Draft

2017 CVFPP Update – Climate Change Analysis Technical Memorandum

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1.0 Introduction

1.1 Purpose of this Document

This technical memorandum (TM) provides an overview of the climate change technical analyses, tools, and information supporting development of the 2017 Central Valley Flood Protection Plan (CVFPP) Update (California Department of Water Resources [DWR], 2016a). This TM is focused on the projected impacts of climate change on the hydrology of the Central Valley, and does not address sea-level rise.

Considering climate change is necessary to prudently define the State of California's long-term flood management investment portfolio, and to comply with Governor Brown's Executive Order B-30-15 and Assembly Bill 1482, which require State agencies to account for climate change in project planning and investment decisions. Future floods are projected to be different from past floods in timing, frequency, magnitude, and form. Therefore, to achieve the same levels of protection, the design and operations of individual facilities, as well as basin-wide facilities, would need to be changed. A systematic approach was developed to identify and evaluate potential effects of climate change on the Central Valley, and findings have been applied to refine and implement the State Systemwide Investment Approach described in the 2012 CVFPP (DWR, 2012). This TM describes the multi-phase climate change analysis efforts that build upon current knowledge and tools for evaluating climate change in the context of flood management.

The purpose of this TM is as follows:

- Describe the climate change analyses that were undertaken to support development of the Sacramento and San Joaquin River Basin-Wide Feasibility Studies (BWFSs) (DWR, 2016b; DWR, 2016c)
- Describe the refinements and enhancements to the climate change analyses that continued in parallel with the BWFSs, and which supported development of the 2017 CVFPP Update

1.2 Background

To date, evaluations of California Central Valley flood control improvements have been based on climate and hydrologic conditions that occurred over the past 100 years. This historical period includes significant flood events caused by intense precipitation, rapid snowmelt and watershed conditions that, in combination, result in the hydrologic conditions that have shaped our current flood infrastructure and management.

Future climate projections indicate the potential for increased flood peak flows and flood volumes, which is likely to affect flood risk in the Central Valley. DWR began a three-phase process for assessing potential changes in future climatic conditions in the Central Valley and accounting for those changes in the BWFSs. Phase I, completed in 2013, included a pilot study that evaluated the sensitivity of the Feather-Yuba watershed and Oroville operations to a range of changes in flood volumes.

In addition, three DWR-supported research studies were initiated in 2013 as follows:

- Climate Variability Sensitivity Study, led by the United States Army Corps of Engineers, evaluating the effects of warming on flood flows

- Atmospheric River Study, led by Scripps Institute of Oceanography/United States Geological Service (USGS), investigating indices and future projections of the major flood-producing atmospheric processes

- Watershed Sensitivity Study, led by the University of California at Davis (UC Davis) Center for Watershed Sciences, investigating the atmospheric and watershed conditions contributing to the extreme flows in several Central Valley watersheds (Null, 2010)

The methodology and findings of the Climate Variability Sensitivity Study were reviewed when preparing analysis for the current work. The Atmospheric River Study and Watershed Sensitivity Study are in progress.

In Phase II, expanded analyses were designed to provide information about potential climate vulnerabilities for the BWFSs. The analyses used existing and updated tools and climate change projections in two subsequent sub-phases, Phases IIA and IIB, to fit within the risk framework being applied in CVFPP analyses.

The result of the Phase IIA effort, completed in June 2014, was a set of adjustments to historical flow volume-frequency curves that could be used as a preliminary assessment of the effects of climate change in the Central Valley Flood Management Planning Program planning area. Phase IIA used climate scenarios based on climate model simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3). The CMIP3 climate model data were the basis for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) released in 2007 (IPCC, 2007). The results of Phase IIA where applied directly to the BWFS technical evaluations.

Phase IIB work continued in parallel to BWFS development. Phase IIB provided updated estimates of potential changes in unregulated flows throughout the Central Valley based on newer climate projections and refined hydrologic modeling. The Phase IIB work was based on climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) (Taylor et al., 2012) to ensure that the 2017 CVFPP Update incorporated the most current science available at the time of its release. The CMIP5 climate model data are the basis for the most recently released IPCC Fifth Assessment Report (AR5) (IPCC, 2013). Changes in unregulated flow volumes were estimated by applying climate scenarios (i.e., temperature and precipitation projections) to the historical variability in climate, and simulating the hydrologic responses.

2.0 Overview of Climate Change Analyses

The climate change analyses conducted over the course of the BWFSs and 2017 CVFPP Update program are outlined in the following sections.

2.1 Overview of Phase IIA

The Phase IIA climate change analysis was conducted in 2014. Phase IIA aimed to provide preliminary estimates of potential changes in unregulated flows throughout the Central Valley based on available climate projections and coarse-scale hydrologic modeling. This information was prepared to fit within the risk analyses framework of the BWFSs.

Changes in historical unregulated flow volumes were derived through hydrologic modeling of the Central Valley watersheds. Unregulated flows under projected climate change conditions were computed with a continuous simulation run for more than 80 years. The climate change results were compared to the current climate results to compute climate change factors. A climate change factor is calculated by dividing an unregulated volume-frequency curve from the climate change simulations by an unregulated volume-frequency curve from the historical simulations.

The climate change factors were computed based on variable infiltration capacity (VIC) simulations using historical climate forcing and future climate change scenarios at major analysis points. The climate change factors were applied to the historical unregulated volume-frequency curves used in the BWFSs' risk analyses to compute future climate change unregulated volume. Attachment A details this analysis which estimated climate change factors during Phase IIA. In earlier BWFS and CVFPP documentation of technical analyses, the terms "scaling factor" and "climate change ratio" were used; these terms are the same as "climate change factor" used here.

Figure 2-1 presents the general steps linking atmospheric processes, precipitation, temperature fields, and watershed conditions to changes in flood risk.

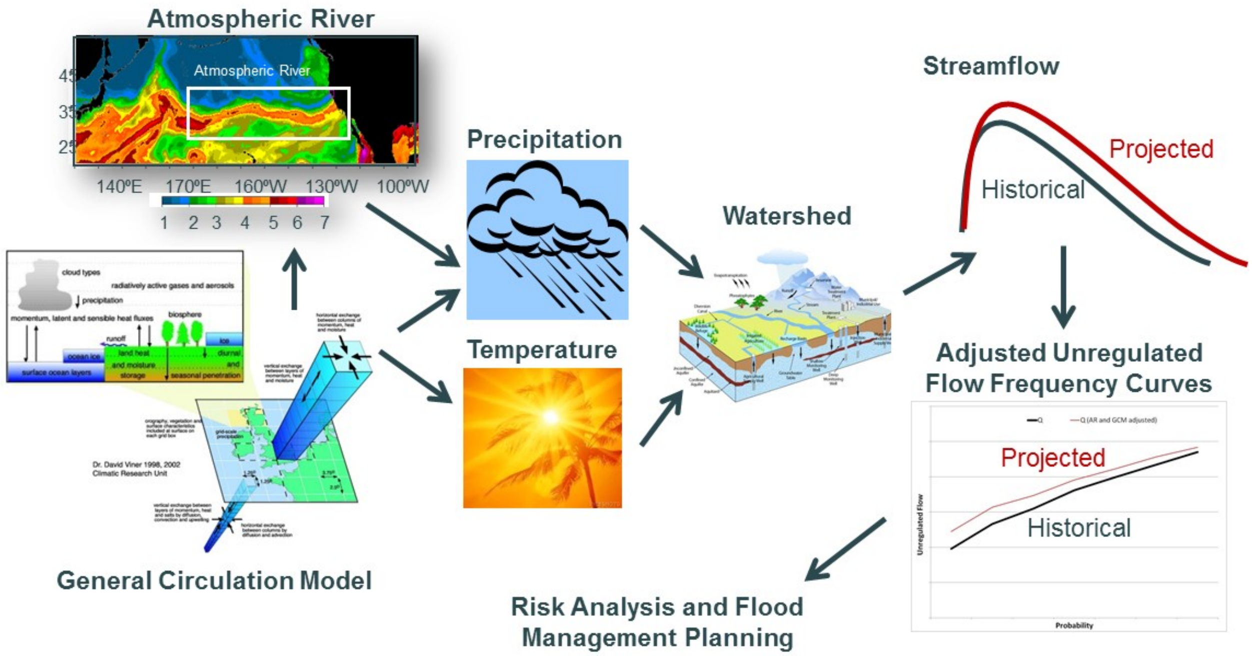


Figure 2-1. Schematic Framework for Linking Atmospheric Processes, Precipitation and Temperature Fields, and Watershed Conditions to Inform Changes in Flood Risk

MBK Engineers and David Ford Consulting Engineers conducted peer reviews of the Phase IIA TM for DWR (Attachment A). Recommendations from these reviews were addressed during subsequent Phase IIB technical analyses.

2.2 Overview of Phase IIB Analyses

Although the BWFSs results are founded on Phase IIA climate change analysis results, Phase IIB climate change efforts continued in parallel to BWFS technical work. Newer climate projections such as CMIP5 are currently available, are consistent with the most recent IPCC AR5, and represent the current state of the practice for incorporation in the Phase IIB analyses. Additionally, the VIC model was used at a coarse resolution during Phase IIA, and analysts identified a need to refine model resolution and recalibrate the model. Specifically, analysts determined that additional information about the potential spatial and temporal changes to flood hydrograph characteristics under climate change could improve further technical evaluations.

The approach used climate change factors for each annual exceedance probability at each analysis point to adjust historical events. Uniform changes to scaled historical events increase the hydrograph volumes, but do not change other characteristics of the hydrographs, such as duration and spatial correlation, that may be impacted under climate change. Analysts identified a need to understand the projected changes in hydrograph characteristics such as storm duration, timing, peak flow magnitude, and flow volume.

The overall goals of Phase IIB climate change analysis were as follows:

- Update the climate change analysis for the most current global and regional climate projections (CMIP5)
- Improve understanding of the hydrologic responses in various watersheds to future climate conditions
- Refine the climate change factors, using a higher spatial resolution and improved watershed delineations, that can be used to modify unregulated flow frequency curves for CVFPP risk analysis

An overview of Phase IIB efforts is below. Attachment B describes analysis details.

2.2.1 Future Climate Scenarios in Phase IIB

Future climate scenarios used for Phase IIB of the CVFPP climate change analysis were based on climate model simulations from CMIP5 (Taylor et al., 2012). Climate models in CMIP5 were driven using a set of newly developed emission scenarios called representative concentration pathways (RCPs) to reflect possible trajectories of greenhouse gas emissions over the course of the century (van Vuuren et al., 2011). The CMIP5 climate model data are the basis for the most recently released IPCC AR5 (IPCC, 2013). The RCPs differ from the scenarios used for the AR4 (IPCC, 2007).

Climate scenarios used in this analysis were developed using two different approaches: the ensemble-informed approach using bias-corrected and spatially downscaled climate projections from more than 100 climate simulations, and an approach using downscaled climate projections based on the locally organized constructed analog (LOCA) method (Pierce et al., 2014) for 20 selected climate projections selected by the DWR Climate Change Technical Advisory Group (CCTAG).

2.2.2 Projections of Future Climate Change

Figure 2-2 shows the median annual mean temperature and precipitation changes for California and Nevada derived from the full ensemble of climate projections. The current suite of general circulation models (GCMs), when simulated under potential future greenhouse gas emission pathways and current atmospheric greenhouse gases, exhibit warming both globally and regionally over California. The median, or central, tendency scenario indicates substantial warming by the end of mid-century. Warming is projected to increase more rapidly inland than in coastal areas, reflecting a continued ocean cooling influence. Statewide trends in annual precipitation are not as apparent as those for temperature. Regional trends are more pronounced for the upper Sacramento Valley, which may experience equal or greater precipitation; the San Joaquin Valley may experience equal or drier conditions, and the Tulare Lake hydrologic region may experience drier conditions. Future projections for southern California are for drier conditions. The north-south transition of precipitation change may be attributable to a more northerly push of storm tracks caused in part by increased sea level pressure blocking systems under future climate conditions.

Projected changes in future climate contain significant uncertainties. Uncertainties exist with respect to understanding and modeling of the earth systems, future development and RCPs, and to simulating changes at the local scale. However, climate models suggest that the projected temperature increase signal is strong and temporally consistent (Figure 2-3). All projections are consistent in the direction of the temperature change, but vary in terms of climate sensitivity. Projected annual average temperature increase by end of century under the CMIP5 ensemble is in the range of 0.9 degrees Celsius (°C) to 5.9 °C with a median estimate of 3.2 °C for the Sacramento River Basin. Projected annual average temperature increase by end of century under the CMIP5 ensemble is in the range of 0.8 °C to 6.3 °C with a median estimate of 3.1 °C for the San Joaquin River Basin. While increased warming is consistent between CMIP3 and CMIP5 for the region, inland valley and mountain ridges are projected to exhibit a larger degree of warming in the CMIP5 projections.

Projections of annual precipitation change are not always directionally consistent in both the CMIP3 and CMIP5 ensembles, with some projections suggesting wetter future conditions and others suggesting slightly drier future conditions (Figure 2-4). The strong natural precipitation variability over multiple decades complicates the determination of wet-dry trends. The CMIP5 ensemble suggests a significant reduction in the areas projected to be drier in the future as compared to the CMIP3 ensemble, and includes less uncertainty than the CMIP3 ensemble as expressed by the range. The CMIP5 ensemble also provides greater clarity about wetter conditions in the Sacramento Valley, while suggesting more neutral (i.e., little change) in projected annual precipitation for the San Joaquin and Tulare basins. Median changes in annual precipitation by the end of the century for the Sacramento River Basin are projected to be about 6 percent, and in the San Joaquin River Basin are projected to be about 4.5 percent. The CMIP5 ensemble continues to project future drier conditions in Southern California, but to a lesser degree when compared to the CMIP3 ensemble. However, despite relative uncertainty in annual precipitation changes, about two-thirds of the projections suggest increases in 3-day annual maximum precipitation, which is commonly the driver for flooding. The median changes in 3-day annual maximum precipitation by the end of the century for the American River Watershed are projected to be about 9 percent, and are projected to be about 4 percent in the Merced River Watershed.

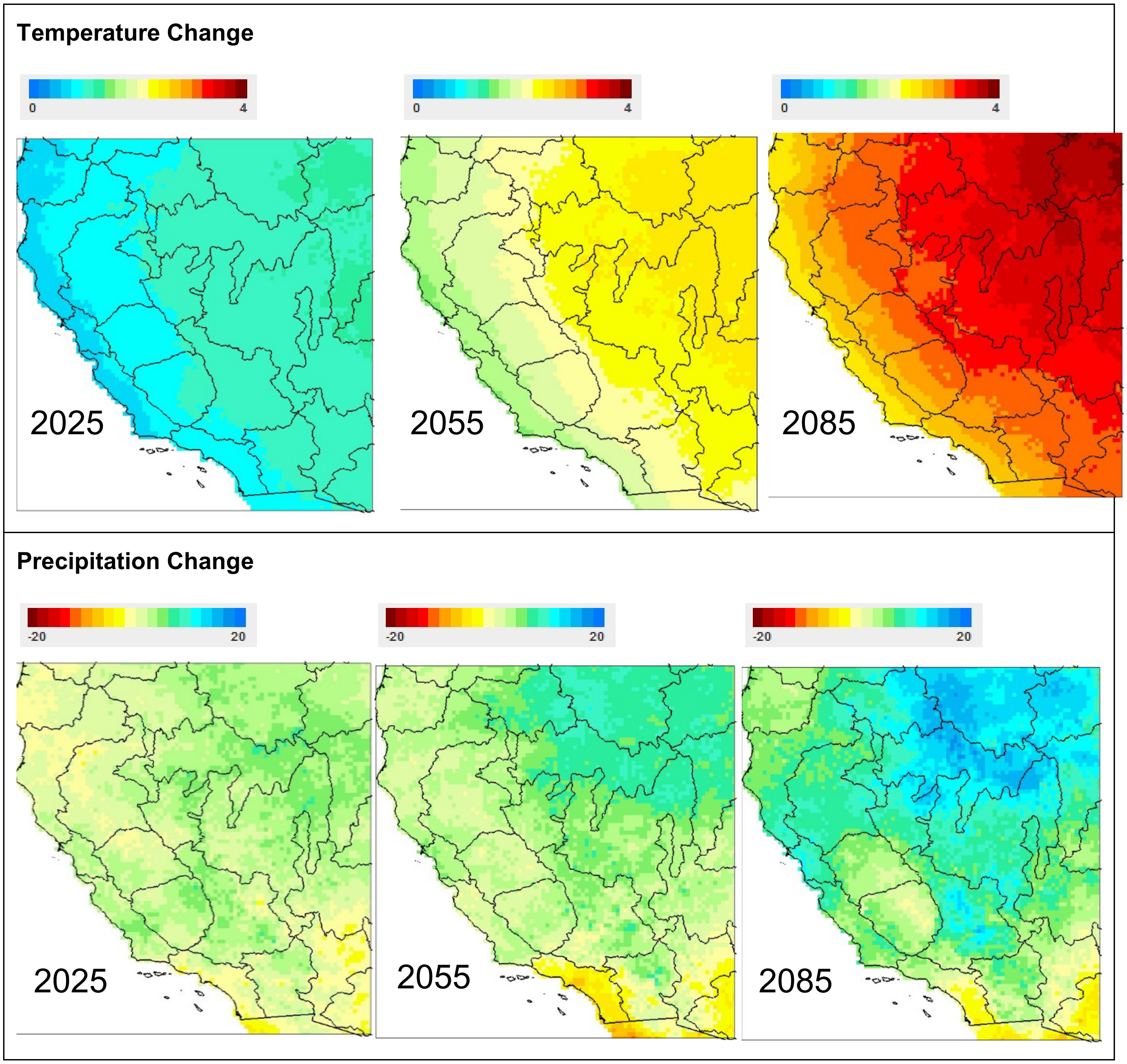
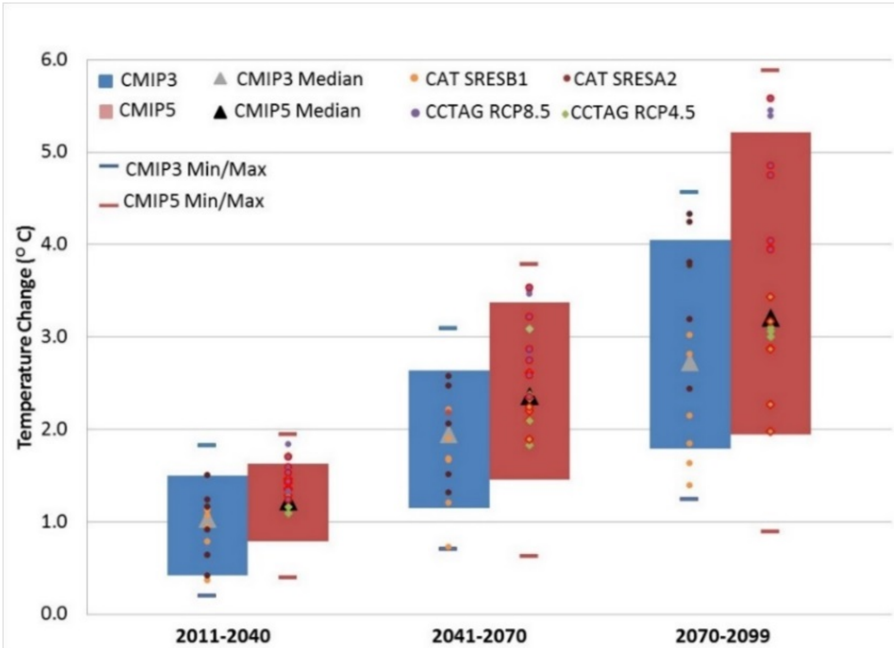


Figure 2-2. Projected Changes in Annual Mean Temperature and Precipitation Using the CVFPP Median Climate Change Scenario for 2011 to 2040 (2025), 2041 to 2070 (2055) and 2070 to 2099 (2085)

Notes: Figures show change as compared to the 1981 to 2010 model simulated period. Top panel shows °C. Bottom panel shows percent change. Hydrologic basin boundaries are shown.



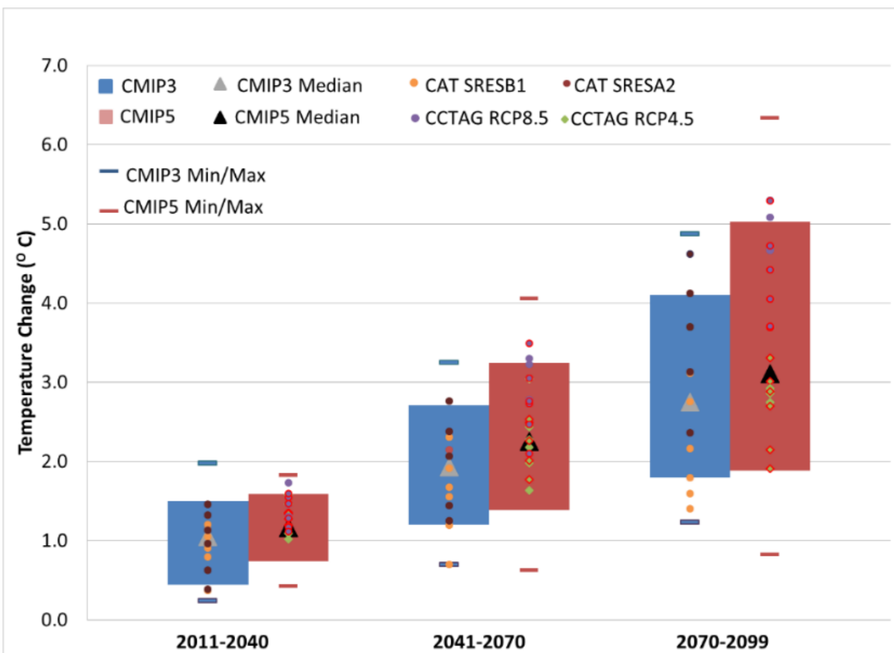


Figure 2-3. Projected Changes in Mean Annual Temperature for the Sacramento River Basin (Top) and San Joaquin River Basin (Bottom) based on CMIP3 and CMIP5 Projections

Notes: Projected changes for CMIP3 and CMIP5 were computed using more than 100 downscaled climate projections. For CMIP3, under the Special Report on Emission Scenarios, projections were simulated for emission scenarios A2, A1B, and B1 for the IPCC's AR4. For CMIP5, projections were simulated under representative concentration pathways emission scenarios RCP8.5, RCP6.0, and RCP4.5 for the IPCC's AR5. Changes were computed with respect to a 1971 through 2000 model simulated period for both CMIP3 and CMIP5. The bars represent the range between the 10th and 90th percentiles. Circles represent projections from CMIP3 GCMs selected by the Climate Action Team (CAT). The CMIP5 GCMs were selected by DWR's CCTAG for California climate and water assessments. CMIP3 and CMIP5 climate model projections were bias-corrected and spatially downscaled (Maurer et al., 2007; United States Bureau of Reclamation [Reclamation], 2013). GCMs selected by the CAT included: CNRM CM3.0, GFDL CM2.1, MIROC3.2 (med), MPI ECHAM5, NCAR CCSM3, and NCAR PCM1. GCMs selected by the DWR CCTAG included: ACCESS-1.0, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, and MIROC5.

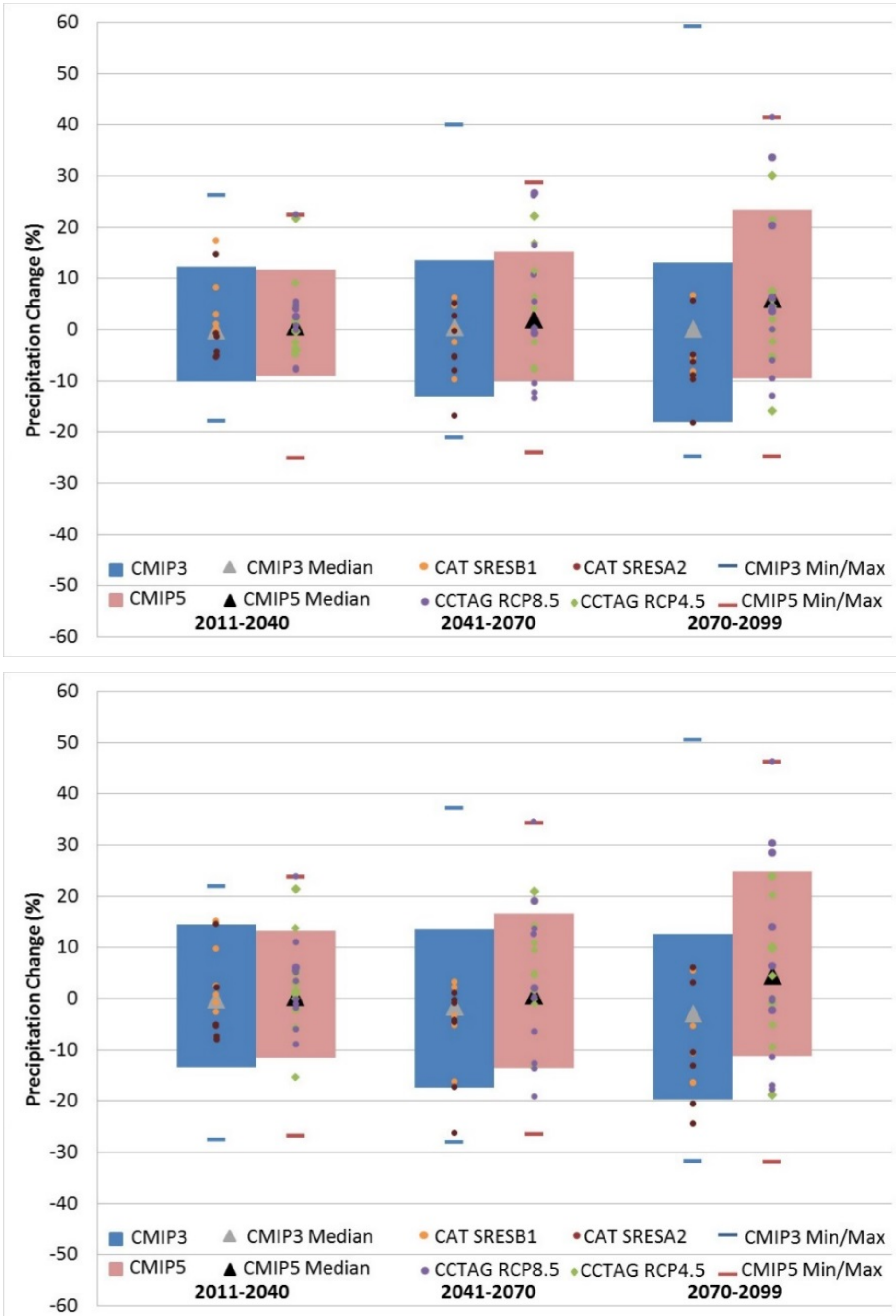


Figure 2-4. Projected Changes in Mean Annual Precipitation for the Sacramento River Basin (Top) and San Joaquin River Basin (Bottom) based on CMIP3 and CMIP5 Projections

Notes: Projected changes for CMIP3 and CMIP5 were computed using more than 100 downscaled climate projections. For CMIP3, under the Special Report on Emission Scenarios, projections were simulated for emission scenarios A2, A1B, and B1 for the IPCC's AR4. For CMIP5, projections were simulated under representative concentration pathways emission scenarios RCP8.5, RCP6.0, and RCP4.5 for the IPCC's AR5. Changes were computed with respect to a 1971 through 2000 model simulated period for both CMIP3 and CMIP5. Bars represent the range between the 10th and 90th percentiles. Circles represent the projections from the CMIP3 GCMs selected by the CAT and the CMIP5 GCMs selected by DWR's CCTAG for California climate and water assessments. CMIP3 and CMIP5 climate model projections were bias-corrected and spatially downscaled (Maurer et al., 2007; Reclamation, 2013). GCMs selected by the CAT included: CNRM CM3.0, GFDL CM2.1, MIROC3.2 (med), MPI ECHAM5, NCAR CCSM3, and NCAR PCM1. GCMs selected by DWR's CCTAG included: ACCESS-1.0, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, and MIROC5.

The median's magnitude of potential late-century temperature increase projections (i.e., the black triangles on the right of Figure 2-3, which are a statistical value and not an output from a single projection) is within the upper range of potential mid-century temperature increases (i.e., the middle red bars on Figure 2-3). Since the intended design life of flood management facilities evaluated in the CVFPP is beyond 50 years, the late-century statistical distributions of temperature and precipitation changes in CMIP5 projections that fall between the 25th and 75th percentiles (i.e., all projections in the right red bars of Figures 2-3 and 2-4) were used to represent projected climate change for the 2017 CVFPP Update.

2.2.3 VIC Hydrological Model Refinements and Calibration

The VIC model is a spatially distributed hydrologic model that solves the water balance at each model grid cell (Liang et al., 1994). It accepts inputs such as meteorological data directly from global or national gridded databases, or from climate model projections, and simulates runoff and other hydrological variables while considering features like land cover, soil infiltration, and snow coverage. Runoff from each grid cell is routed to various river flow locations; as a result, flow hydrographs can be developed at analysis points throughout the Sacramento, San Joaquin, and Tulare river basins.

As part of Phase IIB model refinements, two improvements to the Phase IIA VIC hydrologic model were made. First, the model was refined to include a higher resolution grid and re-delineation of watershed boundaries and stream flow routing. Second, the VIC model was calibrated at upper watershed locations for selected extreme historical flood events.

2.2.4 VIC Model Calibration

The VIC model underwent limited calibration for monthly stream flow for selected major river basins over the conterminous United States (Livneh et al., 2013). Further VIC model calibration was performed for the CVFPP application for the 12 upper watershed locations in the Sacramento and San Joaquin river basins. The VIC model was calibrated for the 3-day maximum flow volume for selected historical events from February to March 1986, and from December 1996 to January 1997. VIC model performance was also evaluated for selected other historical events from November to December 1950 and from December 1955 to January 1956. However, insufficient precipitation and snow observations limited the assessment of early periods.

Figures 2-5 and 2-7 show the model-simulated flows and observed flows for the 1986 and 1996-97 events on the Feather River at Oroville Dam and at Tuolumne River at New Don Pedro Dam. As shown in the figures, the calibrated VIC model reproduces the 3-day flood hydrograph volumes to within 10 percent of observed volumes at both locations. Differences in flood volumes are approximately 5 to 7 percent for the Feather River and are approximately 6 to 9 percent for the Tuolumne River for these events. The simulated hydrographs generally match the rising and falling limbs that were observed, reflecting good model performance of the watershed response. Most errors appear to be at peak daily discharge, and are likely due to inaccuracies of the available observed peak rainfall depths in the station and gridded data used as input for the VIC model. Attachment B details VIC model calibration during Phase IIB.

Figures 2-6 and 2-8 show the flow frequency for 3-day annual maximum flows using the entire period of water years from 1916 to 2008. These plots demonstrate that the VIC model simulations provide reasonable estimates for a wide range of high flow events compared to the observed record over the entire historical period.

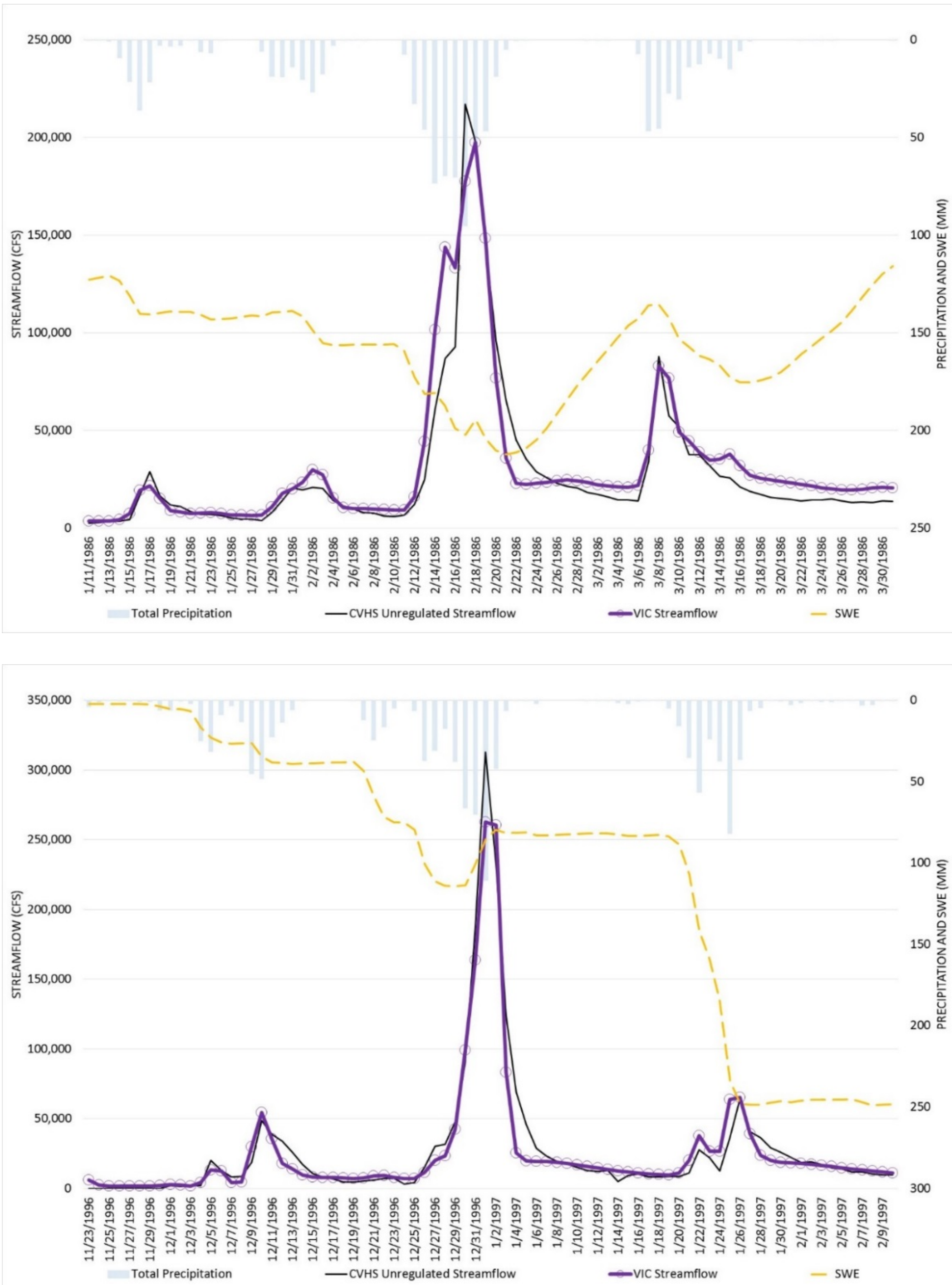


Figure 2-5. Simulated and Central Valley Hydrology Study (CVHS) Unregulated Stream Flow Hydrograph for Feather River at Oroville Dam During 1986 (Top) and 1996-97 (Bottom) Flood Events

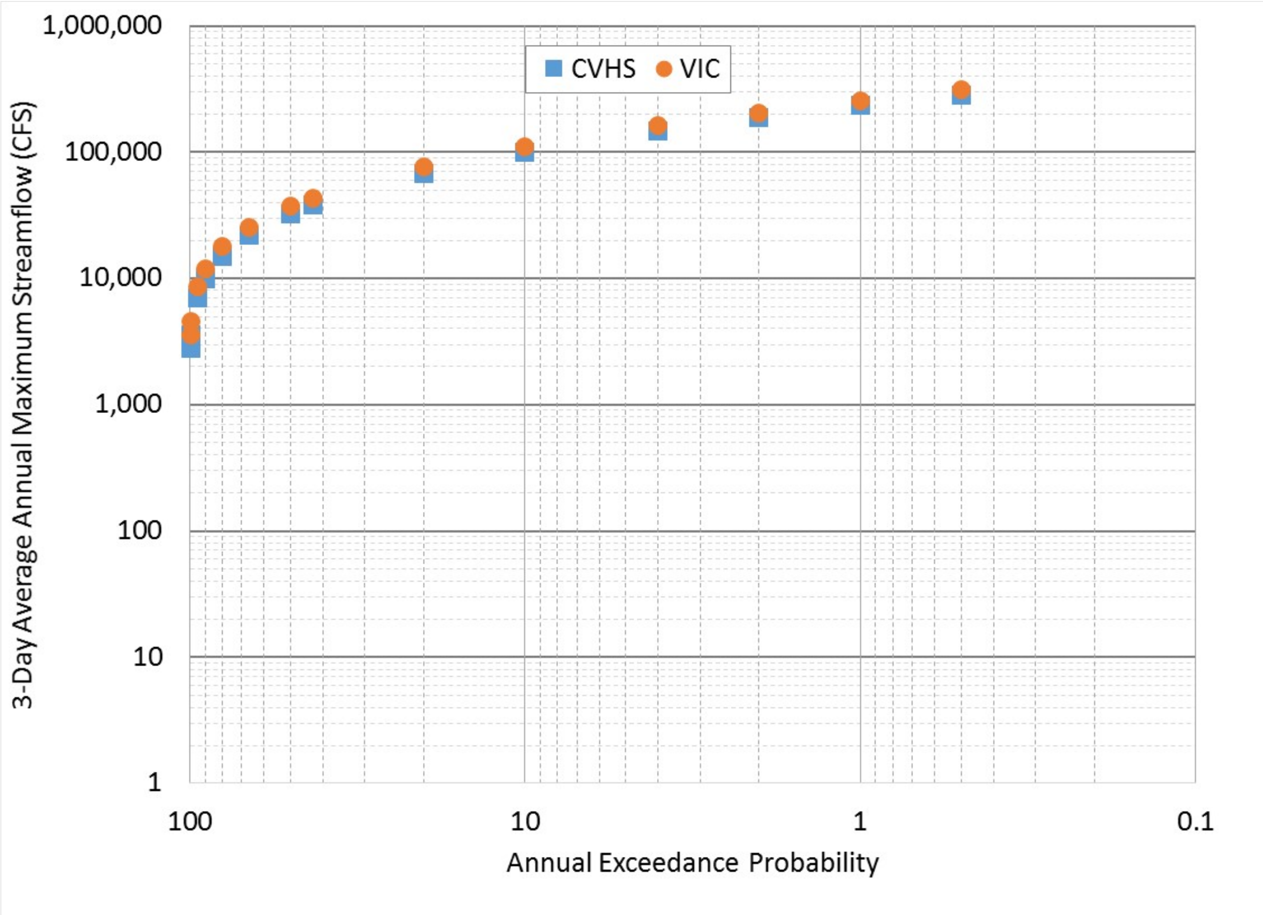
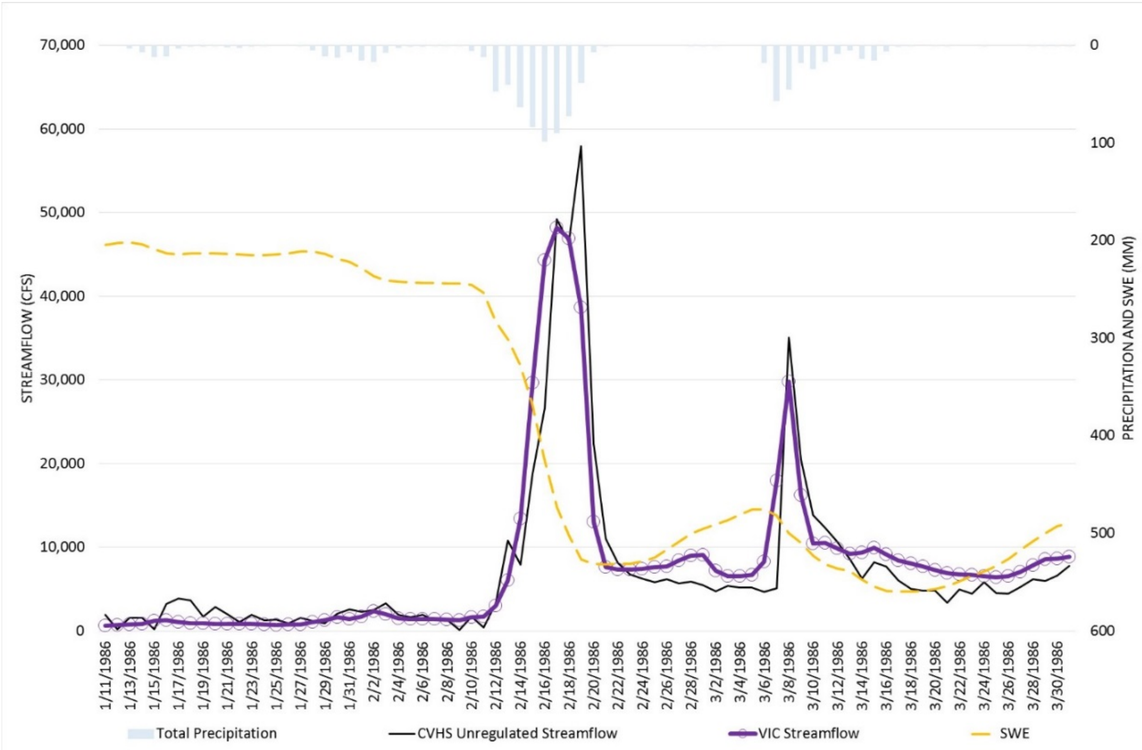


Figure 2-6. Flood Flow Frequency Plots at Feather River at Oroville

Notes:Simulated stream flows on the Feather River at Oroville Dam were derived using a Bulletin 17B flood flow frequency plot from the 3-day annual maximum of CVHS unregulated stream flows and the VIC hydrological model. Annual 3-day average maximum flows were computed for each water year from 1916 to 2008. Annual 3-day average maximum flows were computed based on the predetermined time window for each water year in which rain-flood events occurred. The time windows for the water years are identical to the time windows used for CVHS unregulated rain-flood frequency curves development. Log Pearson Type 3 distribution was fitted to annual maximum unregulated stream flows using the Bulletin 17B method in the USGS's PeakFQ software (USGS, 1982). The Bulletin 17B method employs the Method of Moments with Grubbs-Beck outlier test. The skew coefficient was computed based on the annual maximum stream flow for the flow location.



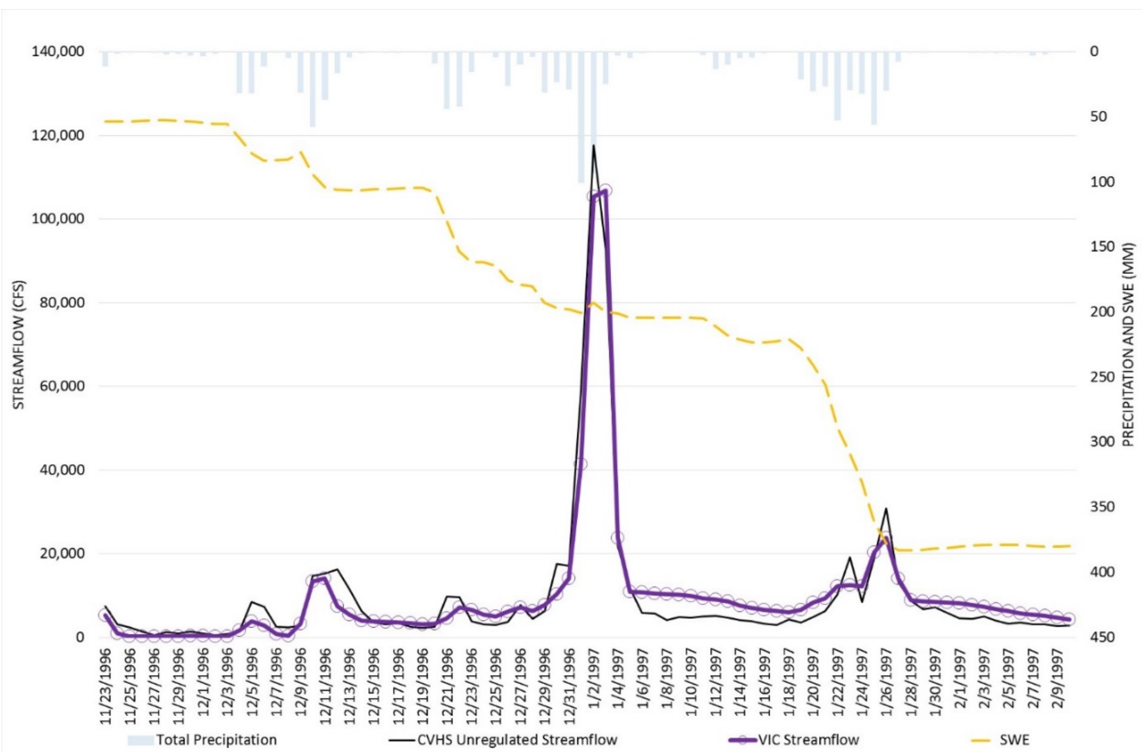


Figure 2-7. Simulated and Observed Hydrograph for Tuolumne River at New Don Pedro Dam in 1986 (Top) and 1996-97 (Bottom) Flood Events

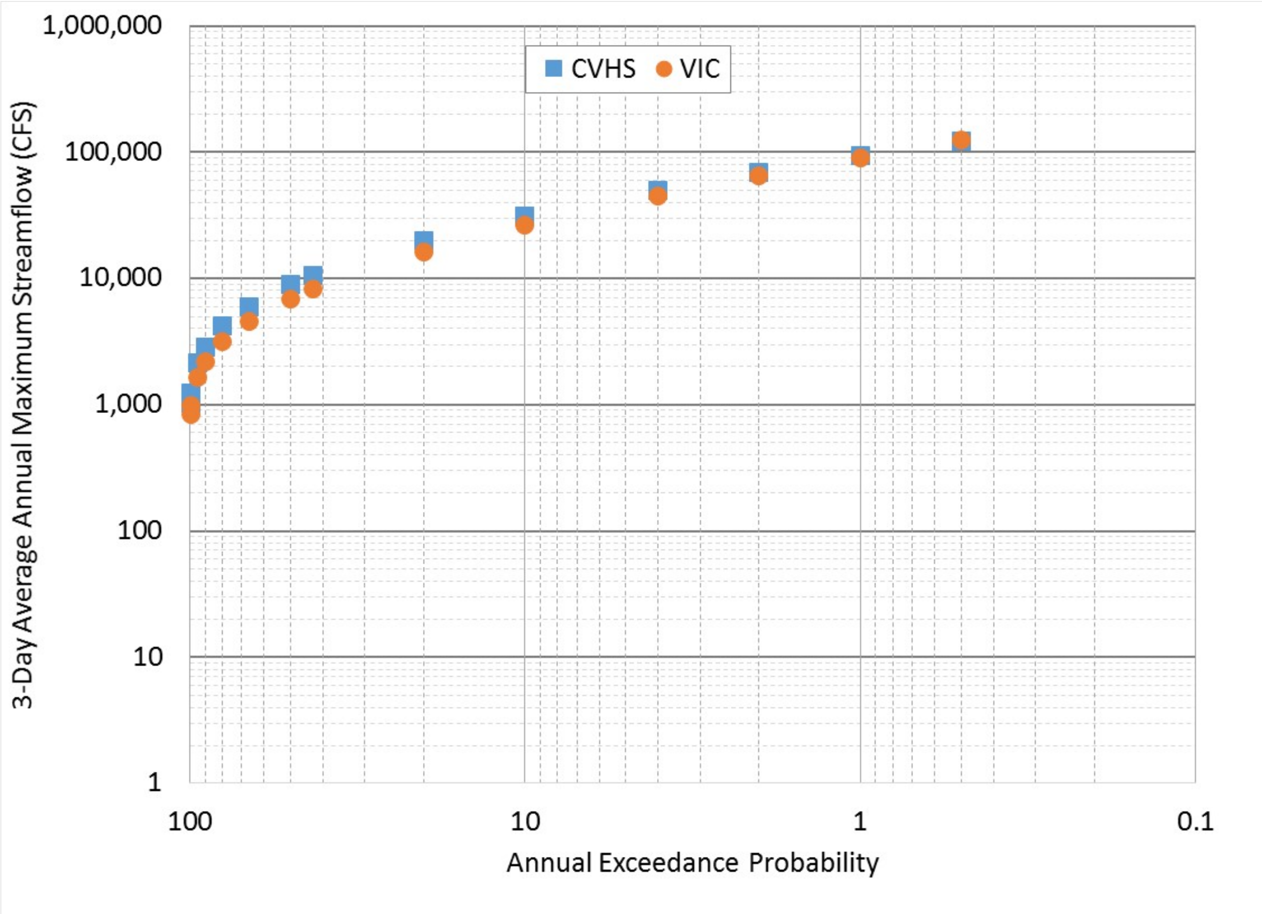


Figure 2-8. Flood Flow Frequency Plot at Tuolumne River at New Don Pedro Dam

Notes: Simulated stream flows on the Tuolumne River at New Don Pedro Dam were derived using a Bulletin 17B flood flow frequency plot from the 3-day annual maximum of CVHS unregulated stream flows and the VIC hydrological model. Annual 3-day average maximum flows were computed for each water year from period 1916 t0 2008. Annual 3-day average maximum flows were computed based on the predetermined time window for each water year in which rain-flood events occurred. The time windows for the water years are identical to the time windows used for CVHS unregulated rain-flood frequency curves development. Log Pearson Type 3 distribution was fitted to annual maximum unregulated stream flows using the Bulletin 17B method in the USGS's PeakFQ software (USGS, 1982). The Bulletin 17B method employs the Method of Moments with Grubbs-Beck outlier test. The skew coefficient was computed based on the annual maximum stream flow for the flow location.

2.2.5 VIC Model Simulations

The refined and re-calibrated Phase IIB VIC model was used to evaluate hydrologic responses under conditions of future change in climate. The following steps were used with the VIC model to generate climate change factors at each analysis point:

1. Configured the VIC model for California at a one-sixteenth-degree spatial resolution (i.e., approximately 6-kilometer or 3.75-mile resolution).
2. Applied the VIC model with historical daily precipitation and temperatures to produce daily hydrographs under current climate conditions. Routed stream flows were developed for over 150 specific analysis points across California's Central Valley.
3. At each analysis point, computed the annual maximum unregulated flow rates for 1-, 3-, 7-, and 15-day durations for each water year from VIC model results under current climate conditions, and fitted the Log Pearson Type 3 distributions to develop unregulated flow-frequency curves.
4. Applied climate change-adjusted precipitation and temperatures to the VIC model to compute daily hydrographs at all analysis points under the projected climate change conditions. It is important to note that temperature and precipitation inputs for the VIC model were *not* adjusted uniformly for the entire 96-year simulation period (i.e., 1915 through 2010). The adjustments were based on the statistical distributions described and varied by month.
5. Repeated Step 3 with VIC model results from Step 4 to develop climate change-adjusted, unregulated, flow-frequency curves.
6. At each CVHS analysis point for a specific duration and specific annual exceedance probability, computed a climate change factor by dividing future climate flow by current climate flow.
7. Applied climate change factors to the CVHS-generated, unregulated flow-frequency curves to develop unregulated flow-frequency curves under projected climate change conditions.

Using the climate change-adjusted unregulated flow-frequency curves, a flood risk evaluation was conducted, as described in the 2017 CVFPP Update's Scenario Technical Analyses Summary Report (DWR, 2017).

2.2.6 Climate Scenarios Used for Hydrologic Analyses

In general, temperature change projections are more robust and stable than precipitation change projections. To distinguish the effects of precipitation and temperature, and to characterize changes over time, the following scenarios were developed for use during hydrologic analyses:

- Warming-only scenarios (i.e., no precipitation changes):
  - Near-term: projected warming of about +1 ^{o}C (+1.8 ^{o}F)
  - Mid-century: projected warming of about +2 ^{o}C (+3.6 ^{o} F)
  - Late-century: projected warming of about +3 ^{o}C (+5.4 ^{o}F)

- Combined warming and precipitation change scenarios:
  - Near-term: projected precipitation and temperature changes
  - Mid-century: projected precipitation and temperature changes
  - Late-century: projected precipitation and temperature changes

The warming-only scenarios apply temperature warming uniformly to all VIC grid cells, while the combined warming and precipitation change scenarios apply changes as spatially projected through downscaled climate modeling. The median estimates of projected climate change under the ensemble-informed approach were used in this study to reflect combined future projected warming and precipitation changes.

2.2.7 Computation of Flood Frequency Statistics

Using the VIC model, analysts performed daily hydrologic modeling for the period from 1915 to 2010 using both historical meteorology and adjusted meteorology reflecting future climate projections. Flows were routed to various river locations, and changes between the climate scenario and historical reference period flows were computed as a percentage change. For each year of the historical reference period and the future climate scenario, the maximum 1-, 3-, 7-, and 15-day unregulated flows were calculated for routed flows at specific locations. Log Pearson Type 3 fitting was then performed based on the Bulletin 17B method used in the USGS's PeakFQ software from maximum 1-, 3-, 7-, and 15-day durations for each year, both with and without climate change (USGS, 1982). Next, the percentage change in flow was calculated for the specific frequency, such as the 200-, 100-, 50-, 25-, 10-, and 2-year flows by comparing the two frequency curves.

Table 2-1 compares the 3-day unregulated stream flow climate change factors from Phase IIA and Phase IIB analysis results for key locations in the Central Valley. As shown in the table, changes in Phase IIB analysis results are generally higher than those from Phase IIA for most of the major watersheds. The differences in the climate change factors for Phases IIA and IIB are attributable to a number of causes, including the following:

- Changes in climate change scenarios from CMIP3 used for Phase IIA analysis to CMIP5 used for Phase IIB analysis

- Use of a more refined hydrological model (i.e., higher resolution and improved watershed delineation)

- Use of a different statistical method in Phase IIB to develop flood frequency curves (i.e., the Bulletin 17B method in USGS's PeakFQ software)

The results are consistent for watersheds of similar location and characteristics. All Sacramento Valley watersheds show increases in the 100-year flow volumes of about 20 to 30 percent, while high elevation watersheds in the San Joaquin Valley show increases of about 60 to 70 percent. The total unregulated 100-year flow on the Sacramento River below Sacramento Weir is projected to increase by about 30 percent, while the unregulated flow on the San Joaquin River near Vernalis is projected to increase by about 75 percent.

Some anomalies identified in Phase IIA analysis results have been resolved during Phase IIB refinements. The largest differences between the two phases of analyses occur in the upper San Joaquin and Kings rivers due to improved delineation of the high elevation watershed in Phase IIB analysis. Previous modeling used during Phase IIA had relatively coarse delineations, and were not validated with updated digital elevation model information. Similar refinements also occurred in the Yuba, Cosumnes, and Mokelumne river watershed responses.

Table 2-1. Projected 100-Year, 3-Day Unregulated Flow Climate Change Factors for 2070 to 2099 (2085) in Phase IIA and Phase IIB Analyses at Key Locations

Location	Climate Change Factors (Phase IIB)	Climate Change Factors (Phase IIA)	Difference (IIB minus IIA in %)
Sacramento River at Shasta Dam	1.28	1.11	18
Feather River at Oroville Dam	1.25	1.20	5
Yuba River at Smartville	1.18	1.07	12
American River at Folsom Dam	1.22	1.24	-2
Cosumnes River at Michigan Bar	1.25	1.11	13
Mokelumne River at Pardee	1.61	1.46	14
Calaveras River at New Hogan	1.26	1.32	-6
Stanislaus River at New Melones Dam	1.65	1.72	-7
Tuolumne River at New Don Pedro Dam	1.63	1.68	-4
Merced River at Lake McClure	1.73	1.70	3
San Joaquin River at Millerton Lake	1.70	1.16	54
Kings River at Pine Flat Dam	1.60	1.23	37
Sacramento River below Sacramento Weir	1.28	1.15	12
San Joaquin River near Vernalis	1.76	1.50	26

Figure 2-9 shows that the potential changes in flow magnitude would not be uniform across the Central Valley. Changes in flood magnitudes and frequencies are projected to vary from north to south within the Central Valley. Watershed characteristics strongly influence the hydrological response to climate change, with the high-elevation San Joaquin watersheds showing the largest increases in flood volumes due to a reduction in precipitation falling as snow and more rapid melting of snow packs.

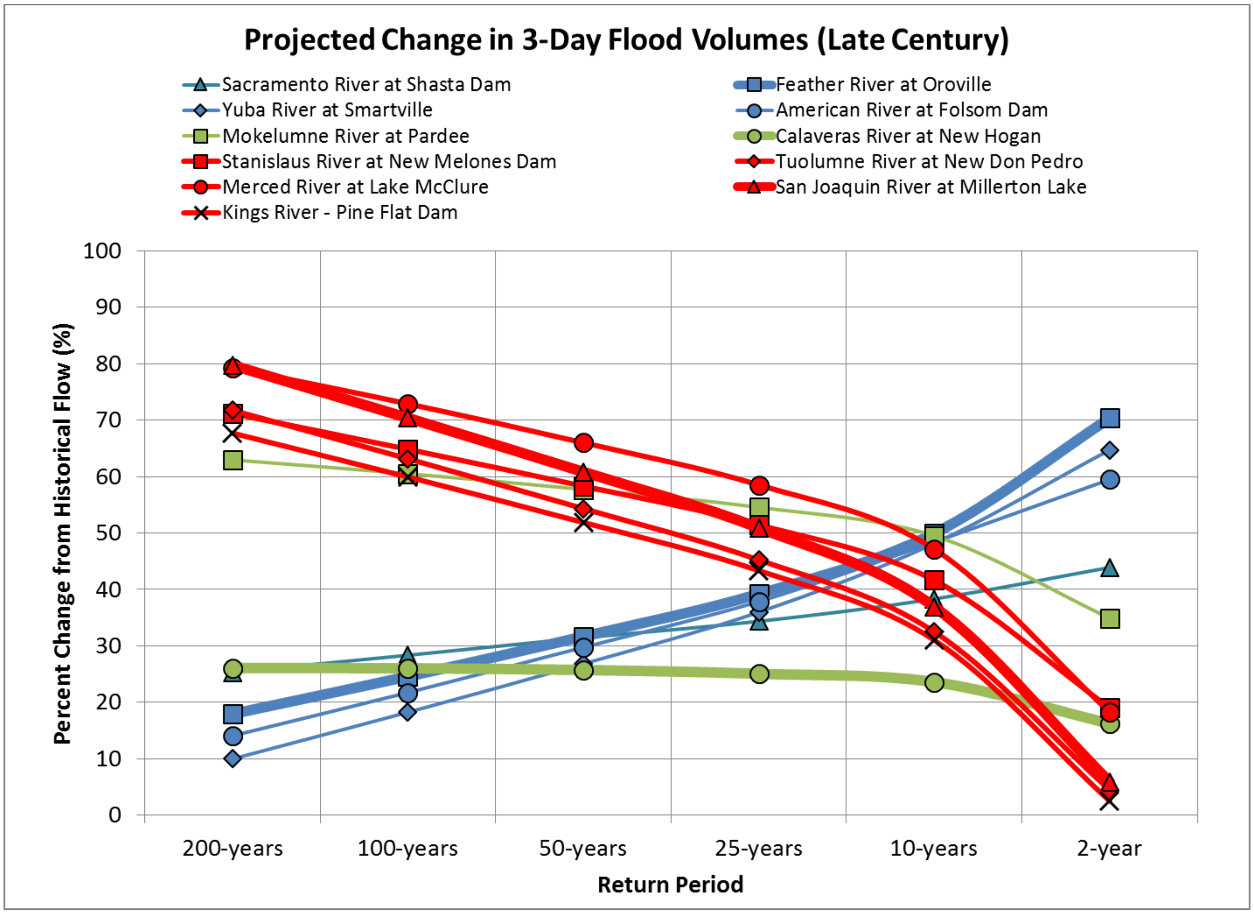


Figure 2-9. Phase IIB Late-Century Climate Change: Changes in Flood Magnitudes with Different Return Periods

2.2.8 Changes in Hydrograph Characteristics under Climate Change

The climate change factors for each annual exceedance probability at each location were used to adjust historical flood frequencies and assess overall climate risk to flood management systems for the 2017 CVFPP Update. Changes to the scaled historical events increase hydrograph volume, but do not change other hydrograph characteristics such as duration and spatial correlation that may be impacted under climate change.

Although not applied to 2017 CVFPP Update flood risk analyses, additional analysis was undertaken to assess changes in the characteristics of future simulated hydrographs. VIC simulations were developed; these were driven by 20 individual daily downscaled climate projections using the LOCA daily downscaling method. These climate projections were made available by the Scripps Institution of Oceanography, and were recommended by DWR's CCTAG for use in California water resources analysis. Attachment B presents detailed analyses results.

3.0 Summary and Next Steps

Climate change technical analyses results, their use in supporting the 2017 CVFPP Update flood risk analyses scenarios, and potential next steps to advance understanding of possible future climate impacts on the Central Valley are discussed in the following sections.

3.1 Results Summary

The analytical work informing the 2017 CVFPP Update relied on the most recent future climate model simulations from CMIP5 and refined VIC hydrologic modeling to represent a range of potential future changes to unregulated flow volumes due to climate change. The following summary observations are based on these evaluations:

- Projections of increased warming were consistent between CMIP3 and CMIP5 for the region, but inland valley and mountain ridges are projected to exhibit a larger increase in CMIP5.
- Annual precipitation projections are not directionally consistent in either CMIP3 or CMIP5 projections, although the uncertainty appears to be less in CMIP5 models. Greater clarity about wetter conditions in the Sacramento Valley and more neutral projections for the San Joaquin and Tulare basins are projected in CMIP5 climate model simulations. Southern California projections continue to predict drier future conditions, but not to the same extent as indicated in CMIP3 projections.
- Extreme precipitation, the driver for most flood events, is likely to intensify, even with projections of overall drier conditions.
- Changes in flood magnitudes and frequencies at the basin-wide scale vary spatially so that the Sacramento and San Joaquin basins respond differently. Watershed characteristics strongly influence the hydrological response to climate change, with the high elevation San Joaquin watersheds showing the largest increases in flood volumes due to a reduction in precipitation falling as snow (instead falling as rain) and the more rapid melt of snow packs (See Figure 3-1).
- Changes in flood magnitude in the Phase IIB analysis are higher than those from earlier Phase IIA analysis for most of the major watersheds. The differences in change of flood magnitude between Phases IIA and IIB result from multiple factors, including the following:
  - Changes in climate change scenarios—scenarios in CMIP3 used during Phase IIA were different than scenarios in CMIP5 used during Phase IIB
  - Use of a refined hydrological model (spatial resolution and re-calibration)
  - Use of a different statistical method to develop flood frequency curves for Phase IIB (i.e., the Bulletin 17B method in the USGS's PeakFQ software [USGS, 1982]).

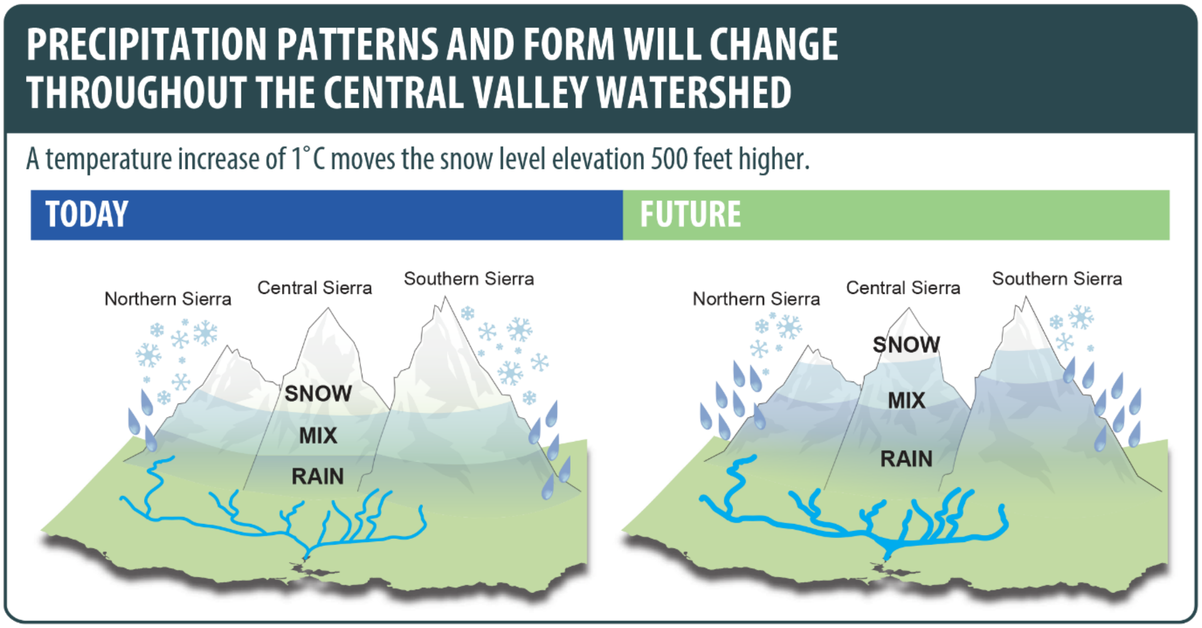


Figure 3-1. Projected Future Climate Change Impacts on Central Valley Precipitation Patterns

3.2 Using Climate Change Analyses Outputs

A series of scenarios representing different points in time through the 50-year analysis period (i.e., 2017 to 2067) were evaluated, using outputs from the following tools or studies:

- Climate change analyses undertaken for the 2017 CVFPP Update
- CVHS hydrological tools
- Hydraulic modeling tools developed by Central Valley Floodplain Evaluation and Delineation Program updated since 2012

Analyses have generated estimates of flood risk in terms of both potential economic damages and life loss, thus enabling an understanding of how the 2017 CVFPP Update refined State Systemwide Investment Approach changes and reduces flood risk in the future.

Flood risk analyses supporting the 2017 CVFPP Update are described in the 2017 CVFPP Update's Scenario Technical Analyses Summary Report (DWR, 2017).

3.3 Next Steps and Recommendations

Next steps and recommendations are summarized below.

- **Address uncertainty.** In all uses of hydroclimatic analysis results, uncertainty should be addressed. Specific climate change scenarios were developed for hydrologic analysis to illustrate the relative sensitivity of unregulated flood hydrology to changes in future climate. Scenarios used in the analysis, however, are closely associated with median change conditions. Other scenarios that exist are more or less extreme. Future work could evaluate a broader set of future climate scenarios and provide a broader range of projected outcomes. Alternatively, sensitivity analysis could be performed on a limited subset to improve the understanding of climate risk and uncertainty.

- **Conduct additional study.** This study's methods and findings relate to changes in unregulated flows. DWR has identified a future need to gain insight about reservoir climate vulnerability and adaptation. Specifically, DWR seeks to improve understanding of climate change risk to reservoirs and existing flood control operations, and to evaluate strategies to adapt to future changes. The work described in this TM should serve as the basis for conducting a reservoir vulnerability study.

- **Incorporate new findings.** Subsequent phases of climate evaluations for CVFPP should incorporate any new findings that arise from ongoing research about atmospheric rivers, watershed controls on precipitation, and runoff processes. This research is being conducted at the Scripps Institution of Oceanography and at UC Davis.

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5.0 Acronyms and Abbreviations

°C .... degree Celsius
AR4.......................... Intergovernmental Panel on Climate Change Fourth Assessment Report
AR5.......................... Intergovernmental Panel on Climate Change Fifth Assessment Report
BWFS .... Basin-Wide Feasibility Study
CAT .... Climate Action Team
CCTAG .... Climate Change Technical Advisory Group
CMIP3...................... Coupled Model Intercomparison Project 3
CMIP5...................... Coupled Model Intercomparison Project 5
CVFPP..................... Central Valley Flood Protection Plan
CVHS....................... Central Valley Hydrology Study
DWR........................ California Department of Water Resources
GCM .... general circulation model
IPCC .... Intergovernmental Panel on Climate Change
LOCA....................... locally organized constructed analog
RCP .... representative concentration pathway
Reclamation .... United States Bureau of Reclamation
SIO .... Scripps Institute of Oceanography
SPFC .... State Plan of Flood Control
TM .... technical memorandum
UC Davis.................. University of California at Davis
USGS .... United States Geological Survey
VIC model .... variable infiltration capacity macroscale hydrologic model

STATE OF CALIFORNIA
THE NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES

TECHNICAL MEMORANDUM

CH2MHILL®

Preliminary Climate Change Analysis for the CVFPP - Phase IIA

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Introduction

Current evaluations of Central Valley flood control improvements are based on climate and hydrologic conditions that occurred over the past 100 years. This historical period includes significant flood events caused by intense precipitation, rapid snowmelt, and watershed conditions that, in combination, result in the hydrologic conditions that have shaped our current flood infrastructure and management.

Future climate projections indicate the potential for increased flood peak flows and flood volumes, which is likely to affect flood risk in the Central Valley. DWR has begun a three-phase process for assessing potential changes in future climatic conditions in the Central Valley and accounting for those changes in the Basin-Wide Feasibility Studies. Phase I, completed in 2013, included a pilot study which evaluated the sensitivity of the Feather-Yuba watershed and Oroville operations to an estimate of change in 100-year flood volume.

This technical memorandum provides preliminary information for Phase IIA of the climate change analysis. Phase IIA aims to provide preliminary estimates of potential changes in unregulated flows throughout the Central Valley based on available climate projections and coarse-scale hydrologic modeling. Changes in unregulated flow volumes are estimated by applying climate scenarios (temperature and precipitation projections) to the historical variability in climate, and simulating the hydrologic responses. The methods and draft results of this phase are described in this technical memorandum.

Purpose

Phase IIA of the climate change analysis is designed to provide advanced information for the Basin Wide Feasibility Studies in order to consider climate change in the development of SSIA configurations and in preliminary estimates of the performance of various alternatives. In order to provide useful information in the timeframe needed to for the study evaluation, Phase IIA relies upon existing, available climate projections and coarse-scale hydrologic modeling to represent a range of potential future changes to **unregulated flow volumes** due to climate change. This information has been prepared to fit within the risk framework currently being applied in the CVFPP analyses. Changes to historical unregulated flow volumes are derived by hydrologic modeling of Central Valley watershed unregulated flows for over 80 years and described as scaled flows (percent change) at major analysis points. Through the use of these results, adjustments can be made to the historical unregulated flow statistics that are central to the CVFPP risk analyses.

Study Area and Watershed Characteristics

The Basin Wide Feasibility Studies include analysis of all major rivers and floodplains in the Sacramento River and San Joaquin River Basins. However, since the Kings River can occasionally provide flood flows to the San Joaquin River, the study area for the climate assessment was expanded to include the Tulare Lake Basin, in addition to the Sacramento River and San Joaquin River Basins as shown in Figure 1. Over 200 “analysis points” are included in the study area and are the reference points for which historical unregulated flows have been measured or derived.

As shown in Figure 2, the topography of the Central Valley is striking. The southern Cascades in the north-northeast and the Sierra Nevada range in the east form the high elevation boundaries to the Sacramento River Basin. The higher elevation southern Sierra Nevada range forms the eastern boundary of the San Joaquin River Basin. The lower elevation portions of the both the Sacramento and San Joaquin River Basins are dominated by the foothills and valley floor. In the major watersheds of the Sacramento River Basin, most of the watershed area (over 90%) is *below* 7,000 ft elevation. In contrast, most major watersheds in the San Joaquin River Basin have over half of the watershed area *above* 7,000 ft elevation (Figure 3).

In the high elevation watersheds of both the Sacramento and San Joaquin River Basins, snow falls during most winter and spring storms, accumulates during the cold winter and early spring, and melts during the spring and summer. The hydroclimatic processes that allow precipitation to fall in the form of snow in the higher elevations and to be stored in the form of snowpack are major contributors for attenuating flood hydrographs. It is anticipated that climate change will contribute to warmer storms that enable a greater percentage of the watershed to receive rain (as compared to snow) with less attenuation of flood flows. In addition, warmer temperatures will result in more rapid melt of the snowpack that does develop, essentially compressing the period in which the precipitation is routed downstream to rivers and into reservoirs. The lower elevation portions of the Sacramento and San Joaquin River Basins predominantly receive rain as the primary form of precipitation and thus provide little attenuation of the storm hydrograph.

Figure 1. Study Area Consisting of Sacramento and San Joaquin River Basins

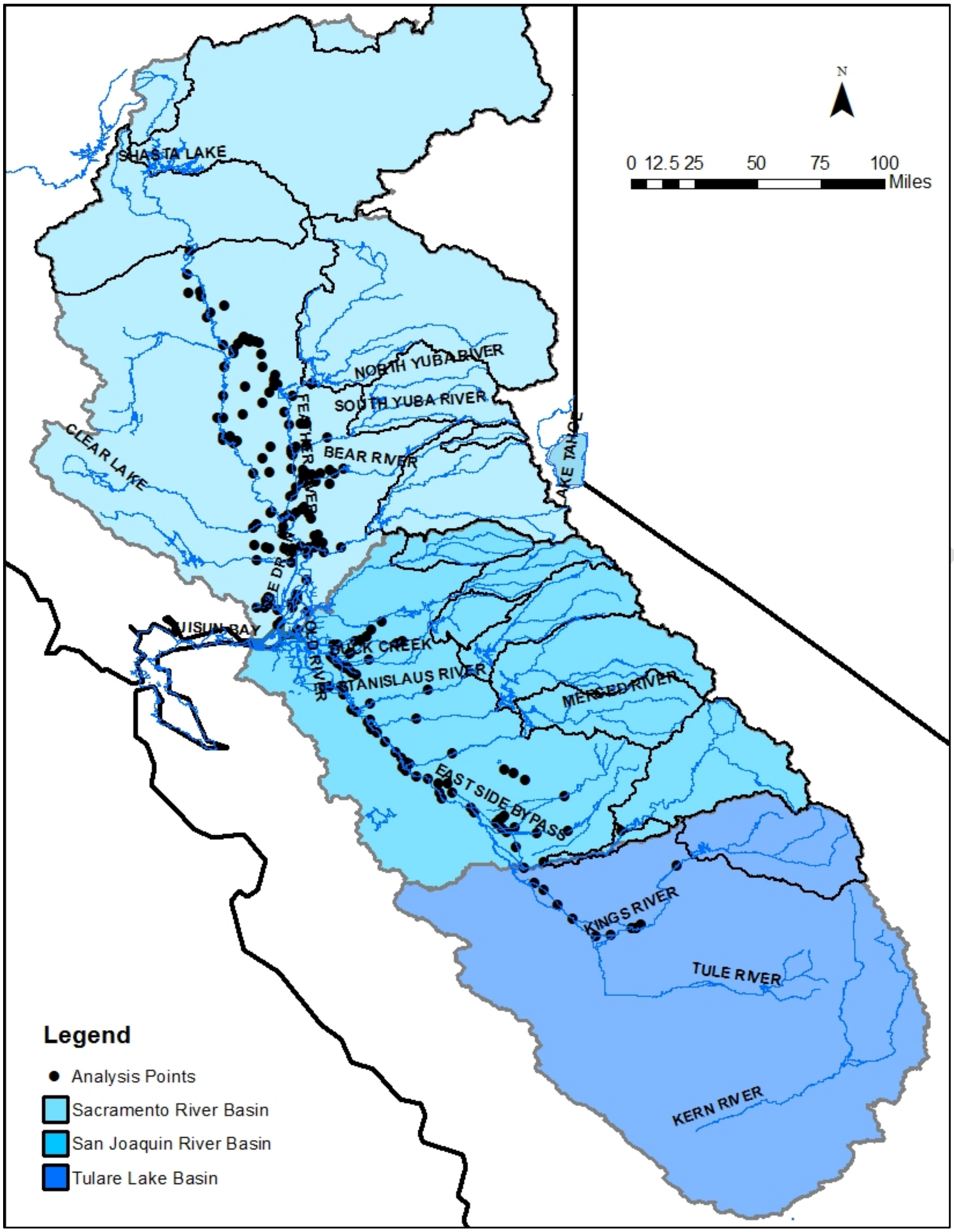

Figure 2. Study Area Elevation (feet above mean sea level)
Derived from National Elevation Dataset, USGS, (HTTP://NED.USGS.GOV).

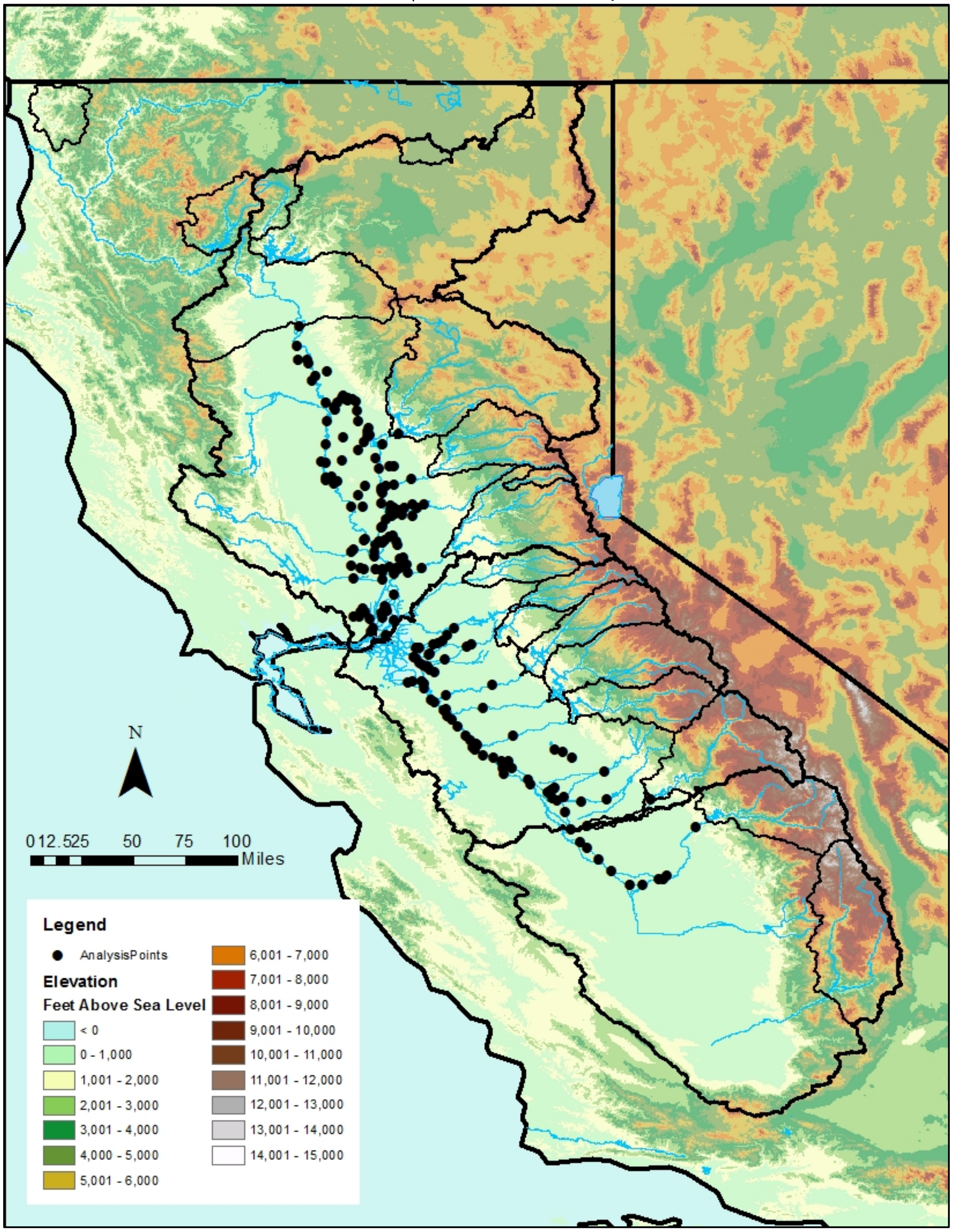

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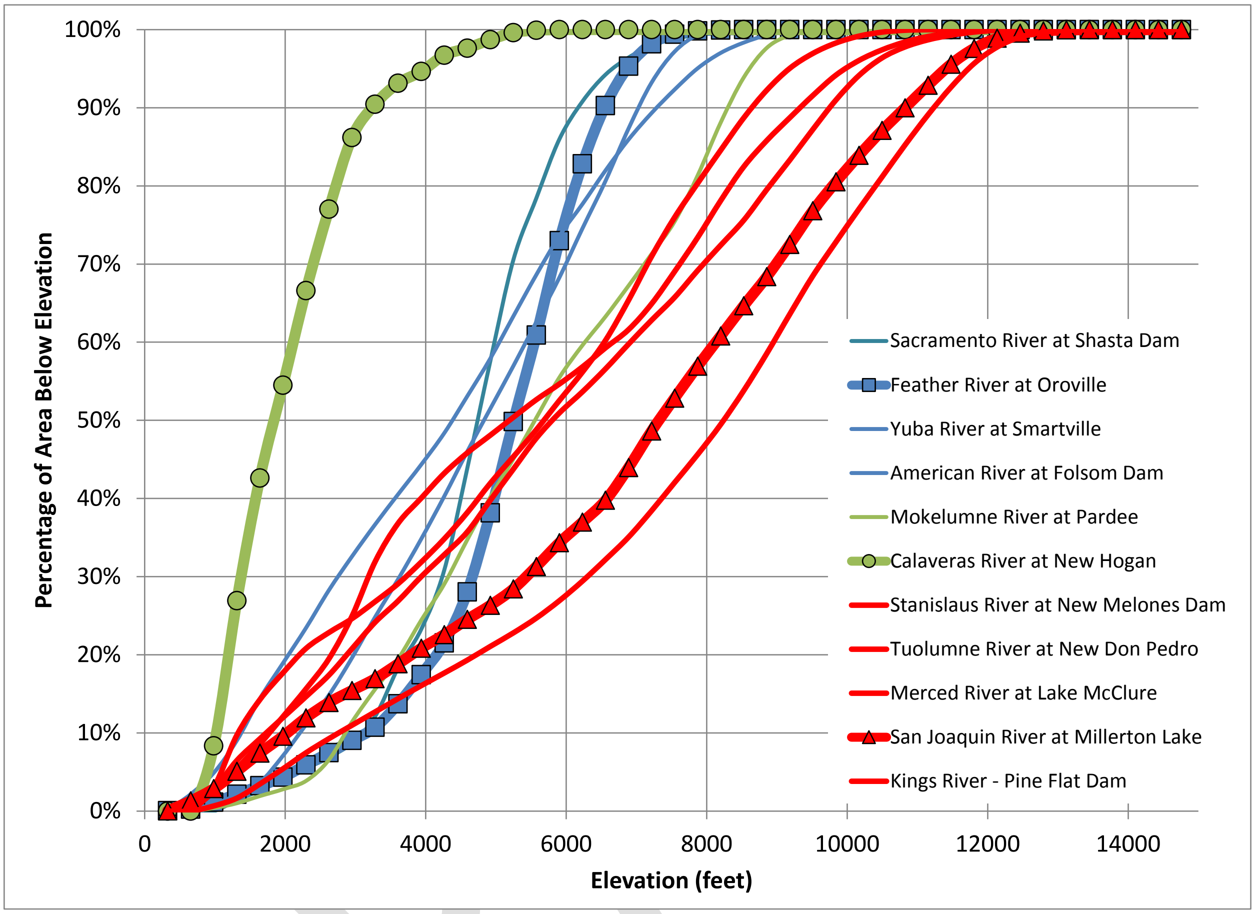
Figure 3. Percentage of Area below Certain Elevation for Major Headwater Catchments



Future Climate Scenarios

Future climate scenarios were derived from existing available climate scenarios used in the Bay Delta Conservation Plan (DWR 2014). These future climate scenarios are derived from the change in temperature and precipitation considering over 100 downscaled climate projections from the Coupled Model Intercomparison Project 3 (CMIP3) (Maurer et al. 2007a). A "median" ensemble scenario was derived from approximately thirty climate projections that surrounded the median of the entire set of available projections. Future climate projections are available for the period 2010 through 2099 and were prepared for the entire Central Valley on a 1/8th degree (~12 kilometer) (~7.5 mile) grid.

Changes in future climate were calculated as differences in the statistical properties of temperature and precipitation for three future periods as compared to the properties over an historical reference period. The historical reference period was defined as the period 1971 through 2000, reflecting a thirty-year period over which historical climate can be referenced (NOAA). Three future periods were selected to represent the periods of potential change over the time horizon of the flood improvements: (1) near-term (2011 through 2040), (2) mid-century (2046 through 2075), and (3) end of century (2070 through 2099). The changes in statistical properties of temperature and precipitation for each of the three periods as compared to the historical reference period were computed.

[1] baydeltaconservationplan.com

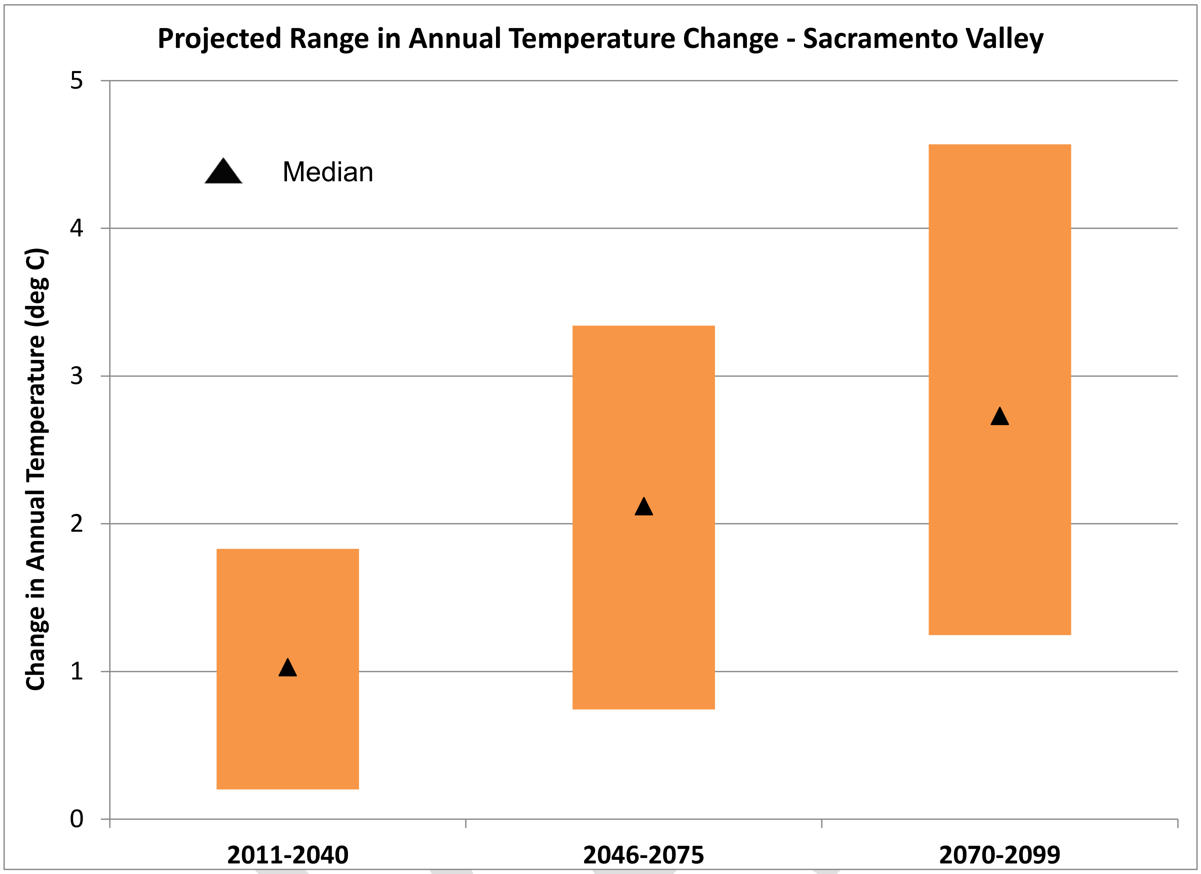
Historical daily climate information was available for the entire study area for the period of 1915 through 2003 (Hamlet and Lettenmaier, 2005). Statistical changes calculated for each of the three future climate periods were then mapped onto the historical information to develop and “adjusted” historical record with climate changes for one of the three future periods. In this fashion, the natural variability, which is best characterized through the observed records, is combined with the projected changes in climate patterns.

Projected changes in future climate contain significant uncertainties. Uncertainties exist with respect to understand and modeling of the earth systems, uncertainties with respect to future development and greenhouse gas emission pathways, and uncertainties with respect to simulating changes at the local scale. Climate models suggested projected temperature signal is strong and temporally-consistent (Figure 4). All projections are consistent in the direction of the temperature change, but vary in terms of climate sensitivity. Annual precipitation projections are not directionally consistent. Multi-decadal variability complicates period analysis. Regional trends indicate that it is more likely for the upper Sacramento Valley to experience equal or greater precipitation, while the San Joaquin Valley is likely to experience drier conditions. However extreme precipitation is likely to increase (Figure 5).

In general, temperature change projections are more robust (and stable) than changes in precipitation. In order to be able to distinguish the effects of precipitation and temperature separately and to characterize changes over time, the following scenarios were developed:

1. Warming Only Scenarios (no precipitation changes)
    a. Near-Term: Projected warming of about +1^{o}C (+1.8^{o} F),
    b. Mid Century: Projected warming of about +2^{o} C (+3.6^{o} F), and
    c. Late Century: Projected warming of about +2.5^{o} C (+4.5^{o} F) to +3.0^{o} C (+5.4^{o} F).
2. Combined Warming and Precipitation Change Scenarios:
    a. Near-Term: Projected precipitation and temperature changes,
    b. Mid Century: Projected precipitation and temperature changes, and
    c. Late Century: Projected precipitation and temperature changes.

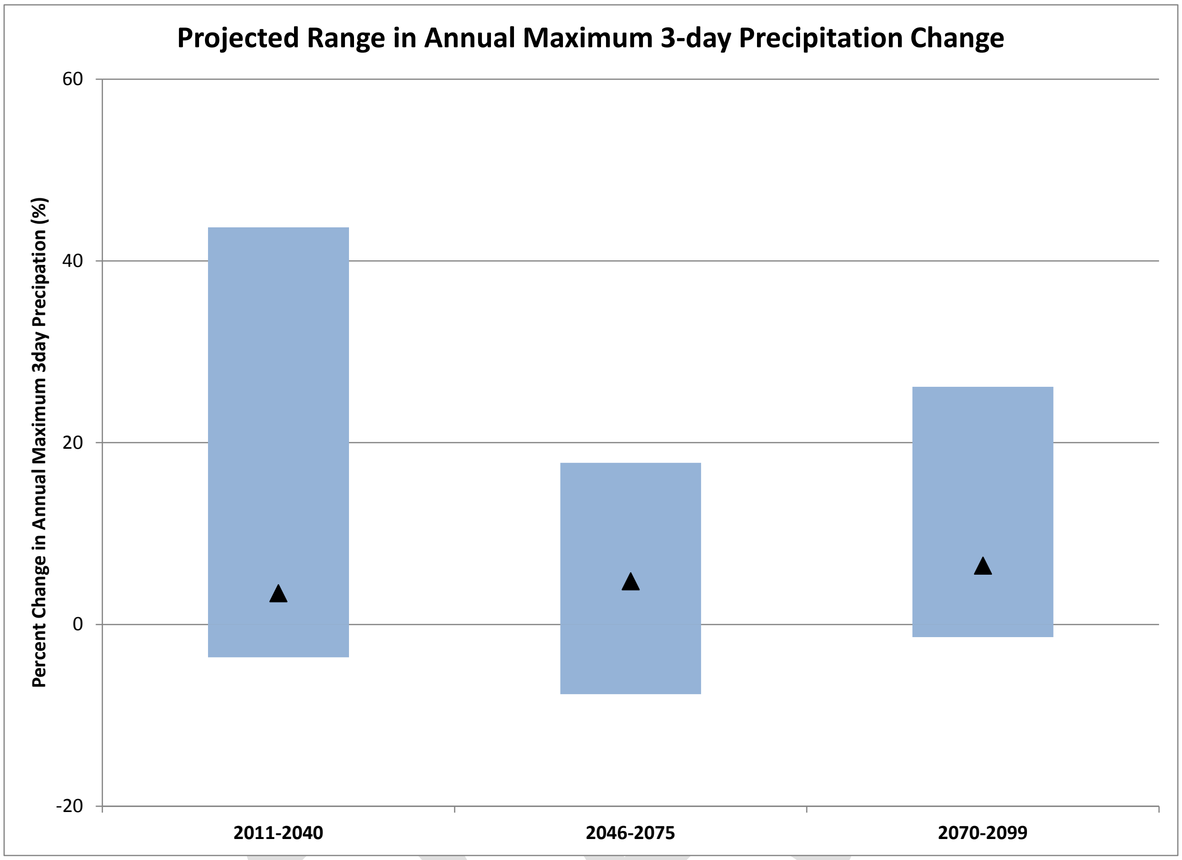
Figure 4. Temperature Projections for Sacramento Valley



Notes:

The projected changes are computed using more than 100 downscaled climate model projections used in the IPCC's AR4 and the WCRP CMIP3 have been bias-corrected and spatially downscaled (Maurer et al. 2007a).

Figure 5. 3-days Annual Maximum Precipitation Projections for Sacramento Valley



Notes:

The projected changes are computed using the CAT scenarios were developed as part of a series of reports released by the CAT in 2009 that serve as a summary update of the latest climate change science and response options for decision makers in California (Cayan et al. 2008). This document included twelve climate change scenarios (6 GCMs x 2 emission scenarios).

Hydrological Model Simulations

For each of the future climate scenarios, regional hydrologic modeling was performed for the entire Central Valley using the Variable Infiltration Capacity (VIC) hydrology model. The VIC model (Liang et al. 1994; Liang et al. 1996; Nijssen et al. 1997) is a spatially distributed hydrologic model that solves the water balance at each model grid cell. The VIC model incorporates spatially distributed parameters describing topography, soils, land use, and vegetation classes. VIC is considered a macro-scale hydrologic model in that it is designed for larger basins with fairly coarse grids. In this manner, it accepts input meteorological data directly from global or national gridded databases or from GCM projections. To compensate for the coarseness of the discretization, VIC is unique in its incorporation of subgrid variability to describe variations in the land parameters as well as precipitation distribution. Five elevation bands are included for each grid cell. In addition, VIC also includes a sub-daily (1-hour) computation to resolve transients in the snow model. The soil column is represented by three soil zones extending downward from the land surface to capture the vertical distribution of soil moisture. The VIC model represents multiple vegetation types using the National Atmospheric and Space Administration's Land Data Assimilation System (NLDAS) databases as the primary input data set.

Parameterization within VIC is performed primarily through adjustments to parameters describing the rates of infiltration and baseflow as a function of soil properties, as well as the soil layers depths. When simulating in water balance mode, as done for this California application, VIC is driven by daily inputs of precipitation, maximum and minimum temperature, and windspeed. The model internally calculates additional meteorological forcings such short-wave and long-wave radiation, relative humidity, vapor pressure and vapor pressure deficits. Rainfall, snow, infiltration, evapotranspiration, runoff, soil moisture, and baseflow are computed over each grid cell on a daily basis for the entire period of simulation. An offline routing tool then processes the individual cell runoff and baseflow terms and routes the flow to develop streamflow at various locations in the watershed. Figure 6 shows the hydrologic processes included in the VIC model.

The runoff simulated from each grid cell was routed to various river flow locations using VIC's offline routing tool. The routing tool processes individual cell runoff and baseflow terms and routes the flow based on flow direction and flow accumulation inputs derived from digital elevation models. For the simulations performed for the CVFPP, streamflow was routed to the major CVHS analysis points throughout the Sacramento and San Joaquin River Basins. It is important to note that VIC routed flows are considered "naturalized" in that they do not include effects of diversions, imports, storage, or other human management of the water resource.

The VIC model has been applied to many major basins in the United States, including large-scale applications to California's Central Valley (Liang et al. 1994; Maurer et al. 2002; 2007b; Maurer 2007; Hamlet and Lettenmaier 2007a; Barnett et al. 2008; Cayan et al. 2008; Raff et al. 2009; Dettinger et al. 2011a; Dettinger et al. 2011b; Das et al. 2011a; 2013), Colorado River Basin (Christensen and Lettenmaier, 2007; Das et al. 2011b; Vano et al. 2012; 2014a,b), Columbia River Basin (Hamlet and Lettenmaier, 1999; Hamlet et al. 2007a,b), and for several basins in US (Maurer et al 2003; CH2M HILL 2008).

The model grid consists of approximately 3000 grid cells at a 1/8th degree latitude by longitude spatial resolution. The VIC model domain is shown in Figure 7 and covers all major drainages in California. The routing network for routing runoff to rivers is show in Figure 8.

Although the VIC model contains several sub-grid mechanisms, the coarse-grid scale should be noted when considering results and analysis of local-scale phenomenon. The VIC model is currently best applied for the regional scale hydrologic analyses. The VIC model has been applied without re-calibration. The model is reasonable for capturing flow changes at the larger watersheds in the Basin, but has significant bias at smaller scales. In addition, the inputs to the model do not include any transient trends in the vegetation or water management that may affect streamflows; they should only be analyzed from a naturalized flow change standpoint.

Figure 6. Hydrologic Processes Included in the VIC Model (Source: University of Washington 2010)

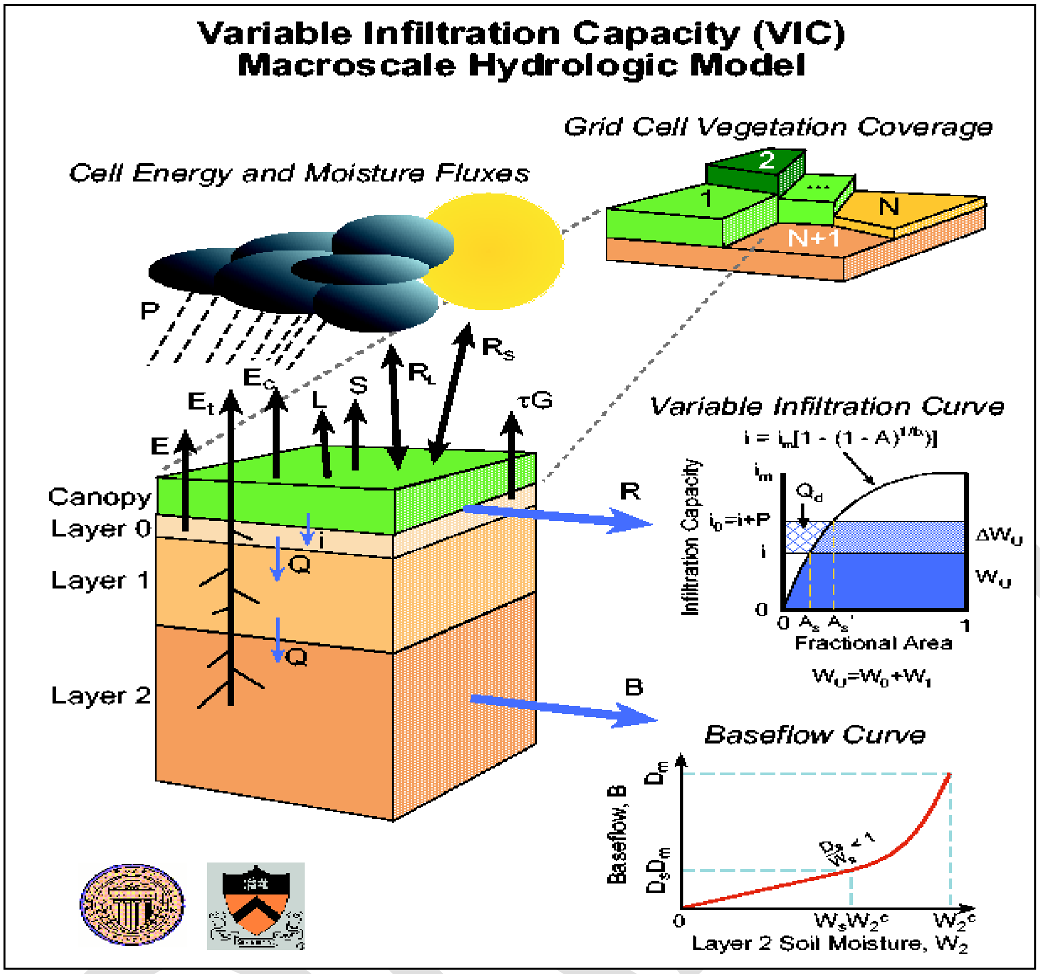


Figure 7. VIC model domain and grid.

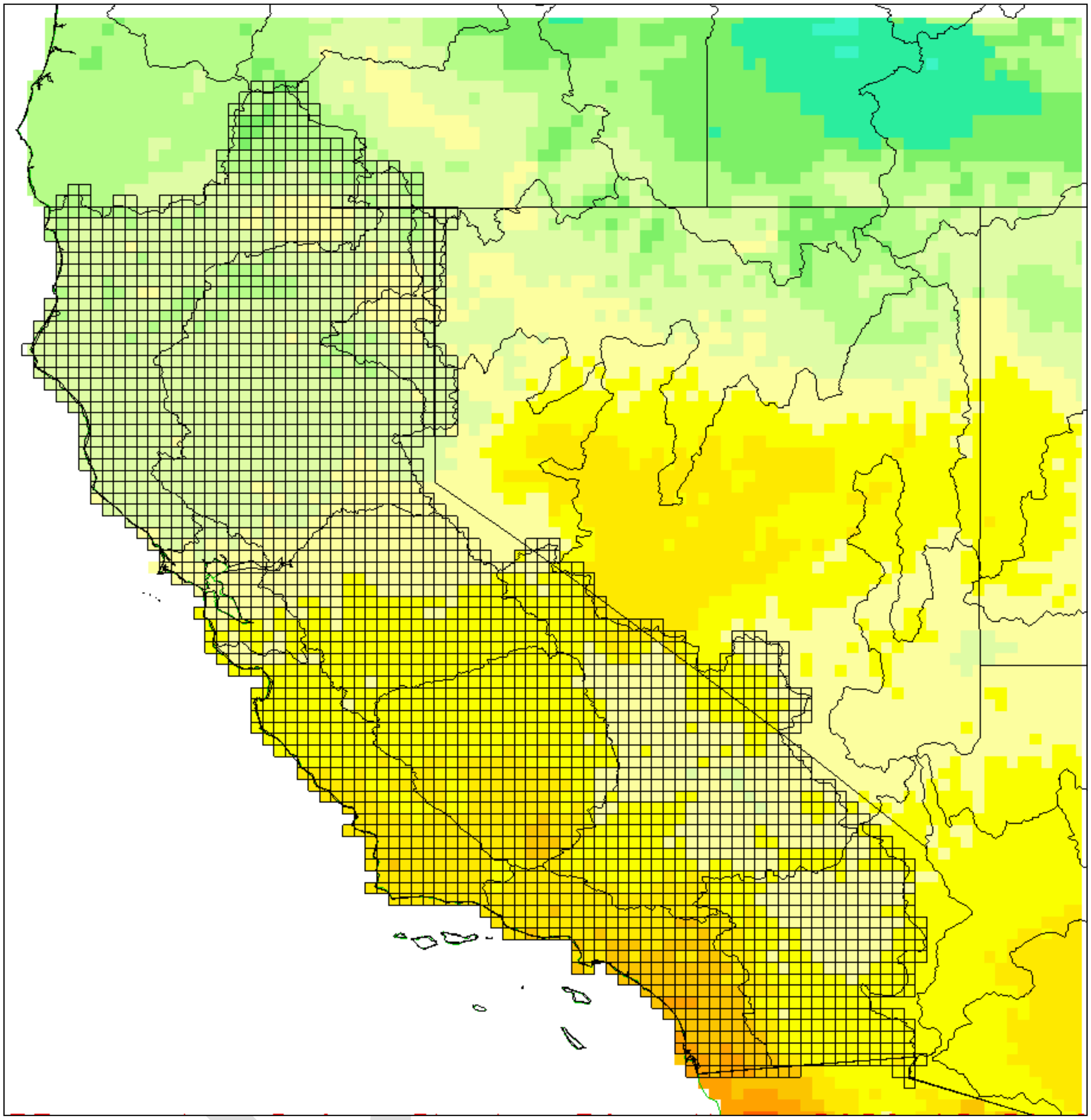
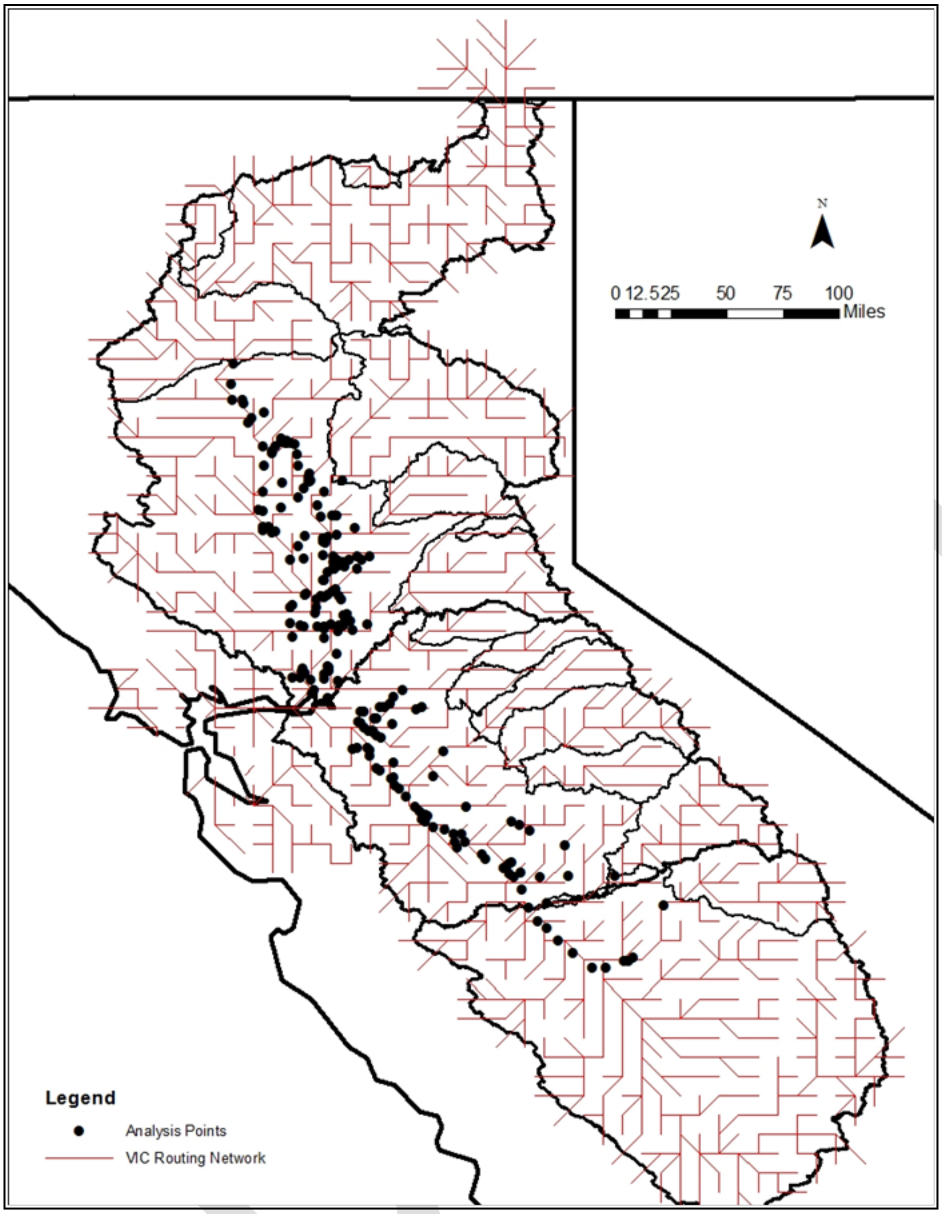


Figure 8. VIC model routing network as applied for the CVFPP application



Hydrologic Modeling Results for Major Watersheds

Daily hydrologic modeling was performed for the period of 1915 through 2003 with both historical meteorology and that adjusted for climate change. Flows were routed to various river locations and changes between the climate scenario and historical reference period flows were computed as a percentage change. For the purposes of this technical memorandum, the following locations in Table 1 are presented.

Table 1. Representative Flow Locations included in Results Summary

1	Sacramento River at Shasta Dam
2	Sacramento River at Bend Bridge
3	Feather River at Oroville
4	Yuba River at Smartville
5	North Fork American River at North Fork Dam
6	American River at Folsom Dam
7	Cosumnes River at Michigan Bar
8	Mokelumne River at Pardee
9	Calaveras River at New Hogan
10	Stanislaus River at New Melones Dam
11	Tuolumne River at New Don Pedro
12	Merced River at Lake McClure
13	San Joaquin River at Millerton Lake
14	Kings River - Pine Flat Dam

For each year of either the historical reference period and the future climate scenario, the maximum 1-day, 3-day, 7-day, and 15-day unregulated flows were calculated routed to specific flow locations. Log Pearson Type 3 fitting was then developed from the maximum 1-, 3-, 7-, and 15-day durations for each year with and without climate change. The percentage change in flow was next recorded for the specific frequency such as the 200-, 100-, 50-, 25-, 10-, and 2-year flows from comparison of the two frequency curves.

Figure 9 through Figure 14 show the changes in 3-day annual maximum flow for the 14 locations and 6 frequencies of occurrence. The figures are organized with watersheds ordered from north to south, and depict the effect of the warming-only scenarios and the combined warming and precipitation change scenarios (labeled as 2025, 2060, and 2085).

As can be seen in the figures, the effect of warming-only is relatively small (less than 10% change) for watersheds in the Sacramento River Basin. This result is due to the relative low elevation of the major contributing areas of these watersheds. Warm storms that produced rainfall up to the top of the watershed have already occurred in these watersheds and are included in the historical flow records. The additional warming included in the climate scenarios did not substantially alter the rain-snow fractions or the hydrologic response. However, in the San Joaquin River Basin, the effect of warming is considerable. For example, projections suggest that the 100-year and 200-year flood flows may be 40% to 50% greater than those experienced in the observed record in the high elevation watersheds due to warming alone. The warming in these watersheds allows more watershed area to experience rain and to contribute to more rapid melt of snow that was present. Both of these factors contribute to the substantially larger impact of warming on flood flows.

When considering the combined effect of temperature changes and precipitation changes, every major watershed demonstrates a response with greater flood flows. Even in the southernmost watersheds where annual reductions in precipitation are projected, the extreme precipitation is projected to increase and flood flows are correspondingly increased. Sacramento River Basin watersheds are projected to exhibit increased flood flows on the order of 20% to 40% due precipitation and temperature changes. San Joaquin River Basin watersheds demonstrate an even larger response due to the combine effect of temperature and precipitation changes and low frequency floods are projected to be on the order of 60% to 80% larger than the historical reference.

Figure 15 and Figure 16 show the asymmetrical climate response of watersheds for various return periods. In the Sacramento River Basin, the largest percentage change in flood magnitudes occurs with the 10-year return interval and the smallest percentage change occurs with the 200-year return interval. This counterintuitive response is due to the nature of the watershed characteristics and historical storm behavior. In the Sacramento River Basin, rain has been experienced to the top of watershed (above 7,000 or 8,000 ft) during specific storms but this is relatively unusual. More commonly, storms bring a mixture of snow and rain. Thus, the greatest changes are during those conditions where historically the storms were snow-dominated or of mixed snow-rain regime.

Conversely, in the high elevation San Joaquin River Basin, most watersheds are dominated by snow accumulation and melt, and large storms with rainfall to the top of the watershed (above 10,000 ft) have not been experienced historically. Thus, climate change poses a significantly greater threat to increased flood magnitudes. The hydrologic response due to climate change is symmetrical in this watershed, in that the 100-year percentage change is larger than the 10-year percentage change. However, it should be noted that the increase in flows of more frequent events (such as the 10-year event) has the potential to impact flood risks significantly due to more frequent stress on levees and consequently more frequent erosion and seepage.

Figure 9. Changes in 200-yr flood magnitudes under different climate change scenarios

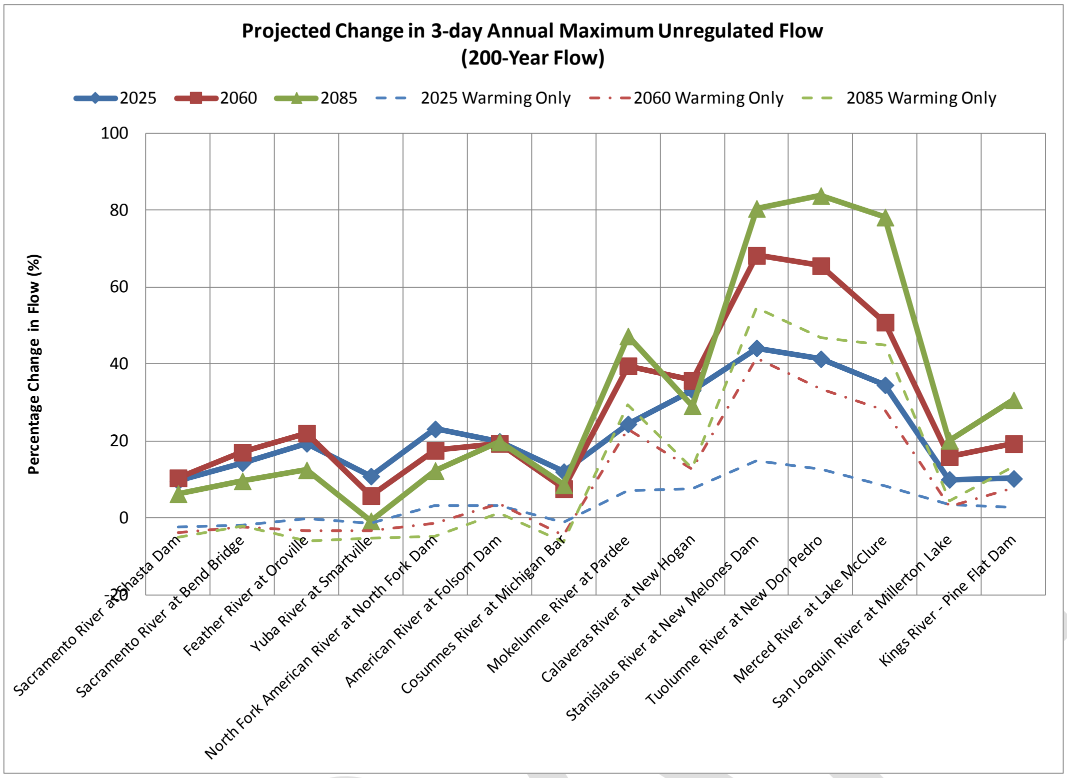


Figure 10. Changes in 100-yr flood magnitudes under different climate change scenarios

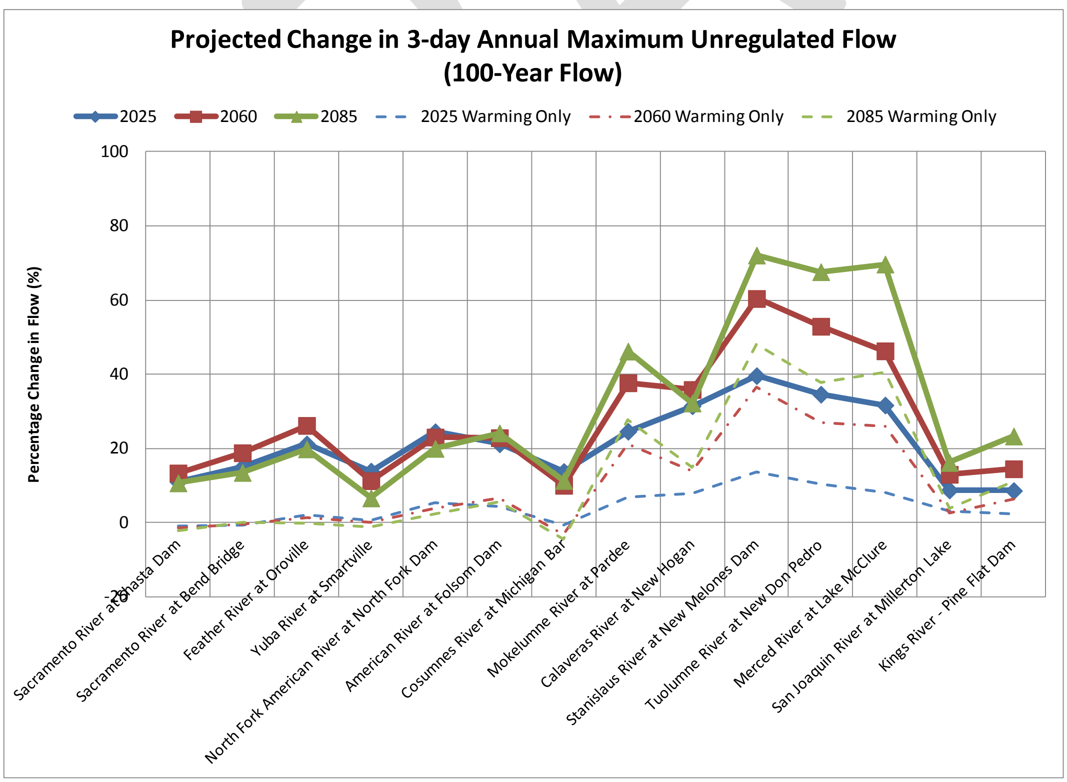


Figure 11. Changes in 50-yr flood magnitudes under different climate change scenarios

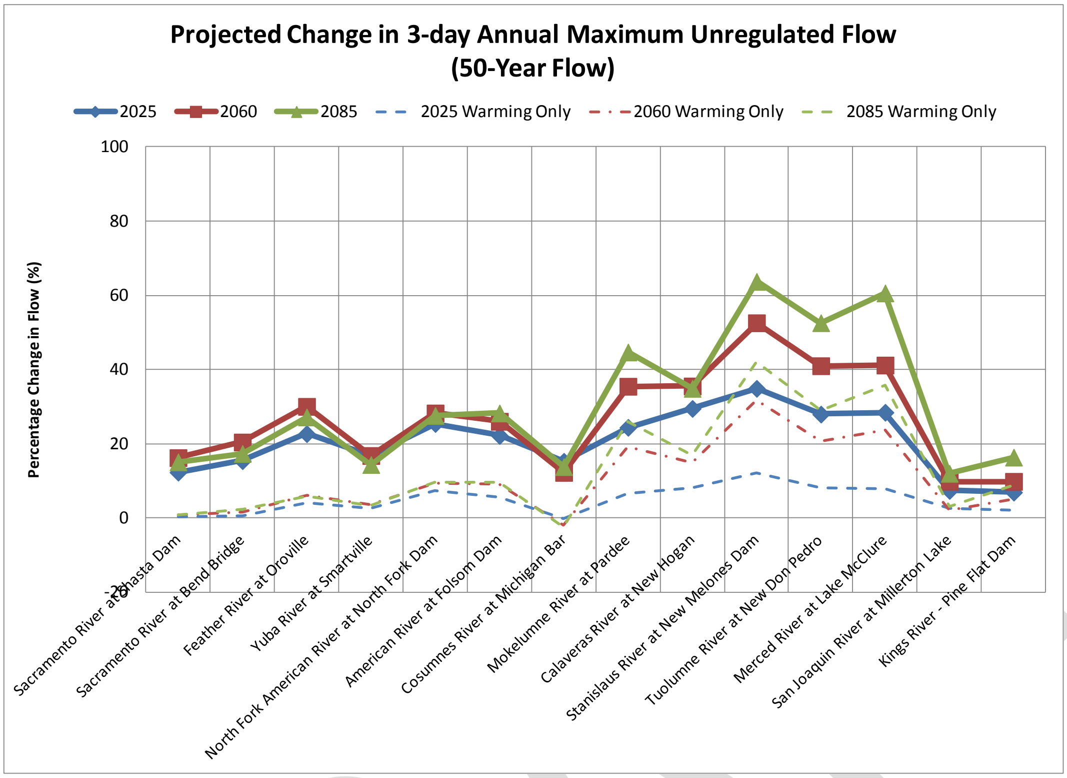


Figure 12. Changes in 25-yr flood magnitudes under different climate change scenarios

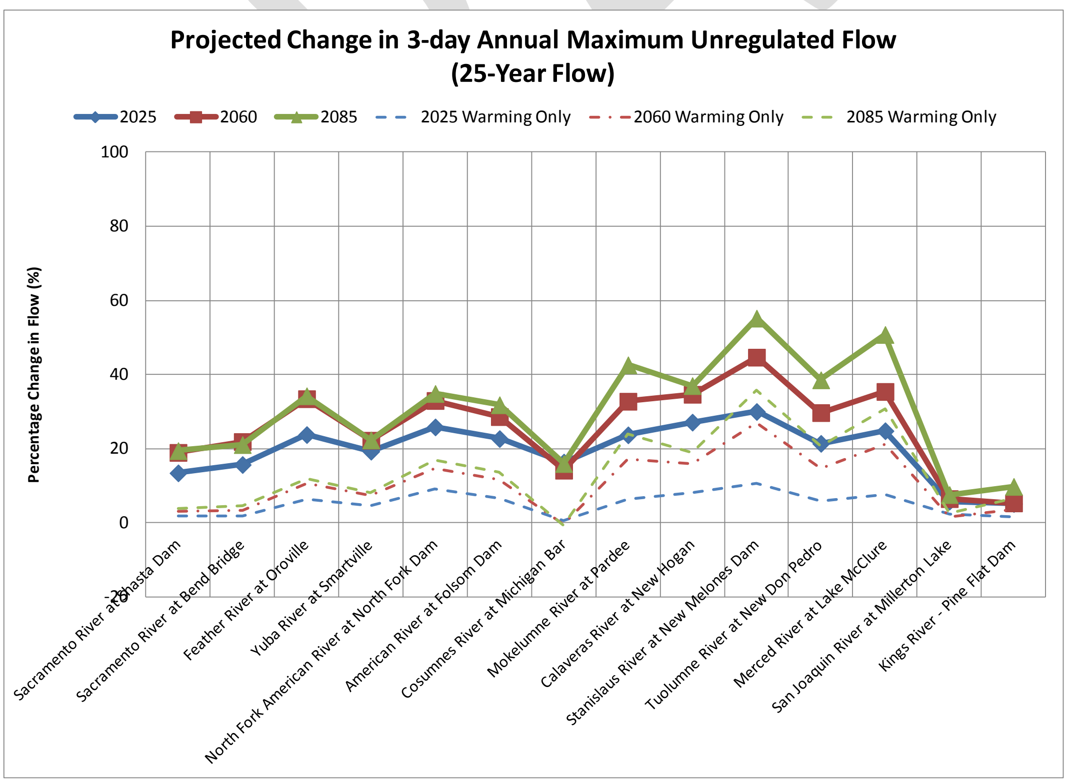


Figure 13. Changes in 10-yr flood magnitudes under different climate change scenarios

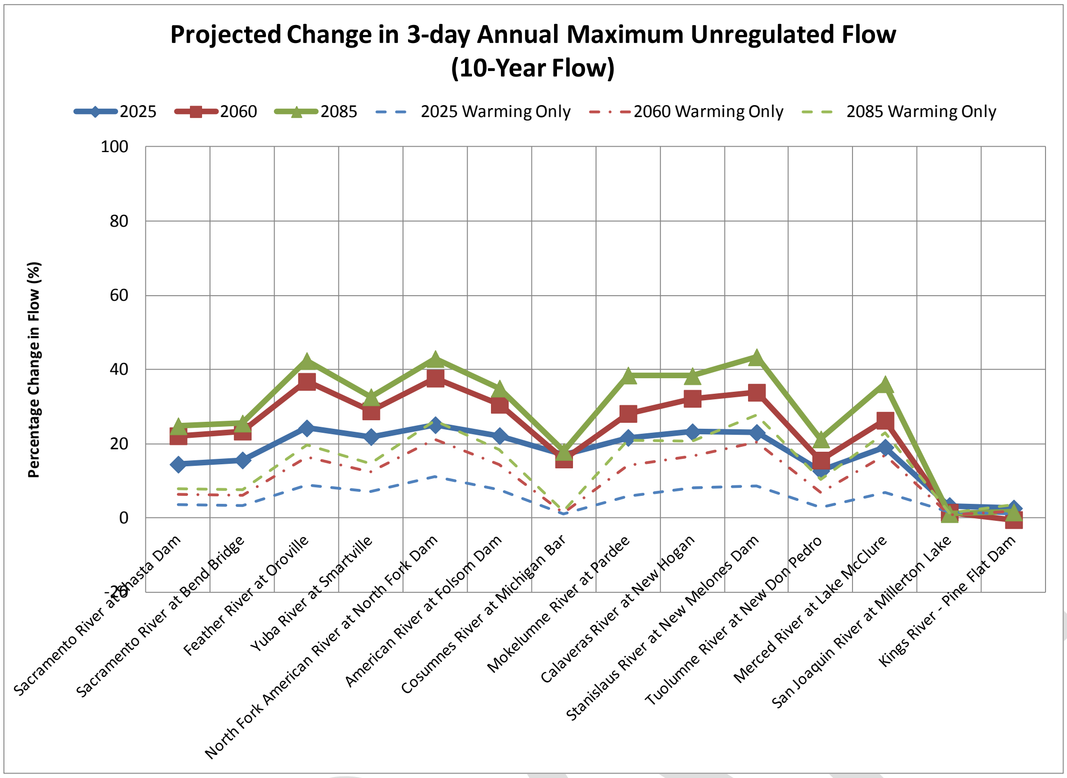


Figure 14. Changes in 2-yr flood magnitudes under different climate change scenarios

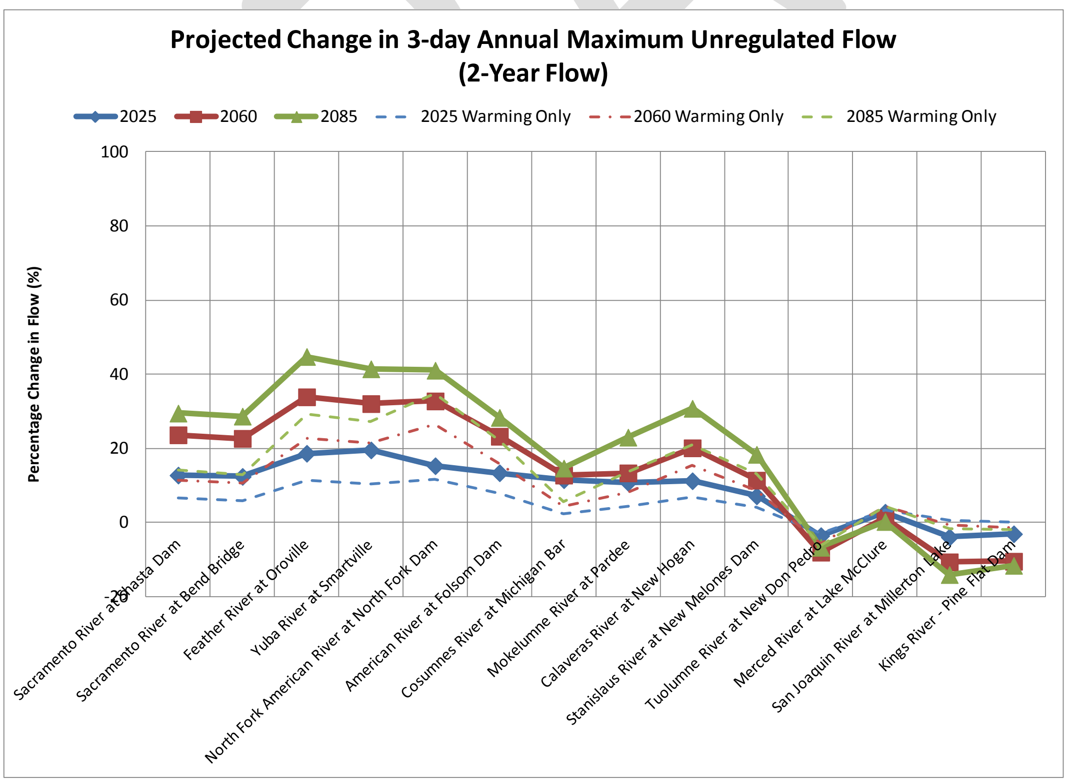


Figure 15. Changes in 3-day flood magnitudes with different return periods under the 2060 climate scenario

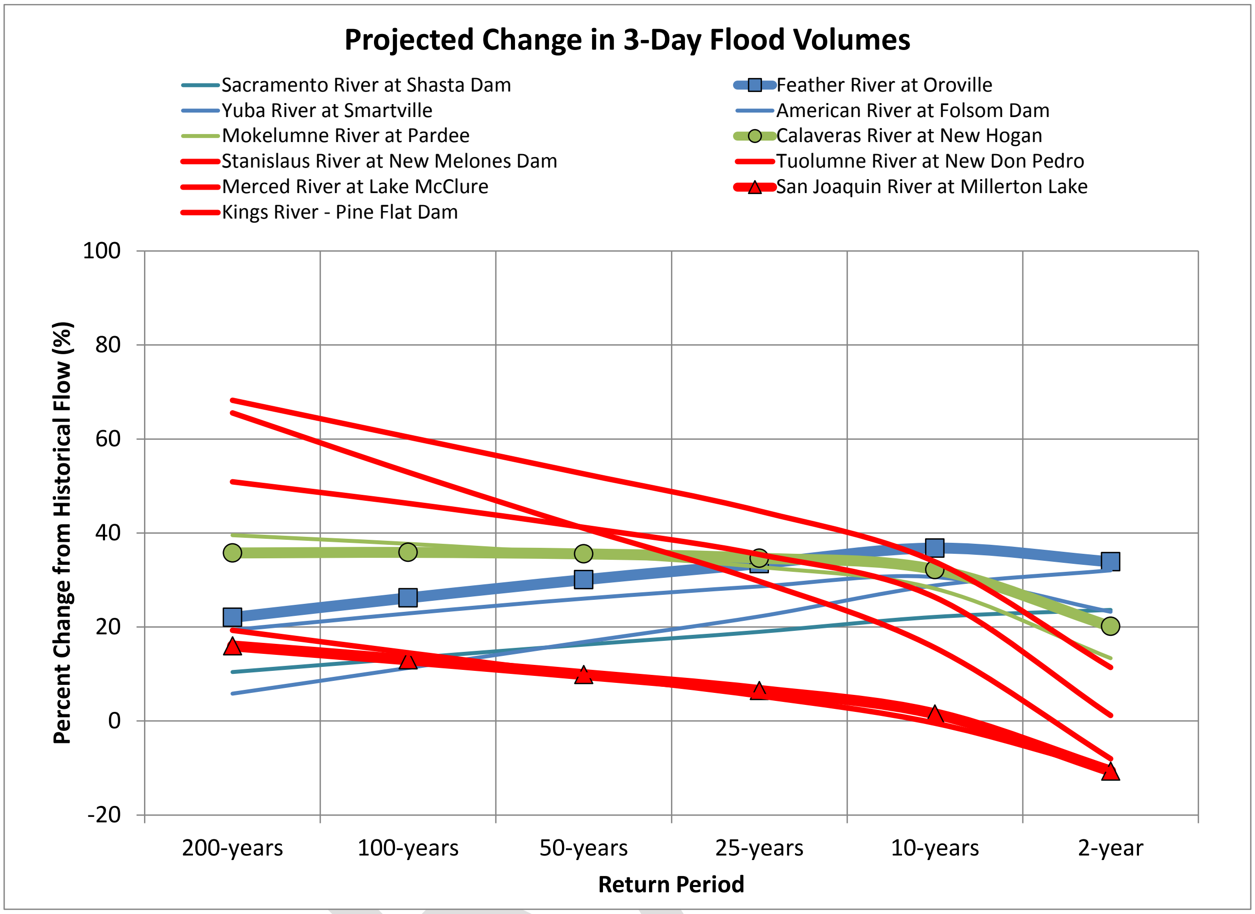
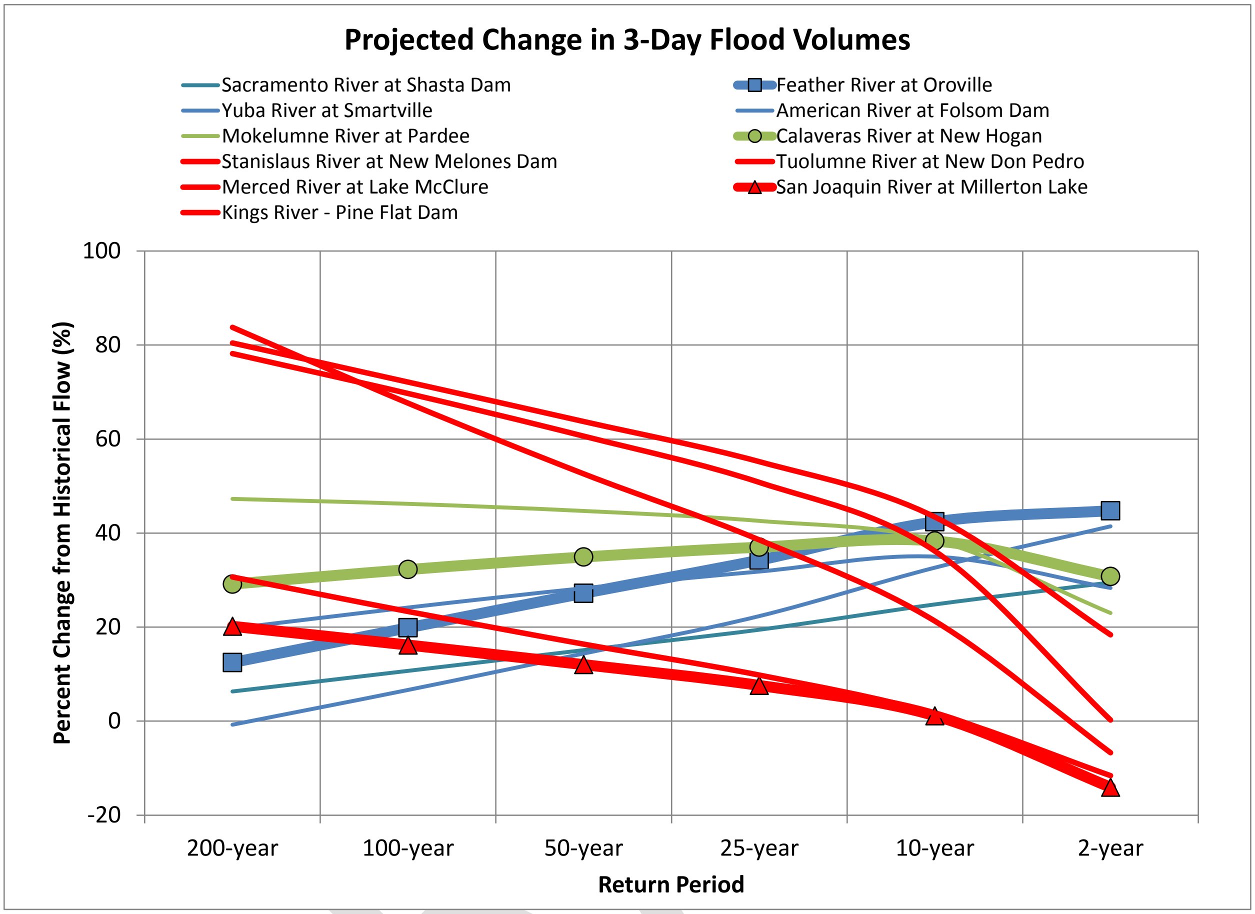
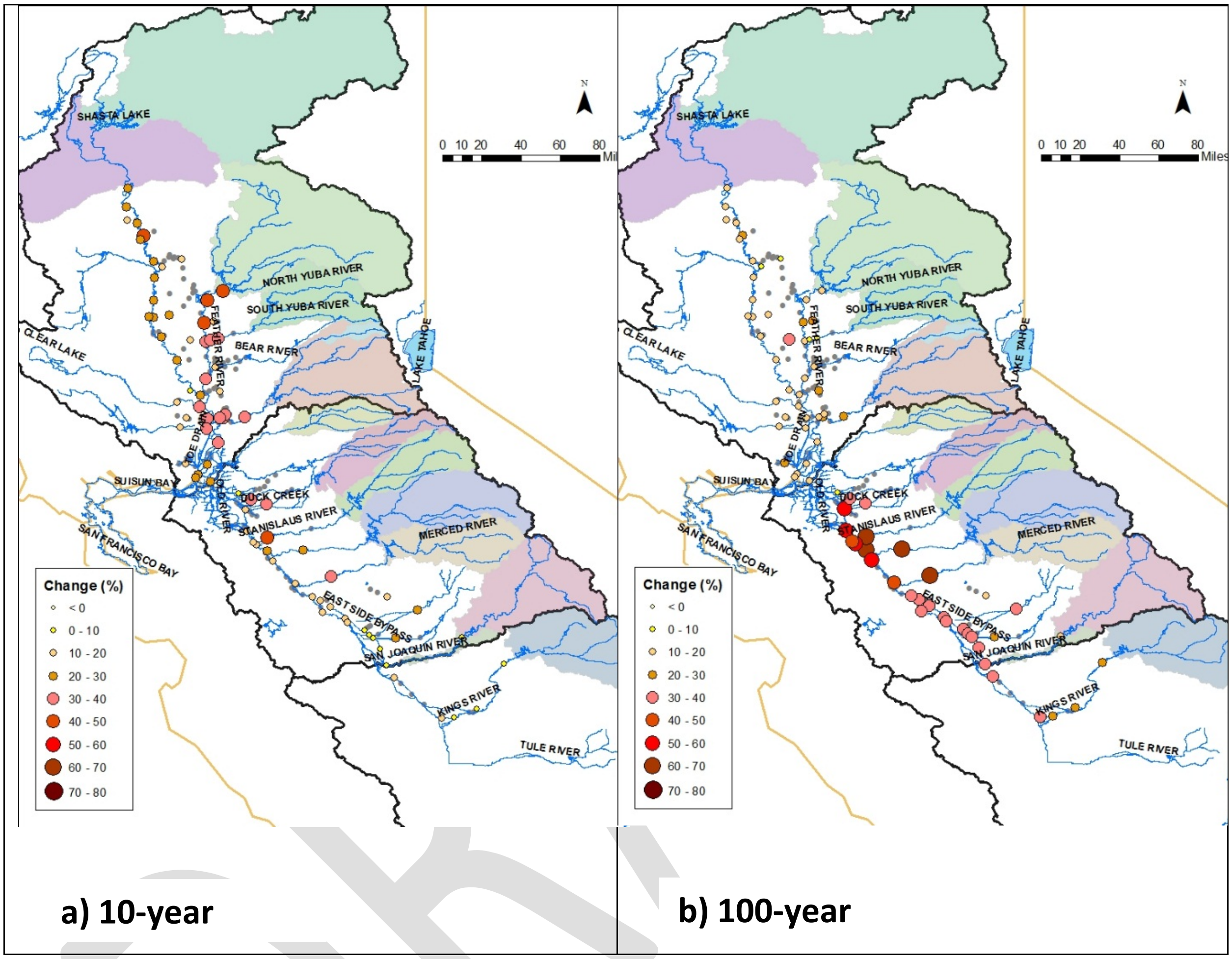


Figure 16. Changes in flood magnitudes with different return periods under the 2085 climate scenario



There are more than 75 locations across the Central Valley where the change factors have been derived (Figure 17). The changes from these locations have been mapped to more than 200 analysis points to modify the unregulated flow frequency curves that are used in the risk assessment.

Figure 17. Spatial patterns of changes in flood magnitudes under the 2085 climate scenario in the Central Valley a) with 10-years return period and b) with 100-years return period



Next Steps

In the current effort, preliminary adjustments to the unregulated flow frequencies have been suggested by the application of climate scenarios and coarse-scaled hydrological modeling. However, since the impacts to humans and the environment are most significantly the result of regulated flows (and stage and failure modes), the unregulated flow frequencies will need to be transformed to regulated flow frequencies in order to make assessments of overall climate risk on flood management systems. Tables of changes in unregulated flow frequencies are being developed to support the application of robust risk assessments as part of the CVFPP. The tables include suggested adjustment factors for all analysis points, including those presented in this memorandum.

The Phase IIA climate analysis described in this memorandum was meant to be a preliminary assessment based on available information. Newer climate projections (CMIP5) are currently available are consistent with the most recent Intergovernmental Panel on Climate Change (IPCC) Assessment Report 5 (AR5) (Taylor et al. 2012). Work is currently underway to process these downscaled climate projections for use in the CVFPP. Similarly, the VIC model can be reconfigured to simulate watershed hydrology at more refined scale. The current model has been reconfigured in test form with a doubling of the spatial resolution and will form the basis for refined hydrological modeling.

Finally, three on-going, DWR-supported, research studies were initiated in 2013 and are expected to be completed in the coming months. These studies are the Climate Variability Sensitivity Study (led by USACE) evaluating the effects of warming on flood flows, the Atmospheric River Study (led by Scripps Institute of Oceanography/USGS) investigating indices and future projections of the major flood-producing atmospheric processes, and the Watershed Sensitivity Study (led by UC Davis) investigating the atmospheric and watershed conditions that contribute to the extreme flows on several Central Valley watersheds. Comparisons of the current results and the CVSS are currently being developed based on preliminary information. In addition, Phase IIB will include methods to derive predicted watershed responses based on the results of the Atmospheric River Study to refine or adjust the precipitation-based responses. The Watershed Sensitivity Study has been focused on pilot watersheds at this point in time. Phase IIB will include an evaluation of whether new information from this study can be incorporated into the unregulated flow frequency analysis.

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CENTRAL VALLEY
FLOOD MANAGEMENT
PLANNING PROGRAM

FloodSAFE
CALIFORNIA

DRAFT Technical Memorandum

Climate Change Analysis – Phase IIB

June 2016

STATE OF CALIFORNIA
THE NATURAL RESOURCES AGENCY
DEPARTMENT OF WATER RESOURCES

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1.0 Introduction

Current evaluations of California Central Valley flood control improvements are based on climate and hydrologic conditions that occurred over the past 100 years. This historical period includes significant flood events caused by intense precipitation, rapid snowmelt and watershed conditions that, in combination, result in the hydrologic conditions that have shaped our current flood infrastructure and management.

Future climate projections indicate the potential for increased flood peak flows and flood volumes, which is likely to affect flood risk in the Central Valley. DWR has begun a three-phase process for assessing potential changes in future climatic conditions in the Central Valley and accounting for those changes in the Basin-Wide Feasibility Studies. Phase I, completed in 2013, included a pilot study which evaluated the sensitivity of the Feather-Yuba watershed and Oroville operations to a range of changes in flood volumes.

In addition, three DWR-supported research studies were initiated in 2013 as follows:

- Climate Variability Sensitivity Study (CVSS), led by the United States Army Corps of Engineers (USACE), evaluating the effects of warming on flood flows
- Atmospheric River Study, led by Scripps Institute of Oceanography/United States Geological Service (USGS), investigating indices and future projections of the major flood-producing atmospheric processes
- Watershed Sensitivity Study, led by the University of California at Davis (UC Davis), investigating the atmospheric and watershed conditions contributing to the extreme flows on several Central Valley watersheds

The methodology and findings of the Climate Variability Sensitivity Study were reviewed in preparing the analysis for the current work. The Atmospheric River Study and Watershed Sensitivity Study are in progress.

In Phase II, expanded analyses were designed to provide information about potential climate vulnerabilities for the BWFS. The analyses used existing and updated tools and climate change projections in two subsequent sub-phases, Phases IIA and IIB, to fit within the risk framework currently being applied in CVFPP analyses.

The result of the Phase IIA effort, completed in June 2014, was a set of adjustments to historical flow volume-frequency curves that could be used as a preliminary assessment of the effects of climate change in the Central Valley Flood Management Planning Program (CVFPP) planning area. Phase IIA used climate scenarios based on climate model simulations from the Coupled Model Intercomparison Project Phase 3 (CMIP3). The CMIP3 climate model data was the basis for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) released in 2007 (IPCC, 2007).

This technical memorandum provides information for Phase IIB of the climate change analysis. Phase IIB aims to provide updated estimates of potential changes in unregulated flows throughout the Central Valley based on newer climate projections and refined hydrologic modeling. The Phase IIB effort is based on climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5) to ensure that the study reports the most current science available at the time of its release. The CMIP5 (Taylor et al., 2012) climate model data are the basis for the most recently released Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (AR5) (IPCC, 2013). Changes in unregulated flow volumes are estimated by applying climate scenarios (temperature and precipitation projections) to the historical variability in climate, and simulating the hydrologic responses. The methods and draft results of this phase are described in this technical memorandum.

1.1 Background

Phase IIA of the climate change analysis was designed to provide advanced information for the Basin Wide Feasibility Studies in order to consider climate change in the development of State Systemwide Investment Approach (SSIA) configurations and in preliminary estimates of the performance of various alternatives. In order to provide useful information in the timeframe needed for the study evaluation, Phase IIA relied upon existing, available climate projections and coarse-scale hydrologic modeling to represent a range of potential future changes to unregulated flow volumes due to climate change. This information has been prepared to fit within the risk framework currently being applied in the CVFPP analyses. Changes to historical unregulated flow volumes are derived by hydrologic modeling of Central Valley watershed unregulated flows for over 80 years and described as scaled flows (percent change) at major analysis points. Through the use of these results, scaling factors that reflect the potential future flood volume changes were applied to the historical unregulated flow statistics to develop climate change scenarios for the CVFPP risk analyses.

Under the Phase IIA of the Climate Change Analysis, CH2M HILL developed coarse-scale climate scenarios reflecting the historical climate and several scenarios of potential future climate change. The historical climate was adjusted for the “change” projected in each of the scenarios (“warming only,” “warming plus precipitation changes”). Hydrologic modeling was conducted using the 12-km resolution Variable Infiltration Capacity (VIC) model to generate unimpaired (unregulated) river flow at major analysis points in the Central Valley. The results were documented in the technical memorandum dated September 25, 2014. Archive model files and results were transmitted to DWR in December 2014. The Phase IIA effort was based on existing climate scenarios (CMIP3 based climate models and scenarios) and 12 km resolution VIC modeling. No updates to the more recent climate scenarios or model recalibration for specific watersheds were included in Phase IIA.

1.2 Need for Phase IIB Climate Change Hydrology

The Phase IIA climate analysis was intended to be a preliminary assessment based on available climate information and modeling analyses. Newer climate projections (CMIP5) currently available are consistent with the most recent Intergovernmental Panel on Climate Change (IPCC)

Assessment Report 5 (AR5) and represent the current state of the science. Similarly, the VIC model was utilized in coarse resolution in Phase IIA, and the need to refine the model resolution and perform re-calibration was identified. Specifically, additional information on the potential spatial and temporal changes to flood hydrographs under climate change would improve the evaluation. The current investigation uses scale factors for each Annual Exceedance Probability (AEP) at each location to adjust the historical events. Uniform changes to the scaled historical events increase the hydrograph volume, but do not change other characteristics of the hydrograph such as duration and spatial correlation that may be impacted under climate change. The need to understand the projected changes in hydrograph characteristics such as storm duration, timing, peak flow magnitude, and flow volume was identified.

The overall goals of the Phase IIB climate change analysis are:

1. To update the climate change analysis for the most current global and regional climate projections

2. To improve understanding of the hydrologic responses in various watersheds to future climate conditions

3. To develop climate change scaling factors at a higher spatial resolution that can be used to modify unregulated flow frequency curves for the CVFPP risk analysis.

1.3 Principal Data Sources Used in the Phase IIB Climate Change Analysis

Various watershed, climate, and hydrological data sources were used in the Phase IIB Climate Change analysis. A summary of the principal data sources used in the climate change analysis is included in Table 1. Additional detail on the use of these data sets is described in the relevant sections of this technical memorandum.

Table 1: Principal watershed, climate, and hydrological data sources used in the Phase IIB climate change analysis

Data	Use in Climate Change Analysis	Spatial and Temporal Resolution	Source
Digital Elevation Model	Used in watershed delineation and VIC streamflow routing model input files (Chapter 2)	30 meter Spatial resolution	USGS National Elevation Dataset
Dates and Characteristics of Pineapple Express Events	Mapping of PE characteristics for selected historical large flood events (Chapter 3)	Daily point data over the period 1948-2013	Dr. Michael Dettinger at U.S. Geological Survey and Scripps Institution of Oceanography
Station Precipitation Data	Used in adjusting precipitation bias for the calibration and validation events (Chapter 5, Appendix B)	Daily point data	Various sources, including NOAA, CDEC, and CVSS
Daily Gridded Historical Climate Data (Livneh et al)	Used in VIC model simulations and used in developed climate change scenarios (Chapters 4, 5, 6, Appendix B)	Daily data at 1/16-degree (~6 km) spatial resolution over the period 1915-2011	Surface Water Modeling Group at the University of Washington (http://www.hydro.washington.edu
Monthly Historical Gridded Climate Data (PRISM)	Used in adjusting Livneh et al. daily gridded historical climate data (Chapter 5, Appendix B)	Monthly data at ~4-km spatial resolution over the period 1895-2015	PRISM Climate Group at Oregon State University (http://www.prism.oregonstate.edu/)
CMIP3 and CMIP5 Downscaled Climate Projections (BCSD method)	Used in developing climate change scenarios based on Ensemble-Informed Climate Scenarios method (Chapter 4, 6)	Monthly data at 1/8th-degree spatial resolution over the period 1950-2099	Lawrence Livermore National Laboratory (LLNL) at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/
CMIP5 Downscaled Climate Projections (LOCA method)	Used in analyzing projected changes in flood hydrograph characteristics (Chapter 4, 6, Appendix A)	Daily data at 1/16-degree (~6 km) spatial resolution over the period 1950-2099	Scripps Institution of Oceanography
Unregulated Historical Streamflow (CVHS)	Used in VIC model calibration (Chapter 5, Appendix B)	Daily point data over the period 1896-2008	Central Valley Hydrology Study

2.0 Study Area and Watershed Characteristics

The Basin Wide Feasibility Studies include analyses of all major rivers and floodplains in the Sacramento River and San Joaquin River Basins. However, since the Kings River can occasionally provide flood flows to the San Joaquin River, the study area for the climate assessment was expanded to include the Tulare Lake Basin, in addition to the Sacramento River and San Joaquin River Basins as shown in Figure 1. Over 200 “analysis points” are included in the study area and are the reference points for which historical unregulated flows have been measured or derived.

As shown in Figure 2, the topography of the Central Valley is striking. The southern Cascades in the north-northeast, and the Sierra Nevada range in the east, form the high elevation boundaries to the Sacramento River Basin. The higher elevation southern Sierra Nevada range forms the eastern boundary of the San Joaquin River Basin. The lower elevation portions of the both the Sacramento and San Joaquin River Basins are dominated by the foothills and valley floor. In the major watersheds of the Sacramento River Basin, most of the watershed area (over 90 percent) is *below* 7,000 feet elevation. In contrast, most major watersheds in the San Joaquin River Basin have over half of the watershed area *above* 7,000 feet elevation (Figure 3).

In the high elevation watersheds of both the Sacramento and San Joaquin River Basins, snow falls during most winter and spring storms, accumulates during the cold winter and early spring, and melts during the spring and summer. The hydroclimatic processes that allow precipitation to fall in the form of snow in the higher elevations and stored in the form of snowpack are major contributors for attenuating flood hydrographs. It is anticipated that climate change will contribute to warmer storms that enable a greater percentage of the watershed to receive rain (as compared to snow) with less attenuation of flood flows. In addition, warmer temperatures will result in more rapid melt of the snowpack that does develop, essentially compressing the period in which the precipitation is routed downstream to rivers and into reservoirs. The lower elevation portions of the Sacramento and San Joaquin River Basins predominantly receive rain as the primary form of precipitation and thus provide little attenuation of the storm hydrograph.

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3.0 Historical Climate Conditions Related to Flood Risks

Floods are particularly dangerous in California, where topography, exposure to heavy moisture-laden storm systems, and extensive human development and infrastructure in low lying areas add to the risks. In the Central Valley, most of the large historical floods have arisen from two general mechanisms: (1) winter floods covering large areas and (2) spring and early summer snowmelt floods, mostly from the higher elevations of the central and southern Sierra Nevada (Roos, 1997).

The major historical system-wide flood events in the Central Valley since 1950 have occurred in the water years 1951, 1956, 1965, 1986, and 1997 based on 1-day and 3-day unregulated flows (CVHS 2012). While the magnitude and nature of the floods vary between the Sacramento and San Joaquin River Basins for these events, each of these large flood events have been associated with tropical atmospheric moisture transport from near Hawaii to the U.S. west coast (Dettinger 2004). These type of storms have been long-described as "Pineapple Express" events

Pineapple Express (PE) storms are now recognized to correspond to a subset of a phenomenon known as Atmospheric Rivers (ARs) (NOAA 2016). Atmospheric Rivers are narrow corridors of moisture and moisture transport in the atmosphere. The moisture transport is concentrated into narrow and intense corridors 2,000 and more kilometers long, a few hundreds of kilometers wide, in the lowest approximately 2.5 kilometers (km) of the atmosphere (Ralph et al., 2006; Dettinger, 2011; Dettinger et al., 2011a, 2011b). Atmospheric River storms that impact California are a result of low-level jets along the pre-cold frontal edge of the warm sectors of major winter cyclones over the eastern North Pacific. Figure 4 shows the landfalling atmospheric river on December 11, 2014 with moisture transport extending from the tropics near Hawaii to California.

Atmospheric river storms contribute an average of one third to one half of all the State's precipitation (Florsheim and Dettinger, 2015). Based on the review of the timing of 128 well-reported (unintended) levee breaks since 1951, Florsheim and Dettinger (2015) found 81 percent of levee breaks along the Central Valley Rivers occurred during floods generated by wintertime ARs and only 15 percent occurring during snowmelt floods.

Historical occurrences of land falling ARs are generally identified based on Special Sensor Microwave Imager (SSM/I) imagery of vertically integrated water vapor in the atmosphere developed from satellite information (Ralph et al., 2006). The historical AR chronology is available for the past two to three decades. Dettinger (2004) developed a Pineapple Express meteorological events chronology based on NCEP/NCAR Reanalysis data for a longer period since 1948. Dettinger et al. (2011b) showed that on average, along the West Coast of the conterminous U.S., the AR chronology records 16 AR episodes per November-April, while the PE chronology records 6.4 PE episodes per November-April based on the analysis conducted for the period of water year 1998 through 2008. Due to the longer availability of PE measurements, the PE chronology is used to support a longer term assessment.

Figure 5 shows the chronologies of the PE events over the period 1948-2013, calculated by Michael Dettinger at U.S. Geological Survey. A PE event is calculated based on the daily water-vapor transport pathways from the NCEP Reanalysis data (Dettinger, 2011b, and updates thereto). PE circulations mainly occurred between October and April.

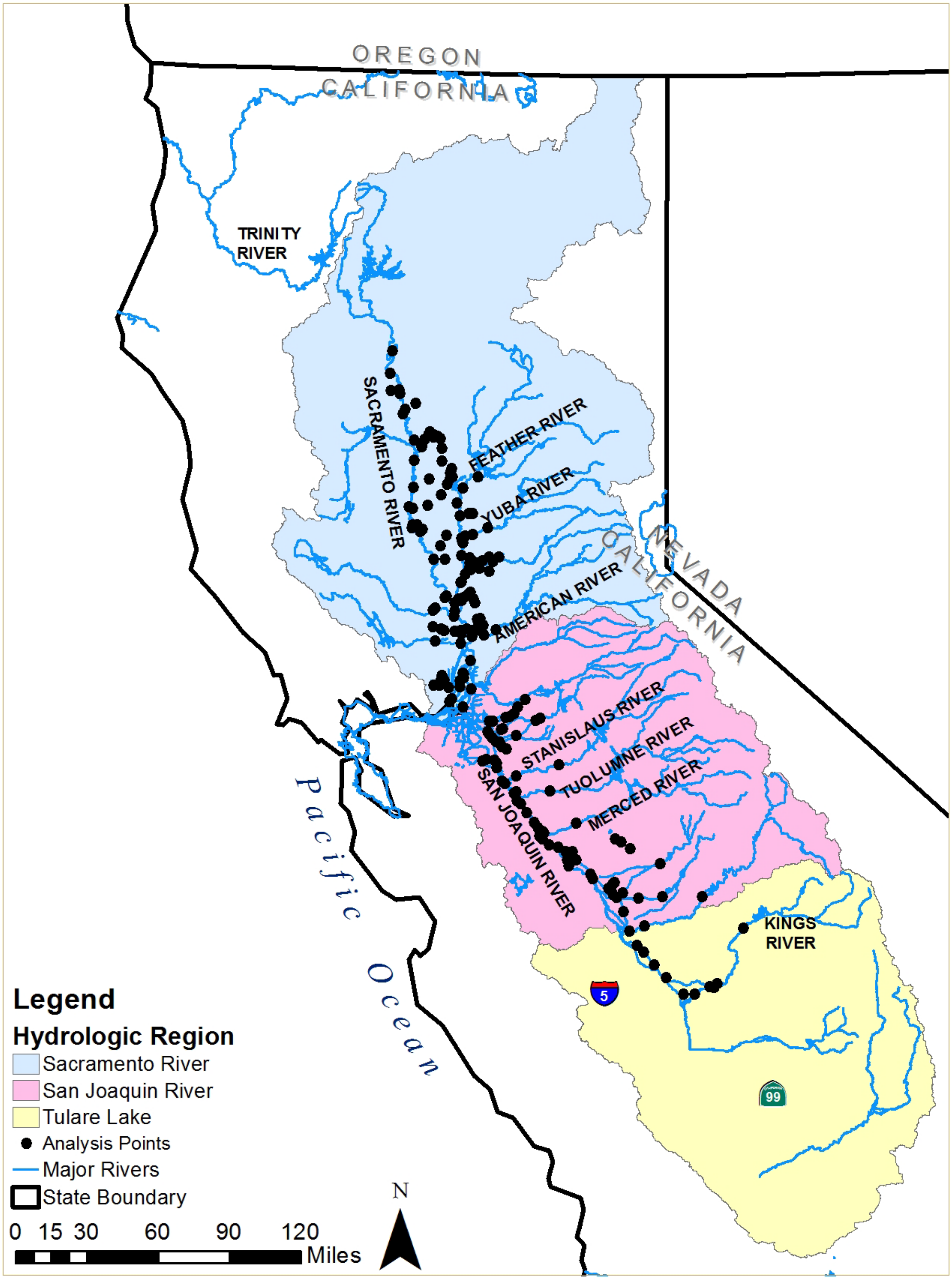

Figure 1. Study Area Consisting of Sacramento and San Joaquin River Basins

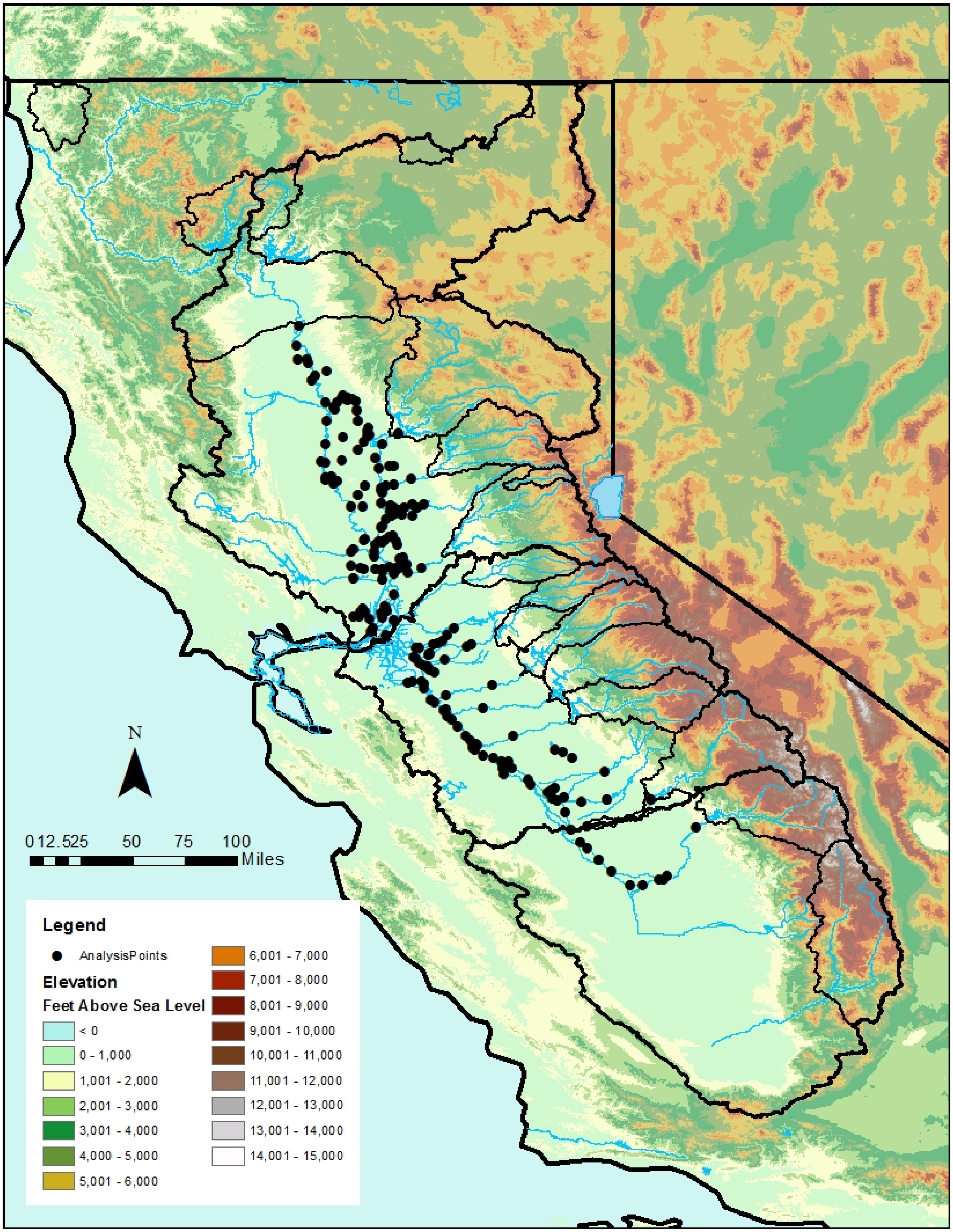

Figure 2. Study Area Elevation (feet above mean sea level, NAVD88)
Derived from National Elevation Dataset, (USGS, 2014).

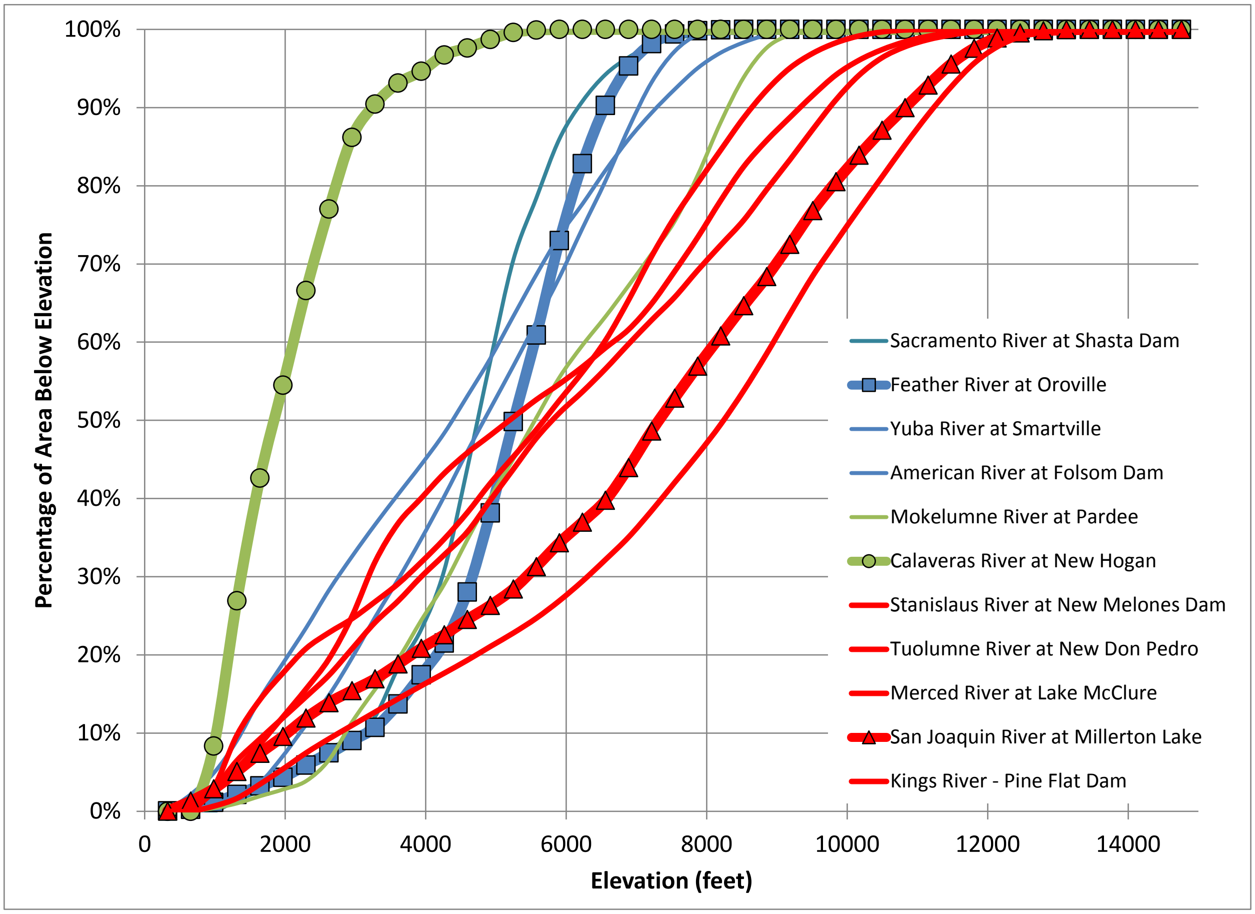

Figure 3. Percentage of Area below Defined Elevation for Major Headwater Watersheds

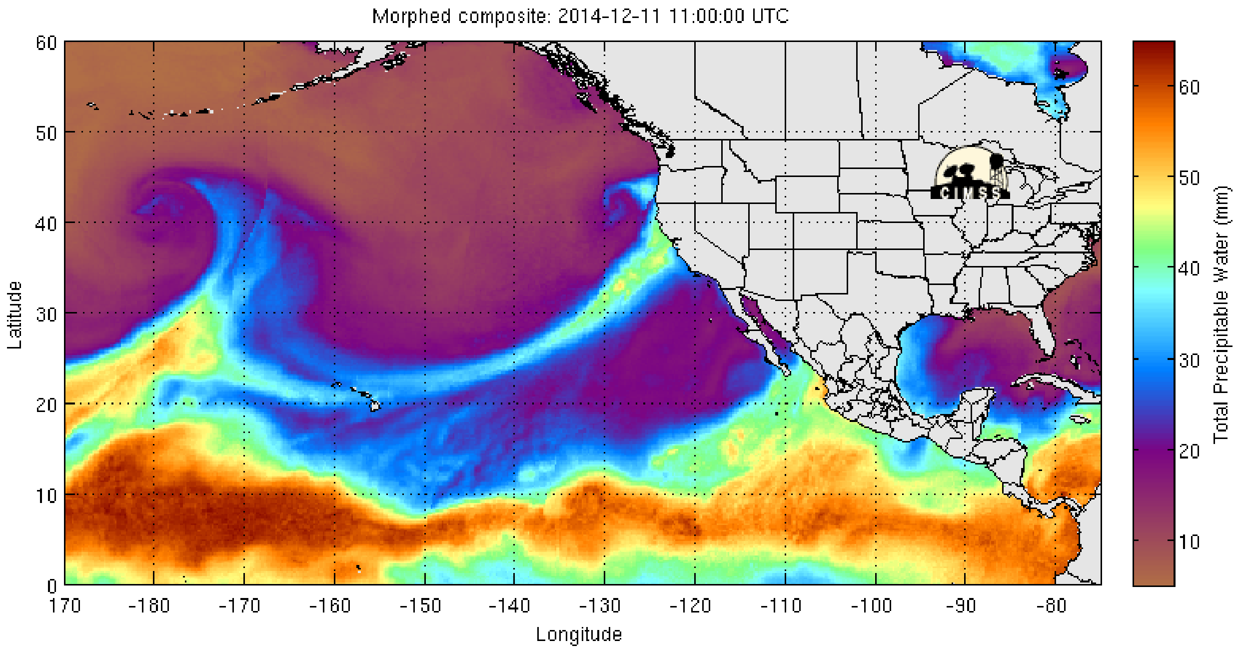

Figure 4. Landfalling Atmospheric River in December 2014

Source: CIMSS

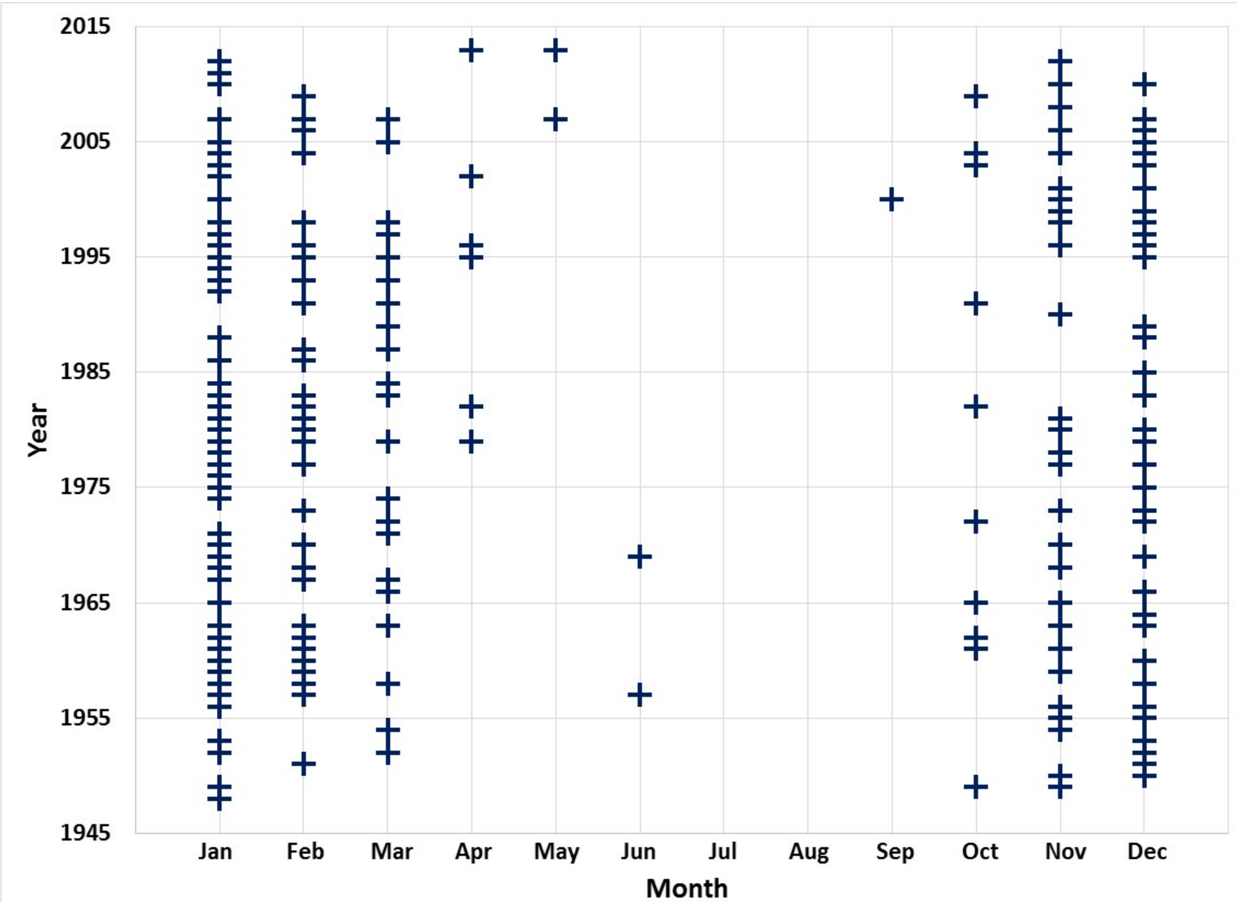

Figure 5. Dates of Pineapple Express Events during the 1948-2013 Period in Western U.S. Pacific Coast

The PE characteristics for selected historical large flood events (e.g., December 1955, December 1964, February 1986, and New Year Day 1997) have been mapped to facilitate understanding of these events. These four historical events were selected in developing CVHS regulated frequency curve. In the Sacramento River Basin, the events that occurred in water years 1956, 1965, 1986, and 1997 were the largest system-wide events based on 1-day and 3-day unregulated flows. For the San Joaquin River Basin, the events that occurred in water years 1951, 1956, 1986, and 1997 were the largest system-wide events based on 1-day and 3-day unregulated flows. Figures 6 through 9 show the dates, latitude, and moisture transport of PE events; 3-day precipitation and annual expected precipitation probability; and, extent of watershed with temperatures capable of producing snow. The atmospheric and meteorological conditions associated with each event are summarized below.

December 1955 Flood

Between December 15, 1955 and January 27, 1956 a series of storm events brought significant precipitation to the Western United States causing record runoff in California streams and rivers. Groundwater and soil-moisture conditions prior to the principal storm period were moderately high due to precipitation events in early December. Prior to December 15, approximately 50 inches of snow had accumulated in the Sierra Nevada at 7,500 feet. As is characteristic of most Pacific Coast winter storms, the cumulative effect of moist unstable air-masses, strong west-southwest winds, and coastal mountain ranges oriented at near right angles to wind patterns, had produced significant runoff events in California (Hoffman and Rantz, 1963).

The first of the principal storms occurred from December 15 to December 21 bringing about 2-3 inches of precipitation, falling mainly as snow. During this storm the Sierra Nevada snowline ranged from about 5,000 to 9,000 feet with snow depths increasing to about 75 inches at 9,000 feet. The second of the principal storm events occurred from December 21 to December 24 during which the freezing level rose to about 10,000 feet in the Sierra Nevada. As a result most precipitation fell as rain. Recorded precipitation amounts during this storm ranged from 8 inches in the northern Sierra Nevada and 16 inches in the southern Sierra Nevada Mountains. Due to the warm temperatures and high wind velocities considerable snow melt occurred with the snowline retreating anywhere from 500 to 1,000 feet in altitude. Snow depths decreased about 15 inches at all altitudes (Hoffman and Rantz, 1963).

Four other storm events occurred between December 24 and January 27. None of these storms were significantly noteworthy in terms of precipitation amounts. However, due to nearly four times the normal amount of precipitation in December, soils were saturated and rivers were still running high. It is reported that streamflow was maintained at bankfull discharge for most of January.

Damage as a result of these storm events included the loss of life of 72 persons, and an estimated $190 million in total damage. The largest concentration of damage occurred in Yuba City where 38 people drowned and property damage exceeded $40 million (Hoffman and Rantz, 1963).

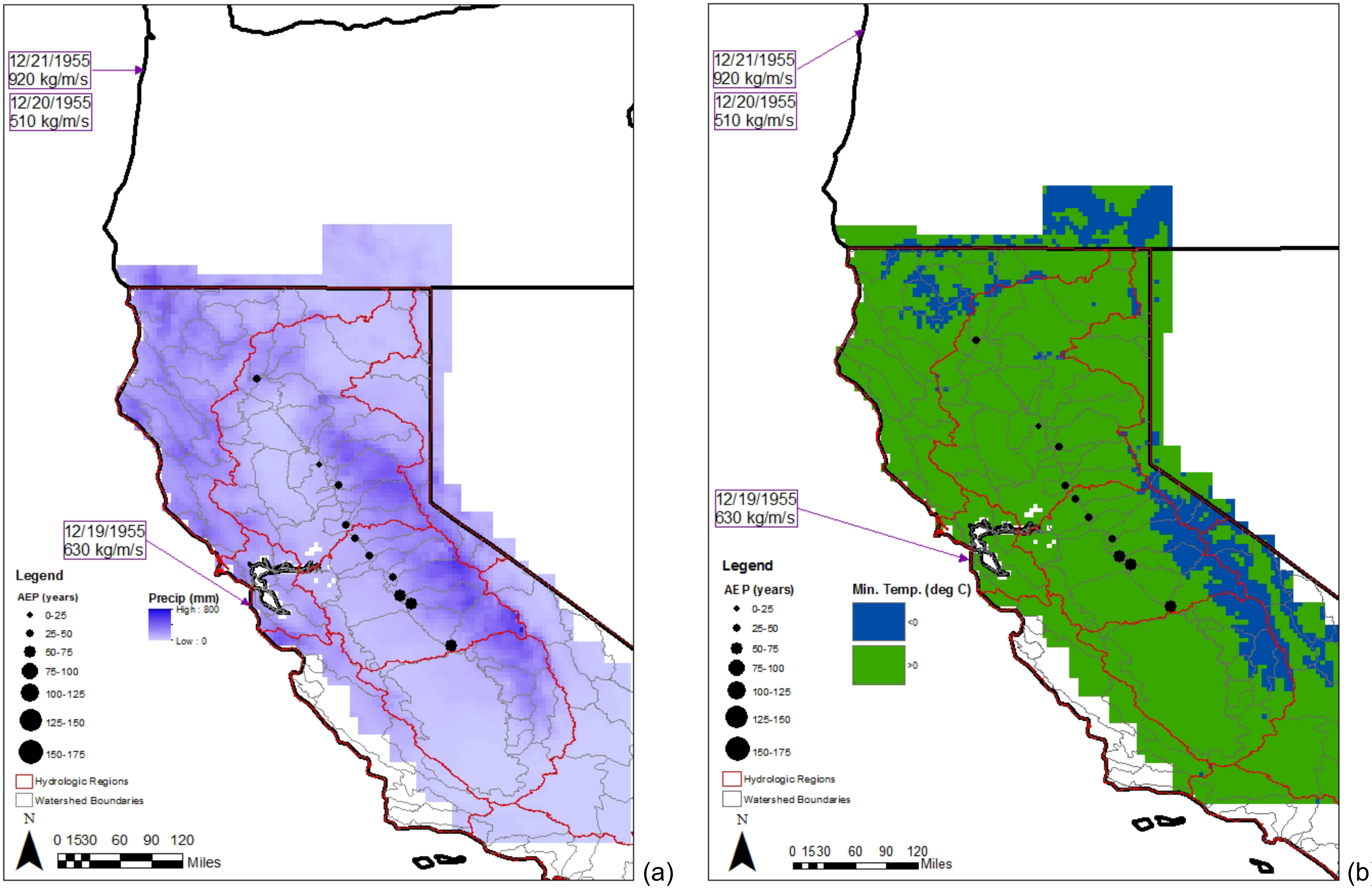

Figure 6. Spatial Maps of Daily Precipitation (a) and Minimum Temperature (b) for the Dec/Jan 1955-56 Flood Event

The daily precipitation is summed over 3 days. The daily minimum temperature is averaged over 3 days. Landfall dates, location, integrated moisture flux (kg/m/s) of PE events shown in boxes The map also shows annual exceedance probability (in years) of the unregulated flood flows at major upper watershed locations for the Dec/Jan 1955-56 flood event.

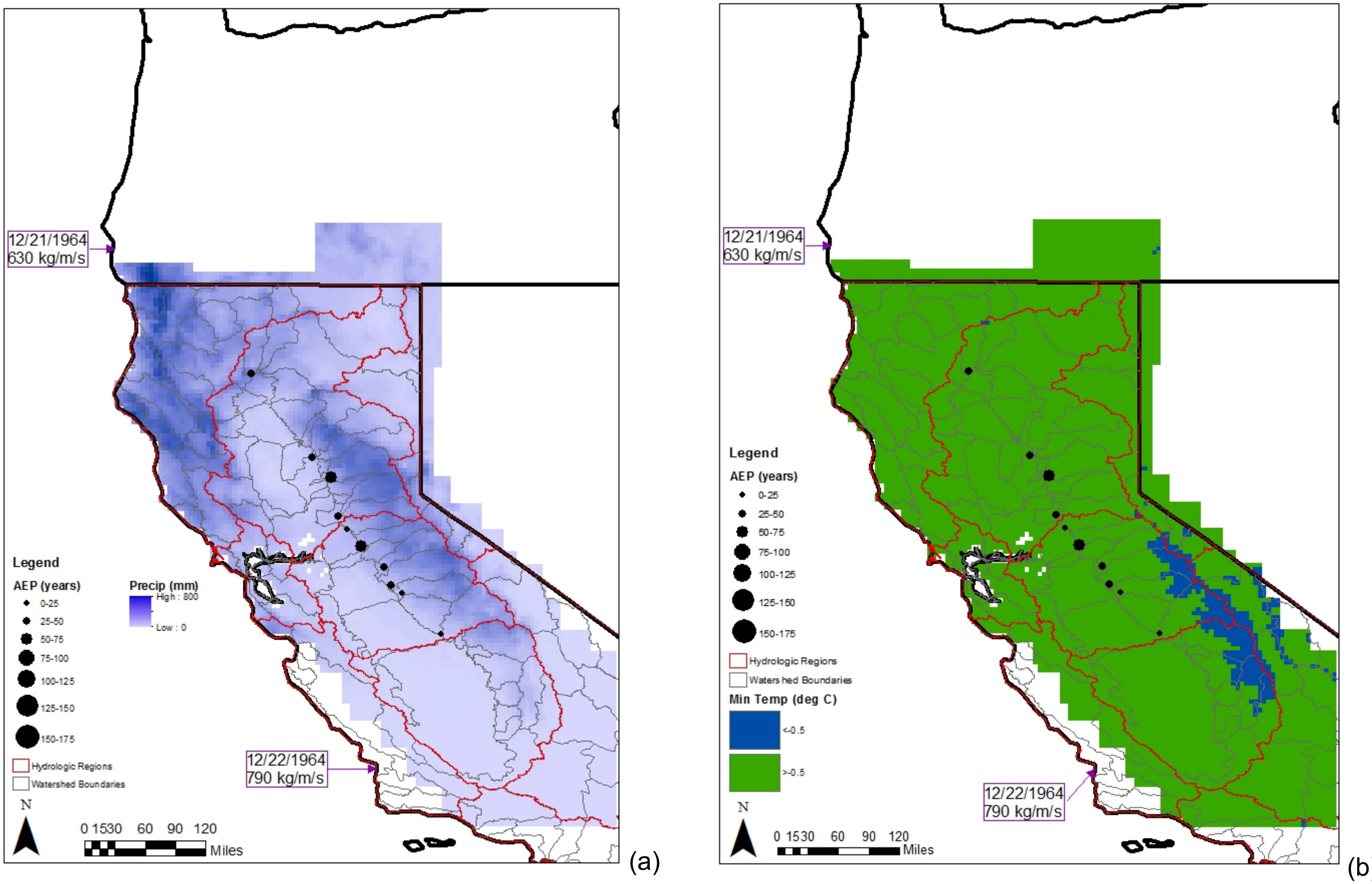

Figure 7. Spatial Maps of Daily Precipitation (a) and Minimum Temperature (b) for the 1964 Flood Event

The daily precipitation is summed over 3 days. The daily minimum temperature is averaged over 3 days. Landfall dates, location, integrated moisture flux (kg/m/s) of PE events shown in boxes The map also shows annual exceedance probability (in years) of the unregulated flood flows at major upper watershed locations for the 1964 flood event.

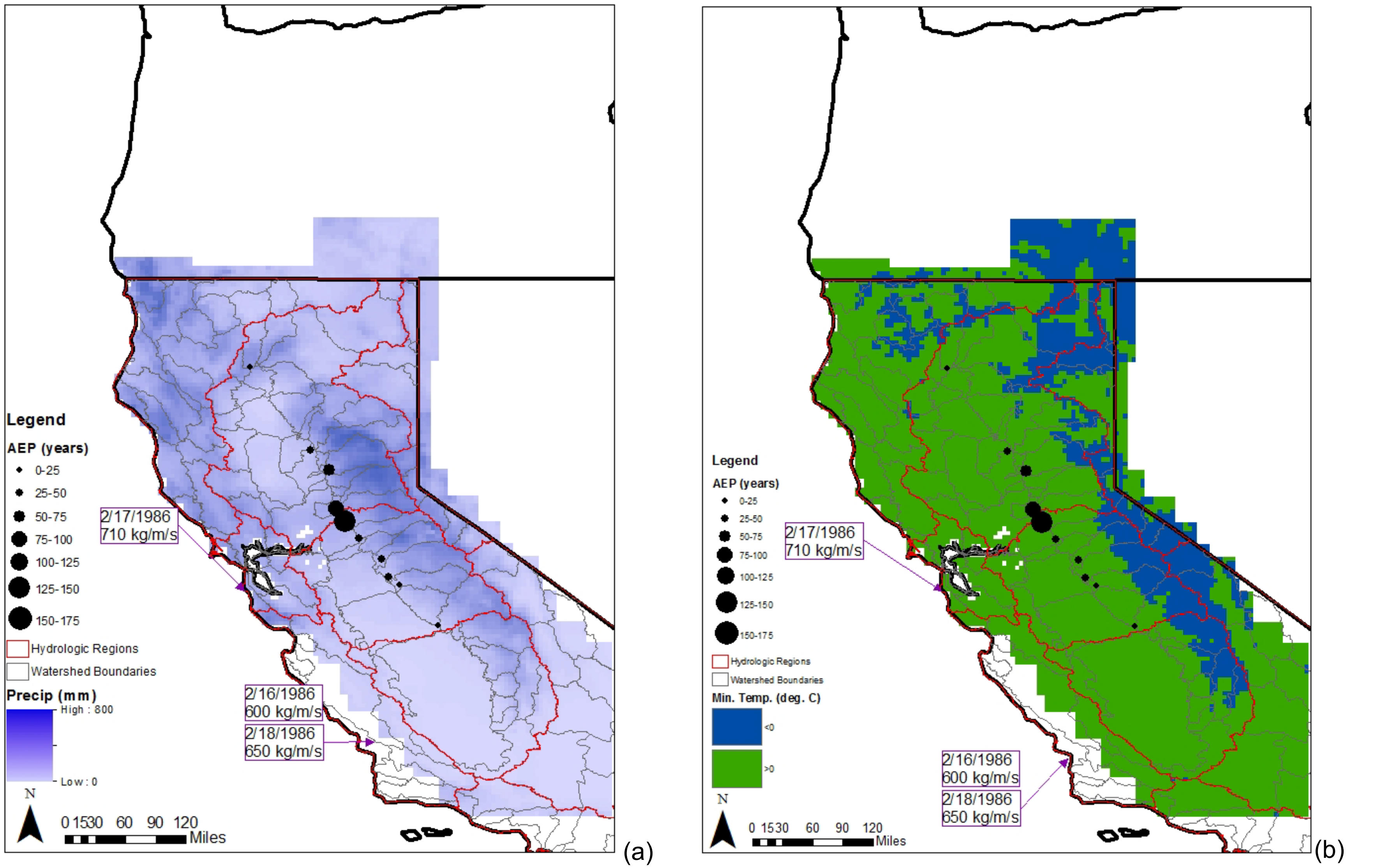

Figure 8. Spatial Maps of Daily Precipitation (a) and Minimum Temperature (b) for the Feb/Mar 1986 Flood Event

The daily precipitation is summed over 3 days. The daily minimum temperature is averaged over 3 days. Landfall dates, location, integrated moisture flux (kg/m/s) of PE events shown in boxes The map also shows annual exceedance probability (in years) of the unregulated flood flows at major upper watershed locations for the Feb/Mar 1986 flood event.

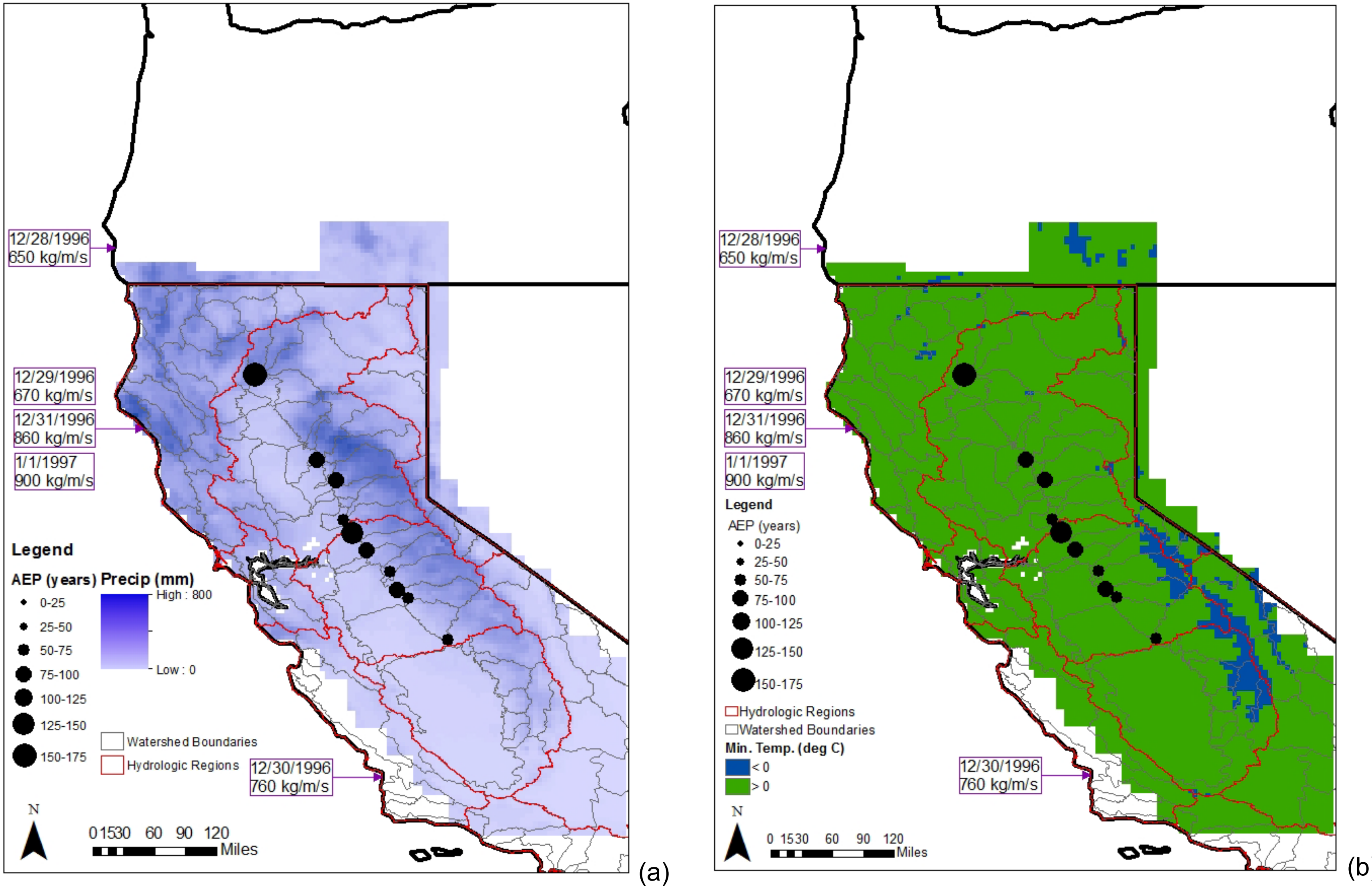

Figure 9. Spatial Maps of Daily Precipitation (a) and Minimum Temperature (b) for the Dec/Jan 1996-97 Flood Event

The daily precipitation is summed over 3 days. The daily minimum temperature is averaged over 3 days. Landfall dates, location, integrated moisture flux (kg/m/s) of PE events shown in boxes The map also shows annual exceedance probability (in years) of the unregulated flood flows at major upper watershed locations for the Dec/Jan 1996-97 flood event.

December 1964 Flood

Between December 19, 1964 and January 31, 1965 the most devastating flood since the 1955 flood occurred in the western United States. During the months of December and January, over 60 inches of rain was recorded at several stations in the Sierra Nevada. Based on runoff events these precipitation measurements were likely greater in higher altitude regions. The following peak flows were measured during the 1964 flood: 281,000 cfs in the Feather River at Nicolaus, 74,200 cfs in the Sacramento River at Verona, 214,000 cfs flowing into Folsom Lake, and 370,000 cfs in the Yolo Bypass near Lisbon. Damage from this event included 47 lives lost and an estimated $430 million in direct property damage with much of the damage occurring in Northern and Coastal California (Waananen et al., 1971).

From December 18 to December 20 a high-pressure system formed over the Pacific Ocean occupying most of the area between Hawaii and Alaska preventing warm moist air from moving to the west coast. As a result, low temperatures brought precipitation consisting mostly of snow at high altitudes. By December 20 the high pressure systems began to be eroded away and a storm track 500 miles wide began to form and move at lower altitudes. Cold Arctic air moved in to mix with the moist tropical air intensifying the storms as they moved towards the west coast. Between December 21 and December 23, temperatures began to increase causing the freezing level to rise to 10,000 feet. Almost all precipitation during this period fell as rain with approximately 8 to 11 inches of rainfall in 24 hours being recorded at several stations in California. From December 24 to December 31 the storm system changed with a rising pressure system moving into the Pacific Ocean near Hawaii cutting off the flow moist warm air. During this period heavy snow fell at low altitudes with intermittent rain and hail falling at sea level (Waananen et al., 1971).

February 1986 Flood

In February 1986 three distinct storm events over a ten day period from February 11-20 occurred causing wide spread flooding across northern California. Many precipitation monitoring stations exceeded 50% of the annual average accumulation during the 10-day storm period. Rainfall totals for the 10-day period in Sierra Nevada measured in excess of 50 inches, nearly 40 inches in the Russian and Napa basins, and over 30 inches in the American, Stanislaus, and San Joaquin basins (Meier et al., 2016). These totals represented record setting totals for February that still stand. Even though freezing elevations were high during the three events, snowpack increased from 85 percent of average to 140 percent of average after the events. Record-setting streamflow and stages were recorded on the Russian, Napa, lower Sacramento, American, Cosumnes, and Mokelumne Rivers. At its peak on February 20, the Sacramento River and Yolo Bypass moved over 1.3 million acre-feet past the latitude of Sacramento which is the largest volume measured at the time. Weir flow on the Sacramento River system continued into late March.

The first storm took place between February 12 and February 13. During this period, snow levels peaked at around 9,000 feet and lowered to about 8,000 feet at the tail-end of the storm (Meier et al., 2016). Peak precipitable water of 1.2 inches occurred on February 12. The second storm occurred from February 14 through February 15 with a precipitable water peak of 1.3 inches on the 14th. Significant cooling behind the cold front brought freezing levels down to around 6,000 feet after starting at 9,000 feet. The wettest of the three storms lasted from February 17th through the 20th with freezing elevations peaking near 10,000 feet. Peak precipitable water was nearly 1.4 inches on the afternoon of the 17th. From February 12th through the 19th, precipitable water measurements at Oakland, CA remained at or above 0.8 inches. The peak values were near or above the 99th percentile for February for all three events. Saturation levels extended from the surface to near 500 mb which would be at or above the Sierra Nevada crest.

Multiple factors contributed to the widespread flooding that occurred in February 1986. A wet January ensured saturated conditions in the watershed prior to the extreme events. The extended duration of heavy precipitation from the series of three extreme events back to back to back resulted in the record setting volume of water input into Northern California watersheds. The high snow lines and deep saturation ensured heavy precipitation extended to the crest of the Sierra Nevada with large contributing areas of direct runoff. This resulted in record flows and stages at many locations challenging the flood management infrastructure. Some of the record stage and flows recorded in this event remain to this day. Flood damage from the event included 13 lives lost, 67 injuries, 50,000 people displaced by flooding, and $400 million in damages (Blodgett and Lucas, 1988; NOAA, 2016).

New Year Day 1997 Flood

From December 21, 1996 through January 4, 1997 significant storm events brought flooding to California. Leading up to this flooding event, the month of November received 120% normal precipitation and in the 25 days of December precipitation amounts were at 200% of normal precipitation (Hereth et al., 1999). Such conditions left California watersheds significantly saturated leading up to series of storms through then end of December into January. During a 9-day period of this storm, precipitation totals ranged from 15 to 30 inches at various stations, and over 40 inches in the Feather River Basin during a 9-day period (Kozlowski and Ekern, 2016).

Due to the orographic effect on California storms, precipitations totals were significantly less at lower elevations than at higher elevations. Between the Sierra Nevada and Sacramento Valley a climatological precipitation ratio of 3:1 is observed for most storm systems. During the peak period of the 1997 flood, the climatological precipitation ratio was nearly 10:1 (Kozlowski and Ekern, 2016).

From December 21 to December 22 a cool storm system brought valley rain and several feet of mountain snow. On December 24, the weather pattern began to shift and bring warm moist air to the western United States. Warmer temperatures came as a result of a high pressure ridge aligned with the west coast began to move back towards the west as cool air dropped southwest across British Columbia allowing for a warm moist jet stream to pull in from the eastern Pacific. A second source of moisture merged with the eastern Pacific system near the Hawaiian Islands and began to move in a north east direction towards the United States. Due to the warm nature of this system, freezing levels increased to near 10,000 feet with precipitation falling primarily as rain (Kozlowski and Ekern, 2016).

During the 1997 flood event the following observed peak discharges were observed: 104,000 cfs in the Sacramento River at Verona, 116,000 cfs at the Sacramento Weir, 75,600 in the San Joaquin at Vernalis, and 163,000 in the Feather River at Gridley (Kozlowski and Ekern, 2016). Estimated damages from the 1997 flood were the highest amount in the State of California's history at $2 billion. In 48 of California's 58 Counties disaster areas were declared.

Figures 10 and 11 show the oceanic and atmospheric meteorological conditions for these four historical storm events. In each figure the top panel shows the geopotential height anomalies, the middle panel shows the vector wind speed, and the bottom panel shows the precipitable water in the atmosphere. Geopotential height anomalies reflect the deviations of the geopotential height field from average values. Negative geopotential height anomalies (indicated in purple and blue in the figures) imply colder than average temperatures, while positive anomalies (indicated by green, yellow, and red in the figures) indicate warmer than average temperatures across the region. Wind fields are depicted in the middle panel showing both the wind speed and the direction. Precipitable water reflects the total moisture in the atmospheric column that is capable of producing precipitation.

All four events demonstrate consistent atmospheric conditions for the generation of atmospheric rivers. Negative geopotential height anomalies occur over Washington and Canada, while positive anomalies occur over Oregon and California. This geopotential height setup enables tropical Pacific moisture flows to be channeled to California. Winds are strong and generally connect tropical moisture from near Hawaii to the West Coast. The atmospheric precipitable water demonstrates the large amount of water in the atmosphere and the relatively narrow corridor in which moisture is transported along the storm paths. While atmospheric conditions such as these are capable of being generated in all years, the most intense events occur during warmer tropical Pacific oceanic conditions associated with El Niño years.

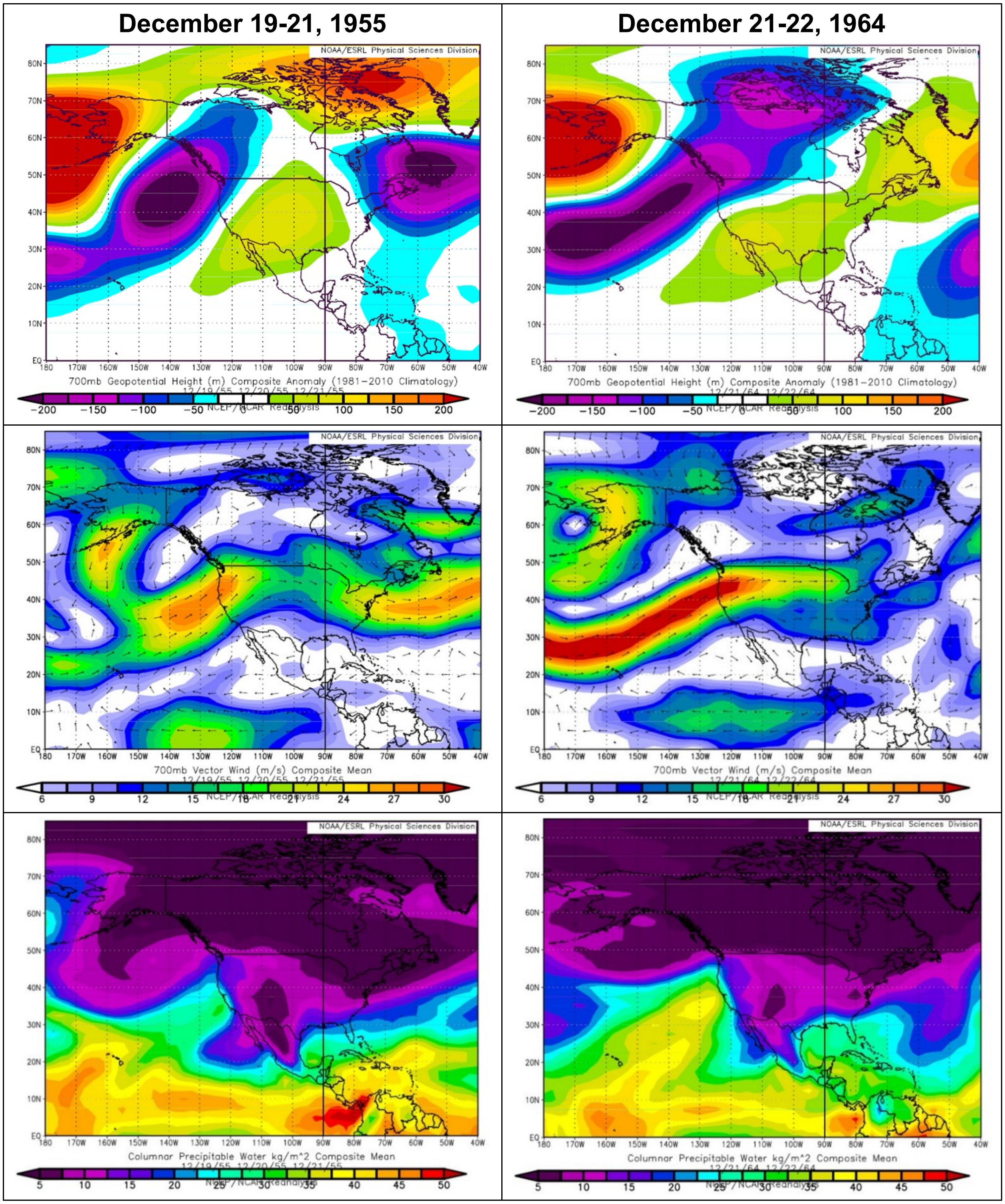

Figure 10. Composites of Geopotential Height Anomalies, Wind Speed, and Precipitable Water for the December 19-21, 1955 and December 21-22, 1964.

Notes: Geopotential height anomalies, Z700 (top); 700 mbar mean wind speeds, U700 (middle); and precipitable water, PW (lower) for the December 19-21, 1955 (left panel) and December 21-22, 1964 (right panel). Panels created using online compositing tools provided by NOAA's Climate Diagnostics Center

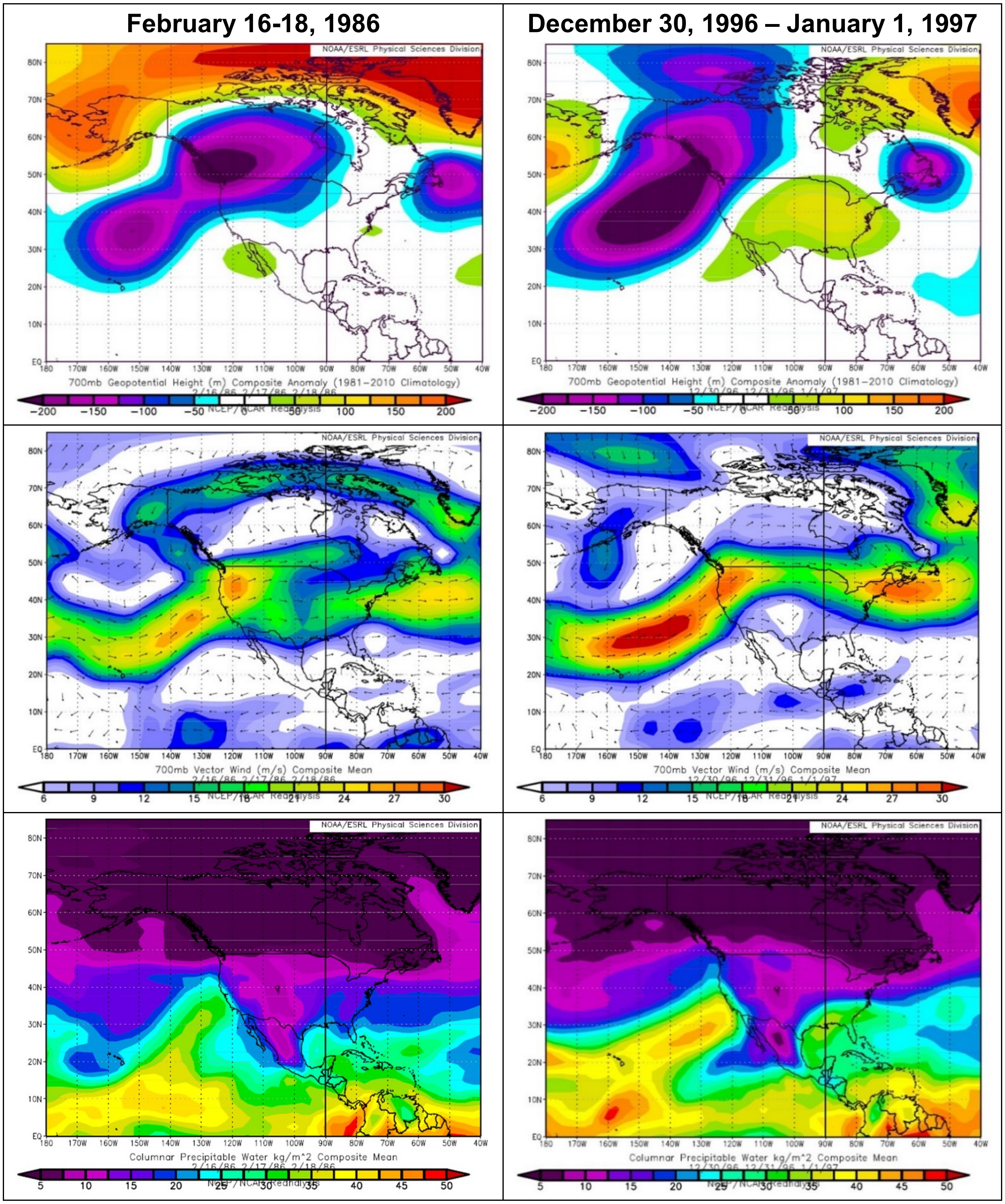

Figure 11. Composites of Geopotential Height Anomalies, Wind Speed, and Precipitable Water for February 16-18, 1986 and December 30, 1996 – January 1, 1997.

Notes: Geopotential height anomalies, Z700 (top); 700 mbar mean wind speeds, U700 (middle); and precipitable water, PW (lower) for the February 16-18, 1986 and December 30, 1996 – January 1, 1997. Panels created using online compositing tools provided by NOAA's Climate Diagnostics Center.

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4.0 Future Climate Scenarios

Future climate scenarios used in the Phase IIB of the CVFPP climate change analysis are based on climate model simulations from the Coupled Model Intercomparison Project Phase 5 (CMIP5). The climate models in the CMIP5 (Taylor et al., 2012; Karl et al., 2012; Rupp et al., 2013) were driven using a set of newly developed emission scenarios (called Representative Concentration Pathways, or RCPs) to reflect possible trajectories of greenhouse gas emissions over the course of the century. There are four scenario pathways (RCP2.6, RCP4.5, RCP6.0 and RCP8.5) used in the CMIP5 (van Vuuren et al., 2011). Each Representative Concentration Pathway (RCP) defines a specific emissions trajectory and subsequent radiative forcing (a radiative forcing is a measure of the influence a factor has in altering the balance of incoming and outgoing energy in the Earth-atmosphere system). The RCPs pathways differ from the scenarios used in the IPCC 2007 report (IPCC, 2007) which were developed based a range of possible future greenhouse gas emissions using assumptions of fossil fuel use, regional political and social conditions, technologies, population, and governance decisions. Both the current RCPs and the older emission scenarios, labeled as Special Report on Emission Scenarios (SRES) are shown in Figure 12.

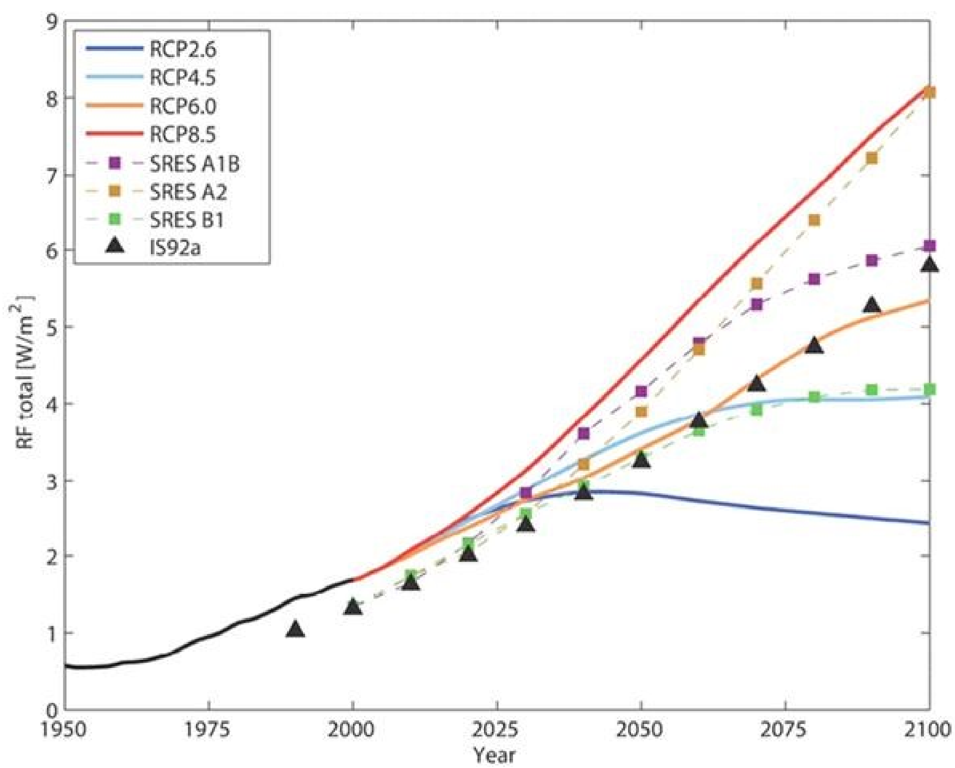

Figure 12. Comparisons of Total Radiative Forcing from Previous IPCC Assessments (SAR IS92a, TAR/AR4 SRES A1B, A2 and B1) with RCP Scenarios

Source: IPCC 2013

The future climate scenarios were derived from the change in temperature and precipitation from 114 climate projections generated from 36 different GCMs using the RCP emission scenarios RCP8.5, RCP6.0, and RCP4.5. These RCP emission scenarios are summarized in Table 2. The projections using these RCP emission scenarios have been bias-corrected spatially downscaled (BCSD) at 1/8th degree (~12 km) (~7.5 miles) spatial resolution by Bureau of Reclamation (Reclamation) and others (Reclamation, 2013) as shown in Table 3. The climate projections simulated under RCP2.6 were not used in this study. RCP2.6 assumes drastic policy intervention; greenhouse gas emissions are reduced almost immediately, leading to a slight reduction from today's levels by 2100 (van Vuuren et al., 2011).

Climate scenarios used in this analysis were developed using two different approaches: the ensemble-informed (EI) approach using BCSD climate projections from over 100 climate simulations, and an approach using downscaled climate projections using the locally organized constructed analog (LOCA) method for 20 selected climate projections. Each of the approaches is briefly described in the following sections.

Table 2. Overview of Representative Concentration Pathways (RCPs)

RCP	Description[a.]
RCP8.5	Rising radiative forcing pathway leading to 8.5 W/m^2 (~1370 ppm CO_2 eq) by 2100.
RCP6	Stabilization without overshoot pathway to 6 W/m^2 (~850 ppm CO_2 eq) at stabilization after 2100
RCP4.5	Stabilization without overshoot pathway to 4.5 W/m^2 (~650 ppm CO_2 eq) at stabilization after 2100
RCP2.6	Peak in radiative forcing at ~3 W/m^2 (~490 ppm CO_2 eq) before 2100 and then decline (the selected pathway declines to 2.6 W/m^2 by 2100)

(Source: van Vuuren et al., 2011)

Note:
a. Approximate radiative forcing levels were defined as ±5 percent of the stated level in W/m^2 relative to pre-industrial levels. Radiative forcing values include the net effect of all anthropogenic GHGs and other forcing agents
GHG = greenhouse gas

4.1 Ensemble-Informed Climate Scenarios

While precise prediction of future climate is impossible, five statistically representative climate scenarios were developed using information from the entire ensemble of available climate projections. These five climate scenarios include one that represents the "central tendency" and four to capture the range of the ensemble uncertainty including: representing drier, less warming (WD); drier, more warming (HD); wetter, more warming (HW); and wetter, less warming (WW) conditions than the median projection (CEN). These climate scenarios are developed based on an ensemble-informed (EI) method that has been applied in many California water resource planning studies including the California Water Fix (CWF) resource impact assessments. A detailed description of the EI method can be found in Appendix A. This method is similar to that applied by the Climate Impacts Group for development of hydrologic scenarios for water planning in the Pacific Northwest (Hamlet et al., 2009).

Historical daily climate information was available for the entire study area for the period of 1915 through 2010 at 1/16th degree (~6 km) (~3.75 miles) degree spatial resolution (Livneh et. al., 2013). Statistical changes calculated for each of the three future climate periods at 1/8th degree (~12 km) (~7.5 miles) grid were then mapped onto the historical information to develop an "adjusted" historical record with climate changes for each one of the three future periods at 1/16th degree (~6 km) (~3.75 miles) degree spatial resolution. In this fashion, the natural variability, which is best characterized through the observed records, is combined with the projected changes in climate patterns.

Changes in future climate were calculated as differences in the statistical properties of temperature and precipitation for three future periods as compared to the properties over an historical reference period. The historical reference period was defined as the period 1981 through 2010, reflecting a thirty-year period over which historical climate can be referenced. Three future periods were selected to represent the periods of potential change over the time horizon of the flood improvements: (1) near-term (2011 through 2040), (2) mid-century (2041 through 2070), and (3) end of century (2070 through 2099). The changes in statistical properties of temperature and precipitation for each of the three periods as compared to the historical reference period were computed.

4.2 LOCA Downscaled Climate Projections

In addition to the climate change scenarios described above, twenty individual downscaled GCM projections were selected from ten different GCMs and two different Representative Concentration Pathways, RCP4.5 and RCP8.5. These ten GCMs were chosen by the DWR Climate Change Technical Advisory Group (CCTAG) based on a regional evaluation of climate model ability to reproduce a range of historical climate conditions (DWR CCTAG, 2015). These twenty climate projections were downscaled using a statistical downscaling method called LOCAs at 1/16th degree (~6 km) (~3.75 miles) spatial resolution by Scripps Institution of Oceanography (Pierce et al., 2014). The primary steps of the LOCA method are described in Appendix A. The LOCA method is a statistical scheme that uses future climate projections combined with historical analog events to produce daily downscaled precipitation and temperature time series. The use of spatial and temporal analogs from historical events likely produces a more realistic storm pattern than the BCSD method.

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Table 3. General Circulation Models from the WCRP's CMIP5 Database Used in CVFPP Climate Change Analysis

WCRP CMIP5 Climate Modeling Group		WCRP CMIP5 Climate Model ID	RCP 4.5[a.]	RCP 6.0[a]	RCP 8.5[a]
Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology, Australia	1	ACCESS1-0	1		1
	2	ACCESS1-3	1		1
Beijing Climate Center, China Meteorological Administration	3	BCC-CSM1-1	1	1	1
	4	BCC-CSM1-1-M	1		1
Canadian Centre for Climate Modelling and Analysis	5	CanESM2	2		2
National Center for Atmospheric Research	6	CCSM4	2	2	2
Community Earth System Model Contributors	7	CESM1-BGC	1		1
	8	CESM1-CAM5	2	2	2
Centro Euro-Mediterraneo per I Cambiamenti Climatici	9	CMCC-CM	1		1
Centre National de Recherches Météorologiques/ Centre Européen de Recherche et Formation Avancée en Calcul Scientifique	10	CNRM-CM5	1		2
Commonwealth Scientific and Industrial Research Organization, Queensland Climate Change Centre of Excellence	11	CSIRO-Mk3-6-0	2	2	2
EC-Earth consortium, representing 22 academic institutions and meteorological services from 10 countries in Europe	12	EC-EARTH	2		2
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, and Center for Earth System Science, Tsinghua University	13	FGOALS-g2	1		1
Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences	14	FGOALS-s2	1		2
The First Institute of Oceanography, State Oceanic Administration, China	15	FIO-ESM	2	2	2
NOAA Geophysical Fluid Dynamics Laboratory	16	GFDL-CM3	1	1	1
	17	GFDL-ESM2G	1	1	1
	18	GFDL-ESM2M	1	1	1
NASA Goddard Institute for Space Studies	19	GISS-E2-H-CC	1		
	20	GISS-E2-R	2	1	1
	21	GISS-E2-R-CC	1		
Met Office Hadley Centre (additional HadGEM2ES realizations contributed by Instituto Nacional de Pesquisas Espaciais)	22	HadGEM2-AO	1	1	1
	23	HadGEM2-CC	1		1
	24	HadGEM2-ES	2	2	2

Table 3. General Circulation Models from the WCRP's CMIP5 Database Used in CVFPP Climate Change Analysis

WCRP CMIP5 Climate Modeling Group		WCRP CMIP5 Climate Model ID	RCP 4.5[a.]	RCP 6.0[a]	RCP 8.5[a]
Institute for Numerical Mathematics	25	INM-CM4	1		1
Institut Pierre-Simon Laplace	26	IPSL-CM5A-LR	2	1	2
	27	IPSL-CM5A-MR	1	1	1
	28	IPSL-CM5B-LR	1		1
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies	29	MIROC-ESM	1	1	1
	30	MIROC-ESMCHEM	1	1	1
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	31	MIROC5	1	1	1
Max-Planck-Institut für Meteorologie (Max Planck Institute for Meteorology)	32	MPI-ESM-LR	2		2
	33	MPI-ESM-MR	1		1
Meteorological Research Institute	34	MRI-CGCM3	1		1
Norwegian Climate Centre	35	NorESM1-M	1	1	1
	36	NorESM1-ME	1	1	1
Total Projections			**46**	**23**	**45**

Notes:
CMIP5 climate model projections have been bias-corrected and spatially downscaled (Reclamation, 2013). The downscaled CMIP5 climate model projections were obtained from the Lawrence Livermore National Laboratory (LLNL) archive at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/

a. The last three columns reflect the number of simulations with the given RCP forcing.

4.3 Projections of Future Climate Change

This section provides a brief summary of the projections of changes in temperature and precipitation over the course of the 21st century. Three future periods have been selected to reflect near-term, mid-century, and end of century changes. Projected changes for the future periods of 2011-2040 (2025), 2041-2070 (2055), and 2070-2099 (2085) are compared to the historical climatological period of 1981-2010.

Figure 13 shows the median annual mean temperature and precipitation changes for California and Nevada derived from the full ensemble of climate projections. The current suite of GCMs, when simulated under potential, future GHG emission pathways and current atmospheric GHGs, exhibit warming both globally and regionally over California. The median, or "central tendency" scenario indicates substantial warming by end of mid-century. Warming is projected to increase more rapidly in inland areas than coastal areas, reflecting a continued ocean cooling influence. Statewide trends in annual precipitation are not as apparent as those for temperature. Regional trends are more pronounced for the upper Sacramento Valley which may experience equal or greater precipitation, the San Joaquin Valley may experience equal or drier conditions, the Tulare Lake hydrologic region may experience drier conditions. Future projections for Southern California are for drier conditions. The north-south transition of precipitation change may be attributable to a more northerly push of storm tracks caused in part by increased sea level pressure blocking systems under future climate conditions.

Projected changes in future climate contain significant uncertainties. Uncertainties exist with respect to understanding and modeling of the earth systems, future development and RCPs, and to simulating changes at the local scale. However, climate models suggest that the projected temperature increase signal is strong and temporally-consistent (Figure 14). All projections are consistent in the direction of the temperature change, but vary in terms of climate sensitivity. Projected annual average temperature increase by end of century under the CMIP5 ensemble is in the range of 0.9°C to 5.9°C with a median estimate of 3.2°C. While increased warming is consistent between CMIP3 and CMIP5 for the entire region, inland valley and mountain ridges are projected to exhibit a larger degree of warming in the CMIP5 projections.

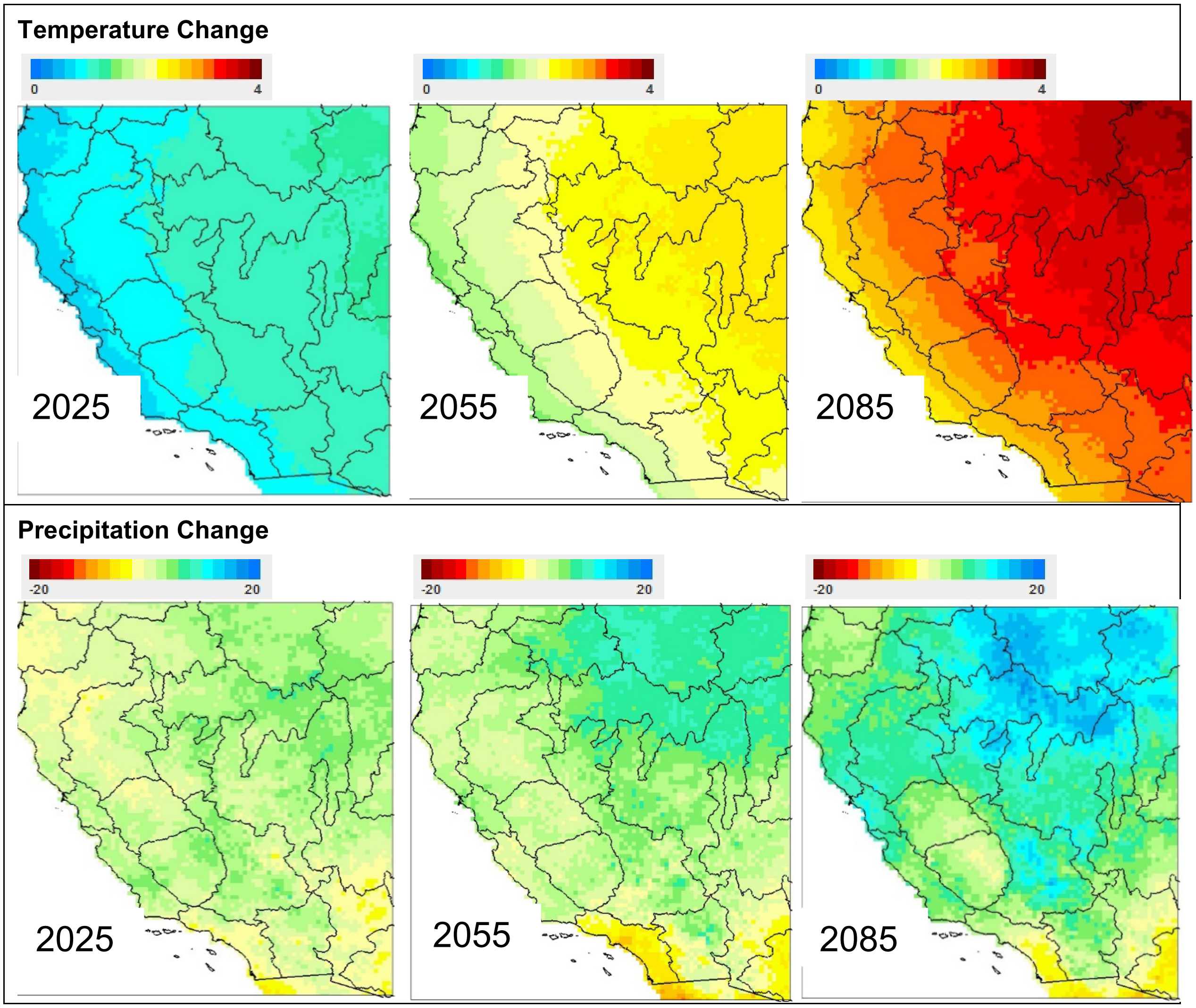
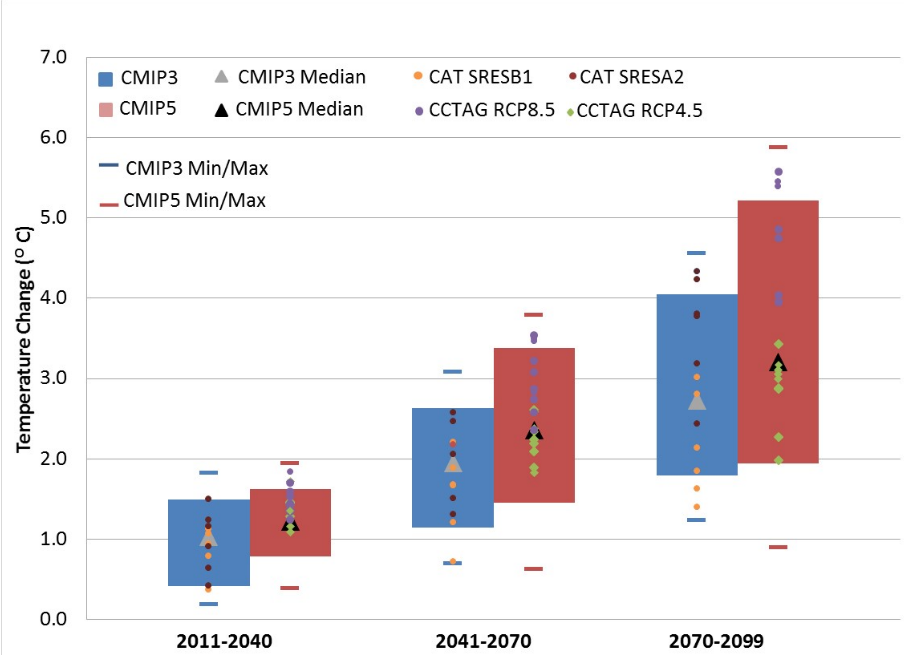


Figure 13. Projected Changes in Annual Mean Temperature and Precipitation using CVFPP Median Climate Change Scenario for 2011-2040 (2025), 2041-2070 (2055) and 2070-2099 (2085)

Notes: Figures show change as compared to the 1981-2010 model simulated period.
Top panel shows °C. Bottom panel shows percent change. Hydrologic basin boundaries are shown.

Projections of annual precipitation changes are not always directionally consistent in both the CMIP3 and CMIP5 ensembles, with some projections suggesting wetter future conditions and others suggesting slightly drier future conditions (Figure 15). The strong natural precipitation variability over multiple decades complicates the determination of wet-dry trends. The CMIP5 ensemble suggests a significant reduction in the areas projected to be drier in the future as compared to the CMIP3 ensemble, and also includes less uncertainty than the CMIP3 ensemble as expressed by the range. The CMIP5 ensemble also provides greater clarity of wetter conditions in the Sacramento Valley, while suggesting more neutral (little change) in projected annual precipitation for San Joaquin and Tulare Basins. The CMIP5 ensemble continues to project future drier conditions in the Southern California, but to a lesser degree as compared to the CMIP3 ensemble. However, despite the relative uncertainty in annual precipitation changes, about two-thirds of the projections suggest increases in 3-day annual maximum precipitation (Figure 16), which is commonly the driver for flooding. The median change in 3-day annual maximum precipitation for the Sacramento River Basin watersheds by end of century is projected to be between 9 and 12 percent greater than historical. For watersheds within the San Joaquin River Basin, the median change in 3-day annual maximum precipitation by end of century is projected to be between 1 and 10 percent greater than historical, with smaller changes in in the south than the north.



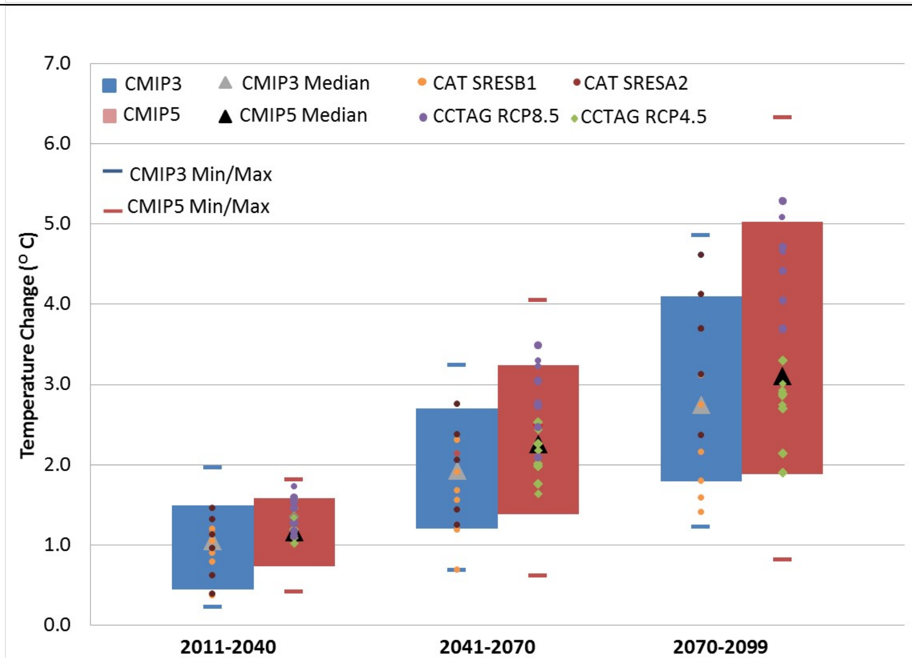
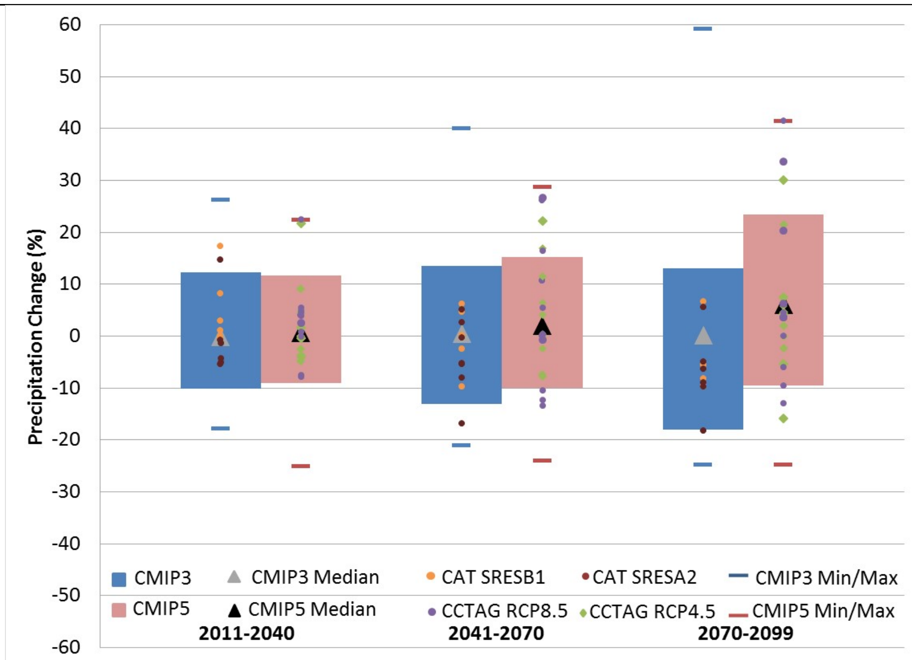


Figure 14. Projected Changes in Mean Annual Temperature for the Sacramento River Basin (top) and San Joaquin River Basin (bottom) based on CMIP3 and CMIP5 Projections

Notes: The projected changes for CMIP3 and CMIP5 are computed using over 100 downscaled climate projections, simulated under SRES emission scenarios A2, A1B, and B1 for CMIP3 and simulated under RCP emission scenarios RCP8.5, RCP6.0, and RCP4.5 for CMIP5, used in the IPCC's AR4 and AR5, respectively. Changes are computed with respect to 1971-2000 model simulated period for both CMIP3 and CMIP5. Bars represent the range between the 10th and 90th percentiles. Circles represent the projections from the CMIP3 GCMs selected by Climate Action Team (CAT) and the CMIP5 GCMs selected by DWR CCTAG for California climate and water assessments. CMIP3 and CMIP5 climate model projections have been bias-corrected and spatially downscaled (Maurer et al., 2007; Reclamation, 2013). GCMs Selected by CAT: CNRM CM3.0, GFDL CM2.1, MIROC3.2 (med), MPI ECHAM5, NCAR CCSM3, NCAR PCM1. GCMs Selected by CCTAG: ACCESS-1.0, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, MIROC5.



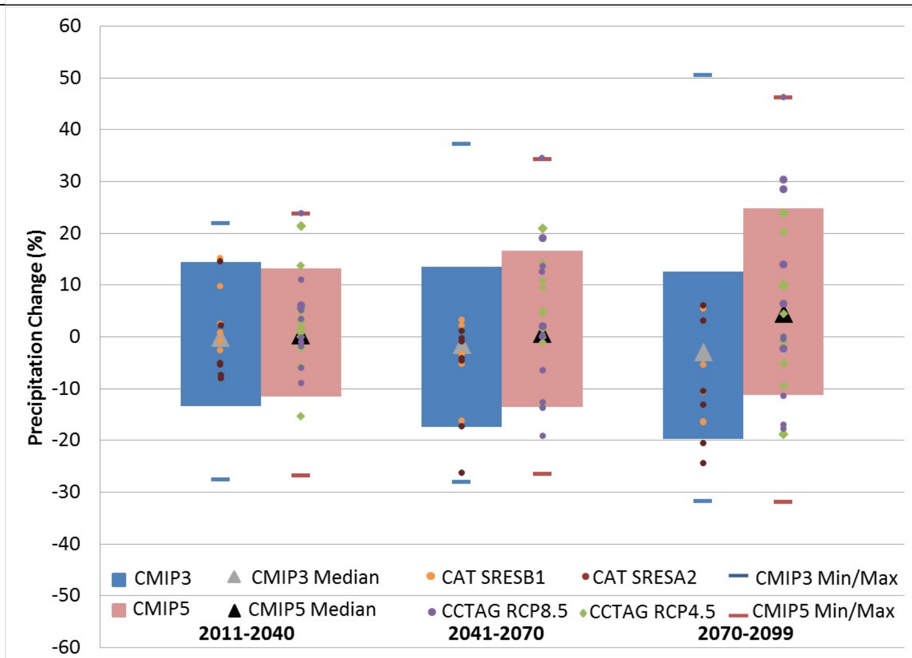


Figure 15. Projected Changes in Mean Annual Precipitation for the Sacramento River Basin (top) and San Joaquin River Basin (bottom) based on CMIP3 and CMIP5 Projections

Notes: The projected changes for CMIP3 and CMIP5 are computed using over 100 downscaled climate projections, simulated under SRES emission scenarios A2, A1B, and B1 for CMIP3 and simulated under RCP emission scenarios RCP8.5, RCP6.0, and RCP4.5 for CMIP5, used in the IPCC's AR4 and AR5, respectively. Changes are computed with respect to 1971-2000 model simulated period for both CMIP3 and CMIP5. Bars represent the range between the 10th and 90th percentiles. Circles represent the projections from the CMIP3 GCMs selected by Climate Action Team (CAT) and the CMIP5 GCMs selected by DWR CCTAG for California climate and water assessments. CMIP3 and CMIP5 climate model projections have been bias-corrected and spatially downscaled (Maurer et al., 2007; Reclamation, 2013). GCMs Selected by CAT: CNRM CM3.0, GFDL CM2.1, MIROC3.2 (med), MPI ECHAM5, NCAR CCSM3, NCAR PCM1. GCMs Selected by CCTAG: ACCESS-1.0, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, MIROC5.

Figure 16. Projected Change in 3-day Annual Maximum Precipitation for the Major Watersheds in the Sacramento and San Joaquin River Basins for three Future Time Periods.

Notes: The projected changes were computed based on 20 downscaled climate projections using LOCA daily statistical downscaling method at 1/16th degree (~6 km) (~3.75 miles) spatial resolution. These climate projections are from 10 GCMs and two RCPs (RCP8.5 and RCP4.5) selected by DWR CCTAG for California climate and water assessments. Changes are computed with respect to 1981-2010 model simulated period. GCMs Selected by CCTAG: ACCESS-1.0, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, MIROC5.

5.0 VIC Hydrological Model Refinements

The VIC model is used to simulate regional hydrology for historical and future conditions for the entire Central Valley. The VIC model (Liang et al., 1994, 1996; Nijssen et al., 1997) is a spatially distributed hydrologic model that simulates land surface-atmosphere exchanges of moisture and energy at each model grid cell. The VIC model incorporates spatially distributed parameters describing topography, soils, land use, and vegetation classes. The model accepts input meteorological data directly from global or national gridded databases or from GCM projections. To compensate for the coarseness of the discretization, VIC is unique in its incorporation of subgrid variability to describe variations in the land parameters as well as precipitation distribution. Figure 17 shows the hydrologic processes included in the VIC model.

The VIC model has been applied to many major basins in the United States (U.S.), including large-scale applications to California's Central Valley (Liang et al., 1994; Maurer et al., 2002, 2007b; Maurer, 2007; Hamlet and Lettenmaier, 2007; Barnett et al., 2008; Cayan et al., 2008; Raff et al., 2009; Dettinger et al., 2011a, 2011b; Das et al., 2011a, 2013; DWR, 2014; CH2M HILL, 2012; Reclamation, 2014), Colorado River Basin (Christensen and Lettenmaier, 2007; Das et al., 2011b; Vano et al., 2012, 2014a,b), Columbia River Basin (Hamlet and Lettenmaier, 1999; Hamlet et al., 2007), and for several basins in U.S. (Maurer et al., 2003; CH2M HILL, 2008; Livneh et al., 2013).

As part of the Phase IIB model refinements, two substantial improvements to the VIC hydrologic model were made. First, the model was refined to include a higher resolution grid and re-delineation of watershed boundaries and streamflow routing. Second, the VIC model was calibrated at upper watershed locations for selected extreme historical flood events. The following sections describe these efforts in detail.

5.1 VIC Model Refinements

As part of the Phase IIB tasks, the VIC hydrological model was configured at $1/16^{th}$ degree (~6 km) (~3.75 miles) spatial resolution over the Central Valley from its 1/8th degree (~12 km) (~7.5 miles) spatial resolution that was used in Phase IIA. Figure 18 shows the refined VIC model grid. The refinements effectively quadrupled the spatial resolution as compared to the Phase IIA VIC modeling analysis. Improvements by Livneh et al. (2013) in the VIC model dataset at $1/16^{th}$ degree (~6 km) (~3.75 miles) were used as a preliminary dataset in Phase IIB. Livneh's improvements from Maurer's original dataset (Maurer et al., 2002) include increased latitude/longitude spatial resolution from 1/8th degree (~12 km) (~7.5 miles) to $1/16^{th}$ degree (~6 km) (~3.75 miles) and an updated version of the VIC land surface model computations (Livneh et al., 2013). These improvements helped to refine the evaluation of climate and hydrological analyses included in this report.

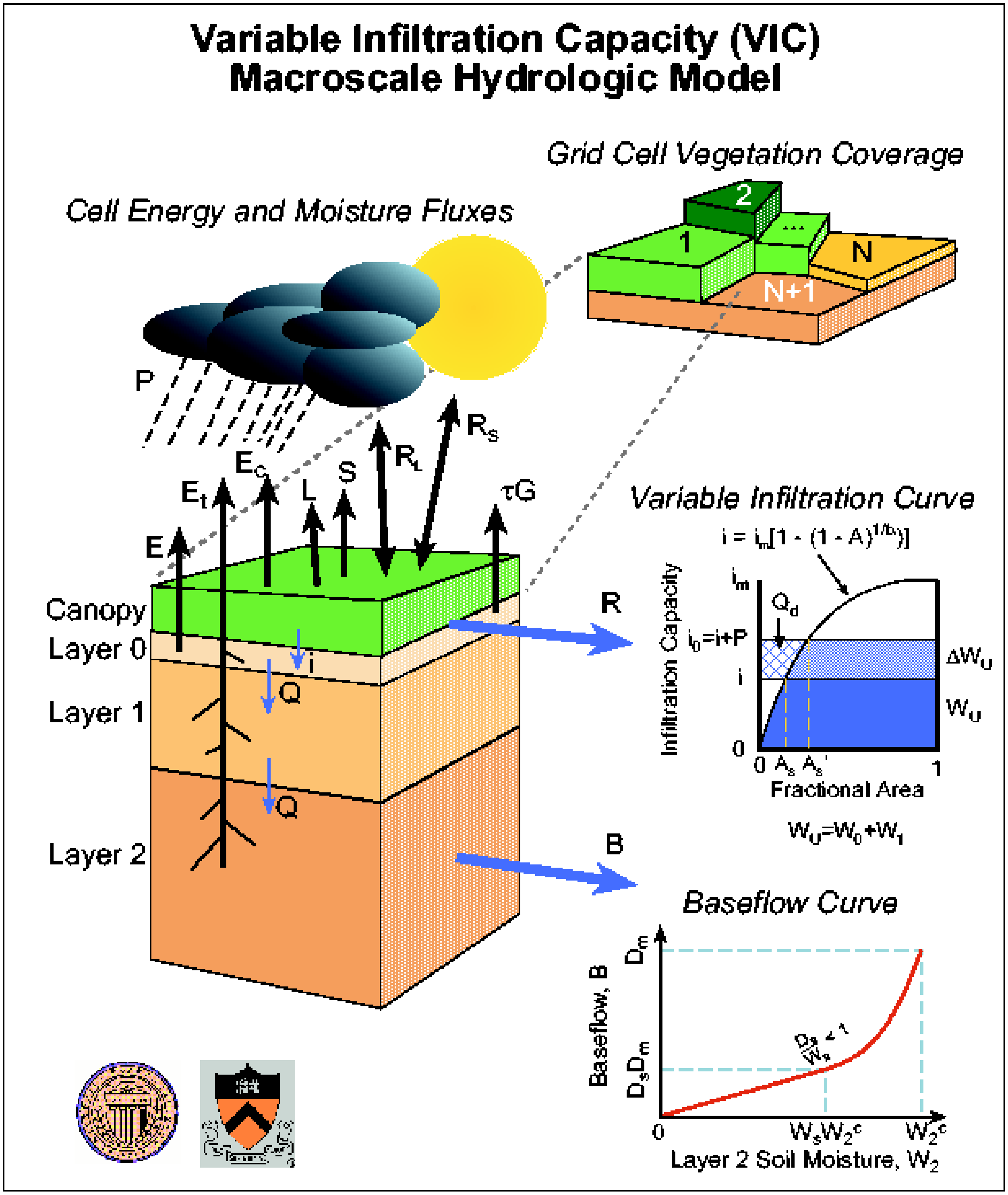


Figure 17. Hydrologic Processes Included in the VIC Model

Source: University of Washington, 2015

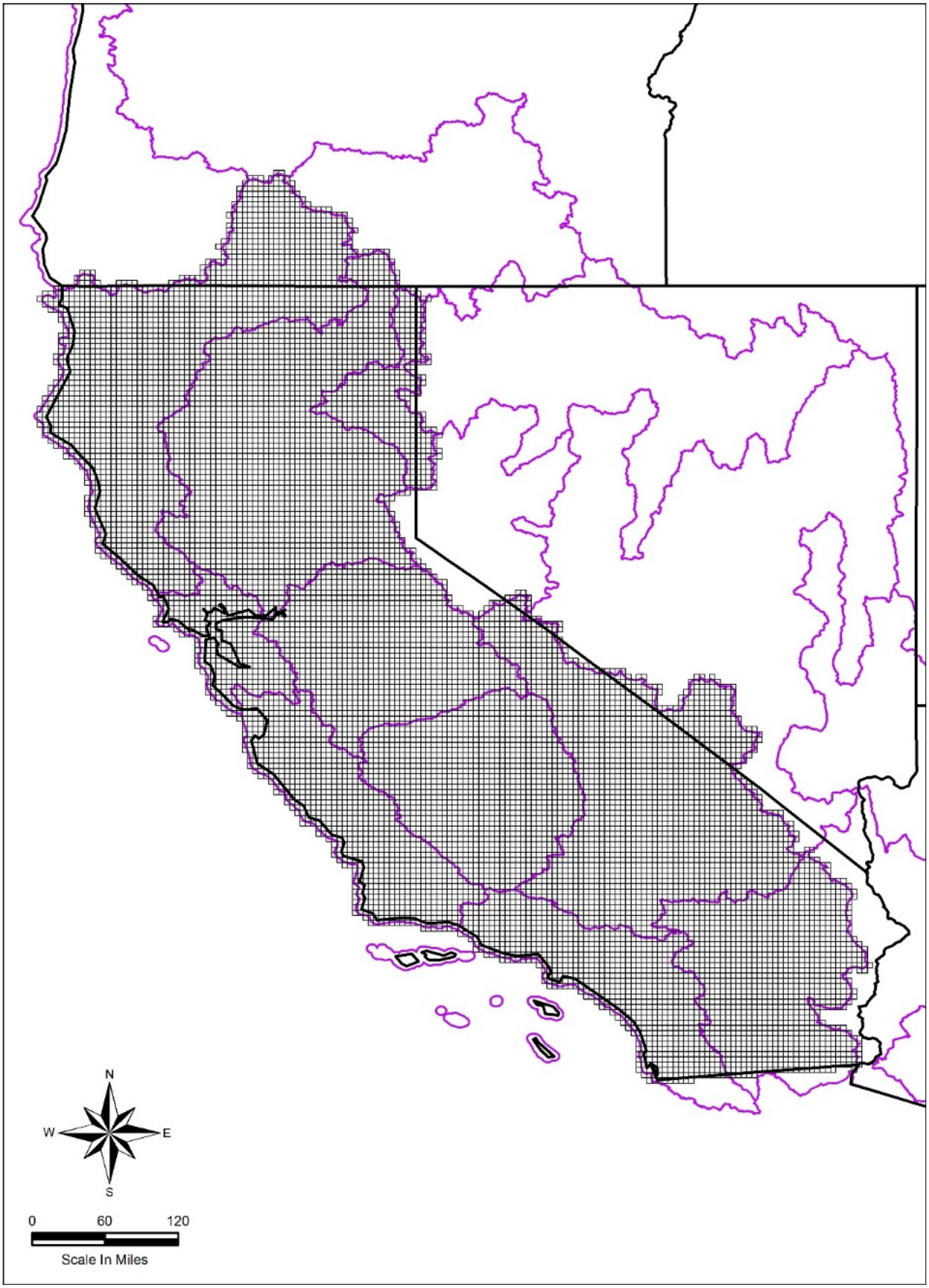


Figure 18. VIC Model Domain and Grid

When simulating VIC in water balance mode, as done for this CVFPP application, VIC is driven by daily inputs of precipitation, maximum and minimum temperature, and wind speed. The model internally calculates additional meteorological forcings, such short- and long-wave radiation, relative humidity, vapor pressure and vapor pressure deficits. Two types of VIC input data were produced from the Livneh improvements. These include (1) station-based daily gridded precipitation and temperature data, and wind fields from the National Centers for Environmental Prediction (NCEP) – National Center for Atmospheric Research (NCAR) reanalysis, and (2) VIC model soil, vegetation, and elevation bands parameters.

Five elevation bands are included for each 1/16th degree (~6 km) (~3.75 miles) grid cell in the VIC model to capture the precipitation and snow variability over the grid cell. In addition, VIC also includes a sub-daily (1-hour) computation to resolve transients in the snow model. The soil column is represented by three soil zones extending downward from the land surface to capture the vertical distribution of soil moisture. The land cover is represented by multiple vegetation types.

Rainfall, snow, infiltration, evapotranspiration, runoff, soil moisture, and baseflow are computed over each grid cell on a daily basis for the entire period of simulation (Figure 17). The VIC routing tool then processes the individual cell runoff and baseflow terms and routes the flow to develop streamflow at various locations in the watershed.

Although the VIC model contains several sub-grid mechanisms, the coarse-grid scale should be noted when considering results and analysis of local-scale phenomenon. The VIC model is currently best applied for the regional scale hydrologic analyses. The model is reasonable for capturing flow changes at the larger watersheds in the Basin, but may have bias at smaller scales primarily due to the model resolution.

5.1.1 VIC Model Watershed Delineation and Routing Network

A streamflow routing network in the VIC model at 1/16th degree (~6 km) (~3.75 miles) was developed using ArcMap's hydrologic tools Flow Direction and Flow Accumulation. The Flow Direction tool first assigns the flow direction for each VIC grid cell to its steepest downslope neighbor. Prior to processing the VIC grid through this tool, a stream network shapefile was burned into the DEM to enhance the performance of the flow direction tool by increasing the slope towards the closest stream. VIC also requires that flow from each grid cell be directed out of the cell and into another one and is unable to process sinks. Sinks in the DEM were filled to accommodate this. The Flow Accumulation tool then creates a raster dataset of accumulated flow to each cell by accumulating the number of all upstream cells that flow into each downslope cell. Results from this process for the VIC grid are shown in Figure 19.

Once the VIC grid is processed through these two tools, watershed delineations were determined based on downstream U.S. Geological Survey (USGS) gage locations, and were compared to USGS watershed boundaries. Due to the topographic complexity of the high elevation regions and the coarseness of the VIC model grid, some adjustments were made to the model watershed delineations to more accurately align with USGS watershed boundary delineation. Final VIC grid watershed delineations for the 12 upper watersheds are shown in Figure 20.

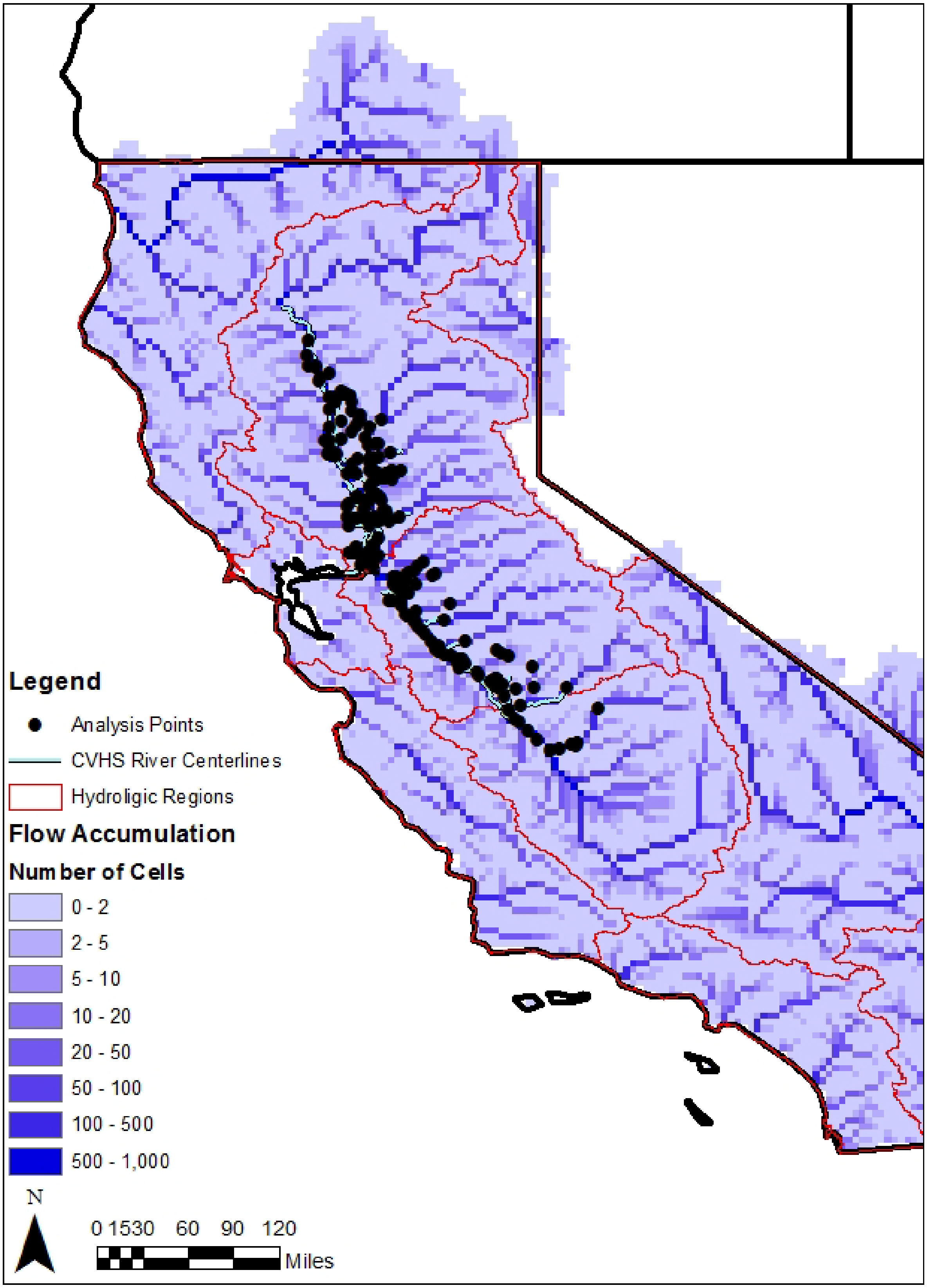


Figure 19. VIC Model Routing Network as Applied for the CVFPP Application

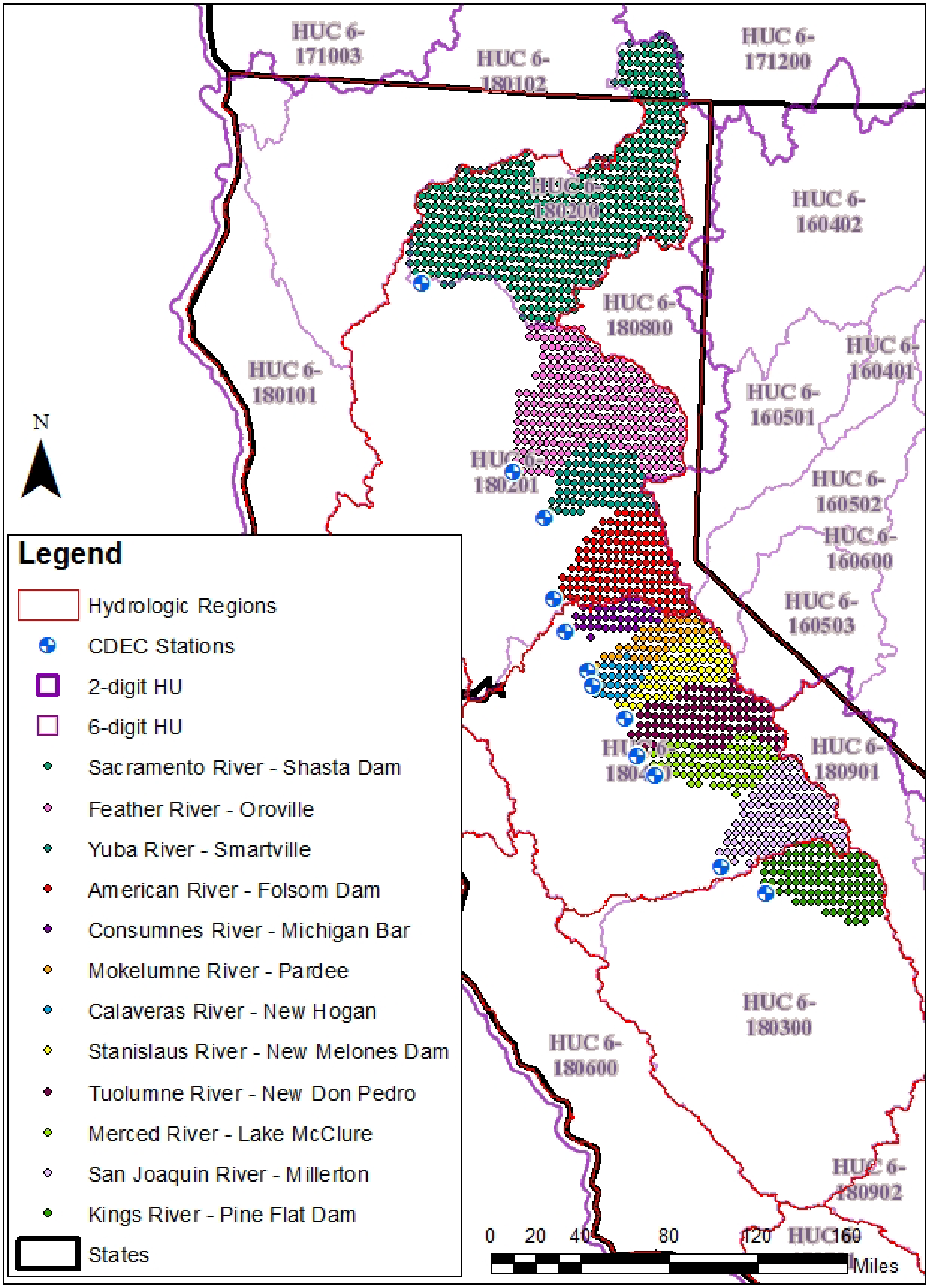


Figure 20. Streamflow Locations used in VIC Model Calibration

5.2 VIC Model Calibration

The existing VIC model had previously undergone only limited calibration for monthly streamflow for selected major river basins over the conterminous U.S. (Livneh et al., 2013). Further VIC model calibration was performed for the CVFPP application by CH2M HILL for the 12 upper watershed locations in the Sacramento and San Joaquin River basins (Figure 20). The VIC hydrological model was calibrated for selected historical events in February-March 1986, and December 1996 - January 1997 (Figure 21). The VIC model performance was also evaluated for selected other historical events in November-December 1950 and December 1955 – January 1956, but insufficient precipitation and snow observations limited the assessment for these early periods.

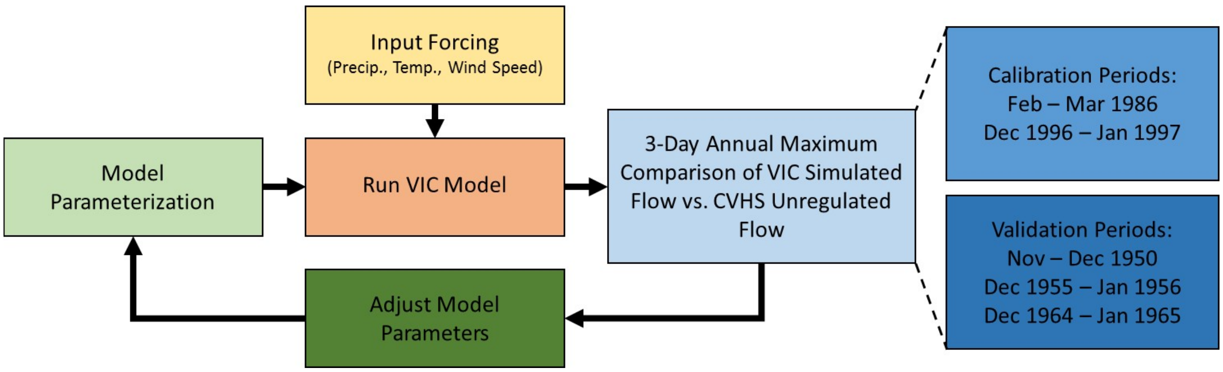


Figure 21. Calibration and Validation Plan Used in VIC Modeling

Daily VIC model simulations were performed for the period of 1915 to 2010. The daily runoff and baseflow simulated from each grid cell was routed to various river flow locations. For the simulations performed for the CVFPP, streamflow was routed to the major CVHS analysis points throughout the Sacramento and San Joaquin River Basins as shown in Table 4. It is important to note that VIC routed flows are considered "naturalized" in that they do not include effects of diversions, imports, storage, or other human management of the water resource.

Table 4. Flow Locations Included in VIC Calibration and Result Summaries

	Flow Locations	California Data Exchange Center (CDEC) Station ID
1	Sacramento River at Shasta Dam	SHA
2	Feather River at Oroville	FTO
3	Yuba River at Smartville	YRS
4	American River at Folsom Dam	AMF
5	Cosumnes River at Michigan Bar	CSN
6	Mokelumne River at Pardee	PAR
7	Calaveras River at New Hogan	NHG

8	Stanislaus River at New Melones Dam	NML
9	Tuolumne River at New Don Pedro	DNP
10	Merced River at Lake McClure	MCR
11	San Joaquin River at Millerton Lake	MIL
12	Kings River – Pine Flat Dam	KGF

VIC model calibration was performed for the 3-day maximum flow volume for the 1986 and 1996/1997 events for the 12 upper watershed locations. Simulated flow volumes were compared with the same period flow volumes computed from CVHS unregulated streamflow data. Model hydrologic parameters describing rates of direct runoff and infiltration, and soil layer depths were adjusted. In addition, daily gridded precipitation data from Livneh et al. (2013) at 1/16th degree (~6 km) (~3.75 miles) was compared to monthly PRISM data (Daly et al., 1994) and station precipitation data. Monthly PRISM data was used to adjust the daily precipitation data for the complete simulation period, but the selected station data was used to adjust the gridded precipitation data for the events used in the CVFPP model calibration and verification.

Figures 22 through 27 show the model simulated flows and observed flows for the 1986 and 1996/1997 events on the Feather River at Oroville, American River at Folsom, and Tuolumne River at New Don Pedro. As shown in the figures, the calibrated VIC model reproduces the 3-day flood hydrograph volumes to within 10 percent of observed volumes at all three locations. Differences in flood volumes are approximately 5-7 percent for the Feather River, approximately 1-5 percent for the American River, and approximately 6-9 percent for the Tuolumne River for these events. The simulated hydrographs generally match the rising and falling limbs that were observed, reflecting good model performance of the watershed response. Most errors appear to be at peak daily discharge and are likely due to inaccuracies of the available observed peak rainfall depths in the station and gridded data used as input in the VIC model. Review of available station data was performed for these two events, but complete re-gridding of daily precipitation fields was not developed.

Figures 23, 25, and 27 show the flow frequency for 3-day annual maximum flows using the entire period of water year 1916 to 2008. These plots demonstrate that the VIC model simulations provide reasonable estimates for a wide range of high flow events as compared to the observed record over the entire historical period.

A summary of the differences between VIC model simulations and historical unregulated flows for all 12 locations for calibration periods is shown in Figure 29. Simulated flood volumes at nearly all locations are less than 10 percent, and many are within 5 percent of observed flood volumes. Directional changes in the simulated versus observed differences at Mokelumne and Mercer Rivers appears to be due to inaccuracies in the extreme precipitation observations and gridded data sets for the 1986 event. The VIC simulated flows were within 5 percent for watersheds such as the American River with robust station and gridded precipitation data sets. The refined and re-calibrated VIC model was found to be sufficient for approximating the watershed responses due to precipitation change and warming conditions in the Central Valley. It should be noted that the VIC model simulates complex hydrologic processes with relatively few model inputs (temperature, precipitation, and wind speed) and performs remarkably well for regional evaluations. The VIC modeling was performed using continuous simulations from 1915 to 2010 and there are no event-specific adjustments to the parameters sets. This continuous hydrological model simulation approach permits the most accurate measure for evaluating hydrologic response to changed conditions over a wide range of conditions as compared to multiple event-specific simulations.

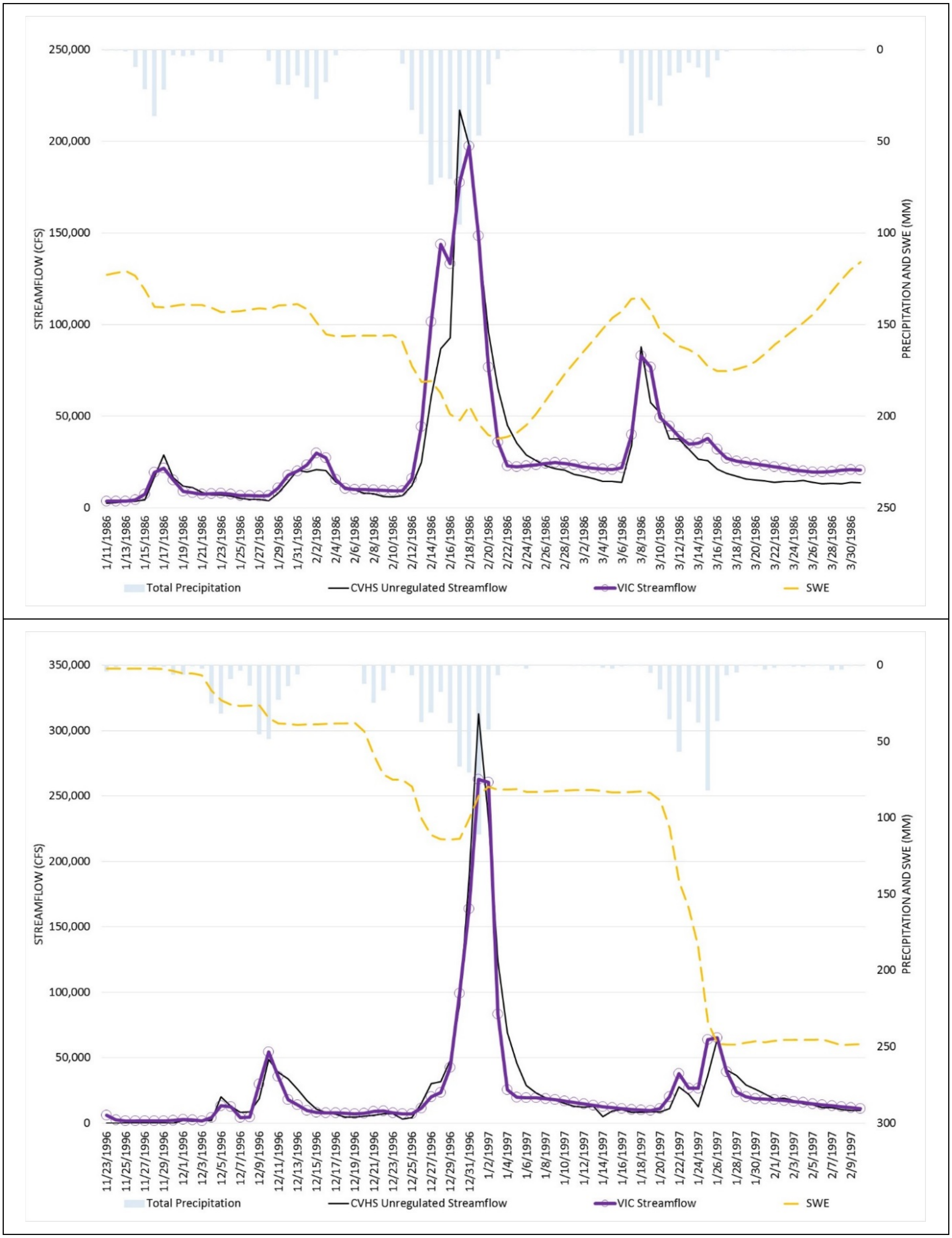


Figure 22. Simulated and CVHS Unregulated Streamflow Hydrograph for Feather River at Oroville in 1986 (top) and 1996/1997 (bottom) Flood Events

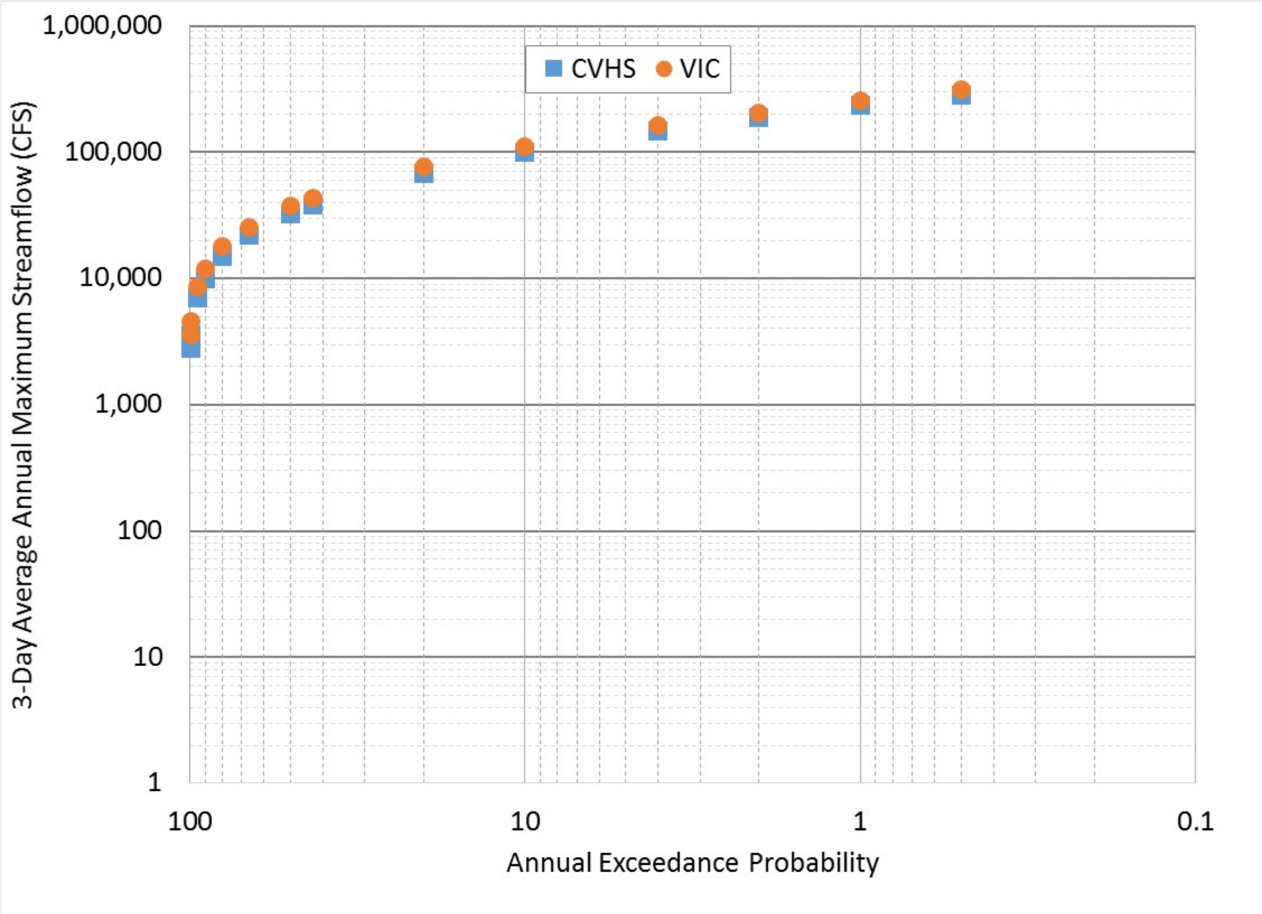


Figure 23. Flood Flow Frequency Plots at Feather River at Oroville

The Bulletin 17B flood flow frequency plot from 3-days annual maximum of CVHS unregulated streamflows and VIC hydrological model simulated streamflows at Feather River at Oroville.

Notes:
Annual 3-day average maximum flows were computed for each water year over the period 1916 through 2008. The annual 3-day average maximum flows were computed based on the pre-determined time window for each water year in which rain-flood events occurred. The time windows for the water years are identical with the time windows used in the CVHS unregulated rain-flood frequency curves development. Log Pearson Type 3 distribution was fitted to the annual maximum unregulated streamflows using the Bulletin 17B (B17B) method in the USGS's PeakFQ software. B17B method employs the Method of Moments (MOM) with Grubbs-Beck (GB) outlier test. The skew-coefficient was computed from the annual maximum streamflows for the flow location.

Figure 24. Simulated and CVHS Unregulated Streamflow Hydrograph for American River at Folsom in 1986 (top) and 1996/1997 (bottom) Flood Events

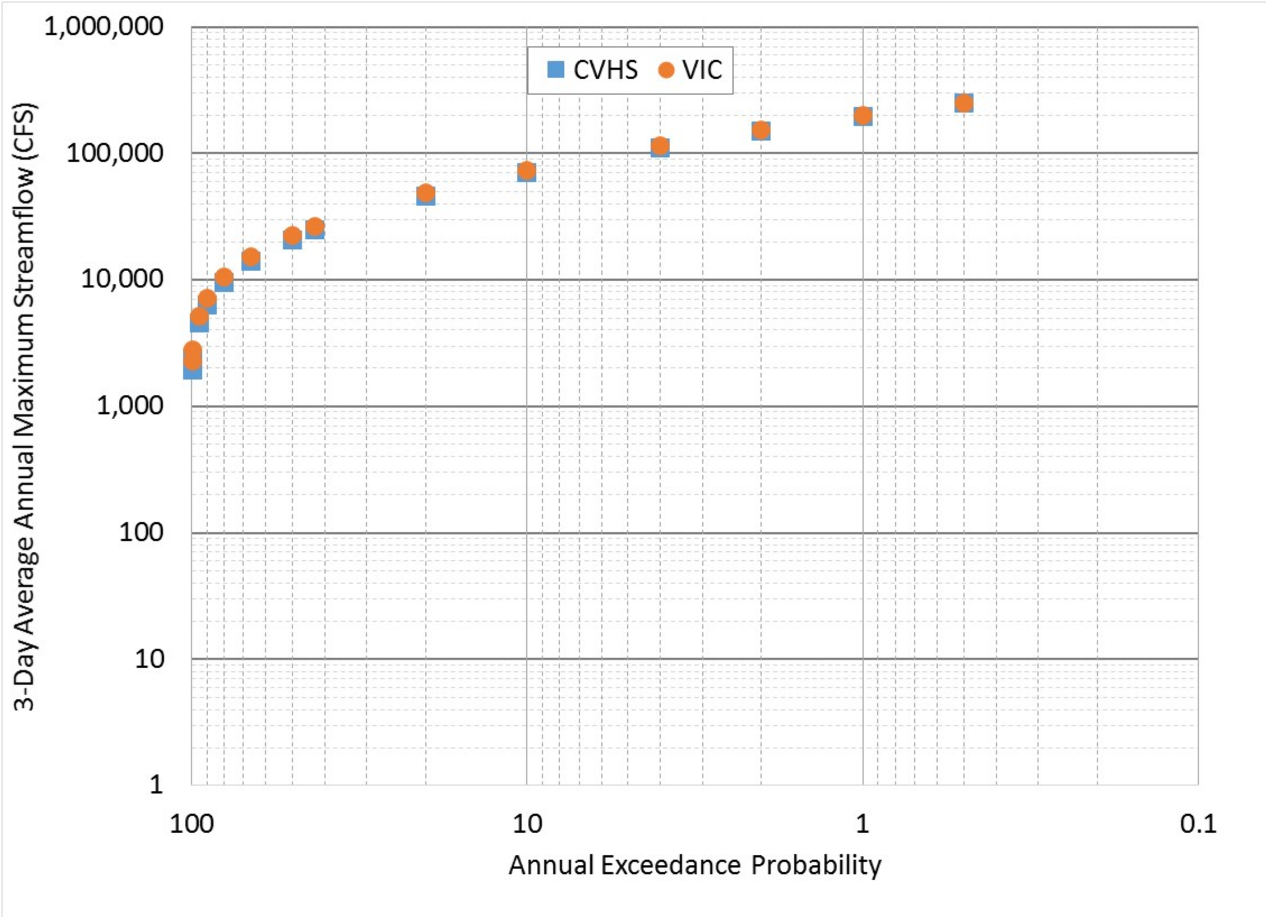


Figure 25. Flood Flow Frequency Plots at American River at Folsom Dam

The Bulletin 17B flood flow frequency plot from 3-days annual maximum of CVHS unregulated streamflows and VIC hydrological model simulated streamflows at American River at Folsom Dam.

Notes:
Annual 3-day average maximum flows were computed for each water year over the period 1916 through 2008. The annual 3-day average maximum flows were computed based on the pre-determined time window for each water year in which rain-flood events occurred. The time windows for the water years are identical with the time windows used in the CVHS unregulated rain-flood frequency curves development. Log Pearson Type 3 distribution was fitted to the annual maximum unregulated streamflows using the Bulletin 17B (B17B) method in the USGS's PeakFQ software. B17B method employs the Method of Moments (MOM) with Grubbs-Beck (GB) outlier test. The skew-coefficient was computed from the annual maximum streamflows for the flow location.

Figure 26. Simulated and observed hydrograph for Tuolumne River at New Don Pedro in 1986 (top) and 1996/1997 (bottom) Flood Events

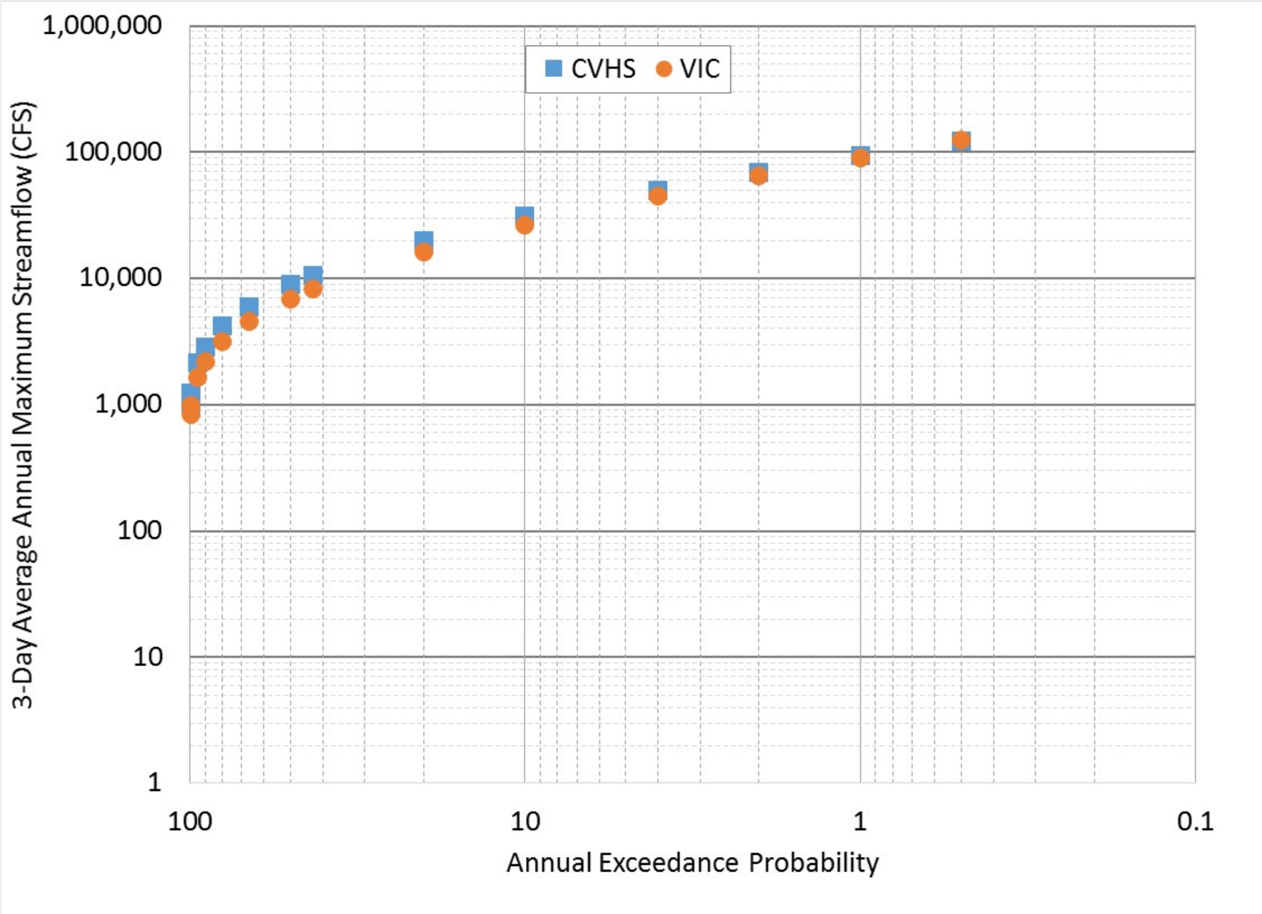


Figure 27. Flood Flow Frequency Plot at Tuolumne River at New Don Pedro

The Bulletin 17B flood flow frequency plot from 3-days annual maximum of CVHS unregulated streamflows and VIC hydrological model simulated streamflows at Tuolumne River at New Don Pedro.

Notes:
Annual 3-day average maximum flows were computed for each water year over the period 1916 through 2008. The annual 3-day average maximum flows were computed based on the pre-determined time window for each water year in which rain-flood events occurred. The time windows for the water years are identical with the time windows used in the CVHS unregulated rain-flood frequency curves development. Log Pearson Type 3 distribution was fitted to the annual maximum unregulated streamflows using the Bulletin 17B (B17B) method in the USGS's PeakFQ software. B17B method employs the Method of Moments (MOM) with Grubbs-Beck (GB) outlier test. The skew-coefficient was computed from the annual maximum streamflows for the flow location.

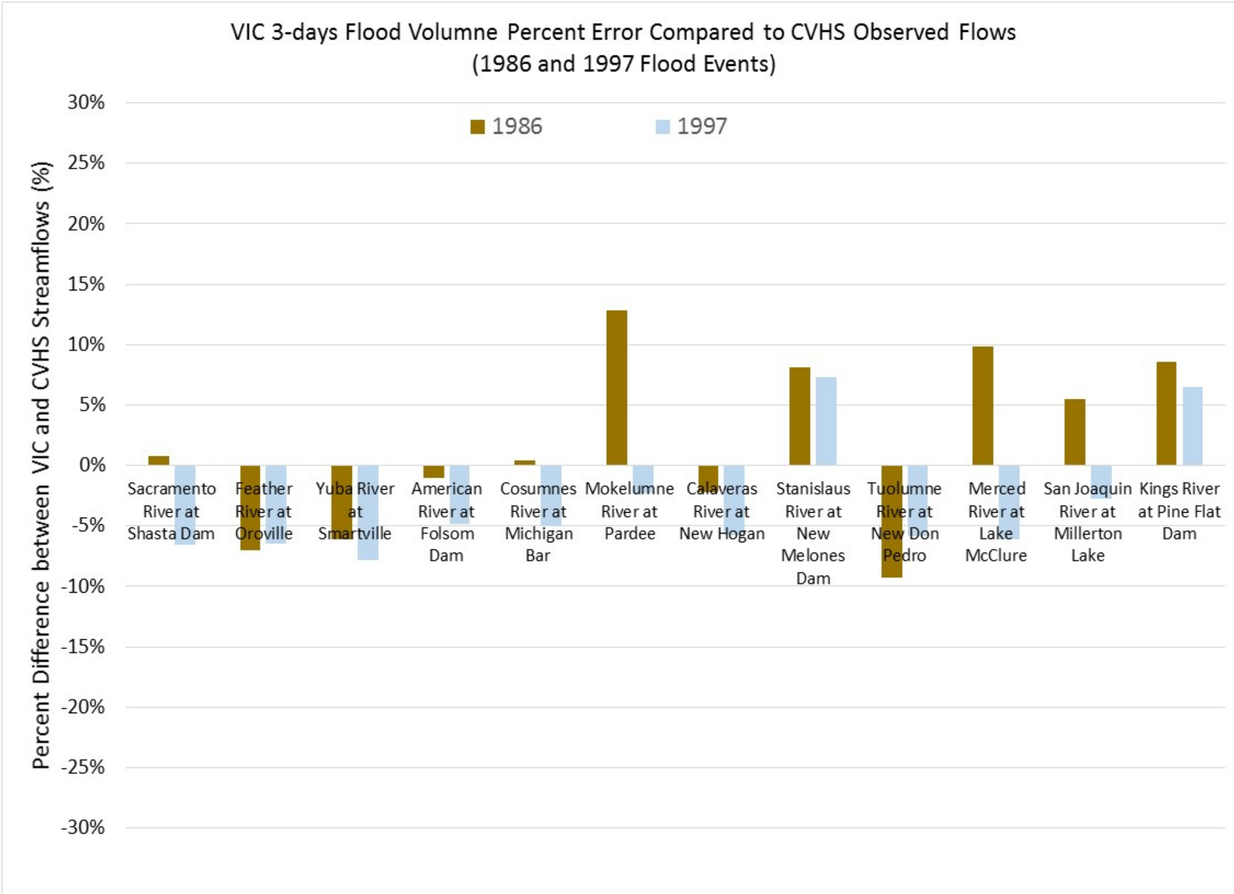


Figure 28. Summary Statistics for the Calibration Events in 1986 and 1996/97 at the Calibration Locations

6.0 Hydrological Modeling Simulations under Climate Change

The refined and re-calibrated VIC model was used to evaluate hydrologic responses under future changes in climate (Figure 29). Two analyses were conducted in this study. First, detailed evaluations of changes in unregulated flow frequency were performed using the ensemble-informed approach to provide scaling factors for use in flood risk evaluations in the CVFPP. Second, an analysis of projected changes in flood hydrograph characteristics using the CCTAG selected projections was developed. The scenarios and results of each are described below.

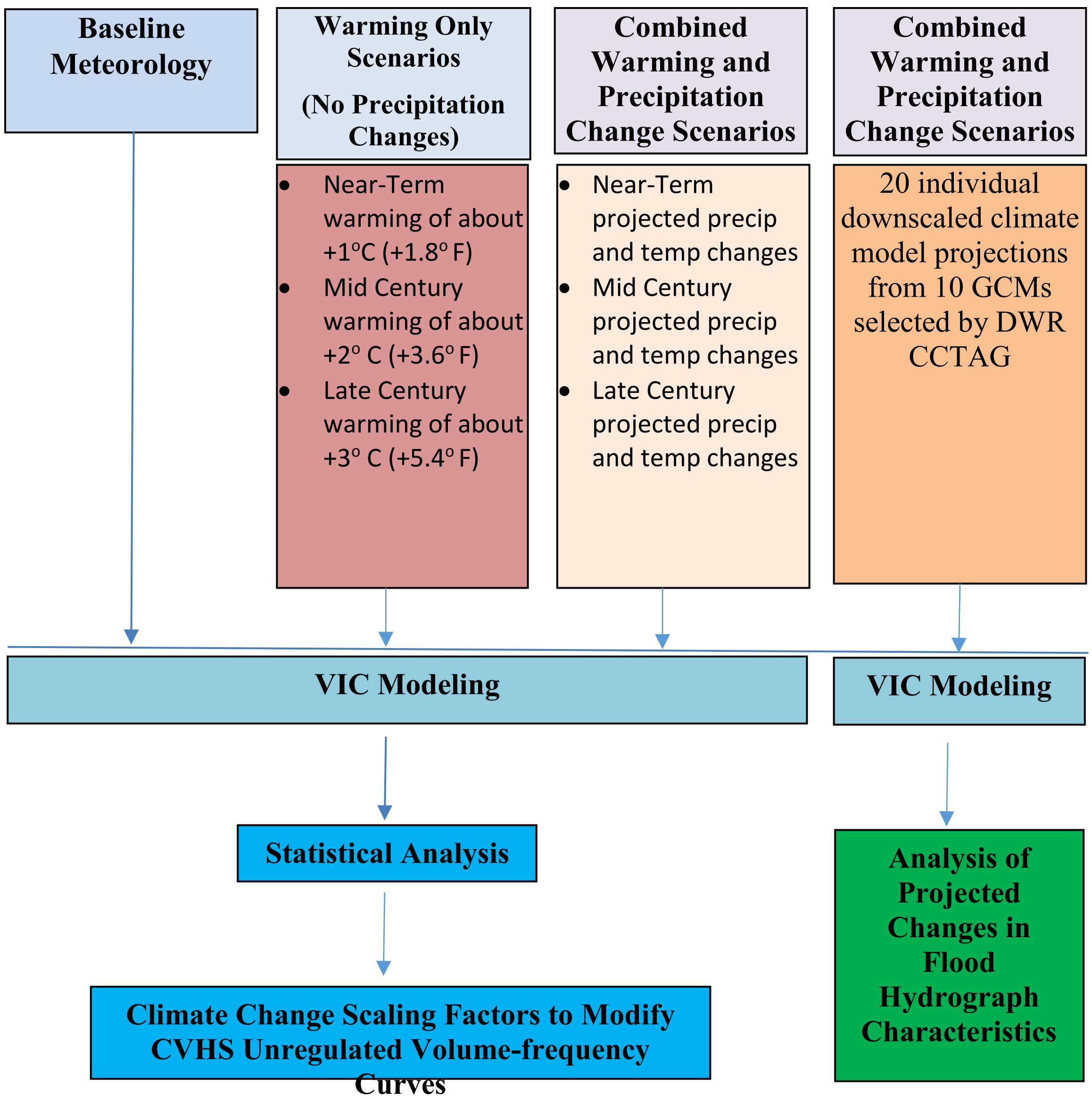


Figure 29. Procedural Schematic for Application of VIC Model for CVFPP Climate Change Analysis Climate Scenarios Used in Hydrologic Analyses

In general, temperature change projections are more robust (and stable) than changes in precipitation. In order to be able to distinguish the effects of precipitation and temperature separately and to characterize changes over time, the following scenarios were developed for use in hydrologic analyses:

1. Warming Only Scenarios (no precipitation changes)
    a. Near-Term Warming: Projected warming of about +1°C (+1.8° F),
    b. Mid Century Warming: Projected warming of about +2° C (+3.6° F), and
    c. Late Century Warming: Projected warming of about +3° C (+5.4° F).
2. Combined Warming and Precipitation Change Scenarios based on CMIP5 Climate Model Simulations:
    a. Near-Term: Projected precipitation and temperature changes,
    b. Mid Century: Projected precipitation and temperature changes, and
    c. Late Century: Projected precipitation and temperature changes.

As described previously, near-term reflect changes over the period 2011 through 2040, mid-century over the period 2041 through 2070, and late century over the period 2070 through 2099. The warming-only scenarios apply the temperature warming uniformly for all grid cells, while the combined warming and precipitation change scenarios apply changes as spatially projected through downscaled climate modeling. The median estimates of projected climate change under the ensemble-informed were used in this study to reflect the combined future projected warming and precipitation changes.

6.1 Computation of Flood Frequency Statistics

Daily hydrologic modeling was performed for the period of 1915 through 2010 with both historical meteorology and an adjusted meteorology reflecting future climate projections. Flows were routed to various river locations and changes between the climate scenario and historical reference period flows were computed as a percentage change. For each year of the historical reference period and the future climate scenario, the maximum 1-day, 3-day, 7-day, and 15-day unregulated flows were calculated for routed flows at specific flow locations. Log Pearson Type 3 fitting was then developed based on the Bulletin 17B (B17B) method in the USGS's PeakFQ software from the maximum 1-, 3-, 7-, and 15-day durations for each year with and without climate change. The percentage change in flow was next recorded for the specific frequency such as the 200-, 100-, 50-, 25-, 10-, and 2-year flows from comparison of the two frequency curves.

The statistical analysis procedure includes the following 8 main steps as described below and shown in Figure 30:

1. Configure the VIC hydrologic model at 1/16th degree (~6 km) (~3.75 mile) spatial resolution
2. Apply the calibrated VIC hydrologic model with historical daily precipitation and maximum and minimum daily temperatures to produce daily runoff and baseflow for the period of 1915 through 2010, representing the reference hydrologic condition. Routed streamflows were developed for over 150 specific analysis points across California's Central Valley.

3. Compute annual maximum streamflows for 1-, 3-, 7-, and 15-day durations for each year over the period October 1 through 31 May from historical VIC simulations.

4. Fit the Log Pearson Type 3 distributions to the annual maximum unregulated streamflows from the historical VIC simulation for various durations using the Bulletin 17B (B17B) method in the USGS's PeakFQ software. B17B method employs the Method of Moments (MOM) with Grubbs-Beck (GB) outlier test. The skew-coefficient was computed from the annual maximum streamflows for each flow location for various durations.

5. Apply the VIC model using modified precipitation and temperatures to produce daily runoff and baseflow under scenarios of future climate change. Precipitation and maximum and minimum temperatures were modified to represent future climate change. Routed streamflows were developed for over 150 specific analysis points.

6. Compute annual maximum streamflows for 1-, 3-, 7-, and 15-day durations from VIC simulation under climate change for each year over the period October 1 through 31 May.

7. Fit a Log Pearson Type 3 distribution to the annual maximum unregulated streamflows from VIC simulation under climate change for various durations using the B17B method in the USGS's PeakFQ software. The skew-coefficient was computed from the annual maximum streamflows for each flow location for various durations.

8. Compute unregulated volume-frequency scaling factors by comparing frequency curves with and without climate change at over 150 specific analysis points for various durations.

For both Sacramento and San Joaquin River basins, the annual maximum streamflows for 1-, 3-, 7-, and 15-day durations for each year were computed over the period October 1 through May 31 from VIC simulations under historical and future climate change conditions. This period was used to accommodate streamflows primarily due to rain flood.

For both Sacramento and San Joaquin River basins, the Method of Moments (MOM) with Grubbs-Beck (GB) outlier test as implemented in the USGS's PeakFQ software were used. The selection of this method was based on the finding of significant inconsistencies in the changes in flood flow frequency curves for different watersheds in the Sacramento River basin when the modified MOM and outlier test was utilized. These inconsistencies were due to significant different total number of outliers from historical simulation and adjusted future climate change simulations. The skew-coefficient was computed from the simulated annual maximum streamflows for each flow location for various durations.

The skew-coefficient was computed from the annual maximum streamflows for both historical and climate conditions instead of using regional skew coefficients available from USGS study (Lamontagne et al., 2012). This was done due to the concern about the applicability of the regional skew coefficients computed from historical conditions, but then also applying to climate change conditions.

The unregulated volume-frequency scaling factors were computed based on the B17B estimate. Separate scaling factors were not produced based on the lower and upper confidence intervals of the B17B estimate.

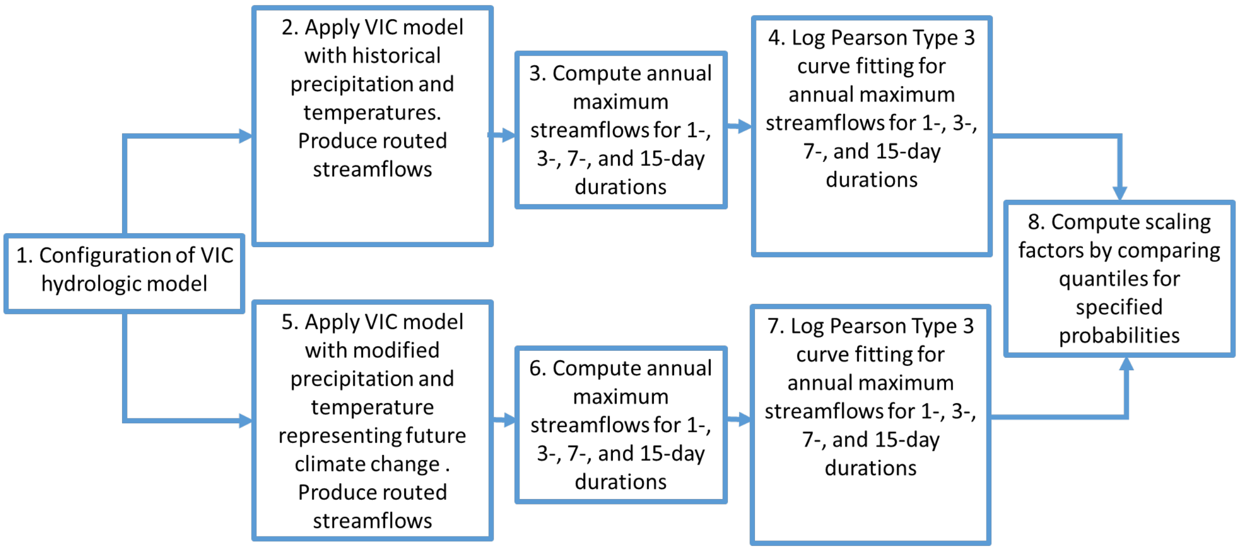


Figure 30. General analysis workflow for incorporation of climate change information into scaling factors to modify CVHS unregulated volume-frequency curves.

6.2 Flood Frequency Change Results

Figure 31 through Figure 36 show the changes in 3-day unregulated annual maximum flow for 12 locations on the major rivers in the Sacramento River and San Joaquin River basins. Graphs are shown separately for 6 frequencies of occurrence (200-, 100-, 50-, 25, 10-, and 2-year) . The figures are organized with watersheds ordered from north to south, and depict the effect of the warming-only scenarios and the combined warming and precipitation change scenarios (labeled as 2011-2040, 2041-2070, and 2070-2099).

As can be seen in the figures, the effect of warming-only is relatively small (less than 10 percent change) for watersheds in the Sacramento River Basin. This result is due to the relative low elevation of the major contributing areas of these watersheds. Warm storms that produced rainfall up to the top of the watershed have already occurred in these watersheds and are included in the historical flow records. The additional warming included in the climate scenarios did not substantially alter the rain-snow fractions or the hydrologic response. However, in the San Joaquin River Basin, the effect of warming is considerable. For example, projections suggest that the 100-year flood flows may be 40 to 50 percent greater than those experienced in the observed record in the high elevation watersheds due to warming alone. The warming in these watersheds allows more watershed area to experience rain and to contribute to more rapid melt of snow that was present. Both of these factors contribute to the substantially larger impact of warming on flood flows.

When considering the combined effect of temperature changes and precipitation changes, every major watershed demonstrates a response with greater flood flows. Even in the southernmost watersheds where annual reductions in precipitation are projected, the extreme precipitation is projected to increase and flood flows are correspondingly increased. Sacramento River Basin watersheds are projected to exhibit increased 100-year flood flows on the order of 10 percent to 30 percent by late century due precipitation and temperature changes. San Joaquin River Basin watersheds demonstrate an even larger response due to the combine effect of temperature and precipitation changes and low frequency floods are projected to be on the order of 60 to 70 percent larger than the historical reference.

Figures 37 through 39 show the asymmetrical climate response of watersheds for various return periods. In the Sacramento River Basin, the largest percentage change in flood magnitudes occurs with the 10-year return interval and the smallest percentage change occurs with the 200-year return interval. This counterintuitive response is due to the nature of the watershed characteristics and historical storm behavior. In the Sacramento River Basin, rain has been experienced to the top of watershed (above 7,000 or 8,000 feet) during specific storms but this is relatively unusual. More commonly, storms bring a mixture of snow and rain. Thus, the greatest changes are during those conditions where historically the storms were snow-dominated or of mixed snow-rain regime. The Cosumnes and Calaveras Rivers demonstrate a hydrologic response that is consistent with their relative low elevation and rainfall dominance for flood events.

Conversely, in the high elevation San Joaquin River Basin, most watersheds are dominated by snow accumulation and melt, and large storms with rainfall to the top of the watershed (above 10,000 feet) have not been experienced historically. Thus, climate change poses a significantly greater threat to increased flood magnitudes. The hydrologic response due to climate change is symmetrical in this watershed, in that the 100-year percentage change is larger than the 10-year percentage change. However, it should be noted that the increase in flows of more frequent events (such as the 10-year event) has the potential to impact flood risks significantly due to more frequent stress on levees and consequently more frequent erosion and seepage.

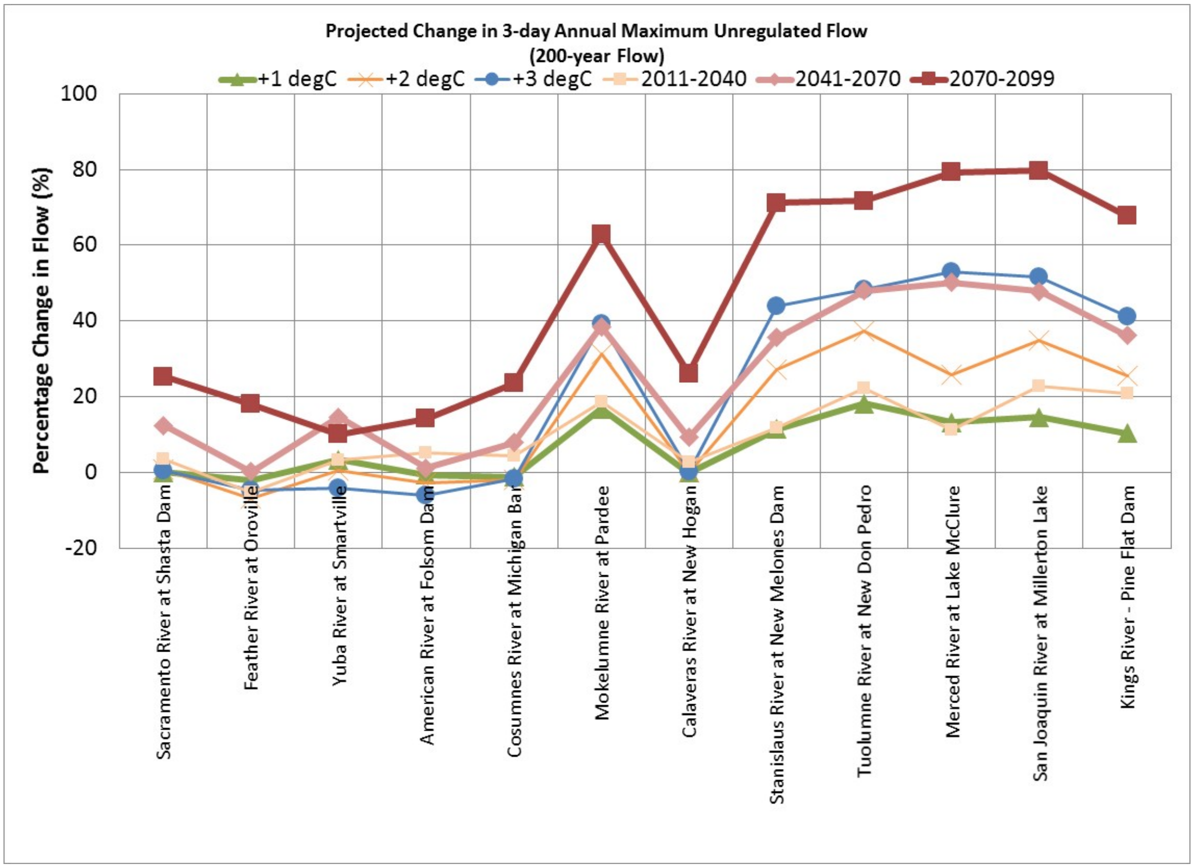


Figure 31. Changes in 200-yr Flood Magnitudes under Different Climate Change Scenarios

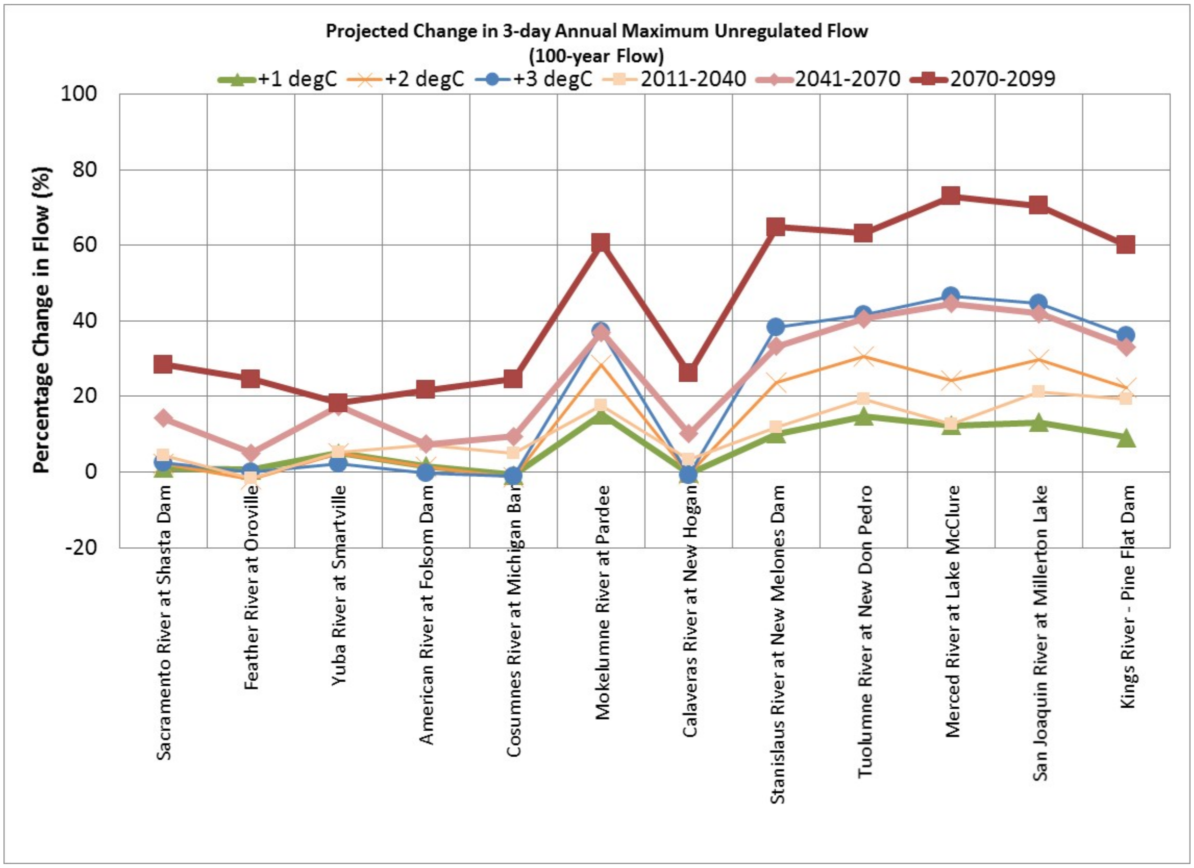


Figure 32. Changes in 100-yr Flood Magnitudes under Different Climate Change Scenarios

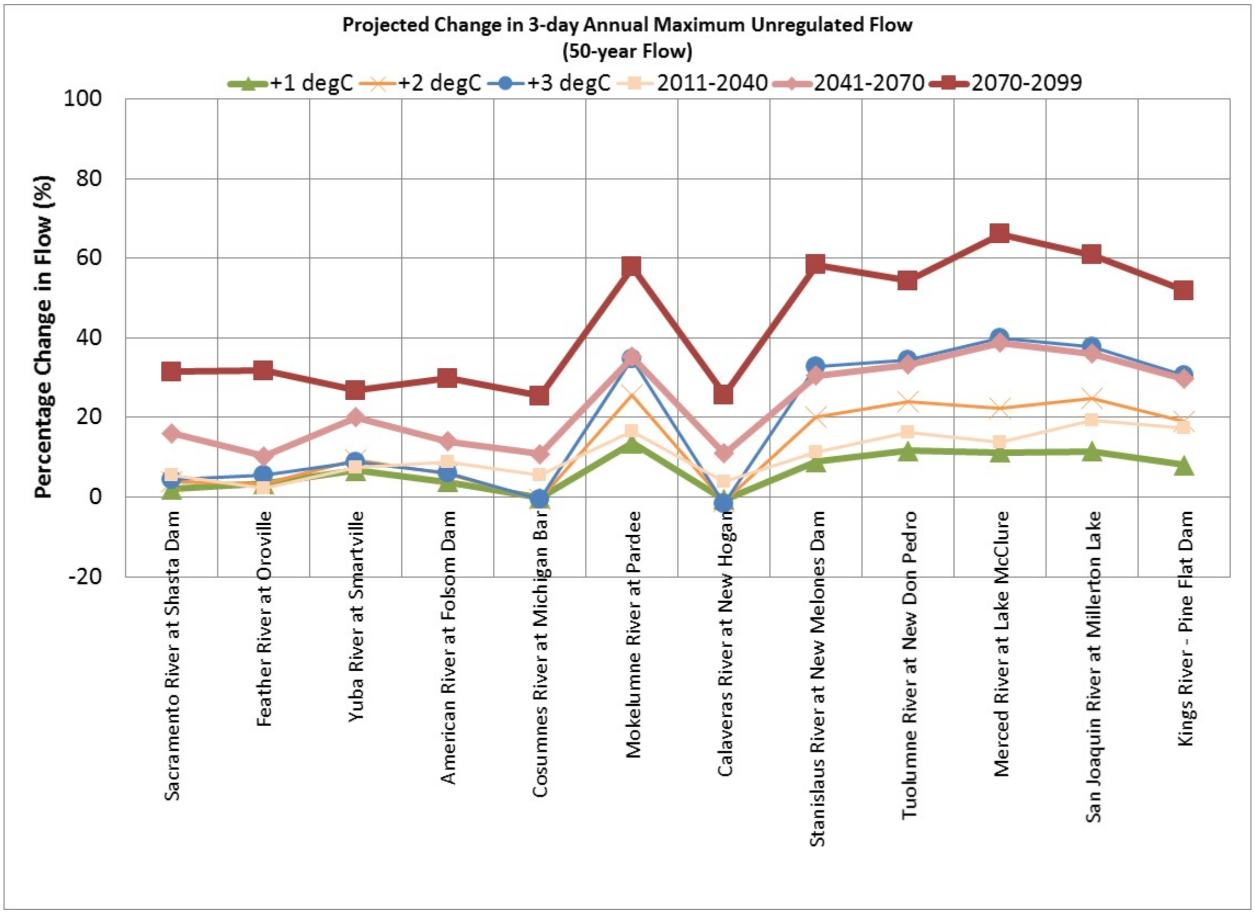


Figure 33. Changes in 50-yr Flood Magnitudes under Different Climate Change Scenarios

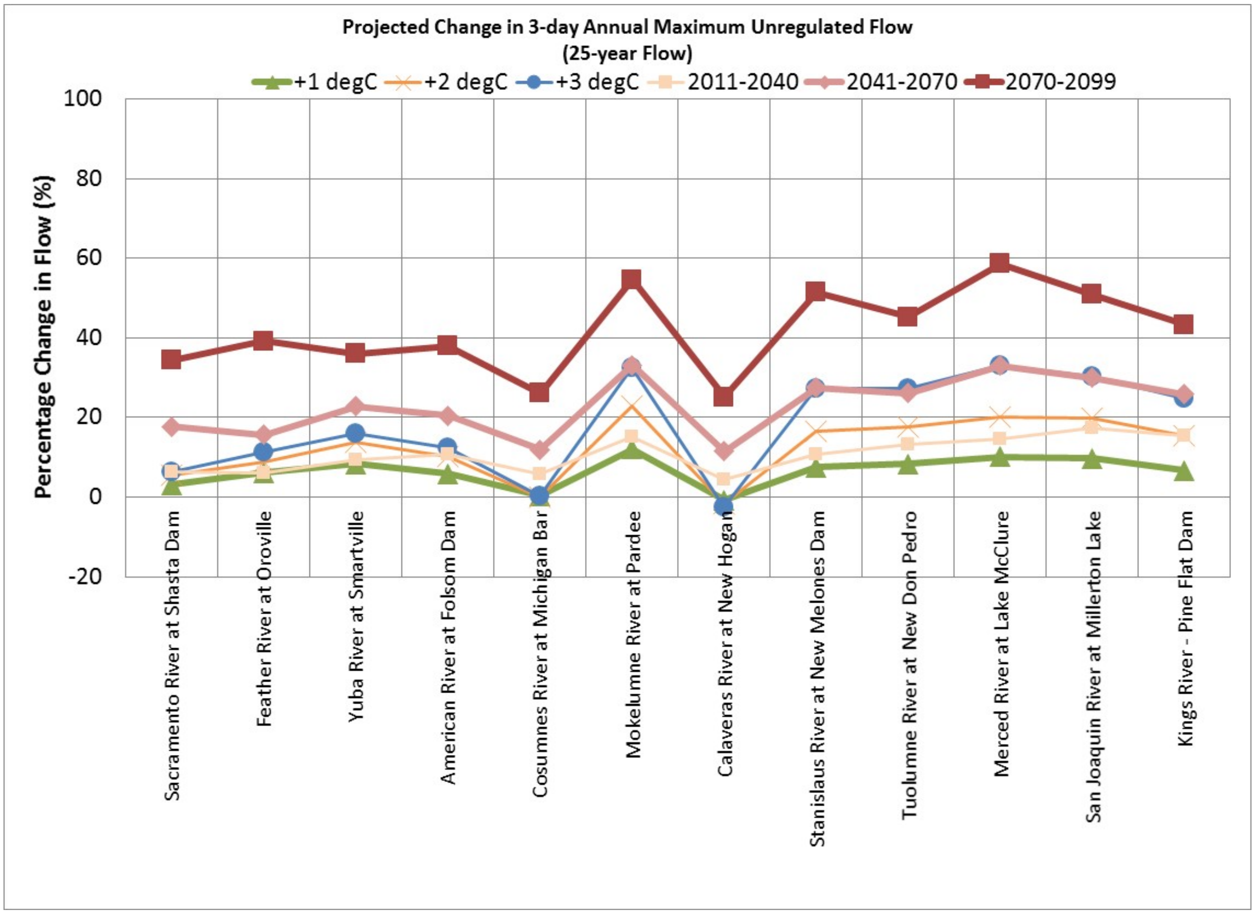


Figure 34. Changes in 25-yr Flood Magnitudes under Different Climate Change Scenarios

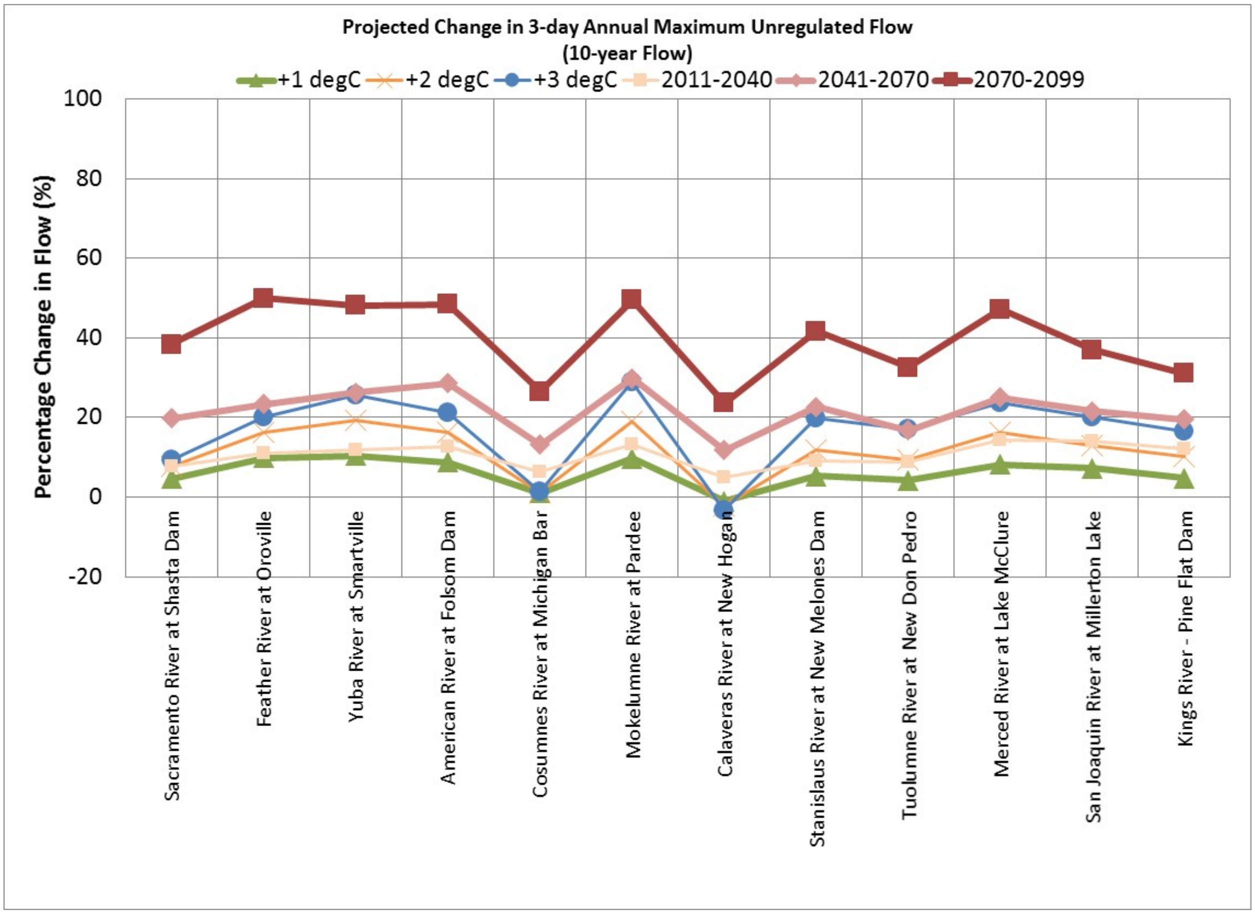


Figure 35. Changes in 10-yr Flood Magnitudes under Different Climate Change Scenarios

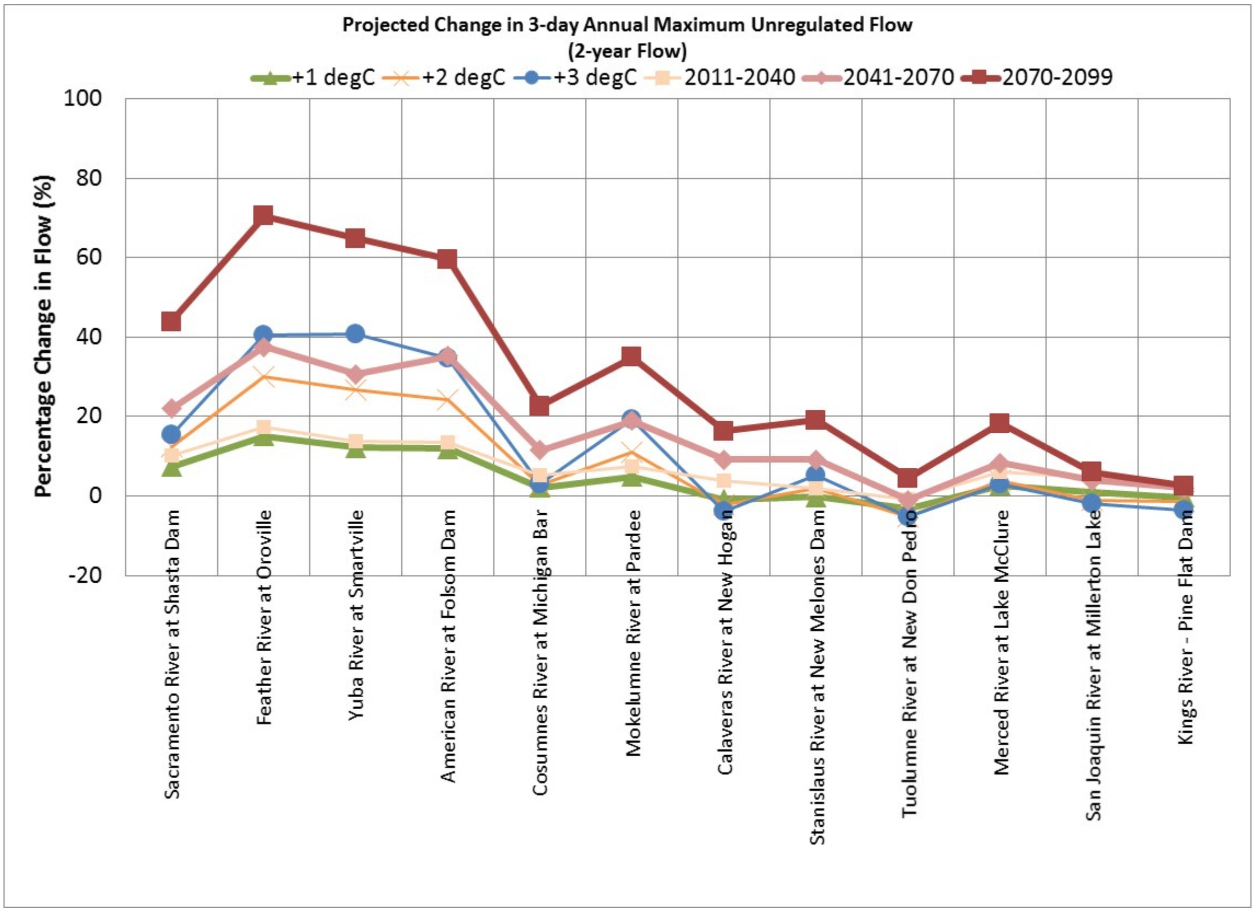


Figure 36. Changes in 2-yr Flood Magnitudes under Different Climate Change Scenarios

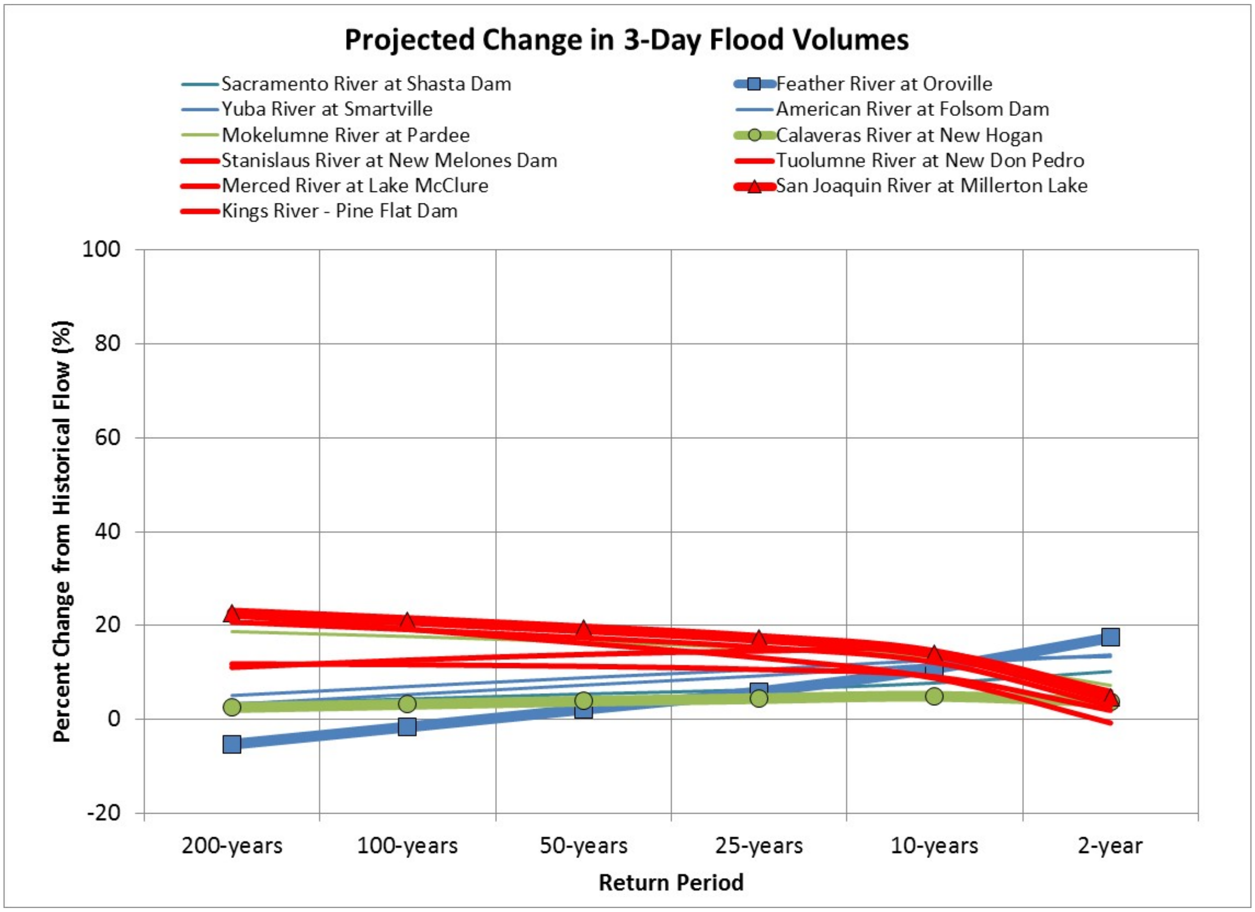


Figure 37. Changes in 3-day Flood Magnitudes with Different Return Periods under the 2011-2040 (2025) Climate Change Scenario

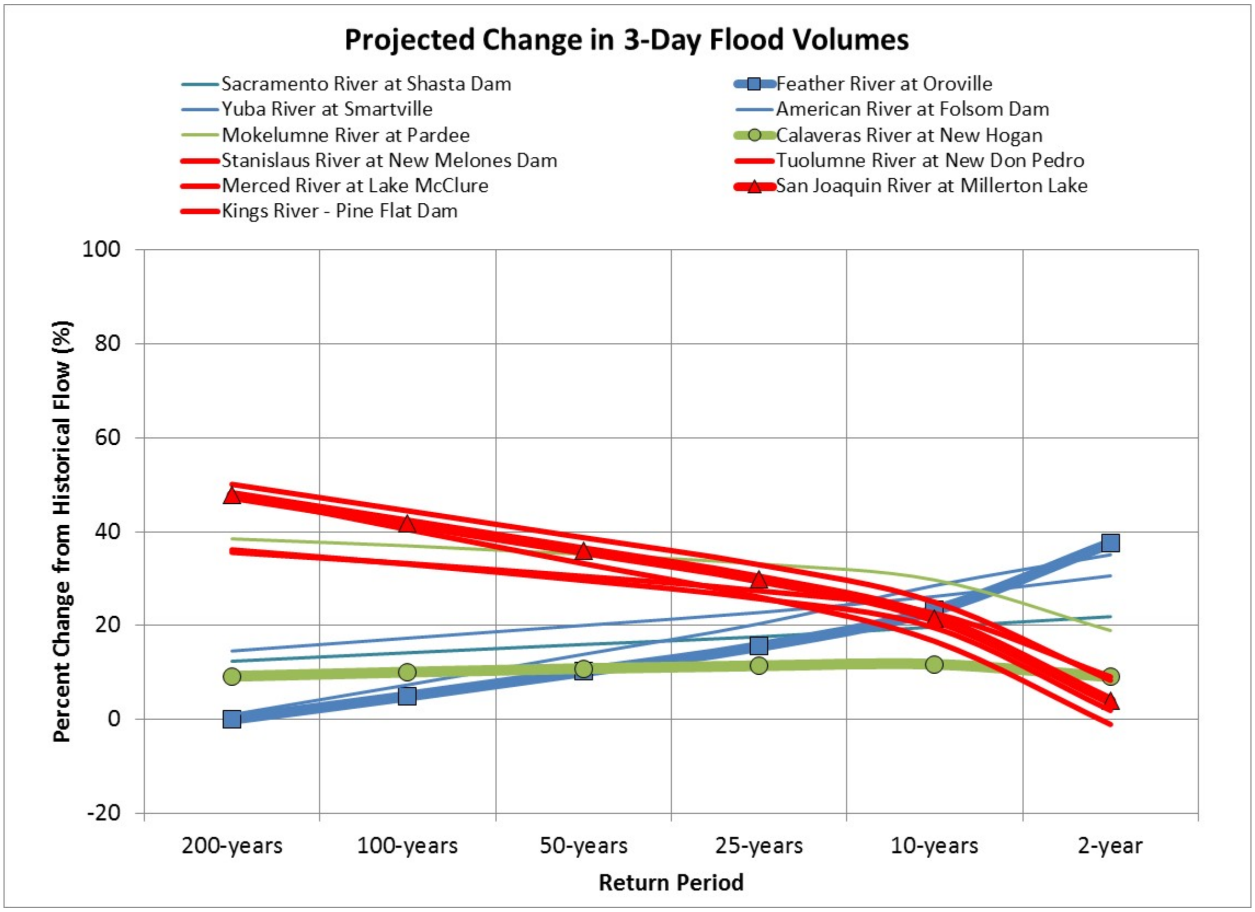


Figure 38. Changes in 3-day Flood Magnitudes with Different Return Periods under the 2041-2070 (2055) Climate Change Scenario

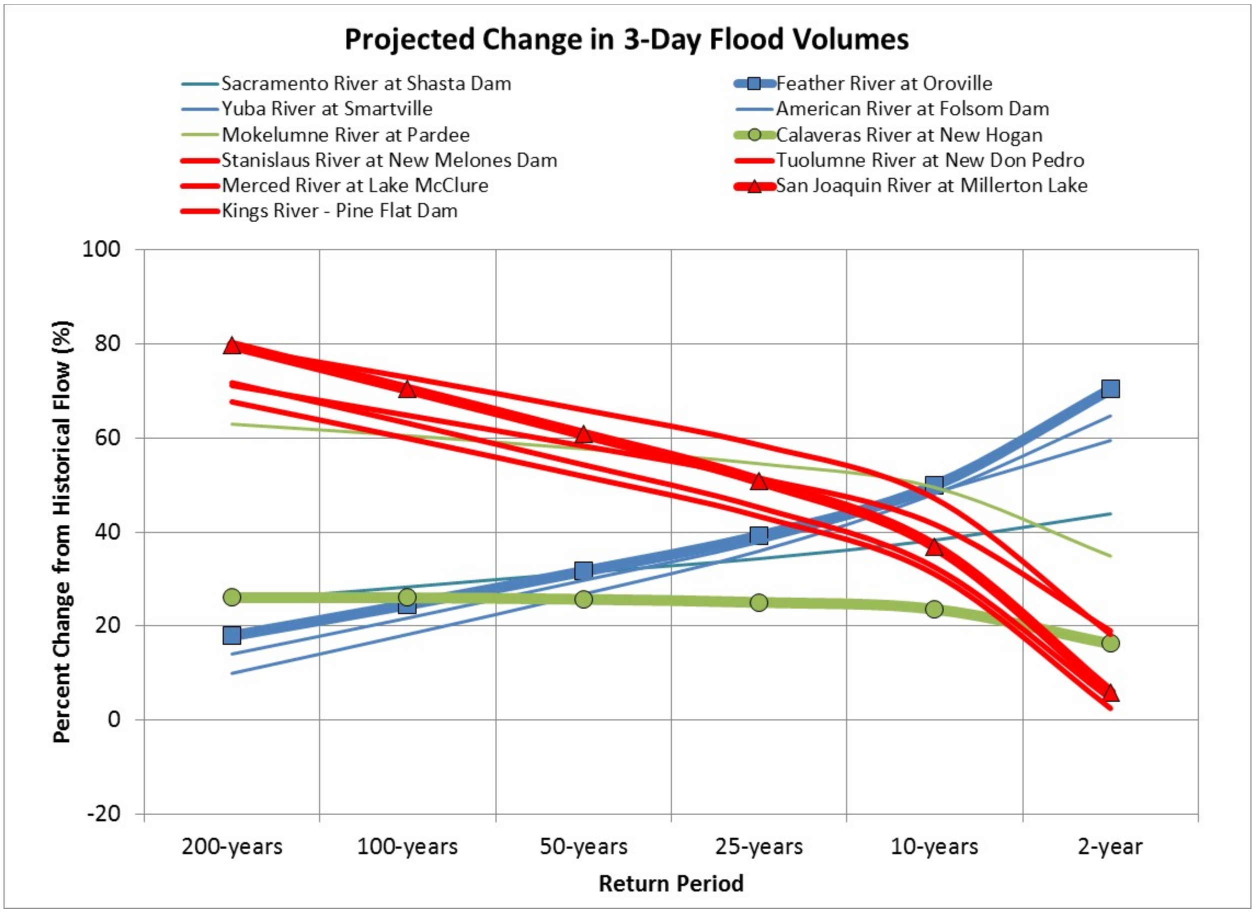


Figure 39. Changes in Flood Magnitudes with Different Return Periods under the 2070-2099 (2085) Climate Change Scenario

Changes in flood volumes at various return periods have been derived for over 150 locations throughout the Central Valley and were used to modify CVHS unregulated volume-frequency curves to incorporate future climate change. Figure 40 shows the changes at these locations for the 10-year and 100-year return periods. Changes computed for these locations have been mapped to more than 200 analysis points to modify the unregulated flow frequency curves that are used in the CVFPP risk assessment. The figure shows the geographic distribution of changes within the Sacramento and San Joaquin River Basins. As previously indicated, the greatest percent increase in unregulated flows is projected to occur in watersheds with substantial area at high elevation in the San Joaquin Valley for the 100-year event. Projected changes are substantially smaller for 10-year return periods, and are similar in both basins.

Appendix C contains the scaling factors for the selected locations for flood durations of 1, 3, 7, and 15 days.

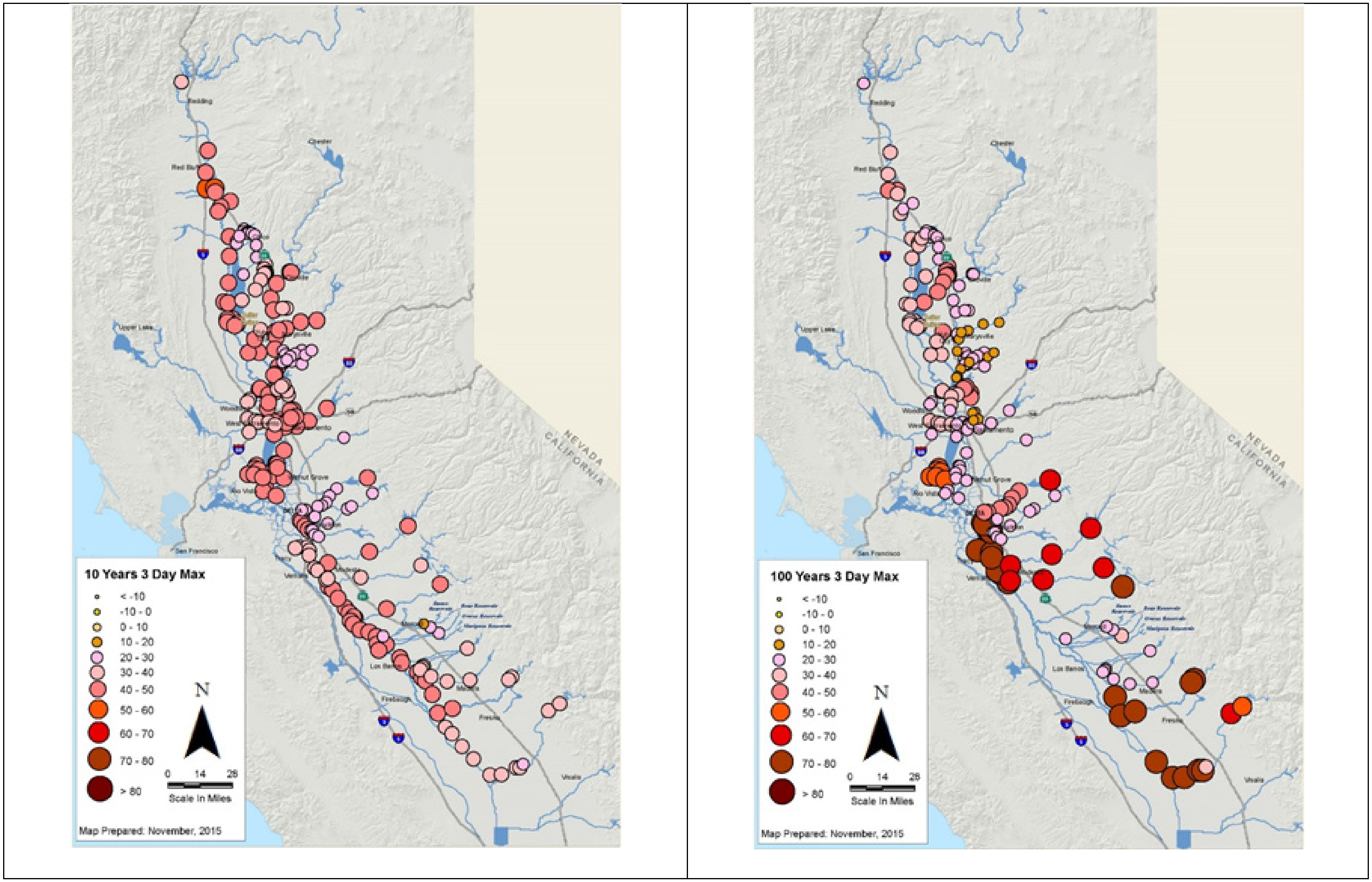


Figure 40. Spatial Patterns of Changes in Flood Magnitudes under the 2070-2099 (2085) Climate Change Scenario in the Central Valley with 10-year Return Period (left) and with 100-year Return Period (right)

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Table 5 compares the 3-day unregulated streamflow scaling factors from Phase IIA and Phase IIB results for key locations over the Central Valley. As shown on the table, the changes in the Phase IIB analysis are generally higher than those from Phase IIA for most of the major watersheds. The differences in the scaling factors for Phase IIA and IIB resulted from multiple factors, including:

- Changes in climate change scenarios from CMIP3 used in the Phase IIA to CMIP5 used in the Phase IIB
- Use of the refined hydrological model (higher resolution and improved watershed delineation)
- Use of a different statistical method to develop flood frequency curves (the Bulletin 17B method in the USGS's PeakFQ software used in the Phase IIB).

The results of the Phase IIB analysis demonstrate a consistent set of results for watersheds of similar location and characteristics. All Sacramento Valley watersheds show increases in the 100-year flow volumes of about 20-30 percent, while high elevation watersheds in the San Joaquin Valley show increases of about 60-70 percent. The total unregulated 100-year flow on the Sacramento River below Sacramento Weir is projected to increase by about 30 percent, while the unregulated flow on the San Joaquin River near Vernalis is projected to increase by about 75 percent.

Some inconsistencies in results identified in the Phase IIA have been resolved in the Phase IIB refinements. The largest differences between the two phases of analyses occurs in the upper San Joaquin River and Kings River due to improved delineation of the high elevation watershed in the Phase IIB. Previous modeling used in Phase IIA had relatively coarse delineations and were not validated with the updated digital elevation model information. Similar improvements can be noted in the Yuba River, Cosumnes River, and Mokelumne River watershed responses.

Table 5. Projected 100-Year, 3-day Unregulated Flow Scaling Factors for 2070-2099 (2085) in Phase IIA and Phase IIB at Key Locations

Location	Scaling Factors (Phase IIB)	Scaling Factors (Phase IIA)	Difference (IIB minus IIA in %)
Sacramento River at Shasta Dam	1.28	1.11	18%
Feather River at Oroville	1.25	1.20	5%
Yuba River at Smartville	1.18	1.07	12%
American River at Folsom Dam	1.22	1.24	-2%
Cosumnes River at Michigan Bar	1.25	1.11	13%
Mokelumne River at Pardee	1.61	1.46	14%
Calaveras River at New Hogan	1.26	1.32	-6%
Stanislaus River at New Melones Dam	1.65	1.72	-7%
Tuolumne River at New Don Pedro	1.63	1.68	-4%
Merced River at Lake McClure	1.73	1.70	3%
San Joaquin River at Millerton Lake	1.70	1.16	54%
Kings River at Pine Flat Dam	1.60	1.23	37%
Sacramento River below Sacramento Weir	1.28	1.15	12%
San Joaquin River near Vernalis	1.76	1.50	26%

6.3 Changes in Hydrograph Characteristics under Climate Change

The Phase IIA and IIB investigations use climate change scaling factors for each AEP at each location to adjust the historical flood frequencies to assess overall climate risk on flood management systems. The changes to the scaled historical events increase the hydrograph volume, but do not change other characteristics of the hydrograph such as duration and spatial correlation that may be impacted under climate change. Additional analysis was prepared to assess changes in the characteristics of future simulated hydrographs. VIC simulations driven by 20 individual daily downscaled climate projections using the LOCA daily downscaling method, made available by Scripps Institution of Oceanography (SIO) and recommended by the DWR CCTAG for use in California water resources analysis, were developed. Results from these analyses were processed to show the changes in annual flood timing, peak 1- and 3-day flood magnitude, and duration.

Figure 41 shows the projected annual time series of 3-day annual maximum streamflow simulated by VIC for the American River and Merced River under each of 20 daily LOCA downscaled climate projections in water years 1951 through 2099. As shown in the figures, there is high variability of year-to-year values for 3-day annual maximum flows. For these projections, the inter-annual variability is not constrained by the historic climate variability, but climate variability results from the representation of physical characteristics of the land surface, ocean and atmospheric processes and initial conditions, RCP emissions scenarios and computational methods used for the individual GCM simulations. However, the magnitude of the events has more high values later in the 21st century than in the model simulated historical period. The 90th percentile computed from 20 climate projections displays obvious increasing trends in both watersheds.

Figure 42 shows the projected monthly pattern of inflow to the Folsom and Lake McClure reservoirs for the 1981-2010 historical period and 2070-2099 future periods. Each watershed has a unique monthly pattern, reflecting differences in hydroclimate and watershed characteristics. In each watershed, the future climate scenarios exhibit a shift in streamflow to the earlier months. This projected shift occurs because higher temperatures during winter and spring cause earlier snowmelt runoff and more changes in precipitation from snow to rain.

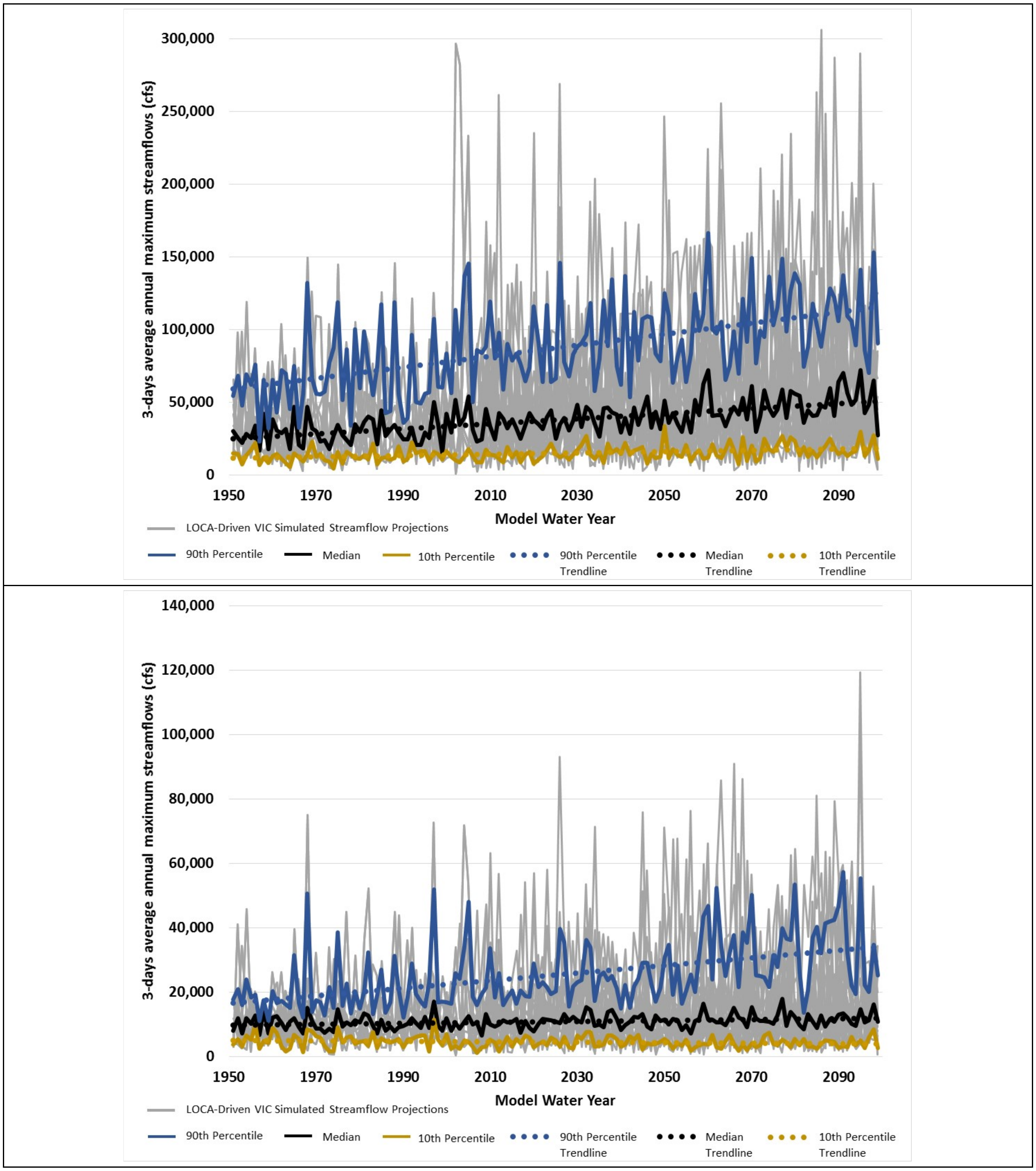
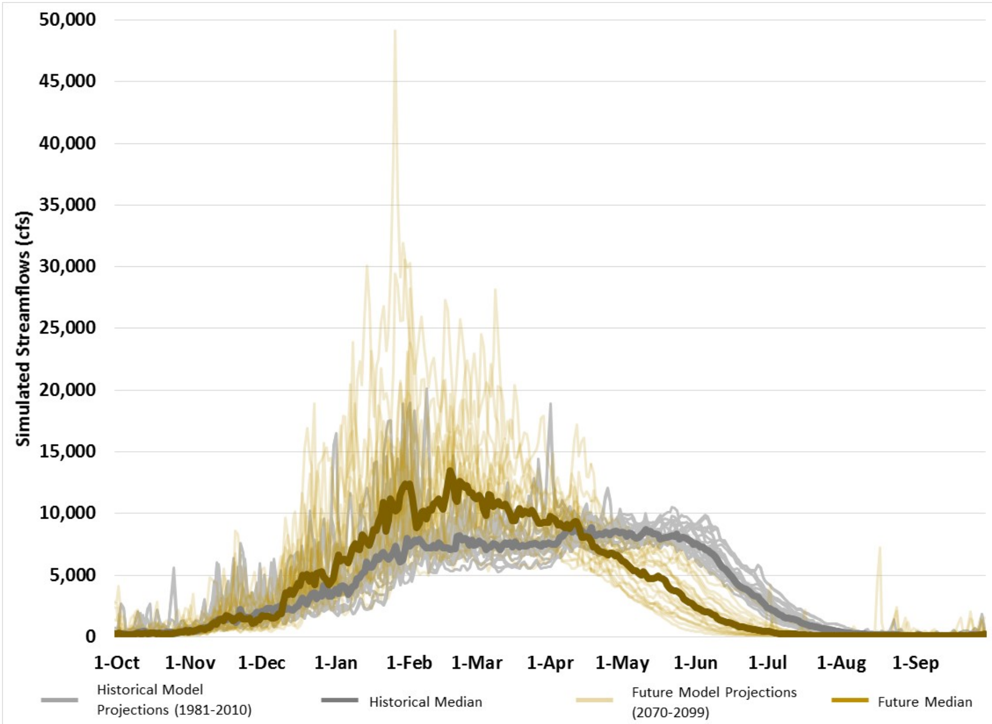


Figure 41. Annual Time Series of VIC Simulated 3-day Average Annual Maximum Streamflow into American River at Folsom (top) and Merced River at Lake McClure (bottom) for each DWR CCTAG Selected Climate Model Projection

Notes:
The annual time series are derived using 20 VIC simulations as driven by 20 LOCA daily downscaled climate model projections simulated under RCP emission scenarios RCP8.5 and RCP4.5 from 10 CMIP5 GCMs selected by DWR CCTAG. GCMs selected by CCTAG: ACCESS-1.0, CCSM4, CESM1-BGC, CMCC-CMS, CNRM-CM5, CanESM2, GFDL-CM3, HadGEM2-CC, HadGEM2-ES, MIROC5. Solid curves represent 10th, 50th, and 90th percentiles computed from the annual time series. Dotted curves represent linear trend lines of the 10th, 50th, and 90th percentiles.



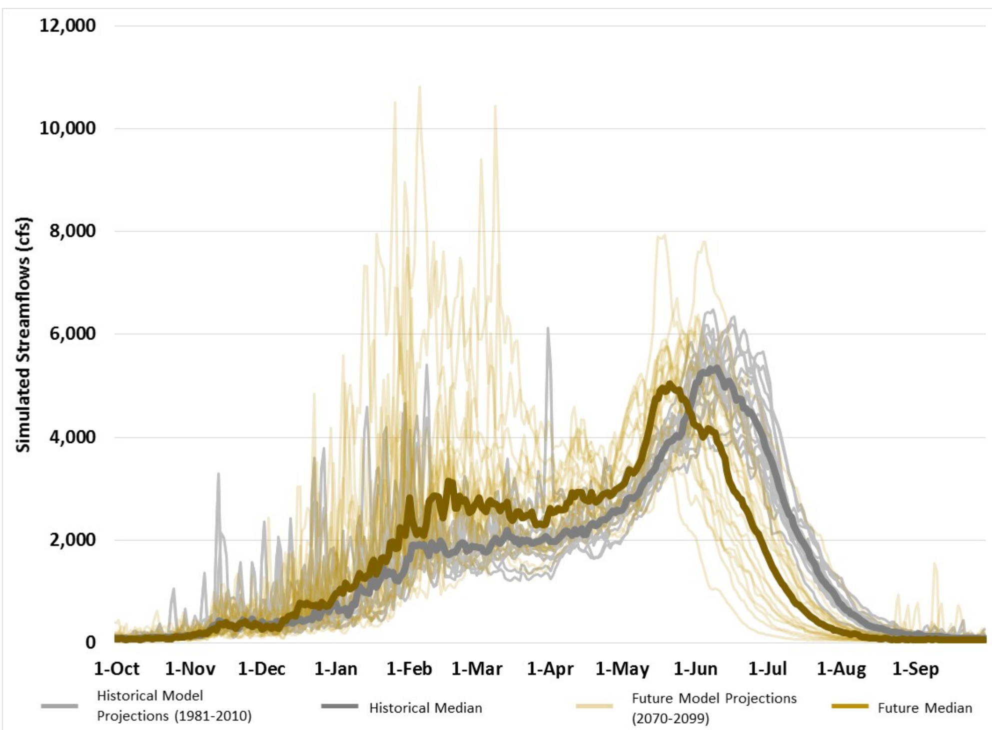


Figure 42. Projected Average Streamflow in Each Month into American River at Folsom (top) and Merced River at Lake McClure (bottom) for Each DWR CCTAG Selected Climate Model Projections for Long-term Average over Water Years 1981-2010 and 2070-2099

From each of the simulations specific parameters were computed to determine changes in hydrograph timing, peak flows, and flood duration. The following steps describe the computations:

1. Compute 1-day annual maximum for each water year over the period 1951-2099

2. Identify the start date center on the 1-day annual maximum when the value first exceeds to 10 percent of the 1-day annual maximum for each water year over the period 1951-2099 (Figure 43)

3. Identify the end date center on the 1-day annual maximum when the value first equals to 10 percent of annual maximum for each water year over the period 1951-2099

4. Compute the flood event duration from the end date and start date computed in 3) and 2)

5. Save the 1-day annual maximum and duration for each water year over the period 1951-2099

6. Identify the date in which 1-day annual maximum flow occur for water year over the period 1951-2099

7. Compute 3-day average annual maximum for each water year over the period 1951-2099

8. Compute period average of annual values of 1-day annual maximum, date of annual peak flow, flood duration, and 3-day average annual maximum for four periods over 1981-2010, 2011-2040, 2041-2070, and 2070-2099

The results of this analysis are presented in the Tables 6 through 8 and are based on VIC simulations using 20 individual daily downscaled climate projections from the LOCA downscaling method. The change in date of peak flow, magnitudes of 1-day and 3-day annual maximum flows, and duration of flood is shown using all years and for a subset of only the upper tercile of flows. Several important observations can be made from these results:

- **Peak flows are projected to occur significantly earlier in the year (on the order of 2-4 weeks by late century) in the San Joaquin watersheds.** This result is likely due to the reduction in precipitation falling as snow, and a greater portion of the watershed contributing to direct runoff. Peak flows may occur later in the year in the Sacramento watersheds, but the trend is weaker except at late century.

- **Maximum annual 1-day and 3-day flows are projected to increase for all watersheds evaluated.** This observation suggests that the increases in flood flows may be robust for durations up to 5-7 days.

- **Storm durations are projected to decrease in all major watersheds.** The signal of shorter duration, but more intense floods is strongest in the San Joaquin, but is also observed for most Sacramento watersheds.

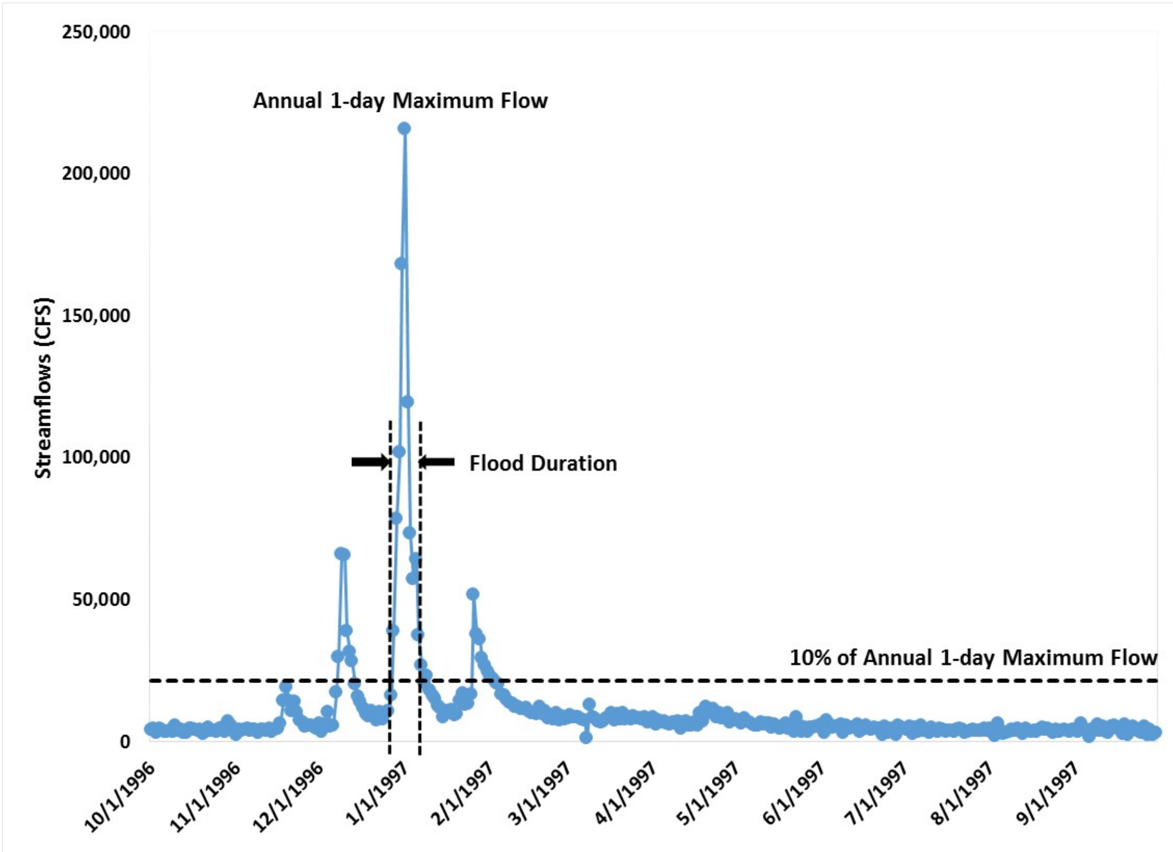


Figure 43. Example Plot for Showing Parameters Used to Describe Hydrograph Shape

The overall observation is that future flood events will likely be significantly more intense (peak increases), and shorter in duration. These more intense floods will likely occur up to a month earlier in the San Joaquin watersheds, and may be up to a couple of weeks later in the Sacramento watersheds. These changes in timing, magnitude, and duration of flood hydrographs, present a substantial challenge to the flood management in the Central Valley and the strategic development of alternative flood management measures.

Table 6. Projected Changes in Simulated Flood Hydrograph Characteristics Over 2011-2040

Location	2011-2040							
	All Annual Events				Annual Events > 66th percentile			
	Change in Date of Peak Flow (days)	Change in Annual 1-day average max flow (%)	Change in Annual 3-days average max flow (%)	Change in Flood Duration (days)	Change in Date of Peak Flow (days)	Change in Annual 1-day average max flow (%)	Change in Annual 3-days average max flow (%)	Change in Flood Duration (days)
Sacramento River at Shasta Dam	7	7	9	-1	14	4	5	5
Feather River at Oroville	0	13	15	-8	9	3	5	4
Yuba River at Smartville	-3	9	9	-2	2	3	4	6
American River at Folsom Dam	1	14	15	-4	9	4	7	5
Cosumnes River at Michigan Bar	8	9	10	2	18	0	1	6
Mokelumne River at Pardee	-7	9	8	-6	2	0	0	2
Calaveras River at New Hogan	8	8	9	2	5	-2	-2	-1
Stanislaus River at New Melones Dam	-8	6	6	-7	-4	1	2	-1
Tuolumne River at New Don Pedro	0	3	5	-2	6	0	3	5
Merced River at Lake McClure	-5	1	2	-4	12	-8	-6	11
San Joaquin River at Millerton Lake	-6	1	2	-4	-3	0	1	-2
Kings River at Pine Flat Dam	-13	3	0	-6	-8	5	2	-3

Notes:
Changes are computed with respect to 1981-2010 climatological average

Table 7. Projected Changes in Simulated Flood Hydrograph Characteristics Over 2041-2070

Location	2041-2070							
	All Annual Events				Annual Events > 66th percentile			
	Change in Date of Peak Flow (days)	Change in Annual 1-day average max flow (%)	Change in Annual 3-days average max flow (%)	Change in Flood Duration (days)	Change in Date of Peak Flow (days)	Change in Annual 1-day average max flow (%)	Change in Annual 3-days average max flow (%)	Change in Flood Duration (days)
Sacramento River at Shasta Dam	7	22	23	-17	11	11	13	-5
Feather River at Oroville	-3	33	36	-23	9	11	14	-1
Yuba River at Smartville	-9	26	28	-12	1	13	15	5
American River at Folsom Dam	-4	30	31	-14	7	11	14	2
Cosumnes River at Michigan Bar	5	15	16	-6	10	4	5	1
Mokelumne River at Pardee	-18	29	26	-18	-6	16	15	-7
Calaveras River at New Hogan	6	14	14	-2	2	-2	-2	-3
Stanislaus River at New Melones Dam	-24	23	20	-15	-19	19	17	-8
Tuolumne River at New Don Pedro	-19	13	9	-9	-11	14	10	-2
Merced River at Lake McClure	-22	19	14	-15	-3	13	9	-2
San Joaquin River at Millerton Lake	-27	9	4	-10	-23	13	8	-8
Kings River at Pine Flat Dam	-26	11	4	-9	-24	14	7	-6

Notes:
Changes are computed with respect to 1981-2010 climatological average

Table 8. Projected Changes in Simulated Flood Hydrograph Characteristics Over 2070-2099

Location	2070-2099							
	All Annual Events				Annual Events > 66th percentile			
	Change in Date of Peak Flow (days)	Change in Annual 1-day average max flow (%)	Change in Annual 3-days average max flow (%)	Change in Flood Duration (days)	Change in Date of Peak Flow (days)	Change in Annual 1-day average max flow (%)	Change in Annual 3-days average max flow (%)	Change in Flood Duration (days)
Sacramento River at Shasta Dam	11	30	32	-28	13	18	20	-14
Feather River at Oroville	1	51	54	-33	10	19	23	-5
Yuba River at Smartville	-7	51	51	-23	3	23	25	1
American River at Folsom Dam	-3	51	51	-25	9	21	24	0
Cosumnes River at Michigan Bar	4	29	29	-9	14	6	7	0
Mokelumne River at Pardee	-25	52	45	-29	-5	24	22	-11
Calaveras River at New Hogan	5	26	26	-4	9	-2	-1	3
Stanislaus River at New Melones Dam	-39	44	37	-26	-29	33	29	-11
Tuolumne River at New Don Pedro	-36	25	17	-15	-30	23	16	-5
Merced River at Lake McClure	-34	32	25	-20	-10	10	7	-6
San Joaquin River at Millerton Lake	-41	15	8	-14	-40	18	11	-8
Kings River at Pine Flat Dam	-39	14	5	-13	-36	20	11	-8

Notes:
Changes are computed with respect to 1981-2010 climatological average

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7.0 Summary and Next Steps

The updated Phase IIB analysis has resulted in a significant advancement to the understanding of climate influences on the flood hydrology of the Central Valley. Phase IIB relies upon most recent future climate model simulations from CMIP5 and refined VIC hydrologic modeling to represent a range of potential future changes to unregulated flow volumes due to climate change. Based on the evaluations included in this effort, the following summary observations can be stated:

- Projections of increased warming are consistent between CMIP3 and CMIP5 for the entire region, but inland valley and mountain ridges are projected to exhibit a larger increase in CMIP5.

- Annual precipitation projections are not directionally consistent in either CMIP3 or CMIP5 projections, although the uncertainty appears to be less for the CMIP5 models. Greater clarity of wetter conditions in the Sacramento Valley, and more neutral projections for San Joaquin and Tulare Basins are projected in CMIP5 climate model simulations. Southern California continues to have projections of drier future conditions, but not to same extent as indicated in CMIP3 projections.

- Extreme precipitation, the driver for most flood events is likely to intensify, even with projections of overall drier conditions.

- Changes in flood magnitudes and frequencies at the basin-wide scale considered in the CVFPP vary in space. Watershed characteristics strongly influence the hydrological response to climate change, with the high elevation San Joaquin watersheds showing the largest increases in flood volumes, due to a reduction in precipitation falling as snow and more rapid melt of snowpacks.

- Changes in flood magnitudes in the Phase IIB analysis are higher than those from Phase IIA for most of the major watersheds. The differences in the changes in the flood magnitudes between Phase IIA and IIB result from multiple factors, including

  - Changes in climate change scenarios from CMIP3 used in the Phase IIA to CMIP5 used in the Phase IIB,

  - Use of a refined hydrological model (spatial resolution and re-calibration), and

  - Use of different statistical method to develop flood frequency curves (the Bulletin 17B method in the USGS's PeakFQ software used in the Phase IIB).

- Completion of the Phase IIB tasks is a significant advancement of the CVFPP climate change efforts. Phase IIB analyses and results are considered superior and should supersede those in Phase IIA.

Next steps and recommendations are summarized below.

- **Address uncertainty**. Near-term future work should address the implications of the changed conditions between Phase IIA and IIB efforts. In all uses of hydroclimatic analysis results, uncertainty should be addressed. Specific climate change scenarios were developed for hydrologic analysis to illustrate the relative sensitivity of unregulated flood hydrology to changes in future climate. Scenarios used in the analysis, however, are closely associated with median change conditions. Other scenarios that are more or less extreme exist. Future work could evaluate a broader set of future climate scenarios and provide a broader range of projected outcomes. Alternatively, sensitivity analysis could be performed on a limited subset to improve the understanding of climate risk/uncertainty.

- **Additional study**. This study's methods and findings relate to changes in unregulated flows. DWR has identified a future need to gain insight about reservoir climate vulnerability and adaptation. Specifically, DWR seeks to improve understanding of climate change risk to reservoirs and existing flood control operations, and to evaluate strategies to adapt to future changes. The work described in this technical memorandum should serve as the basis for conducting a reservoir vulnerability study.

- **Incorporate new findings**. Subsequent phases of climate evaluations for CVFPP should incorporate any new findings that arise from ongoing research about ARs, watershed controls on precipitation, and runoff processes. This research is being conducted at the Scripps Institution of Oceanography and at UC Davis.

8.0 Acknowledgements

1. Daily gridded historical climate data (Livneh et al., 2013) was obtained from the Surface Water Modeling Group at the University of Washington (http://www.hydro.washington.edu). PRISM monthly climate data (Daly et al., 1994) was obtained from PRISM Climate Group at Oregon State University (http://www.prism.oregonstate.edu/). The chronologies of the PE events over the period 1948-2013 were provided by Michael Dettinger at U.S. Geological Survey and Scripps Institution of Oceanography.

2. Unregulated streamflows data used in VIC model calibration were obtained from Central Valley Hydrology Study.

3. BCSD were obtained from Lawrence Livermore National Laboratory (LLNL) at http://gdo-dcp.ucllnl.org/downscaled_cmip_projections/.

4. We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI), and the World Climate Research Programme (WCRP) Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

5. We acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and we thank the climate modeling for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

6. Twenty CMIP5 LOCA downscaled climate model projections were obtained from Scripps Institution of Oceanography. DWR Climate Change Technical Advisory Group (CCTAG) provided the CCTAG CMIP5 GCM selection list.

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10.0 Acronyms and Abbreviations

AEP .... Annual Exceedance Probability
AR(s) .... Assessment Report(s)
AR4........................... Fourth Assessment Report
AR5........................... Fifth Assessment Report
BCSD........................ bias-corrected spatially downscaled
BDCP........................ Bay Delta Conservation Plan
CAT .... Climate Action Team
CCTAG .... Climate Change Technical Advisory Group
CEN .... median projection
CIMSS .... Cooperative Institute for Meteorological Satellite Studies
CMIP .... Coupled Model Intercomparison Project
CMIP3....................... Coupled Model Intercomparison Project Phase 3
CMIP5....................... Coupled Model Intercomparison Project Phase 5
CVFPP...................... Central Valley Flood Management Planning Program
DWR .... California Department of Water Resources
EI .... ensemble-informed
GB .... Grubbs-Beck
GCM .... Group on Coupled Modelling
GHG .... greenhouse gas
HD .... drier, more warming
HW............................ wetter, more warming
ID .... identification
IPCC .... Intergovernmental Panel on Climate Change
LLNL .... Lawrence Livermore National Laboratory
LOCA........................ localized constructed analog
MOM .... Method of Moments
NCAR .... National Center for Atmospheric Research
NCEP........................ National Centers for Environmental Prediction
NOAA .... National Oceanic and Atmospheric Administration
O_2 .... oxygen
PCMDI .... Program for Climate Model Diagnosis and Intercomparison

PE............................ Pineapple Express
PW........................... precipitable water
RCP(s)...................... Representative Concentration Pathway(s)
SIO .... Scripps Institution of Oceanography
SRES........................ Special Report on Emission Scenarios
SSIA .... State Systemwide Investment Approach
SSM/I........................ Special Sensor Microwave Imager
U.S........................... United States
USGS .... U.S. Geological Survey
VIC........................... Variable Infiltration Capacity
WCRP...................... World Climate Research Programme
WD........................... less warming
WGCM..................... Working Group on Coupled Modelling
WW.......................... wetter, less warming