cool season data, the maximum daily precipitation depth that occurred during each cool season for each grid cell was identified to create a seasonal maximum daily precipitation time-series.

The seasonal maximum daily precipitation time-series at each grid cell was pooled together into one regional dataset and used as input into the L-moments regional frequency method. The Type 1 Generalized Extreme Value Distribution (GEV-1 distribution), also commonly referred to as Gumbel Extreme Value Distribution, was fit to the regional dataset, and the precipitation depth associated with the 1-in-50-year return period was computed.

The result of this analysis was the 24 hour, 1-in-50-year precipitation depth for all projections at each of the seven time periods (one historical period and six future periods defined in Table 1). With this information, the percent change in precipitation between the future projections and the simulated historical projection was calculated.

Change in Temperature for Projection Membership Diagrams

The change in temperature was defined as the difference between the average temperature of the simulated historical projections and the average temperature of the future projections. The focus was again on the cool season (September through April) for consistency with the computations for percent change in precipitation. For each day within the cool season, the minimum and maximum temperatures were averaged to create a daily temperature time-series at the grid cell level. The seasonal average of this daily temperature time-series was calculated, and then the overall average for the study domain was found. This process resulted in an average temperature of the LA Basin study area for all projections at each of the seven time periods (one historical period and six future periods). With this information, the change in average temperature between the future projections and the stimulated historical projection was determined.

Projection Membership Diagrams

The percent change in precipitation and the change in average temperature for each projection was plotted on projection membership diagrams for the six future periods. Figure 7 shows a stylized example of the projection membership diagram. The percent change in precipitation was plotted on the horizontal axis of the diagrams, and the change in average temperature was plotted on the vertical axis. The 10th, 50th, and 90th percentiles of the changes in both precipitation and temperature were also labeled on the graphs.

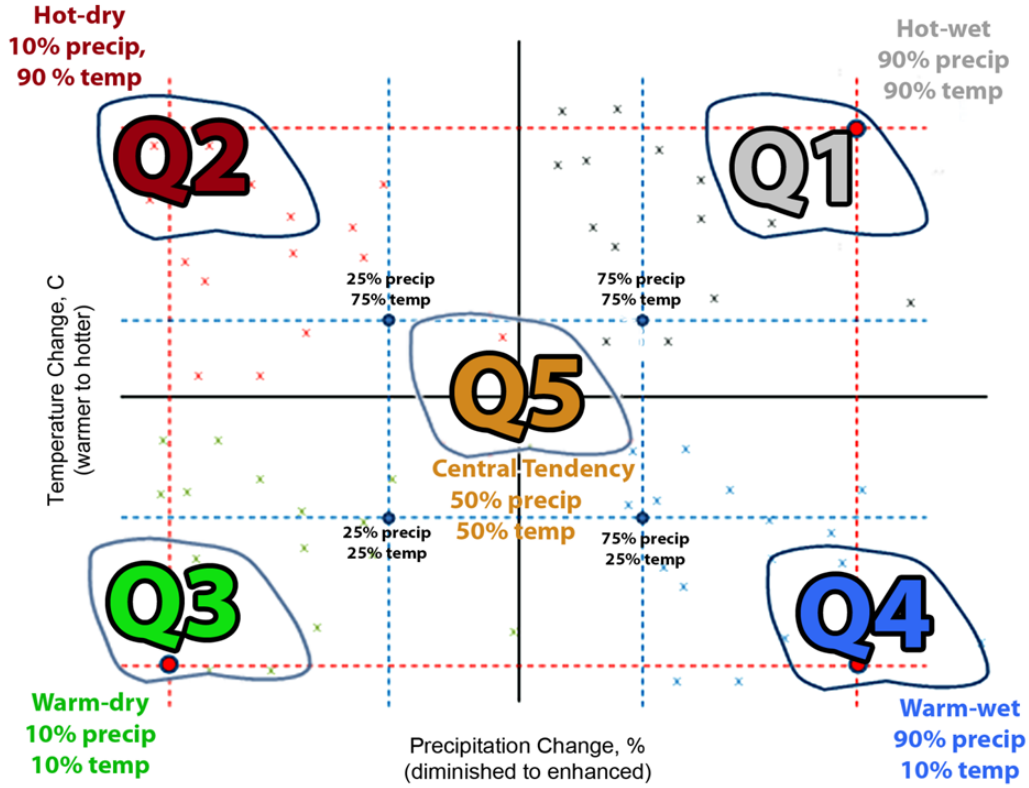

Figure 7. Stylized example of a projection membership diagram.

Each climate scenario consists of ten individual climate projections selected from the full projection set (CMIP3-BCSD or CMIP5-BCSD) based on proximity (i.e., the "nearest neighbor" or, in other words, the closest projection) to the following set of criteria (Figure 8).

- **Hot-wet:** Q1—90th percentile change in precipitation, 90th percentile change in temperature is the enhanced precipitation magnitude with hotter temperature scenario

- **Hot-dry:** Q2—10th percentile change in precipitation, 90th percentile change in temperature is the diminished precipitation magnitude with hotter temperature scenario

- **Warm-dry:** Q3—10th percentile change in precipitation, 10th percentile change in temperature is the diminished precipitation magnitude with warmer temperature scenario

  Warm-wet: Q4—90th percentile change in precipitation, 10th percentile change in temperature is the enhanced precipitation magnitude with warmer temperature scenario

- **Central:** Q5—50th percentile change in precipitation, 50th percentile change in temperature is the middle scenario

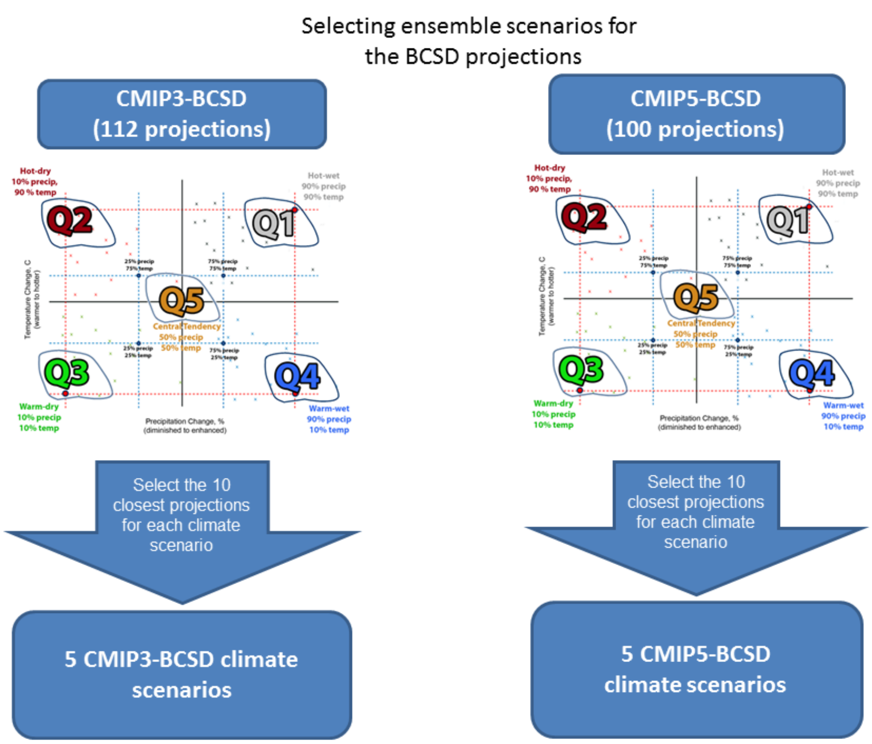

Figure 8. Selection process for the BCSD climate scenarios.

Future Periods

The sets of five climate scenarios for the CMIP3 and the five climate scenarios for the CMIP5 were then compiled for each of the six future periods. The set of ten individual projections included in a given climate scenario may therefore differ between periods (e.g., the projections contributing to hot –wet [Q1] for the period 2025 through 2038 may differ from those contributing to hot –wet [Q1] for period 2039 through 2052). Thus, each scenario had a unique set of projections for the six future periods (Figure 9). Tables that list the ten projections associated with each climate scenario for each future period are provided in Appendix A for CMIP3-BCSD and Appendix B for CMIP5-BCSD.

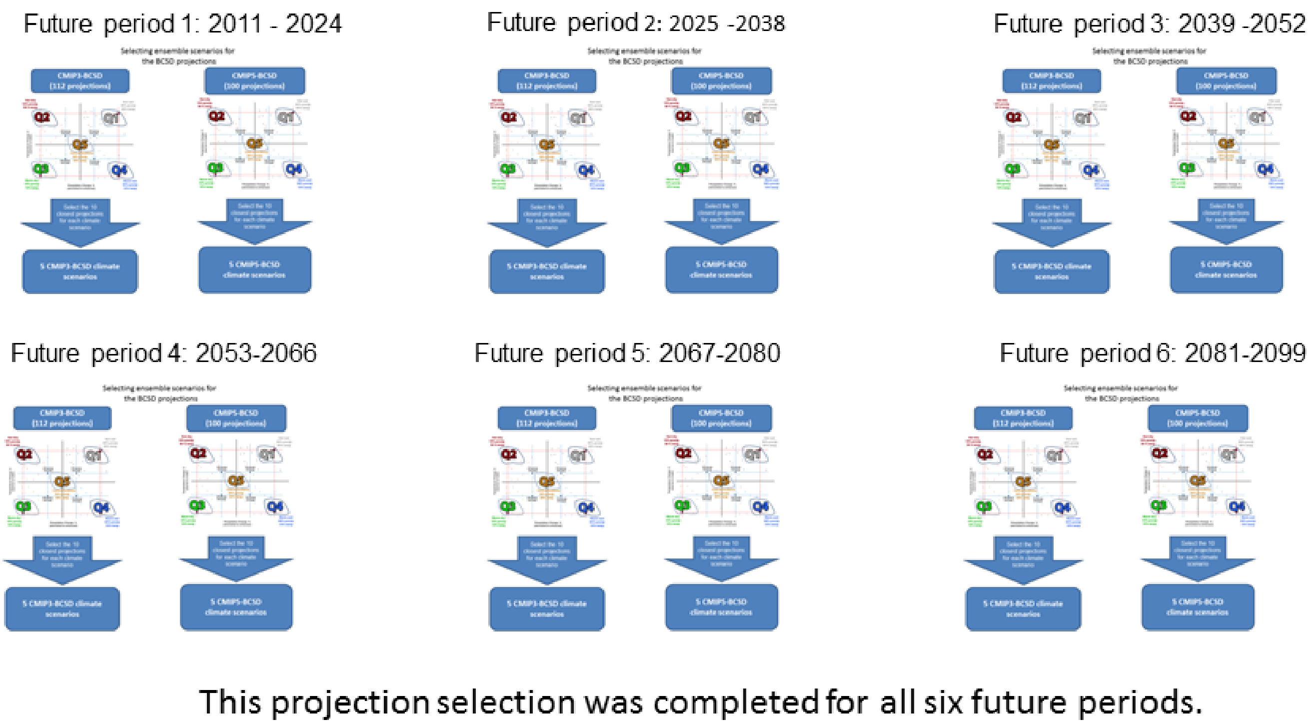

Figure 9. BCSD climate scenario selections for all six future periods.

2.4.2 Hourly Precipitation Time-Series For CMIP3-BCSD and CMIP5-BCSD Projections

WMMS input required hourly precipitation at each gage. However, CMIP3-BCSD and CMIP5-BCSD projections are temporally available on the monthly time-scale and spatially by 1/8° x 1/8° grid cell. Thus, the projections had to be disaggregated in both time and space. The technique for the disaggregation of the precipitation projections involved percentile-specific changes between simulated historical and future cumulative distribution functions (CDF) of precipitation. Figure 10 shows the process involved in calculating the WMMS model inputs for each future period.

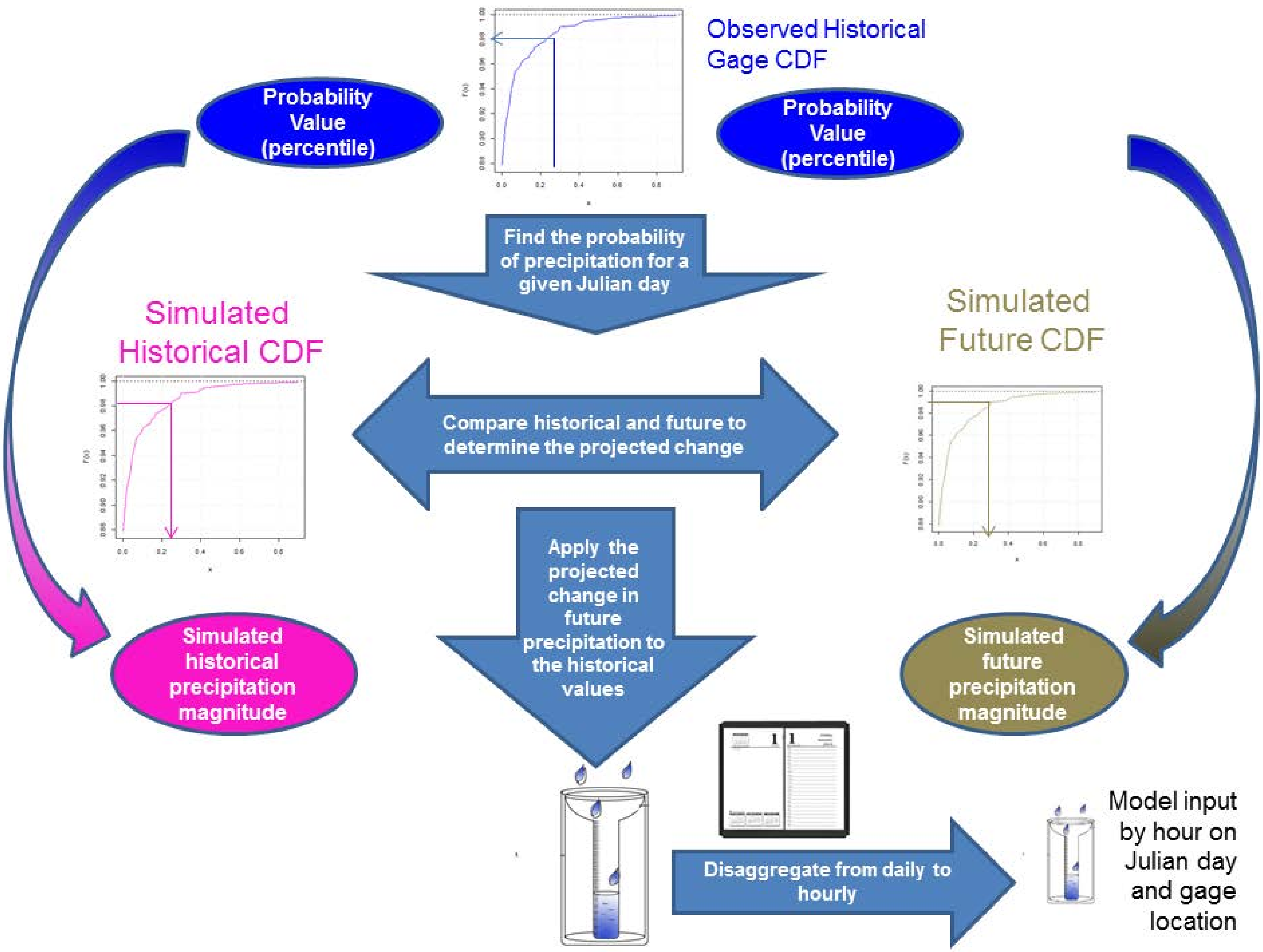

Figure 10. Process to develop hourly precipitation time-series for each gage.

As shown in Figure 10, the steps to calculate the WMMS model inputs for each future period are:

1. Develop cumulative distribution functions (CDF) of precipitation for each Julian day for the future projected conditions and the simulated historical conditions at each grid cell. The precipitation depths for the CDFs are from the ten projections for each scenario (Q1 through Q5). The precipitation depths must occur within a window, or range of Julian days, with an assumed width of ±7 days centered on the Julian day for all years in the relevant period. The future projected conditions used the future period, and the simulated historical conditions used the historical period. This results in a CDF of ([7+1+7] days) * 14 years within the relevant period * 10 projections = 2,100 candidate days.

2. Develop CDFs of precipitation for each Julian day for the observed historical precipitation at each gage. The observed data for the CDFs come from the LACDPW's gage network (locations are shown previously in Figure 2). The precipitation observations must occur within a range of Julian days with an assumed width of ±7 days centered on that Julian day (similar to the CDFs created for the future projected conditions and simulated historical conditions) for all years in the historical period (the 14-year reference period, 1986 through 1999).

3. Determine which grid cell each gage corresponded to.

4. From the CDF of observed historical precipitation (Step 2) for a specific Julian day, obtain the percentile associated with the historical precipitation magnitude.

5. Determine the precipitation magnitude associated with the percentile from Step 4 from the CDFs of precipitation for the future projected conditions and the simulated historical conditions (CDFs created in Step 1). Calculate the percentile specific change (as a scaling factor) between the projected future conditions and simulated historical conditions.

6. Apply the percentile specific change in precipitation to the observed historical precipitation magnitude from the gage to determine the future daily precipitation.

7. Disaggregate the future daily precipitation at each gage to an hourly time-series by using the same proportions of precipitation as the observed hourly proportions for the day in the historical archive with a corresponding daily total precipitation depth.

This approach was applied to all climate scenarios for a future period (Figure 11) and then repeated for all six future periods. The hourly precipitation time-series for all six future periods for each climate scenario (Q1through Q5) were concatenated into a single time-series (Figure 12). This resulted in an hourly precipitation time-series for each climate scenario for the entire future period (2011 through 2099) Figure 12.

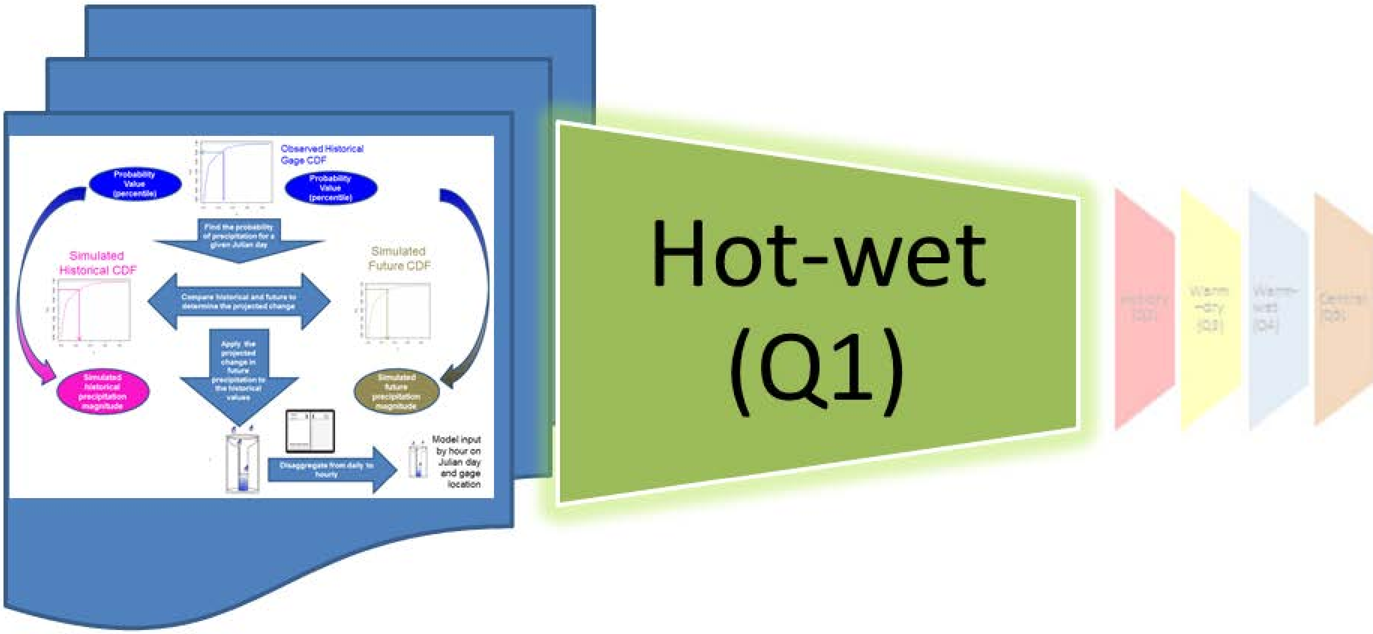

Figure 11. Hourly time series repeated for each projection in each climate scenario.

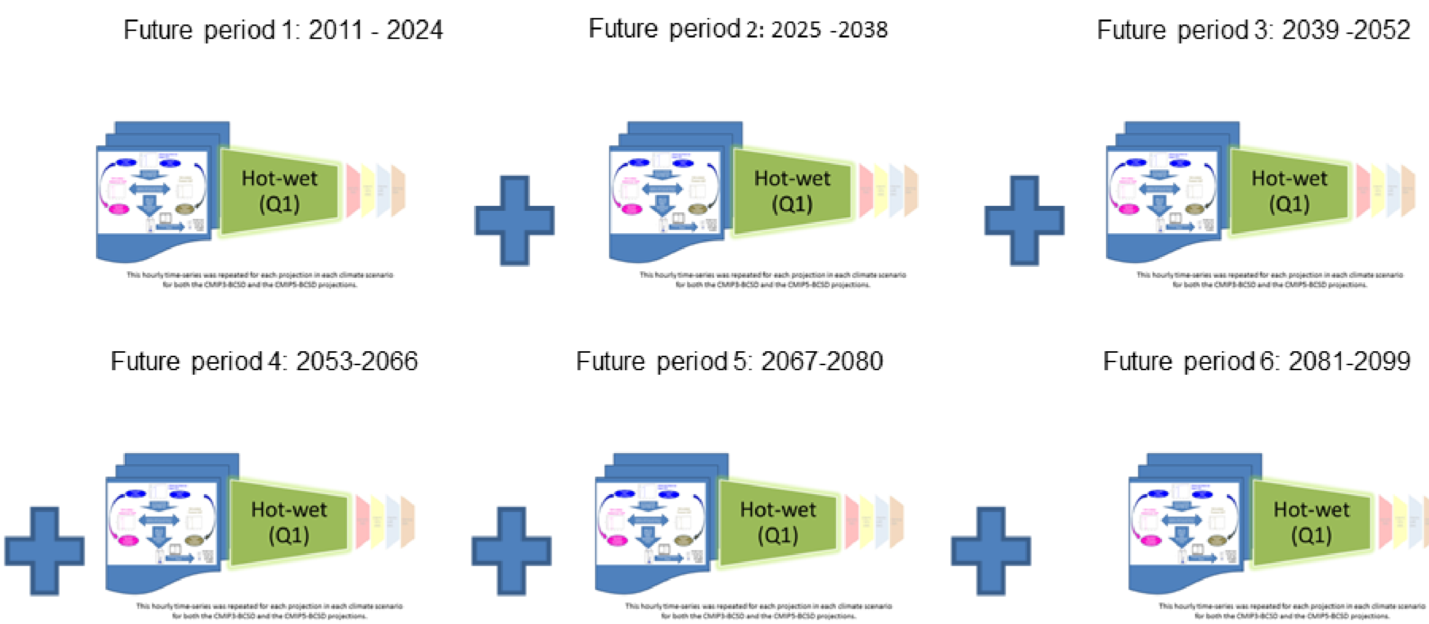

Figure 12. Hourly time series for all future time periods concatenated to provide one time series for each climate scenario (Q1 through Q5).

2.4.3 Hourly Evaporation Time-Series Under CMIP3-BCSD and CMIP5-BCSD Projections

Deriving the hourly evaporation time-series for the CMIP3-BCSD and CMIP5-BCSD datasets used a similar approach as that used for precipitation:

1. Developed CDFs of open water evaporation for each Julian day for the future projected conditions and the simulated historical conditions at each grid cell. The simulated open water evaporation was developed from the Variable Infiltration Capacity (VIC) model (Liang et al., 1994). VIC is a hydrologic model that solves full water and energy balances. The open water evaporation estimates must occur within a window, or range of Julian days, with an assumed width of ±7 days centered on the Julian day for all years in the relevant period. The future projected conditions used the future period, and the simulated historical conditions used the historical period.

2. Developed CDFs of evaporation for each Julian day for the observed historical conditions at each evaporation site. The observed data for the CDFs come from the LACDPW's gage network (locations are shown previously in Figure 2). The observations must occur within a range of Julian days with an assumed width of ±7 days centered on that Julian day (similar to the CDFs created for the future projected conditions and simulated historical conditions) for all years in the historical period (the 14-year reference period, 1986 through 1999).

3. Determined which grid cell each evaporation station corresponded to.

4. Obtained percentile of historical evaporation magnitude for the Julian day from the corresponding observed Julian day CDF (Step 2, above).

5. Used the percentile from Step 4 (above), to calculate the percentile change (as a scaling factor) between the simulated future and simulated historical CDFs.

6. Applied the percentile change in evaporation between the future and simulated historical CDFs from the grid cell to the observed evaporation magnitude to determine the future daily potential evaporation.

7. Disaggregated the future daily potential evaporation at each gage to an hourly time-series by using the same proportions of potential evaporation as the observed hourly proportions from the day in the historical archive with a corresponding daily evaporation observation.

This approach was applied to all scenarios and future periods. To complete the 89-year sequence of hourly evaporation for a particular scenario, the six future time-series were concatenated together into a single time-series. The result is one time-series of evaporation estimates for each climate scenario (Q1 through Q5) for both the CMIP3-BCSD and CMIP5-BCSD projections.

2.5 CMIP5-BCCA Climate Projections

2.5.1 CMIP5-BCCA Projection Selection

The full suite of 134 CMIP5-BCCA projections covering all the four RCPs were too many to run as input into the WMMS model, we selected projections from the lowest and highest emissions runs (See Section 2.2.1):

- **"High mitigation" pathway:** RCP2.6, the low emissions trajectory (16 CMIP5-BCCA projections)

- **"Business-as-usual" pathway:** RCP8.5, the high emissions trajectory (21 CMIP5-BCCA projections)

The RCP4.5 and RCP6.0 emission paths fall within the bounds of RCP2.6 and RCP8.5 and are not included in this study.

A subset of the CMIP5-BCCA climate model projections corresponding to the "high mitigation" pathway (RCP2.6) and "business-as-usual" path (RCP8.5) were used. This subset includes a total of 37 CMIP5-BCCA projections (i.e. 16 RCP2.6 and 21 RCP8.5 projections) (Figure 13). Each projection was created from a different model as listed in Table 2.

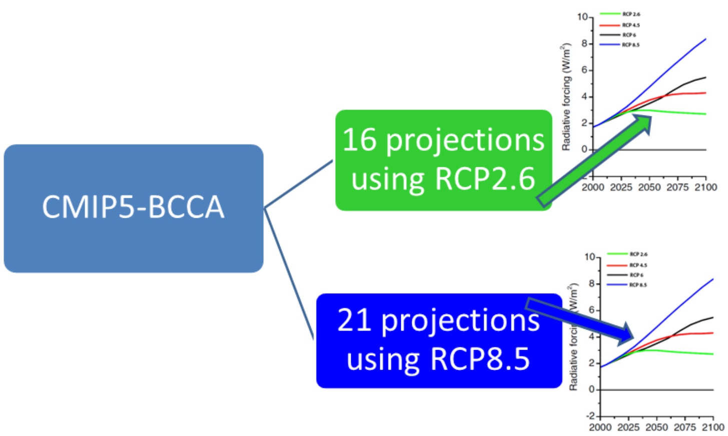

Figure 13. Selecting CMIP5-BCCA projections from lowest and highest emission pathways (RCP2.6 and RCP8.5).

Table 2. CMIP5-BCCA Projections Used in this Study (Reclamation 2013).

RCP2.6		RCP8.5	
Count	Climate Model ID	Count	Climate Model ID
1	bcc-csm1-1	1	access1-0
2	canesm2	2	bcc-csm1-1
3	ccsm4	3	bnu-esm
4	csiro-mk3-6-0	4	canesm2
5	gfdl-cm3	5	ccsm4
6	gfdl-esm2g	6	cesm1-bgc
7	gfdl-esm2m	7	cnrm-cm5
8	ipsl-cm5a-lr	8	csiro-mk3-6-0
9	ipsl-cm5a-mr	9	gfdl-cm3
10	miroc-esm	10	gfdl-esm2g
11	miroc-esm-chem	11	gfdl-esm2m
12	miroc5	12	inmcm4
13	mpi-esm-lr	13	ipsl-cm5a-lr
14	mpi-esm-mr	14	ipsl-cm5a-mr
15	mri-cgcm3	15	miroc-esm
16	noresm1-m	16	miroc-esm-chem
		17	miroc5
		18	mpi-esm-lr
		19	mpi-esm-mr
		20	mri-cgcm3
		21	noresm1-m

2.5.2 Hourly Precipitation Time-Series Under CMIP5-BCCA Projections

Similar to the CMIP3-BCSD and CMIP5-BCSD projections, the 37 CMIP5-BCCA precipitation projections needed to be disaggregated in both time and space as WMMS input required hourly precipitation at each gage. The daily CMIP5-BCCA precipitation projections were firstly bias-corrected using the LACFCD observed gage data, and then subsequently disaggregated to hourly estimates. We used the following approach to complete the hourly disaggregation:

1. Determined the projected future precipitation depth for a Julian day at each grid cell, and then found the precipitation depth for the Julian day before and the day after to create a three-day future precipitation sequence at each grid cell.

2. Pooled together historical observed precipitation data for a window, or range of Julian days, with an assumed width of ±7 days centered on that Julian day) for all years in the historical period (the 14-year reference period, 1986 through 1999) at each gage. For example, a gage with 14 years of historical data would have approximately 210 candidate days in the window, or the range of Julian days, to choose from for any given Julian day. The observed precipitation data are from the LACDPW's gage network (locations are shown previously in Figure 2).

3. Determined which grid cell each gage corresponded to.

4. Used a moving window of three days at a gage in the observed historical precipitation data to identify a sequence of three days of precipitation that most closely matched the three day future precipitation sequence at the corresponding grid cell.

5. Disaggregated the future daily precipitation at the grid cell to an hourly time-series by using the same proportions of precipitation as the observed hourly proportions from the gage.

Daily maximum and minimum temperature data from the CMIP5-BCCA projections were used in the Hargreaves-Samani model (Hargreaves and Samani 1982)[2] to develop future daily continuous potential evaporation time-series. This time-series was then bias-corrected using the LACFCD observed evaporation data at each evaporation station. Then the bias-corrected potential evaporation data were subsequently disaggregated to an hourly time-step based on the average historical hourly distribution at each site for a given Julian day.

2.6 Climate-Adjusted Hydrologic Inputs

Continuous hourly precipitation and potential evaporation time-series were created for each of the five climate scenarios (Q1-Q5) from the CMIP3-BCSD and the five climate scenarios from CMIP5-BCSD projections for the future period (2011 through 2099). Continuous hourly precipitation and potential evaporation time-series were also created from 37 CMIP5-BCCA projections. All time-series were transmitted to LACFCD for subsequent hydrologic modeling and analysis.

Table 3 provides an example of the projected monthly means for the time-series of potential evaporation from the five scenarios of CMIP3-BCSD and the five

[2] The Hargreaves-Samani (H-S) model is used to estimate reference crop evapotranspiration. The reference crop evapotranspiration is then multiplied by a crop coefficient to estimate potential evapotranspiration. Evapotranspiration consists of both evaporation (e.g., bare soil, open water) and transpiration from vegetation cover. For bare soil and open water, where no vegetation cover is present, the transpiration component consequently is absent. Furthermore, under the case of open water, the crop coefficient is nearly equal to one. Hence, the formulation of the H-S model provides an approximation of the potential evaporation.

scenarios of CMIP5-BCSD at the location of a single evaporation station (Site 23129) for the entire future period (2011 through 2099). The table also provides the minimum, maximum, and average estimate of the monthly means of potential evaporation from the 16 “high mitigation” (RCP2.6) and the 21 “business-as-usual” (RCP8.5) projections. The historical monthly mean potential evaporation estimates as observed at the evaporation site are also provided for reference. From this table, it can be seen that projected values of potential evaporation (from the CMIP3-BCSD and CMIP5-BCSD scenarios and the CMIP5-BCCA projections) are greater than current estimates of potential evaporation. The CMIP5-BCCA potential evaporation estimates are notably greater in some months. The historical potential evaporation is lowest in January and February and greatest in August. This temporal pattern is evident in the future projections.

Table 4 provides an example of the projected monthly mean precipitation from the five scenarios (Q1 through Q5) of CMIP3-BCSD and the five climate scenarios from CMIP5-BCSD at a single precipitation gage (Gage 1071) for the entire future period (2011 through 2099). The minimum, maximum, and average estimates of the monthly mean precipitation from the 16 “high mitigation” (RCP2.6) CMIP5-BCCA projections and the 21 “business-as-usual” (RCP8.5) CMIP5-BCCA projections are also provided. For reference, the historical monthly mean precipitation estimates as observed at that gage are also provided. The minimum and maximum values in Table 4 may be considered the spread of possibilities for future precipitation. In general, at this particular gage, the minimum projected precipitation depths are less than current conditions. The maximum projected precipitation by the CMIP3-BCSD and CMIP5-BCSD scenarios is greater than current conditions but not very much. However, the maximum projected precipitation by the CMIP5-BCCA projections is notably greater. It should be noted that the precipitation projections shown here are not representative of the entire study area; the areas of higher terrain are projected to dry in future climates.

Table 3. Historical and Projected Monthly Means of Potential Evaporation (in inches) for Evaporation Measurement Station 23129.

Evaporation Station 23129														
	Monthly Means		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
	Historical		2.94	2.59	4.01	5.25	5.94	7.27	7.43	7.87	6.77	5.59	4.48	3.61
BCSD	CMIP3	Hot dry	3.24	2.86	4.35	5.69	6.52	7.79	7.69	8.07	7.02	5.81	4.74	4.04
		Hot wet	3.07	2.68	4.20	5.46	6.33	7.71	7.58	8.02	6.95	5.74	4.65	3.88
		Central	3.12	2.71	4.17	5.45	6.28	7.62	7.57	8.05	6.94	5.69	4.62	3.89
		Warm dry	2.99	2.73	4.19	5.43	6.25	7.44	7.55	7.94	6.87	5.70	4.56	3.73
		Warm wet	3.00	2.66	4.08	5.35	6.17	7.44	7.53	7.90	6.89	5.68	4.61	3.79
	CMIP5	Hot dry	3.26	2.87	4.40	5.66	6.54	7.65	7.70	8.08	7.04	5.81	4.75	3.98
		Hot wet	3.14	2.77	4.23	5.47	6.27	7.44	7.67	8.12	6.98	5.77	4.82	3.93
		Central	3.13	2.79	4.27	5.55	6.35	7.54	7.62	8.05	6.89	5.71	4.71	3.91
		Warmdry	3.00	2.68	4.12	5.44	6.23	7.46	7.54	7.90	6.86	5.63	4.51	3.72
		Warm wet	2.95	2.61	4.01	5.23	6.01	7.27	7.49	7.86	6.85	5.65	4.56	3.66
	Minimum		**2.95**	**2.61**	**4.01**	**5.23**	**6.01**	**7.27**	**7.49**	**7.86**	**6.85**	**5.63**	**4.51**	**3.66**
	Maximum		**3.26**	**2.87**	**4.40**	**5.69**	**6.54**	**7.79**	**7.70**	**8.12**	**7.04**	**5.81**	**4.82**	**4.04**
CMIP5-BCCA	RCP2.6	Min	2.66	2.51	4.02	5.19	6.08	7.19	7.59	8.14	6.82	5.42	4.26	3.4
		Avg	3.09	2.83	4.21	5.48	6.34	7.73	8.06	8.45	7.21	5.94	4.67	3.83
		Max	3.54	3.21	4.43	5.75	6.77	8.23	8.45	8.93	7.51	6.24	4.98	4.2
	RCP8.5	Min	2.75	2.5	4.02	5.61	6.34	7.46	7.99	8.54	7.2	5.86	4.43	3.64
		Avg	3.32	2.95	4.43	5.82	6.7	8.3	8.62	8.87	7.55	6.3	5.04	4.2
		Max	3.81	3.29	4.89	6.07	7.42	9.18	9.17	9.31	7.77	6.75	5.46	4.76
	Minimum		**2.66**	**2.50**	**4.02**	**5.19**	**6.08**	**7.19**	**7.59**	**8.14**	**6.82**	**5.42**	**4.26**	**3.40**
	Maximum		**3.81**	**3.29**	**4.89**	**6.07**	**7.42**	**9.18**	**9.17**	**9.31**	**7.77**	**6.75**	**5.46**	**4.76**

Table 4. Historical and Projected Monthly Means of Precipitation (in inches) for Precipitation Gage 1071.

Precipitation Gage 1071														
	Monthly Means		Jan	Feb	Mar	Apr	May	Jun	July	Aug	Sept	Oct	Nov	Dec
	Historical		5.42	6.12	4.09	1.05	0.75	0.35	0.09	0.04	0.36	0.91	1.23	2.57
BCSD	CMIP3	Hot dry	4.61	5.50	3.13	0.82	0.64	0.29	0.11	0.06	0.39	0.86	1.08	2.15
BCSD	CMIP3	Hot wet	6.21	6.74	3.92	0.84	0.55	0.38	0.14	0.06	0.40	0.98	1.38	2.36
BCSD	CMIP3	Central	5.46	5.81	3.77	0.91	0.67	0.39	0.14	0.07	0.37	1.03	1.20	2.48
BCSD	CMIP3	Warm dry	4.70	5.24	4.15	1.01	0.67	0.29	0.14	0.06	0.34	1.19	1.30	2.53
BCSD	CMIP3	Warm wet	6.29	6.22	3.84	0.94	0.69	0.32	0.10	0.07	0.47	1.13	1.19	2.68
BCSD	CMIP5	Hot dry	4.90	5.14	3.41	0.94	0.52	0.30	0.12	0.07	0.55	0.94	1.04	2.59
BCSD	CMIP5	Hot wet	7.29	6.11	3.83	1.15	0.70	0.36	0.10	0.09	0.55	0.95	1.01	2.86
BCSD	CMIP5	Central	5.53	5.84	3.66	1.00	0.67	0.38	0.09	0.05	0.51	0.94	1.05	2.41
BCSD	CMIP5	Warm dry	5.52	6.29	3.63	0.95	0.71	0.31	0.11	0.05	0.45	1.22	1.15	2.88
BCSD	CMIP5	Warm wet	7.80	8.02	4.08	1.08	0.79	0.42	0.14	0.07	0.37	0.99	1.28	2.63
BCSD	**Minimum**		**4.61**	**5.14**	**3.13**	**0.82**	**0.52**	**0.29**	**0.09**	**0.05**	**0.34**	**0.86**	**1.01**	**2.15**
BCSD	**Maximum**		**7.80**	**8.02**	**4.15**	**1.15**	**0.79**	**0.42**	**0.14**	**0.09**	**0.55**	**1.22**	**1.38**	**2.88**
CMIP5-BCCA	RCP2.6	Min	3.42	3.84	3.14	0.6	0.31	0.07	0.03	0.02	0.17	0.43	1.07	1.92
CMIP5-BCCA	RCP2.6	Avg	6.33	6.33	4.17	1.22	0.78	0.37	0.12	0.05	0.52	1.08	1.61	2.86
CMIP5-BCCA	RCP2.6	Max	9.36	8.94	5.57	2.53	1.46	0.69	0.18	0.11	1.13	2.38	2.77	3.96
CMIP5-BCCA	RCP8.5	Min	3.62	3.13	2.74	0.63	0.34	0.07	0.05	0.01	0.21	0.40	0.94	1.90
CMIP5-BCCA	RCP8.5	Avg	7.19	7.26	3.76	1.03	0.66	0.35	0.14	0.06	0.49	0.96	1.38	2.79
CMIP5-BCCA	RCP8.5	Max	11.71	13.66	5.02	1.68	1.40	0.80	0.32	0.15	1.17	2.46	2.42	3.75
CMIP5-BCCA	**Minimum**		**3.42**	**3.13**	**2.74**	**0.60**	**0.31**	**0.07**	**0.03**	**0.01**	**0.17**	**0.40**	**0.94**	**1.90**
CMIP5-BCCA	**Maximum**		**11.71**	**13.66**	**5.57**	**2.53**	**1.46**	**0.80**	**0.32**	**0.15**	**1.17**	**2.46**	**2.77**	**3.96**

3. Storm Event Frequency For Future Climate Projections

The magnitude of projected precipitation is important to decision-makers for infrastructure design and flood control. Storm frequency provides the:

- Magnitude of the storm event (as the precipitation depth, given in inches)

- Likelihood of that storm event to occur (e.g., the 50-year recurrence interval has a 2% chance of occurring in any given year).

We developed storm event frequency for the 47 model input runs (i.e. the five climate scenarios for the CMIP3-BCSD projections, the five climate scenarios for the CMIP5-BCSD projections, the 16 “high mitigation” [RCP2.6] CMIP5-BCCA projections, and the 21 “business-as-usual” [RCP8.5] CMIP5-BCCA projections) at each of the 134 precipitation gages in the study area (locations are shown previously in Figure 2). All storm events were calculated at the 24-hour duration for consistency with the design storm duration found in the LACDPW’s Rainfall Frequency Analysis (Willardson et al. 2008). The storm frequency was calculated at the following recurrence intervals:

- 5-year
- 10-year
- 25-year
- 50-year (used as a reference for LACDPW water management and design)
- 100-year
- 200-year

3.1 Storm Event Frequency for the CMIP3-BCSD and CMIP5-BCSD Projections

The frequency of the 24-hour storm events for the five CMIP3-BCSD climate scenarios and the five CMIP5-BCSD climate scenarios was calculated at each of the 134 precipitation gages. The inputs into the analysis were the 24-hour annual maximum precipitation time-series derived from the hourly time-series at each precipitation gage for the future period (2011 through 2099) for each of the five scenarios (Q1 through Q5) from both the CMIP3-BCSD and CMIP5-BCSD projections. We fit the Type 1 Generalized Extreme Value Distribution (GEV-1 distribution), also commonly referred to as Gumbel Extreme Value Distribution, to the 24-hour annual maximum precipitation time-series at each gage to determine the precipitation depths (i.e., storm magnitude) at the above recurrence intervals. Results are provided in Appendix C, where the storm events are organized by precipitation gage, and climate scenarios. For reference, Figure 14 is a map of the gage locations. The storm event frequency tables in Appendix C also display the precipitation depths from the National Oceanic and Atmospheric Administration (NOAA)

Atlas 14 (Perica et al. 2012) for the above recurrence intervals (assumed to represent current climate conditions). Further, for gages that overlapped with the LACDPW's *Regional Frequency Analysis* (Willardson et al. 2008), the precipitation depths from that study are also presented.

3.2 Storm Event Frequency for the CMIP5-BCCA Projections

The frequency of the 24-hour storm events for the CMIP5-BCCA projections was calculated in the same manner as for the CMIP3-BCSD and CMIP5-BCSD projections. As there were 37 projections from CMIP5-BCCA, this resulted in 37 storm event frequency analyses. To simplify the presentation of the 37 storm event frequency analyses, the 1^{st}, 25^{th}, 50^{th}, 75^{th}, and 99^{th} percentiles of the precipitation depths associated with the six recurrence intervals for the 16 "high mitigation" (RCP2.6) CMIP5-BCCA projections and 21 "business-as-usual" (RCP8.5) CMIP5-BCCA projections were calculated. These precipitation depths are also provided in the Appendix C storm event frequency tables.

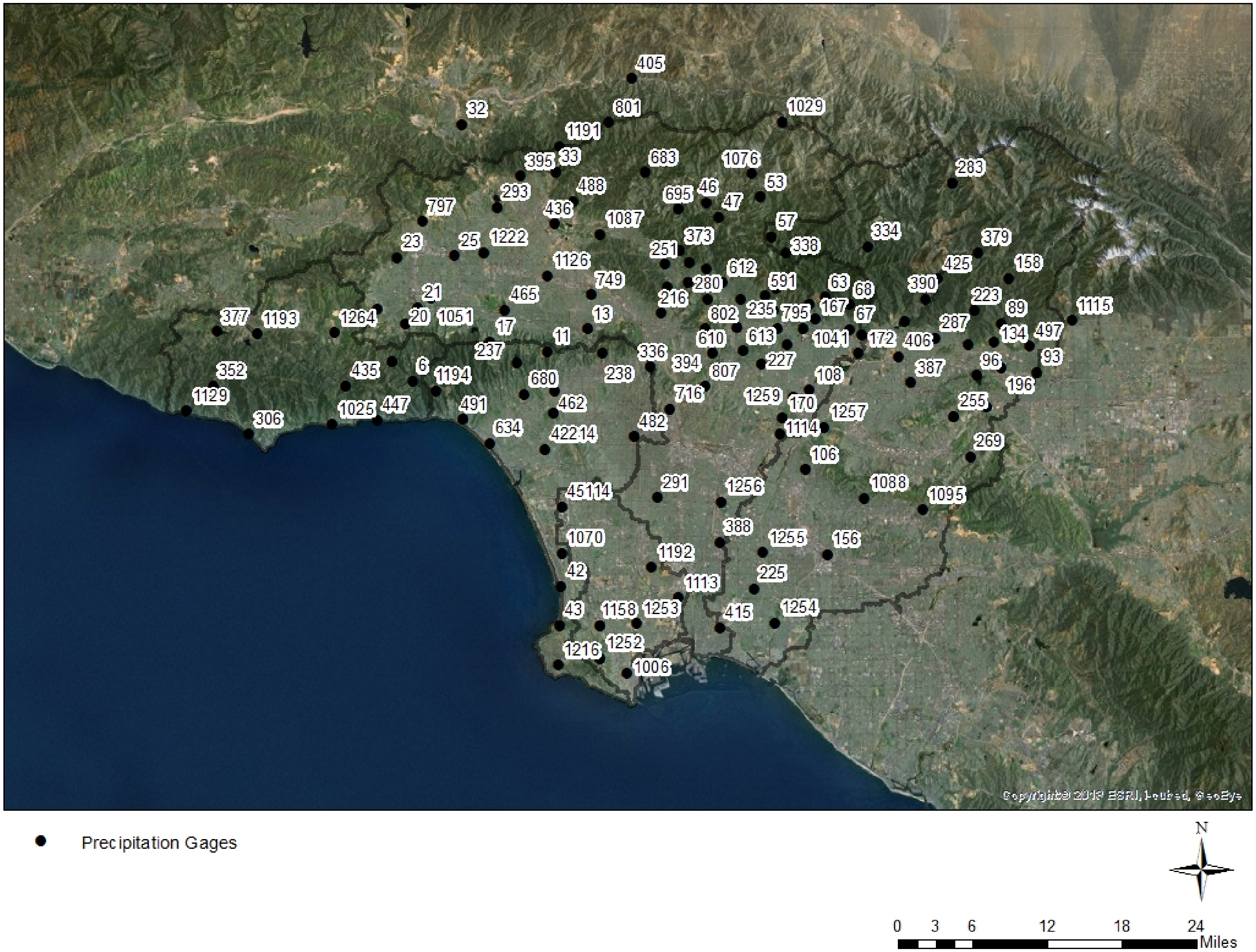

Figure 14. Precipitation gage locations.

3.3 Discussion of Storm Event Frequency Results

In the storm event frequency tables in Appendix C, rows present the minimum and maximum precipitation depths of each recurrence interval for the five climate scenarios of CMIP3-BCSD projections, the five climate scenarios of CMIP5-BCSD projections. Additional rows present the minimum and maximum precipitation depths of each recurrence interval for the 16 “high mitigation” (RCP2.6) CMIP5-BCCA projections, and the 21 “business-as-usual” (RCP8.5) CMIP5-BCCA projections. These minimum and maximum values may be considered the spread of possibilities for future storm events. Generally, the CMIP5-BCCA storm events are generally less intense than the CMIP3-BCSD and the CMIP5-BCSD precipitation depths.

The figures in this section portray the potential change in the 24-hour, 1-in-50-year precipitation depths from the present climate to the future estimates, using the minimum and maximum values from the storm event frequency tables in Appendix C. Figure 15 is a map of the 1-in-50-year precipitation depths for the current climate developed using the precipitation depths provided in NOAA Atlas 14 (Perica et al. 2012).

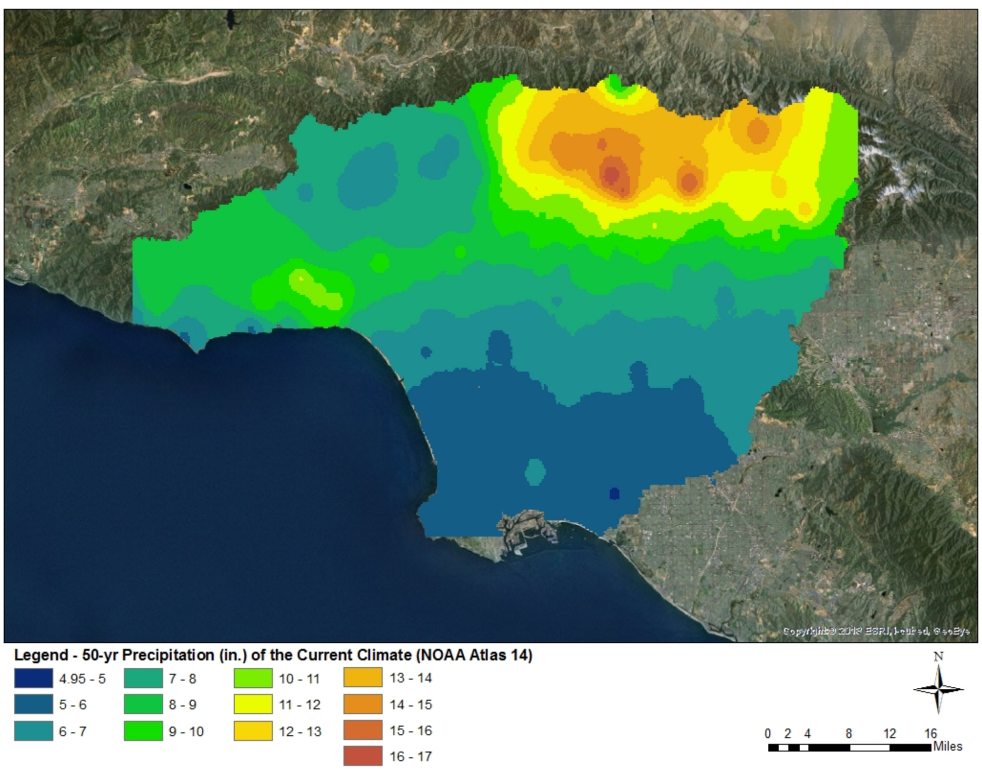

Figure 15. 24-hour, 1-in-50-year precipitation depths for the current climate, from NOAA Atlas 14 (Perica et al. 2012).

We used this map and created subsequent difference maps by:

1. Determining the minimum (or maximum) 1-in-50-year estimate from the BCSD (or BCCA) projections at each precipitation gage within the region (using the values listed in

the storm event frequency tables in Appendix C)

2. Applying Equation 1 to calculate the difference between the minimum (or maximum) 1-in-50-year estimates from the BCSD (or BCCA) projections and the 1-in-50-year estimates for the current climate from NOAA Atlas 14 at each precipitation gage (precipitation depths for the current climate at each gage provided in Appendix C):

difference = (1-in-50-year precipitation depth for future climate) – (1-in-50-year precipitation depth for current climate) **(Equation 1)**

3. Interpolating the difference between the 1-in-50-year current and future estimates between the precipitation gages using an inverse distance squared weighted algorithm

Using this method, we created maps of the change in 24-hour, 1-in-50-year precipitation depths between the current climate and minimum estimates (Figure 16 and Figure 17 correspond to the BCSD and BCCA projections, respectively) and maximum estimates (Figure 18 and Figure 19 correspond to the BCSD and BCCA projections, respectively). The regions with more intense precipitation in the future would be positive (blue shades in the figures), and regions with less intense precipitation in the future would be negative (red shades in the figures).

Both Figure 16 and Figure 17 (comparisons with the minimum estimates) show an overall decrease in storm intensity at the 24-hour, 1-in-50-year storm event for the future. The legend for both figures is the same, with red shades indicating less precipitation for the future. The area of less intense precipitation is greatest in the region of higher terrain in the northeast corner of the study domain and in the western panhandle. Conditions remain relatively neutral throughout the southern portions of the study domain. This same pattern is seen in varying degrees at all recurrence intervals.

Comparisons with the maximum estimates vary, but both Figure 18 and Figure 19 suggest decreasing intensity of the 24-hour, 1-in-50-year storm event in the northeast corner of the study domain and in the western panhandle (similar to the decreases in minimum estimates in Figure 16 and Figure 17). Increased precipitation intensity in the 24-hour, 1-in-50 year storm event is suggested in both figures for the extreme southern areas. For the other recurrence intervals, similar spatial patterns of increased and decreased precipitation can be expected. Overall, the BCCA projections (Figure 19) show a decrease of precipitation intensity in the future, whereas the BCSD projections (Figure 18) show a more neutral to slight increase in precipitation intensity in the future.

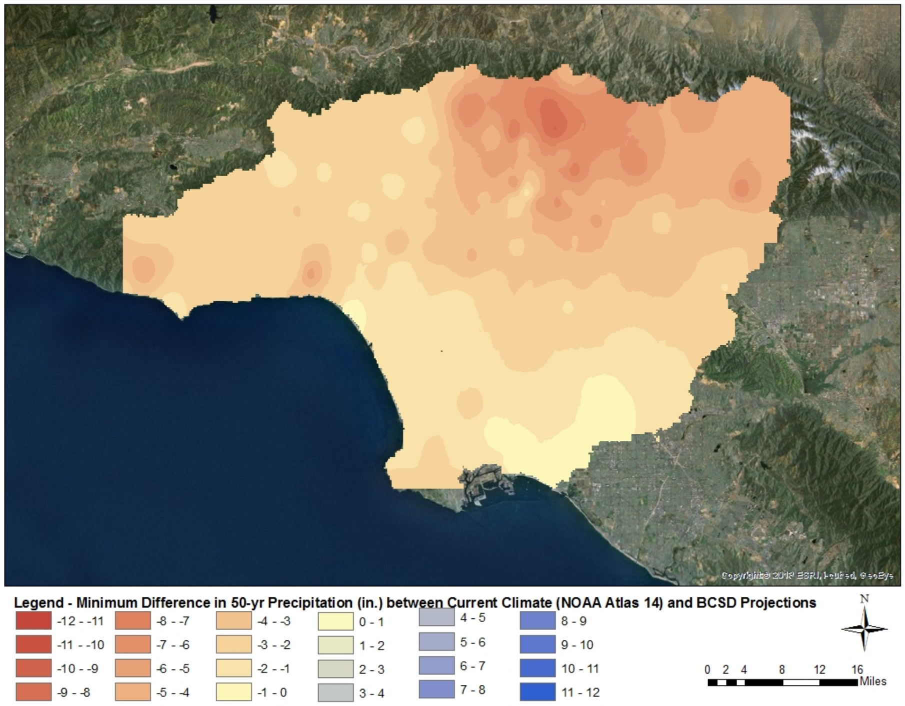

Figure 16. Change in 24-hour, 1-in-50-year precipitation depths in inches between the current climate (NOAA Atlas 14; Perica et al. 2012) and the minimum estimate from the BCSD projections for 2011 through 2099.

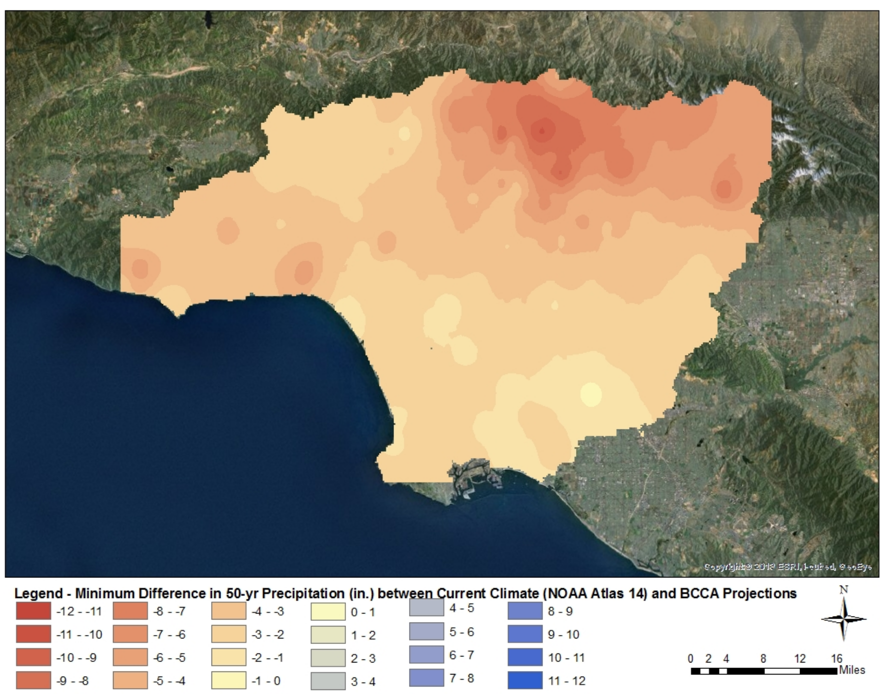

Figure 17. Change in 24-hour, 1-in-50-year precipitation depths in inches between the current climate (NOAA Atlas 14; Perica et al. 2012) and the minimum estimate from the CMIP5-BCCA projections for 2011 through 2099.

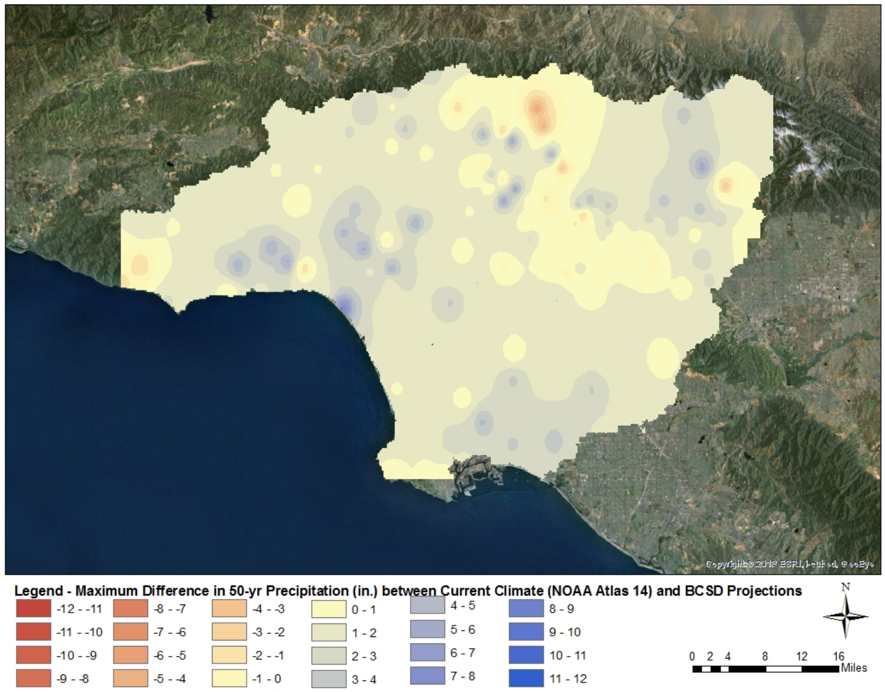

Figure 18. Change in 24-hour, 1-in-50-year precipitation depths in inches between the current climate (NOAA Atlas 14; Perica et al. 2012) and the maximum estimate from the BCSD projections for 2011 through 2099.

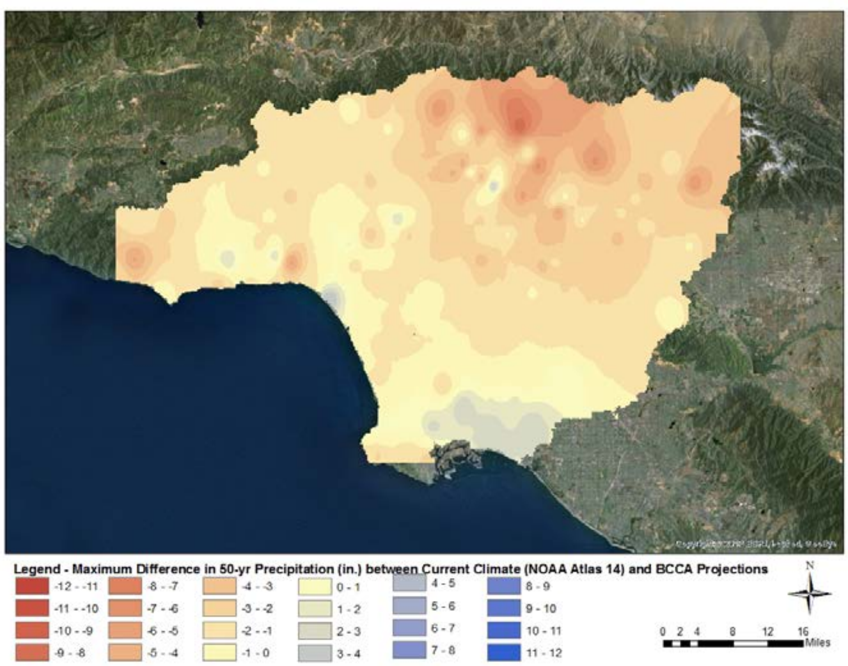

Figure 19. Change in 24-hour, 1-in-50-year precipitation depths in inches between the current climate (NOAA Atlas 14; Perica et al. 2012) and the maximum estimate from the CMIP5-BCCA projections for 2011 through 2099.

4. Summary and Conclusions

The primary objective of Task 3.1 of the Los Angeles Basin Stormwater Conservation Study is to develop climate-adjusted precipitation and evaporation inputs for use in subsequent hydrologic modeling using WMMS. This was accomplished under four subtasks:

- Consider existing projections of climate change in the LA Basin Study area

- Determine appropriate climate scenarios for use in developing precipitation and potential evaporation input datasets to support subsequent hydrologic modeling

- Prepare data (hourly data and potential evaporation) for input into the LACFCD's Watershed Management Modeling system (WMMS)

- Determine storm event frequency for planning purposes

4.1 Existing Projections

We performed a literature review, discussed in Section 1.3. This showed increases in temperature, evaporation rates, and extreme events as well as decreases in annual precipitation

We evaluated three sets of downscaled climate change projections, discussed in Chapter 2:

Three sets of downscaled climate change projections were evaluated:

- **CMIP3-BCSD:** The climate change projections from the World Climate Research Programme's Coupled Model Intercomparison Project, Phase 3 (CMIP3), released in 2006. The projections were downscaled using the Bias-Correction and Spatial Disaggregation (BCSD) process. We used 112 projections from this set.

- **CMIP5-BCSD:** The climate change projections from the World Climate Research Programme's Coupled Model Intercomparison Project, Phase 5 (CMIP5), released in 2013. The projections were downscaled using the BCSD process. We used 100 projections from this set.

- **CMIP5-BCCA:** Selected projections from CMIP5 that represent a range of potential climate futures. These projections were downscaled using the Bias-Correction Constructed Analogue (BCCA) process. We used 37 projections from this set.

4.2 Climate Scenarios

For the CMIP3-BCSD and the CMIP5-BCSD projections, we grouped the projections into five scenarios: Hot-wet (Q1), Hot-dry (Q2), Warm-dry (Q3), Warm-wet (Q4), and Central (Q5), for a total of ten scenarios. Each scenario was comprised of ten projections (see Section 2.3 and Appendices A and B).

For the CMIP5-BCCA projections, we used 37 projections (16 “high mitigation” [RCP2.6] projections and 21 “business-as-usual” [RCP8.5] projections, see Section 2.4). Each projection was analyzed independently from one another.

4.3 Hourly Projections of Precipitation and Potential Evaporation

The time-series comprises the entire future period, 2011 through 2099 (See Chapter 2). To create a continuous hourly precipitation time-series for each of the five climate scenarios from the CMIP3-BCSD and each of the five climate scenarios from the CMIP5-BCSD projections (ten time-series total), percentile-specific changes between simulated historical CDFs and future CDFs were applied to the daily historical precipitation observations from the LACDPW’s gage network. The daily future projected precipitation was subsequently disaggregating to hourly measurements. A similar procedure was used to obtain continuous hourly potential evaporation time-series for the ten BCSD scenarios. For the 37 CMIP5-BCCA projections, the daily future projected precipitation was disaggregated to hourly measurements by using the same proportions of precipitation as observed at a gage. Continuous hourly potential evaporation time-series for the 37 CMIP5-BCCA projections were created by using the Hargreaves -Samani model. All time-series were transmitted to the LACFCD for input into the WMMS and for subsequent hydrologic analysis. By analyzing all 47 time-series, the range of uncertainty and variability for the future climate is expected to be represented. .

4.4 Storm Event Frequency

Even though the annual amount of precipitation may change in a future climate, the more important factor for decision-makers for infrastructure design and flood control is the magnitude of that precipitation. Therefore, we examined the potential intensity and frequency of storm events rather than the annual amount of precipitation and associated trends.

The storm event frequency analysis was completed at each gage for each of the five CMIP3-BCSD climate scenarios, each of the five CMIP3-BCSD climate scenarios, the 16 “high mitigation” [RCP2.6] CMIP5-BCCA projections, and the 21 “business-as-usual” [RCP8.5] CMIP5-BCCA projections for numerous annual exceedance probabilities, with emphasis on the 1-in-50-year storm event to coincide with the LACPDW’s Flood Hydrology Manual (LACDPW 2006). For all of these climate scenarios and projections, the minimum and maximum estimates of the precipitation depths associated with each annual exceedance probability were provided.

The range of precipitation depths between the minimum and maximum values represented the variability in the projected future precipitation intensity. The precipitation frequency analysis of the CMIP3-BCSD and CMIP5-BCSD scenarios indicates an increase in the intensity of the 1-in-50-year storm event over higher elevation portions of the study area. Little change in the intensity of the 24 hour, 1-in-50-year storm event over the central and coastal areas is evident. The 37 CMIP5-BCCA projections indicate a more general decrease in the intensity of the 24-hour, 1-in-50-year storm event (see Chapter 3 and Appendix C).

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