DEVELOPMENT OF STAGE-FREQUENCY CURVES IN THE SACRAMENTO – SAN JOAQUIN DELTA FOR CLIMATE CHANGE AND SEA LEVEL RISE

A Report for:

California's Fourth Climate Change Assessment

Prepared By:
Romain Maendly[1]

1 California Department of Water Resources

Edmund G. Brown, Jr., *Governor*

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PREFACE

California's Climate Change Assessments provide a scientific foundation for understanding climate-related vulnerability at the local scale and informing resilience actions. These Assessments contribute to the advancement of science-based policies, plans, and programs to promote effective climate leadership in California. In 2006, California released its First Climate Change Assessment, which shed light on the impacts of climate change on specific sectors in California and was instrumental in supporting the passage of the landmark legislation Assembly Bill 32 (Núñez, Chapter 488, Statutes of 2006), California's Global Warming Solutions Act. The Second Assessment concluded that adaptation is a crucial complement to reducing greenhouse gas emissions (2009), given that some changes to the climate are ongoing and inevitable, motivating and informing California's first Climate Adaptation Strategy released the same year. In 2012, California's Third Climate Change Assessment made substantial progress in projecting local impacts of climate change, investigating consequences to human and natural systems, and exploring barriers to adaptation.

Under the leadership of Governor Edmund G. Brown, Jr., a trio of state agencies jointly managed and supported California's Fourth Climate Change Assessment: California's Natural Resources Agency (CNRA), the Governor's Office of Planning and Research (OPR), and the California Energy Commission (Energy Commission). The Climate Action Team Research Working Group, through which more than 20 state agencies coordinate climate-related research, served as the steering committee, providing input for a multisector call for proposals, participating in selection of research teams, and offering technical guidance throughout the process.

California's Fourth Climate Change Assessment (Fourth Assessment) advances actionable science that serves the growing needs of state and local-level decision-makers from a variety of sectors. It includes research to develop rigorous, comprehensive climate change scenarios at a scale suitable for illuminating regional vulnerabilities and localized adaptation strategies in California; datasets and tools that improve integration of observed and projected knowledge about climate change into decision-making; and recommendations and information to directly inform vulnerability assessments and adaptation strategies for California's energy sector, water resources and management, oceans and coasts, forests, wildfires, agriculture, biodiversity and habitat, and public health.

The Fourth Assessment includes 44 technical reports to advance the scientific foundation for understanding climate-related risks and resilience options, nine regional reports plus an oceans and coast report to outline climate risks and adaptation options, reports on tribal and indigenous issues as well as climate justice, and a comprehensive statewide summary report. All research contributing to the Fourth Assessment was peer-reviewed to ensure scientific rigor and relevance to practitioners and stakeholders.

For the full suite of Fourth Assessment research products, please visit www.climateassessment.ca.gov. This report provides estimates of future high water-level frequency and duration due to sea level rise in the Sacramento-San Joaquin Delta.

ABSTRACT

Future changes in hydrologic patterns and sea level rise will impact water levels in the Sacramento-San Joaquin Delta (Delta), the hub of California's water supply system and an important ecosystem and agricultural area. An important tool for flood management is stage-frequency curves which indicate how often certain water levels (or stage) occur.

The Delta poses inherent complexity in the determination of stage-frequency and requires a number of considerations. One needs to account for river flows coming into the Delta, as well as the effect of tides from the Delta's connection to the ocean through San Francisco Bay. During storms, Delta water levels are also affected by storm surge from the advancing storm fronts coming from the Pacific Ocean. Under climate change, Delta water levels will also be affected by rising sea levels and expected changes in hydrology, such as shifts in timing and amount of precipitation and runoff and changes in how much of our precipitation falls as rain or snow (referred to as climate change hydrology in this paper).

With these taken into consideration, this study lays out the assumption and method used to develop stage-frequency curves in the Delta for three different conditions: current hydrology conditions, current hydrology with sea level rise, and late-century climate change hydrology with sea level rise. In addition, water surface elevation profiles along the Sacramento and San Joaquin rivers for various magnitudes of flood events were compared to the top of levee elevations.

Both the stage-frequency curves and the water surface elevation profiles comparisons to top of levee elevations provide valuable information to water resources planners and were applied to inform life and flood risk analysis for the Delta in the Central Valley Flood Protection Plan 2017 Update.

Keywords: Flood, climate change, sea level rise, stage-frequency curves, tides, modeling, Central Valley Flood Protection Plan 2017 Update, California, Central Valley

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HIGHLIGHTS

- This study develops stage-frequency curves in the Delta for current conditions, sea level rise only, and combined sea level rise and climate change hydrology. The method uses a first-of-a-kind approach which links the storm surge characteristics to storm intensity through rainfall runoff, while also applying the Central Valley Hydrology Study methodology, the Central Valley Floodplain Evaluation and Delineation hydraulic models, and RMA 2-D Bay Delta model.
- The outcome of the study shows a significant rise of water surface elevations from sea level rise and climate change hydrology. For smaller flood events, sea level rise has a large effect on water surface elevation in locations further downstream in the Delta. For larger flood events, the effect of sea level rise diminishes because flood-flows drive the water surface elevations. Climate change hydrology shifts the stage-frequency curve to more frequent large flood events. Climate change hydrology has a greater consequence on water surface elevation than sea level rise in the San Joaquin River with stage increase up to 7 feet for the 200-year return period flood event, which overtop the levee near the city of Stockton.
- Both stage-frequency curves and water surface elevation profiles provide important information to decision makers regarding the vulnerability of levee overtopping for specific flood events, as well as annual exceedance probability of water surface elevation along the Delta levee system.

WEB LINKS

https://www.water.ca.gov/Programs/Flood-Management/Flood-Planning-and-Studies/Central-Valley-Flood-Protection-Plan

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ACRONYMS AND ABBREVIATIONS

1-D	one-dimensional
2-D	two-dimensional
ACF	auto correlation function
AEP	annual exceedance probability
CMIP5	Coupled Model Intercomparison Project Phase 5
CVFED	Central Valley Floodplain Evaluation and Delineation
CVFPP	Central Valley Flood Protection Plan
CVHS	Central Valley Hydrology Study
Delta	Sacramento-San Joaquin Delta
DWR	California Department of Water Resources
HEC-RAS	Hydrologic Engineering Center's River Analysis System
IP	index point
IPCC	Intergovernmental Panel on Climate Change
MHHW	mean higher high water
NAVD88	North American Vertical Datum of 1988
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
RCP	Representative Concentration Pathways
RMA	Resource Management Associates
USACE	U.S. Army Corps of Engineers

1: Introduction

This paper describes the development of stage-frequency curves for areas of the Sacramento-San Joaquin Delta (Delta) that were evaluated as part of the Central Valley Flood Protection Plan 2017 Update. The areas where the Sacramento and San Joaquin rivers enter the Delta have complex hydrodynamic conditions that affect water surface elevations during flood events and pose inherent difficulty in the determination of stage-frequency curves.

This report lays out the assumption and method used to develop stage-frequency curves in the Delta for three different conditions: current hydrology conditions, current hydrology with sea level rise, and late-century climate change hydrology with sea level rise. In addition, water surface elevation profiles along the Sacramento and San Joaquin rivers for various magnitudes of flood events were compared to the top of levee elevations.

The method uses two sets of hydraulic models: the Central Valley Floodplain Evaluation and Delineation (CVFED) hydraulic models and the Resource Management Associates (RMA) Bay Delta Model. Three major sets of data were used: the Central Valley Hydrology Study (CVHS) hydrology, the eastside river inflows, and the tides at Golden Gate Bridge. The method enables the development of stage frequency curves beyond historical observation and provides flexibility in the evaluation of future climate change projections and project alternatives.

1.1 Background

Under the Central Valley Flood Protection Act, the California Department of Water Resources is required to prepare a sustainable, integrated flood management plan, the Central Valley Flood Protection Plan (CVFPP), every five years. The latest CVFPP (California Department of Water Resources 2017a) followed the foundation set up by the 2012 CVFPP and used the tools and information developed through projects and programs completed since then. Those include the Central Valley Hydrology Study (CVHS) (California Department of Water Resources 2015a), the Central Valley Floodplain Evaluation and Delineation (CVFED) (California Department of Water Resources 2015b), and the Nonurban/Urban Levee Evaluations (California Department of Water Resources 2016).

One important improvement in the CVFPP 2017 Update is the inclusion of the latest climate science, as well as the development of a procedure to develop stage-frequency curves in locations influenced by tidal and riverine conditions. For instance, the future changes in hydrology for the late-century, which include changes in precipitation and temperature, were founded on the Coupled Model Intercomparison Project Phase 5 climate model data under the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Intergovernmental Panel on Climate Change (IPCC) 2013). The analyses specifically tailored to the Central Valley are presented in the CVFPP Climate Change Analysis Technical Memorandum (California Depatment of Water Resources 2017b). Future sea level rise projections incorporated into the analysis are based on the National Research Council projections (National Research Council 2012).

1.2 Objectives

The purpose of this analysis was to produce stage-frequency curves for areas of the Sacramento-San Joaquin Delta (Delta) under various climatic conditions. Incorporating tidal influence in the development of stage-frequency curves is particularly important because water surface elevations in time-varying tidal regions vary temporally, spatially, and with size of flood events. Another objective of this analysis was to produce comparisons of water surface elevation profiles to Delta top of levee elevations for various annual exceedance probabilities (AEP). AEP refers to the probability of a flood event occurring in any year. The probability is expressed as a percentage. For example, a large flood which may be calculated to have a 1% chance to occur in any one year, is described as 1%AEP.

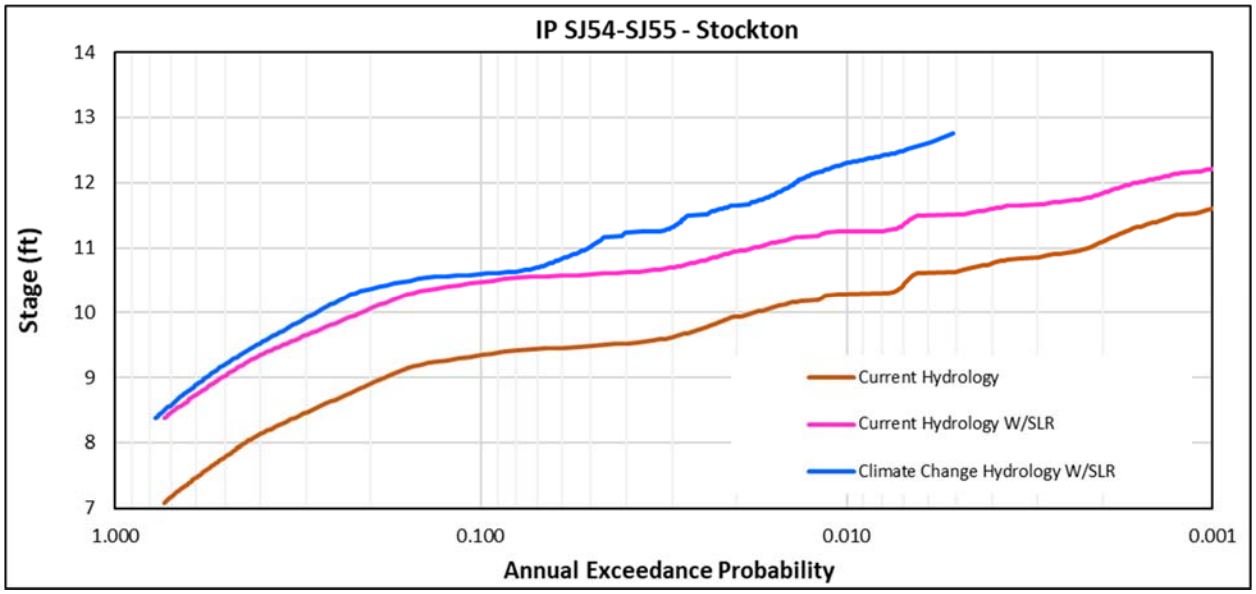
This analysis aimed to use tools and models that were consistent with other state flood planning efforts including the Central Valley Hydrology Study, the Central Valley Floodplain Evaluation and Delineation, and the Central Valley Flood Protection Plan 2017 Update.

For each location analyzed, three stage-frequency curves are generated (see example in Figure 1 and full discussion in section 4.2):

- Current hydrology.
- Current hydrology with sea level rise.
- Climate change hydrology with sea level rise.

By adding sea level rise and climate change hydrology into the analysis in separate steps, these curves can be used to estimate how much of the change in water surface elevations and their frequency are caused by sea level rise (example change from brown line to pink line in Figure 1), and how much is caused by climate change hydrology (example change from pink curve to the blue curve). Note that the scenario with current hydrology and sea level rise is not considered a plausible future but is used for analysis purposes to separate the effects of sea level rise.

For the three same conditions, water surface elevation profiles are also generated for major river reaches. The water surface elevation profiles show that sea level rise has a greater effect on water surface elevation in locations closer to the center of the Delta toward the San Francisco Bay and propagates to some extent up the riverine system, as shown in Figure 2. Climate change hydrology affect the entire water surface elevation profile. The blue lines represent the three different conditions defined above.



Note: Climate change is evaluated for late-century projection

Figure 1: Example Stage-Frequency Curve for Current Hydrology, Current Hydrology with Sea Level Rise and Climate Change Hydrology with Sea Level Rise

Figure 2: Sacramento River Water Surface Elevation Profiles of Flood Scaled Events Meant to Represent the 200-Year Flooding Events with and without Climate Change and Sea Level Rise

2: Study Area

This study focuses on areas of the Delta along the Sacramento and San Joaquin rivers, highlighted in light blue in Figure 3. On the Sacramento River Basin, the study area extends from the Sacramento River junction with the American River down to the confluence of the Sacramento River with the San Joaquin River. On the San Joaquin River, the study area extends from Vernalis down to Stockton, Middle River at Highway 4 and Clifton Court Forebay. This study region coincides with the extent of the Central Valley Flood Protection Plan 2017 Update study area in the Delta. Figure 3 also shows the locations where stage frequency curves were produced. These locations are called index points and are representative of a river reach with consistent hydrologic, hydraulic, and geotechnical characteristics. The study area has 54 index points locations, but 12 index points are situated at the same geo-location.

3: Models, Data, and Method

This section describes in detail the models, data, and method used and developed to create stage-frequency curves in the Delta, considering sea level rise and climate change for late-century projection. This effort used data and modeling tools developed for several State planning efforts as summarized in Table 1. Climate change hydrology and sea level rise information were taken from the latest sources available at the time of analysis.

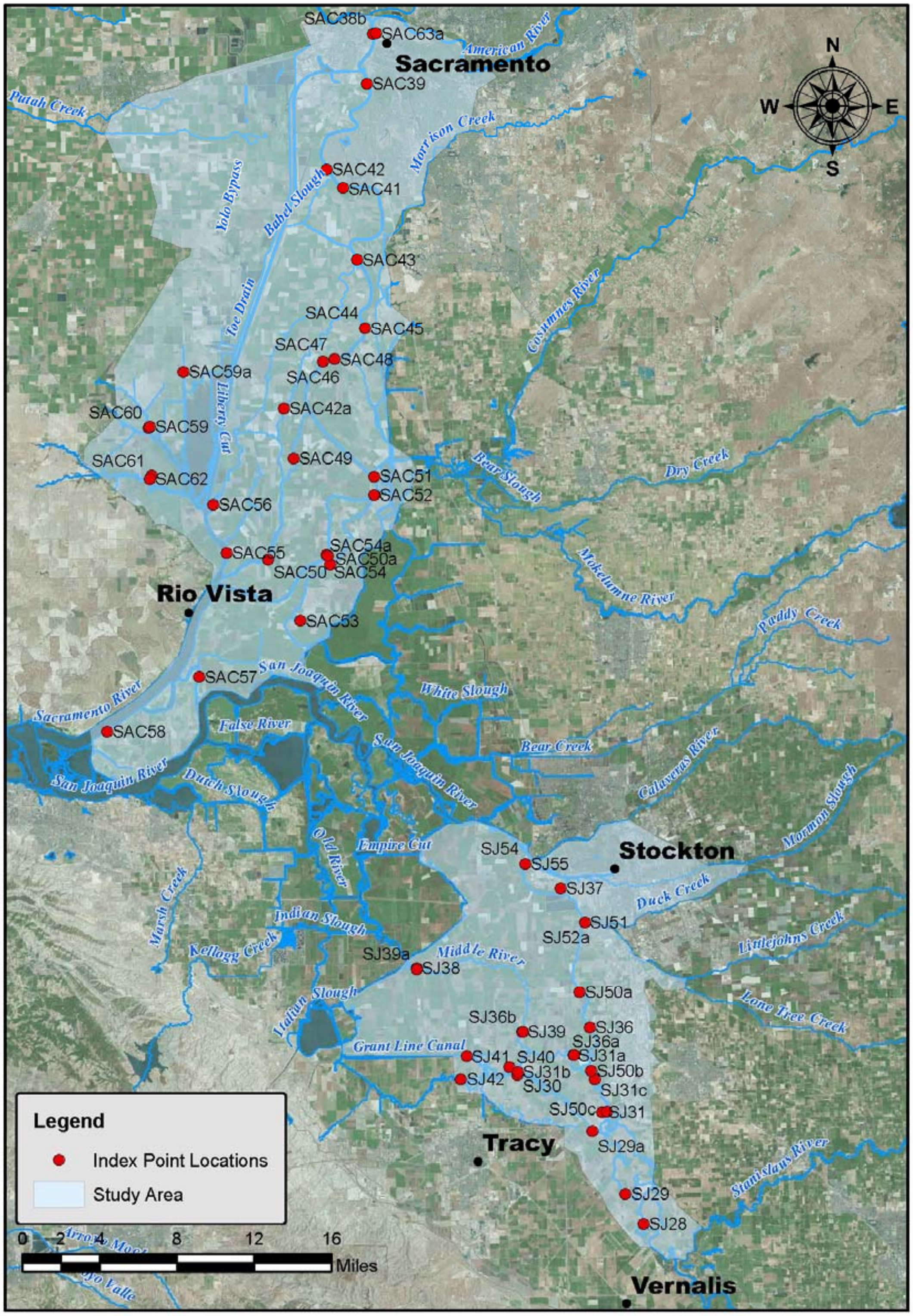


Figure 3 The Study Area is Represented in Light Blue. This Region Coincides with the Extent of the Central Valley Flood Protection Plan 2017 Update Study Area in the Delta.

Table 1: Data Sets and Modeling Tools Used to Develop Delta Stage-Frequency Curves

Data	Description/Model	Source Study
Climate Change Hydrology	114 climate model projections from CMIP5 recommended for California by DWR's Climate Change Technical Advisory Group	IPCC 5th Assessment
Sea Level Rise	Late-century low bound projection of +1.27ft	National Research Council 2012
Water Surface Elevation – Flood Hydraulics	Central Valley Floodplain Evaluation and Delineation (CVFED) hydraulic models (DWR 2015b) run with HEC-RAS 1-D	Central Valley Flood Protection Plan 2017 Update
Tidal Conditions – Delta Hydrodynamics	RMA Bay Delta Model	Central Valley Flood Protection Plan 2017 Update
Flood Hydrology	Scaled event patterns based on 1951, 1956, 1965, 1986 and 1997 flood events.	Central Valley Hydrology Study, year 2015 (CVHS)
Eastside River Inflows	CVHS Hydrographs (Calaveras River) DWR Dayflow (Consumes and Mokelumne rivers)	CVHS 2015 & DWR Dayflow
Golden Gate Tide and Storm Surge	Deterministic tide with storm surge developed by using predicted and verified tides, and unregulated flow.	NOAA and Central Valley Flood Protection Plan 2017 Update

CMIP5	Coupled Model Intercomparison Project Phase 5
CVFED	Central Valley Floodplain Evaluation and Delineation
CVHS	Central Valley Hydrology Study
DWR	California Department of Water Resources
HEC-RAS 1-D	One-dimensional Hydrologic Engineering Center's River Analysis System from the U.S. Army Corp of Engineer's Hydrologic Engineering Center
IPCC	Intergovernmental Panel on Climate Change
NOAA	National Oceanic and Atmospheric Administration
RMA	Resource Management Associates

The method illustrated in Figures 4 and 5 was developed and used to estimate estuarine stages and develop stage-frequency curves for risk assessment. At-latitude flow frequency curves (equivalent to total basin contribution flow from the upstream watershed at a given cross-section from in-channel flows and overbank flows) are created by using the data from the Central Valley Hydrology Study and the output from the Central Valley Floodplain and Delineation (CVFED) hydraulic models (Graph A in Figure 4 and Figure 5). Concurrently, the CVFED hydraulic and Resource Management Associates (RMA) hydrodynamic models are used to simulate Delta water surface elevation for 10 flood scenarios and develop stage-discharge rating curves (Graph A in Figure 4 and Figure 5). Both at-latitude flow frequency and stage discharge rating curves are coupled to create current hydrology conditions stage-frequency curves (Graph C in Figure 4). Those curves are then modified to take into account sea level rise and late-century climate change hydrology (Figure 5). Details of the method and its application to the Delta are provided in Section 3.3.

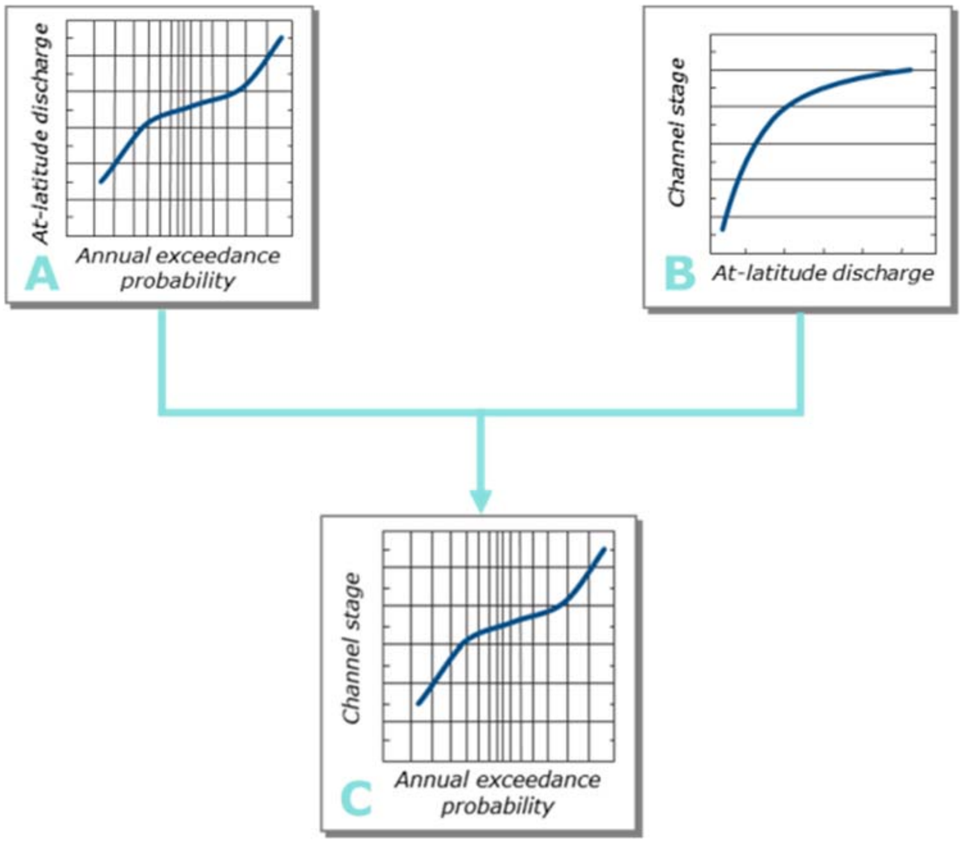


Figure 4: Derivation of Stage-Frequency Curve for Bay-Delta Areas Using At-Latitude Flow-Frequency Curve and Stage-At-latitude Discharge Rating Curve

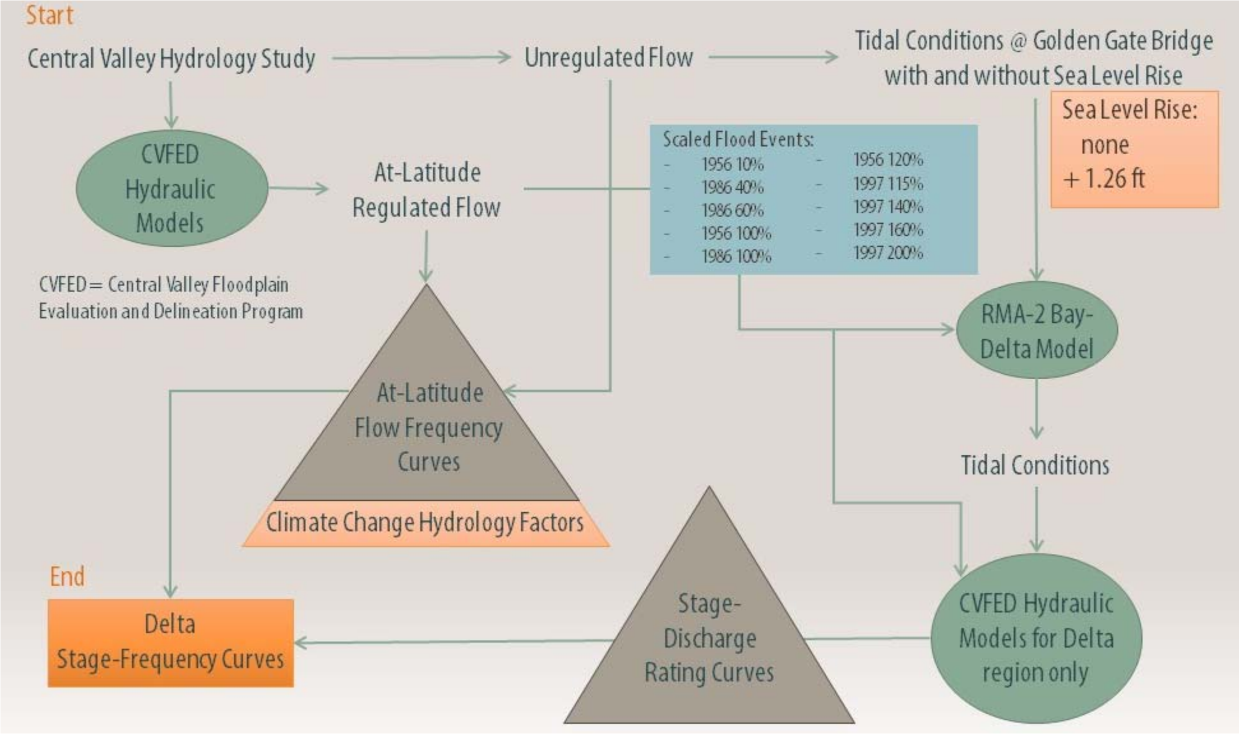


Figure 5: Schematic Representing the Overall Method Used to Develop Stage Frequency Curves in the Sacramento and San Joaquin Delta

3.1 Models

The two sets of hydraulic models used for this study were the Central Valley Floodplain Evaluation and Delineation (CVFED) hydraulic models and the Resource Management Associates (RMA) Bay Delta Model. Both models are described in this chapter.

3.1.1 Hydraulic Models – CVFED Hydraulic Models

The Sacramento and San Joaquin river basins Central Valley Floodplain Evaluation and Delineation (CVFED) hydraulic models were used for this study. The CVFED hydraulic models were developed by the California Department of Water Resources (DWR) using HEC-RAS version 4.2 Beta (dated 2013.08.01). HEC-RAS can simulate one-dimensional (1-D) unsteady flow and stage calculations through a full network of open channels. A model schematic and extents are shown in Figure 6.

Figure 6: Sacramento and San Joaquin River Basins Central Valley Floodplain Evaluation and Delineation (CVFED) Hydraulic Models Extents

Because of their complexity and computation expense, the CVFED hydraulic models were trimmed to the extent of the study area presented in Figure 3. In the Sacramento river basin, the model goes from the junction of the Sacramento River with the American River and midway through the Yolo Bypass. The model ends a few miles downstream of Rio Vista. In the San Joaquin River Basin, the model was trimmed at Vernalis and ends at the Delta Front of the city of Stockton, Middle River, Old River, and Grant Line Canal.

3.1.2 Hydrodynamic Model – RMA Bay Delta Model

For this study, DWR used a numerical model of the San Francisco Bay and Sacramento-San Joaquin Delta (Figure 7) that was developed by Resource Management Associates, Inc. (RMA). The RMA Bay-Delta model was solely utilized to develop tidal influenced boundary conditions at the downstream end of the Central Valley Floodplain Evaluation and Delineation (CVFED) hydraulic trimmed models.

The RMA Bay-Delta model is a combined 1-D and two-dimensional (2-D) element model that simulates velocities and water levels throughout the Bay-Delta using the RMA2 computational engine. The RMA2 engine combines 2-D depth-averaged computational elements and 1-D cross-sectionally averaged elements in a single mesh and solves the shallow-water equations to provide temporal and spatial descriptions of velocities and water depths. The RMA Bay-Delta model was run at an hourly time step.

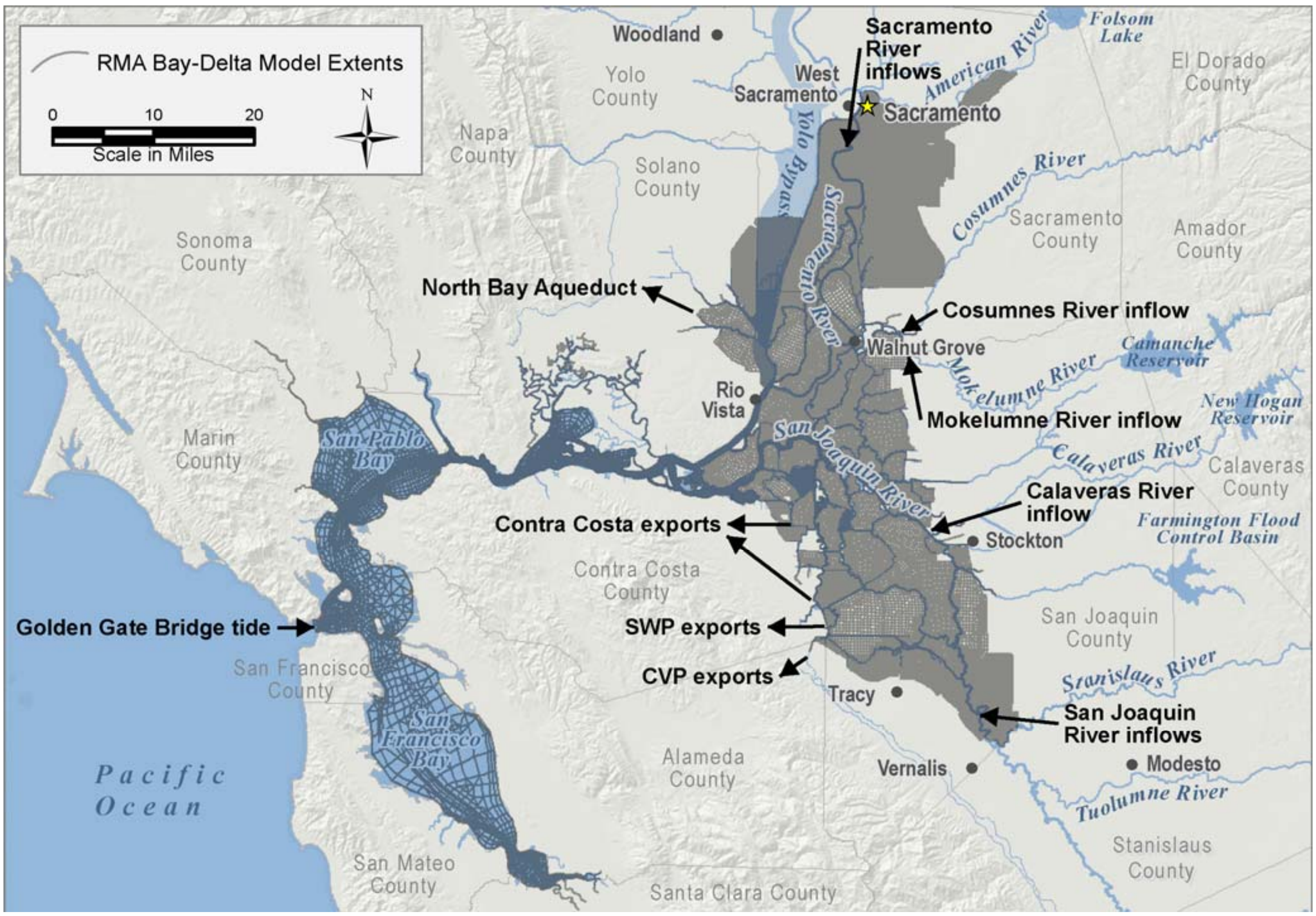


Figure 7: RMA Bay-Delta Model for Central Valley Flood Protection Plan (CVFPP) 2017 Update with Major Boundary Conditions (Arrows)

The RMA Bay-Delta model extends from the confluence of the American and Sacramento rivers, and Vernalis on the San Joaquin River, to the Golden Gate Bridge. The RMA Bay-Delta Model boundary conditions utilized in this study are described in Sections 3.3.3 and 3.3.4.

The RMA Bay-Delta model includes the Central Valley Project and State Water Project exports and other control structures operations in the Delta that affect water discharge and water levels (including Suisun Marsh Salinity Control gate, Delta Cross Channel, Old River near Tracy barrier, temporary barrier at the head of Old River, Middle River temporary barrier, Clifton Court Forebay Gates, Grant Line Canal barrier, and Rock Slough tide gate).

The RMA Bay-Delta model provides multiple advantages over other Delta models in regard to flood risk assessment including but not limited to:

- 2-D representation for floodplains along the Sacramento River, San Joaquin River and tributaries based on the latest geometry data from the Central Valley Floodplain Evaluation and Delineation Program.
- Simulation of overtopping flow above the top of levee and floodplain inundation.
- Extended downstream boundary conditions to the Golden Gate Bridge, minimizing adverse boundary effects on upstream water surface elevation.

3.2 Data

Three major sets of hourly data were used in this study: the Central Valley Hydrology Study (CVHS) hydrology, the eastside river inflows, and the tides at Golden Gate Bridge. The following sections describes the source of the data and some of manipulation done on the data for this analysis. The data used for the climate-change, which include climate change hydrology and sea level rise, is discussed in the Method section (Section 3.3).

3.2.1 CVHS Hydrology

The California Department of Water Resources with the support of the U.S. Army Corps of Engineers, Sacramento District completed the Central Valley Hydrology Study (CVHS), a hydrologic analysis of the Sacramento and San Joaquin river basins. The CVHS provides standardized hydrologic procedures, updated systemwide models, and updated hydrologic information at more than 200 locations in the Central Valley. The CVHS is described in detail in the study’s final report (California Department of Water Resources 2015a).

Key CVHS products used to produce stage-frequency curves in the Central Valley Flood Protection Plan include (California Department of Water Resources 2017c):

1. Unregulated flow-frequency curves at key locations throughout the San Joaquin River and Sacramento River basins upstream from the Delta.
2. A systemwide dataset of inflows based on historical patterns for evaluating regulated flow conditions. These inflows served as model inputs to the CVFED-Hydraulic Models.
3. Systemwide Hydrologic Engineering Center-Reservoir System Simulation (HEC-ResSim) models for the San Joaquin and Sacramento river systems.
4. Standard methods for developing regulated flow-frequency curves and design event hydrographs using the inputs above.

Unregulated flow refers to a flow condition in absence of reservoir and overbank flow. This is similar to “unimpaired flows” and “full natural flows” as used in DWR planning activities but focuses more on the largest events rather than smaller events. The unregulated flow includes an effect of the flow constrictions caused by the engineered channelization of the streams. As a result, unregulated flows in the CHVS are not necessarily the same as the “unimpaired flows” and “full natural flows” used by DWR. The historical unregulated flow set can be used as the basis of a flood-flow-frequency analysis consistent with the requirements of Bulletin 17B guidelines (U.S. Interagency Advisory Committee on Water Data 1982).

Regulated flow refers to a flow condition with the influence of hydraulic constriction(s) or human-made influence(s), which includes reservoir storage, overbank storage as a result of levee overtopping and/or failure, and the effect of bridges and hydraulic structures. This represents the existing state of the flood control system. The regulated condition is evaluated using historical patterns and uniformly scaled (up and down) event patterns inflow datasets. If historical events alone are used to define a flow frequency curve, few to no data points will be available to define the upper end of the curve. Thus, scaled historical events are used to add data points and define the flow frequency curve for these rare events.

This analysis used two key CVHS data sets:

1. The hourly unregulated flow time series from 1921 to 2008.
2. The hourly regulated scaled-inflow datasets, based on multiple historical event patterns to account for variations in temporal and spatial distribution of flows. These events patterns were scaled based on the 1951, 1956, 1986, and 1997 flood events for the San Joaquin River; and the 1956, 1965, 1986, and 1997 flood events for the Sacramento River. Section 3.3.1 and 3.3.3 describes in more detail the scaling and inflow locations of these events, respectively.

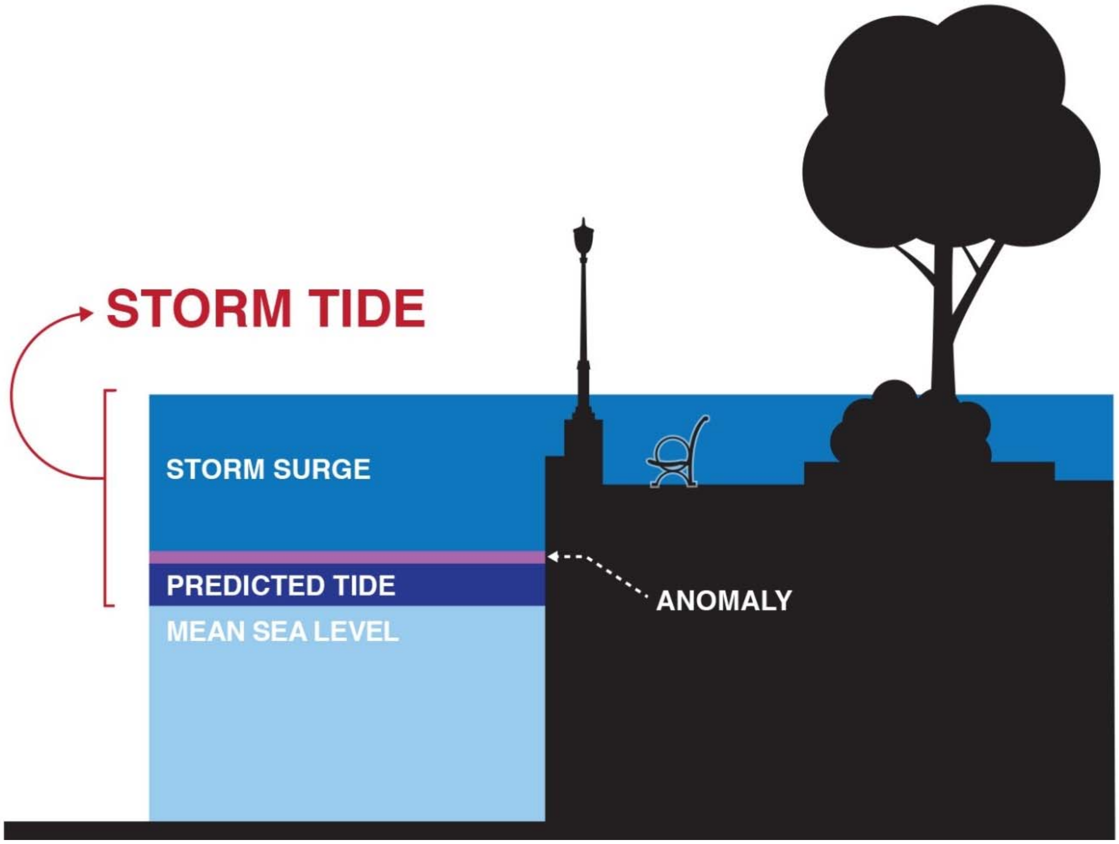
3.2.2 Eastside River Inflows

The Calaveras, Cosumnes, and Mokelumne rivers are river located in the east side of the Delta. Their regulated inflows were collected and used as boundary for the RMA Bay-Delta model. The data source of these rivers differs from one another. The Calaveras River regulated inflows were collected from the Central Valley Hydrology Study hydrographs. The Cosumnes and Mokelumne rivers regulated inflows were collected from DWR’s Dayflow data library website (California Department of Water Resources 2017d).

3.2.3 Tides and Storm Surge at Golden Gate Bridge

During ordinary conditions in the Pacific Ocean, tidal conditions at the Golden Gate Bridge follow the tidal prediction from the National Oceanic and Atmospheric Administration (NOAA). *Tidal predictions*, as used here, is synonymous with astronomical tides, gravitational tides, or predicted tides, and are defined as the periodic rising and falling of the oceans resulting from the gravitational attraction of the moon, sun, and other astronomical bodies acting upon the rotating Earth.

A key process that can affect the times and amplitude of tides are storm surges from wind and barometric pressure change caused by storms. *Storm surge* is an abnormal rise of water generated by a storm. For purposes here, storm surge is defined as the difference between the observed sea level and the predicted tide, with effects of longer term processes, such as the long-term sea level trend, removed. “Negative storm surges” can happen when water is pushed away from the shoreline because of effects such as high barometric pressure or when the wind direction blows the water away from the coast. Storm surge can be measured directly at coastal tidal stations as the difference between the predicted tide and the observed water levels. *Storm tide* is the total observed seawater level during a storm, which is the combination of storm surge, normal high tide plus other factors contributing to anomalous water level. Anomalies in the storm tide can be the result of regional atmospheric conditions. Figure 8 provides a representation of the definitions described above.



Source : http://oceanservice.noaa.gov/facts/stormsurge-stormtide.html

Figure 8: Illustration of Storm Tide

Hourly observed and predicted tides in feet (North American Vertical Datum of 1988 [NAVD 88]) at the Golden Gate Bridge, station 9414290, were collected from the NOAA website. The tide time series overlap with the hourly Central Valley Hydrology Study unregulated flow time series from 1921 to 2008.

In order to calculate the storm surge from 1921 to 2008, a filter was applied to the verified tide and predicted tide by using the Lanczos-window cosine filter, which is commonly used in oceanographic studies (Thomson R.E. and Emery W. 2014). Using the programming language python, a script was created in PyScripter to produce two hour-timestep series: a verified filter tide and a predicted filter tide at the Golden Gate Bridge. The water surface elevation difference between these two curves was calculated to capture the effect of storm surge, sea level rise, and other anomalies from 1921 to 2008 (Figure 9).

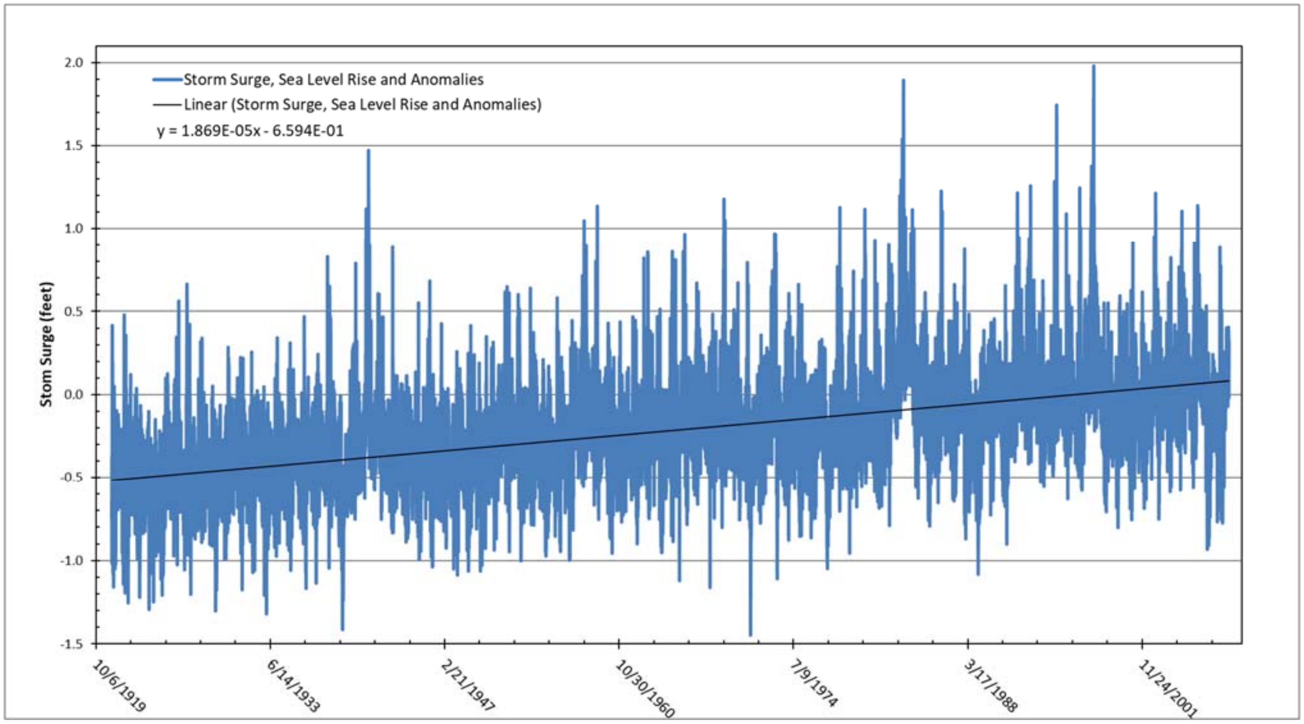


Figure 9: Storm Surge, Sea Level Rise, and Other Anomalies Influence on Water Surface Elevation from 1921 to 2008

In Figure 9, a linear slope can be observed representing sea level rise with a rate of 0.0068 feet per year (1.87 x 10^{-5} feet per day). NOAA estimates the overall sea level rise to be 0.0063 +/- 0.0006 feet per year. The linear trend presented in Figure 9 is in the 95 percent confidence interval of NOAA estimation. Using NOAA's estimates, the water surface elevation from Figure 9 was detrended for sea level rise (Figure 10) and used in this analysis as storm surge time series.

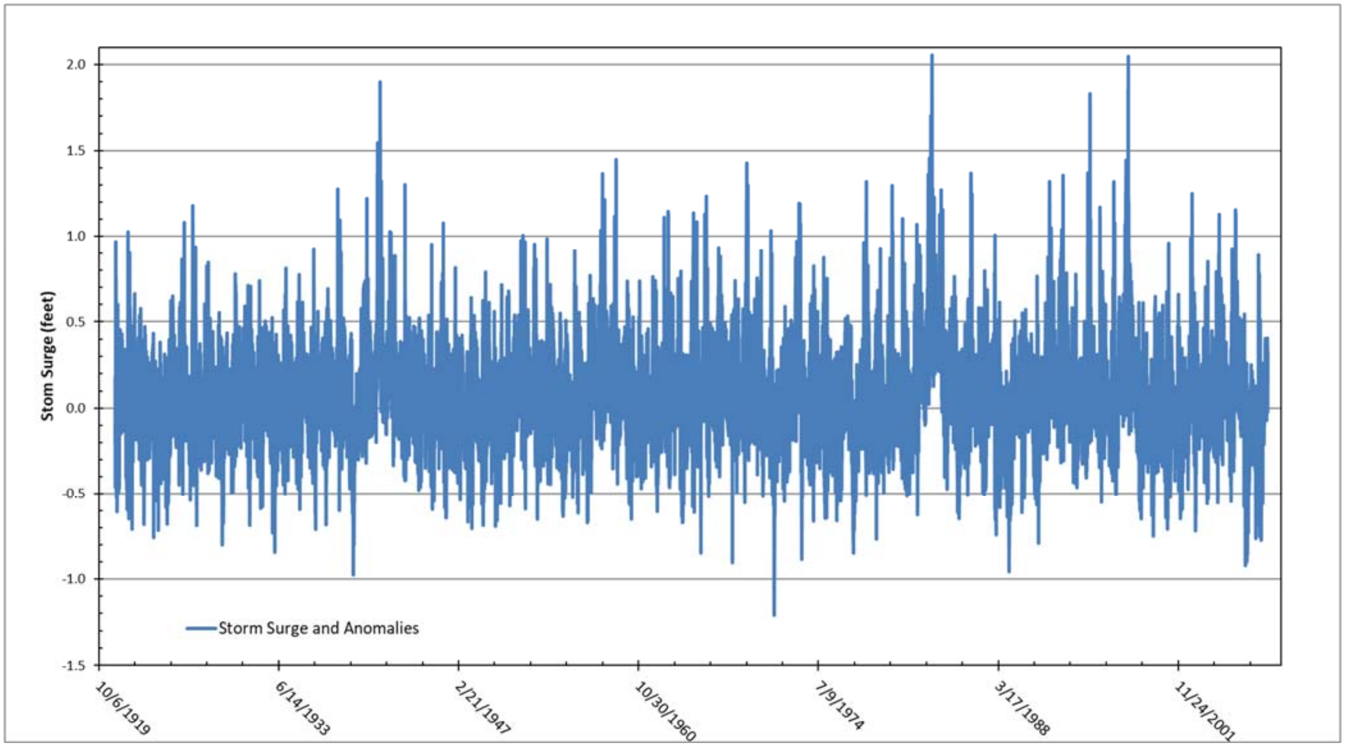


Figure 10: Storm Surge and Anomalies Detrended for Sea Level Rise from 1921 to 2008

3.3 Method

The method illustrated in Figure 4 was developed and used to estimate estuarine stages and develop stage-frequency curves for risk assessment. The method uses the approaches described in Figure 5 and follows nine steps:

1. Develop at-latitude flow frequency curves for the Sacramento River and San Joaquin River using the Central Valley Hydrology Study (CVHS) procedure.
2. Develop climate change factors to represent climate change hydrology for late-century projection. These climate change factors are applied to the historical unregulated volume-frequency curves and alter the regulated flow-frequency curves.
3. Select 10 CVHS flood events, scaled from historical events, to encompass the range of annual exceedance probability of flood from 99% to 0.025% while minimizing the computation expense of the RMA Bay-Delta model and the Central Valley Floodplain Evaluation and Delineation (CVFED) hydraulic models.
4. Define the upstream boundary flow handoff locations from the CVFED hydraulic models to the RMA Bay-Delta model for Sacramento River and San Joaquin River.
5. Develop deterministic time-varying Golden Gate Bridge tidal conditions for the 10 selected flood-scaled event patterns.

6. Incorporate sea level rise, medium projection value, for year 2062 from National Research Council Report estimate.
7. Run RMA Bay-Delta model with the 10 selected flood-scaled event patterns and deterministic tides, with and without sea level rise, at the Golden Gate Bridge, and create a new set of tidal influenced boundary conditions for the CVFED trimmed hydraulic models.
8. Run the CVFED trimmed hydraulic models with the 10 selected flood-scaled event patterns and the tidal influenced boundary conditions from the RMA Bay-Delta model to determine stage discharge rating curves for each index point.
9. Create stage-frequency curves following CVHS hydrology procedure using the CVFED hydraulic models stage discharge rating curves and at-latitude flow frequency curves.

The following sections describe each of these steps.

3.3.1 At-Latitude Flow Frequency

The first step of this study was to develop two at-latitude flow frequency curves (Graph A in Figure 4), one for the Sacramento River and a second for San Joaquin River. *At-latitude flow* is equivalent to total basin contribution flow from the upstream watershed at a given cross-section from in-channel flows and overbank flows.

The use of at-latitude flow is an appropriate representation of the Delta hydrology because there is a strong correlation between flood at-latitude flow rates and Delta channel flow rates. For example, observed Old River flow rates during flood events are highly correlated with total San Joaquin River flows calculated at-latitude of Vernalis (i.e., including all flows in the San Joaquin River main stem at Vernalis and in the floodplain). The same correlation exists for Sacramento River. For example, observed Sacramento River flow rate at Rio Vista varies directly with total Sacramento River flows calculated at-latitude of the city of Sacramento.

The at-latitude flow frequency curves were developed using the procedure described in the Central Valley Hydrology Study (California Department of Water Resources 2015a), which required routing selected historical inflows (unregulated flow time series), and scaled versions of those, through the Central Valley Floodplain and Delineation (CVFED) hydraulic models. These hourly simulations produce the regulated flow time series. For the Central Valley Flood Protection Plan (CVFPP) 2017 Update, four high-flow events (referred to as event patterns) were selected, as well as scaled versions of those. The events were scaled from 0.1 to 3.0. At-latitude flow-frequency curves for current hydrology were developed and are presented in Figures 11 and 12 for the Sacramento River and San Joaquin River, respectively.

One observation from Figures 11 and 12 is that for same expected annual probability of flood, the Sacramento River carries more water than the San Joaquin River by approximately one order of magnitude.

At-latitude Sacramento River flows at the city of Sacramento and at-latitude San Joaquin River flows at Vernalis are used as the upstream boundary conditions of the RMA Bay-Delta model described in Sections 3.3.4.1 and 3.3.4.2.

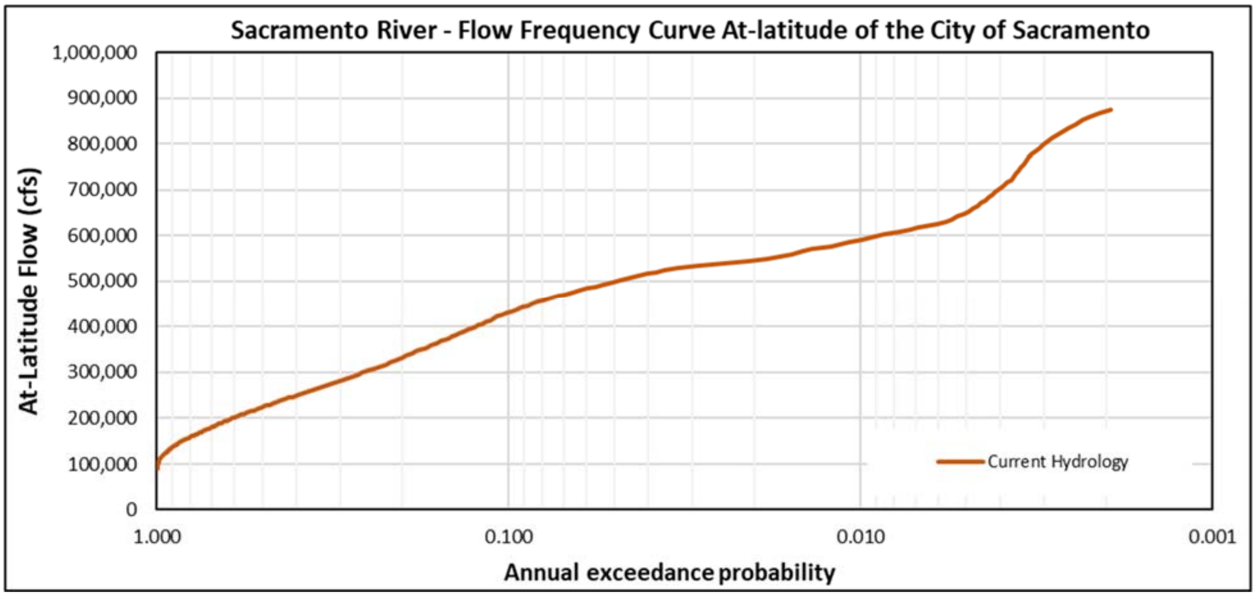


Figure 11: Sacramento River Flow Frequency At-Latitude of the City of Sacramento for Current Hydrology

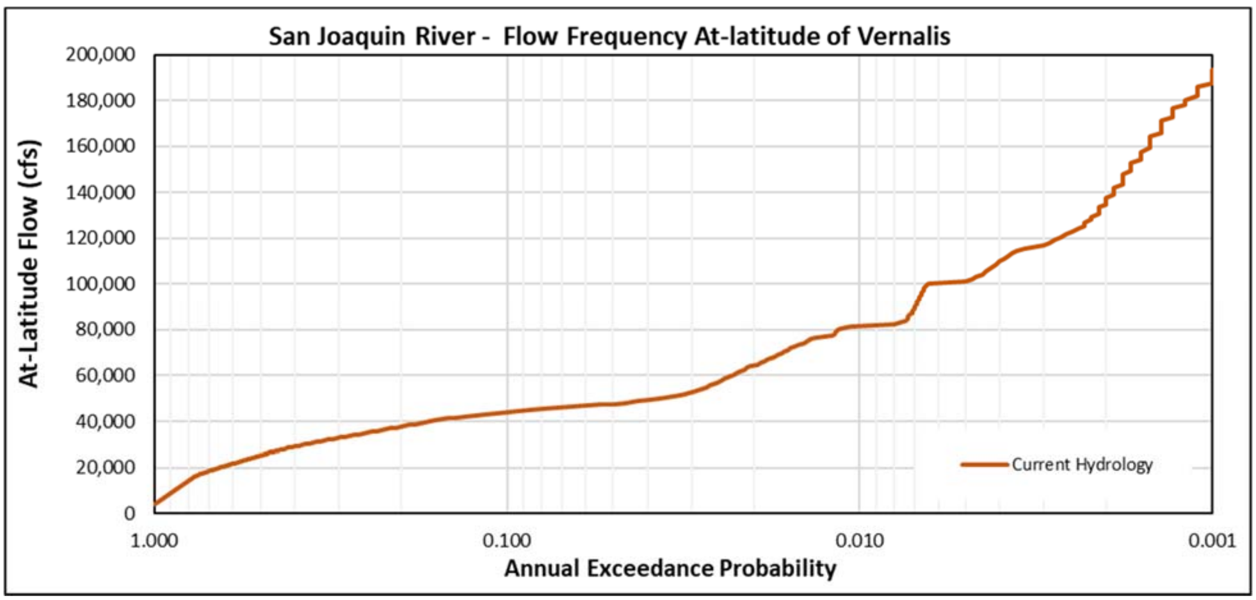


Figure 12: San Joaquin River Flow Frequency At-latitude of Vernalis for Current Hydrology

3.3.2 Climate Change Hydrology

In accordance with State and federal policy and technical guidance, the CVFPP 2017 Update used the latest climate science and understanding. The CVFPP climate change hydrology analysis uses 114 climate models projections from the Coupled Model Intercomparison Project Phase 5 (CMIP5) climate model data, which are the basis for the Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report (Intergovernmental Panel on Climate Change 2013). The climate models in the CMIP5 (Taylor et al., 2012; Rupp et al., 2013) were driven using 36 different general circulation models and 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. For the 2017 CVFPP Update, three scenario pathways (RCP4.5, RCP6.0 and RCP8.5) were used in the CMIP5 (van Vuuren et al., 2011). The climate model projections were then bias corrected and statistically downscaled at 1/8th degree (about 12 km or 7.5 miles) spatial resolution by the Bureau of Reclamation and others (Bureau of Reclamation, 2013).

Changes in future climate were calculated as differences in the statistical properties of temperature and precipitation for a late-century conditions centered around 2084 (2070-2099) as compared to the properties over an historical reference period (1981-2010) focusing on a central tendency scenario. The projected changes were mapped to the observed natural variability sequence over 1915-2010 developed based on monthly PRISM (Daly et al., 1994) and daily Livneh et al. (2013) data sources. Finally, the temperature and precipitation time series for current hydrology and late-century hydrology were run through a hydrologic model to compute unregulated flow and provide estimates of potential changes throughout the Central Valley, based on newer available climate projections. The analyses specifically tailored to the Central Valley are described in detail in the 2017 CVFPP Update — Climate Change Analysis Technical Memorandum (California Depatment of Water Resources 2017b).

An important output from the climate change hydrology analysis are climate change factors, also called climate change ratio. The *climate change factors* are calculated for each annual exceedance probability and flood duration by dividing an unregulated volume-frequency curve from the climate change hydrology simulations with late-century projections by an unregulated volume-frequency curve from the historical simulations.

The climate change factors were applied to the historical unregulated volume-frequency curves used in the CVFPP 2017 Update's risk analyses to compute future climate change hydrology unregulated volume. The unregulated flow frequencies were transformed to regulated flow frequencies following the Central Valley Hydrology Study procedure in order to make assessments of overall climate risk on flood management systems.

From the full range of events, at-latitude flow-frequency curves for climate change hydrology were developed and are presented in Figures 13 and 14 for the Sacramento River and San Joaquin River, respectively.

In Figures 13 and 14, one can observe the impact of late-century climate change projection on the at-latitude flow frequency entering the Delta. The Sacramento River flows may increase as much as 35 percent for extreme flood events under climate change hydrology. In the San Joaquin River, flows may increase significantly more under climate change hydrology. While both basins will likely experience a tendency for heavier precipitation during some extreme storms (Lavers et al. 2015), the San Joaquin Basin expresses greater changes from climate change effects on its historically dominant snowpack. This is because the San Joaquin Basin has higher elevations and a proportionately greater snowpack than the Sacramento River Basin, so temperature increases will produce a larger impact from shifts of precipitation from snow to rain, and thus a stronger increase in storm-related runoff (Hamlet et al. 2007, Das et al. 2011 and 2013).

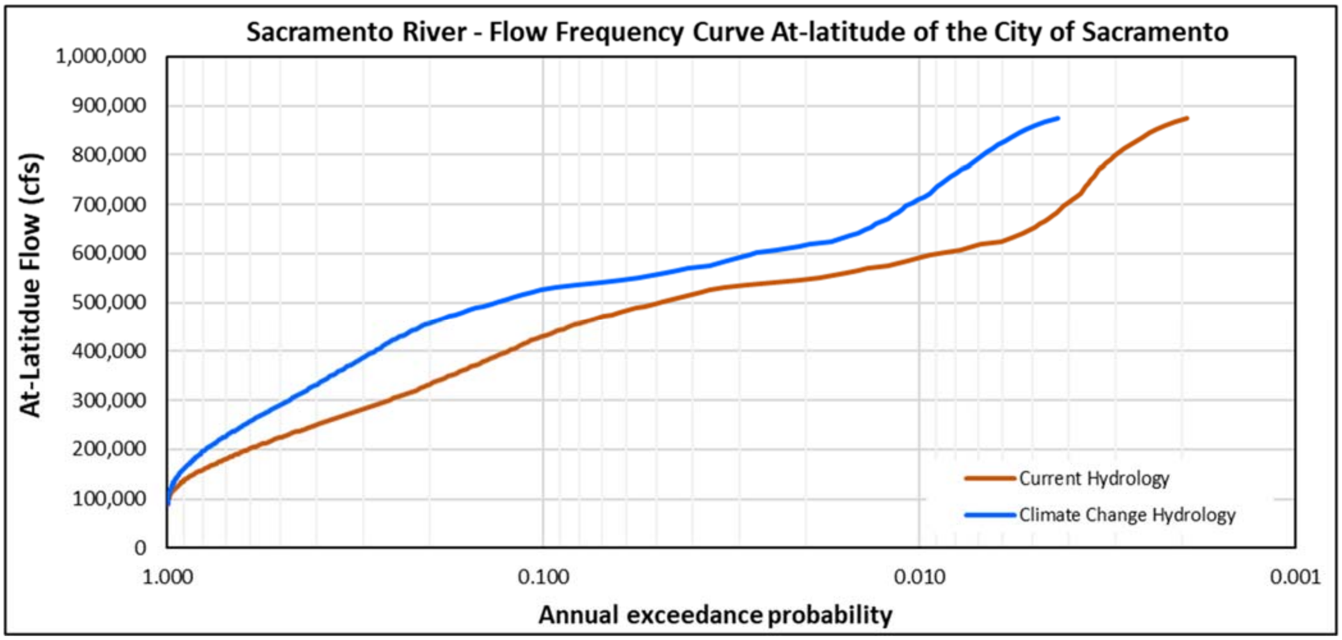


Figure 13: Sacramento River Flow Frequency At-Latitude of the City of Sacramento for Current Hydrology and Climate Change Hydrology

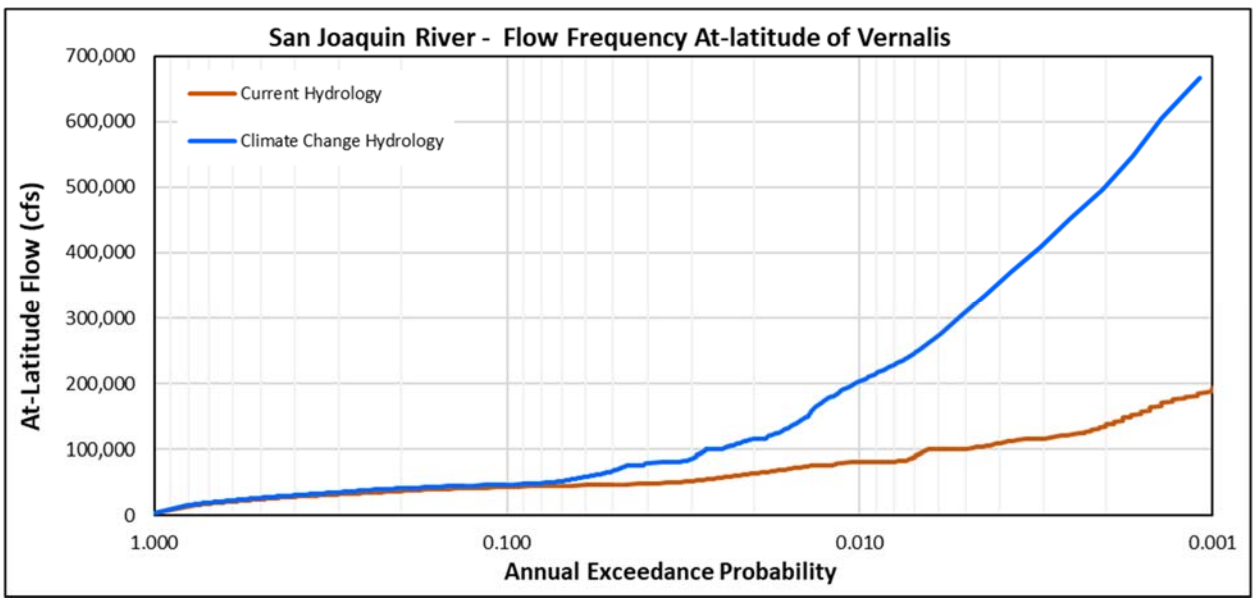


Figure 14: San Joaquin River Flow Frequency At-latitude of Vernalis for Current Hydrology and Climate Change Hydrology

3.3.3 Representative Flood Events for the RMA Bay-Delta model

The RMA Bay-Delta model simulations for the full range of scaled events would require a high computation expense cost because of the complexity of this 2-D model. To accelerate the modeling process without sacrificing representation of a full range of hydrology, DWR selected 10 CVHS flood-scaled event patterns listed in Table 2 based from the at-latitude flow frequency.

In the Sacramento Basin, these 10 CVHS flood-scaled events encompass the frequency range from 1 year to 1,000 years for current hydrology, and from 1 year to 500 years for climate change hydrology. In the San Joaquin Basin, these 10 CVHS flood-scaled events encompass the frequency range from 1 year to 1,000 years for current hydrology, and from 1 year to 200 years for climate change hydrology. Figure 15 shows the inverse of annual exceedance probability (AEP), or annual return period of flood for peak total Sacramento River flows at-latitude of the city of Sacramento. Figure 16 shows the inverse of AEP for peak total San Joaquin River flows at-latitude of Vernalis. Both Figures 15 and 16 show the frequency under current hydrology and climate change hydrology for a CVHS flood scaled event pattern. For example, the 1997 200 percent event in the Sacramento River has a little bit more than a 1,000-year return period of flood under current hydrology (blue bar) and becomes a 600-year return period flood under climate change hydrology (orange bar). For the San Joaquin River, the same scale event pattern is approximately a 4,000-year return period flood (blue bar) and becomes a 200-year return period flood under climate change hydrology (orange bar).

Table 2: CVHS Flood Events for RMA Bay-Delta Model

1956 0.1 scaled event	1997 1.15 scaled event
1986 0.4 scaled event	1956 1.2 scaled event
1986 0.6 scaled event	1997 1.4 scaled event
1986 unscaled event	1997 1.6 scaled event
1956 unscaled event	1997 2.0 scaled event

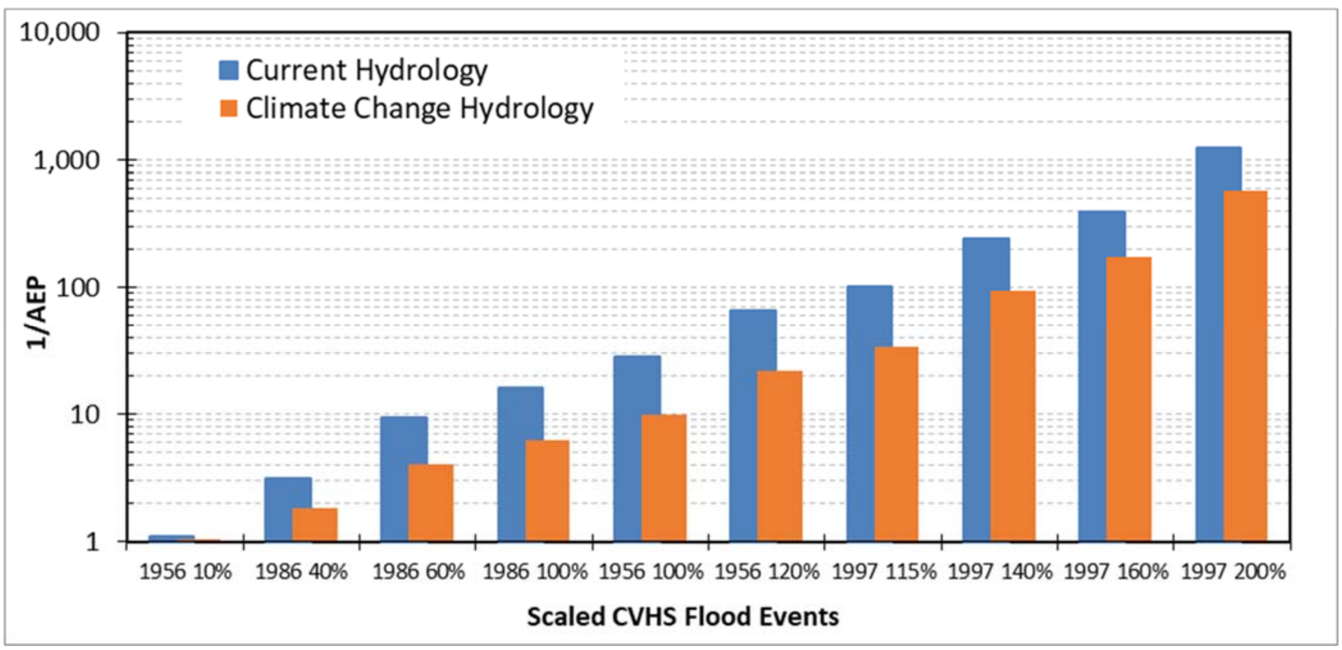


Figure 15: The Inverse of Annual Exceedance Probability (AEP) or Annual Return Period for Peak Total Sacramento River Flow Rate At-latitude of the City of Sacramento for Selected CVHS Flood Events

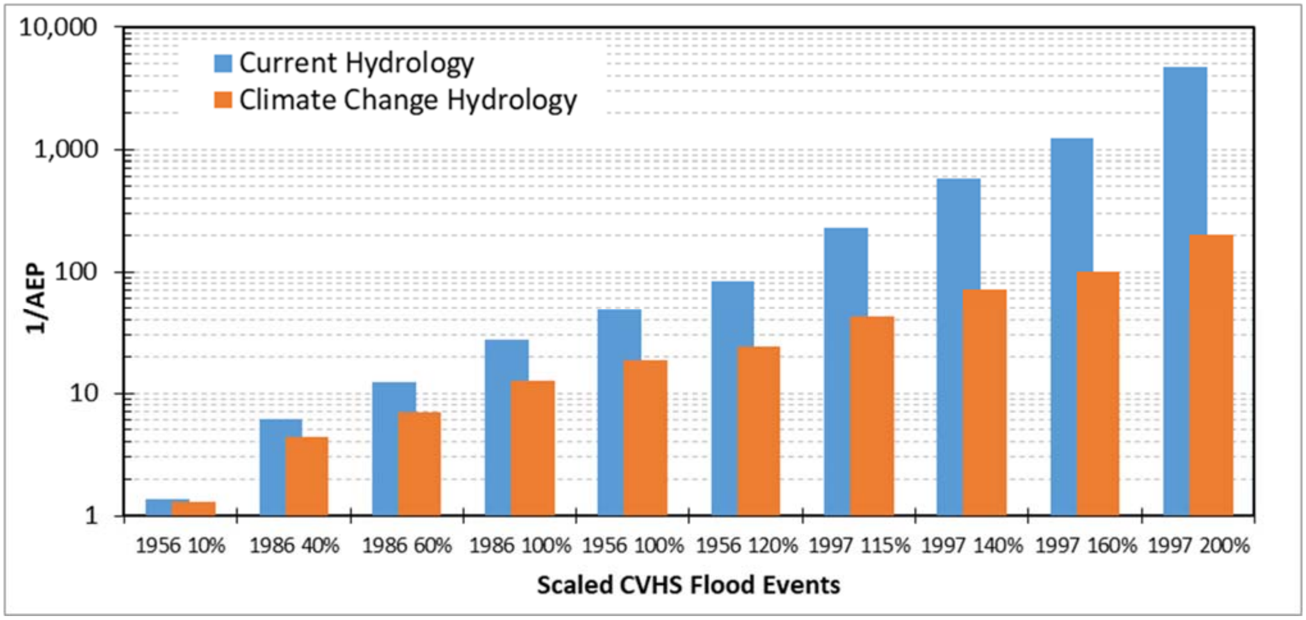


Figure 16: The Inverse of Annual Exceedance Probability (AEP) or Annual Return Period for Peak Total San Joaquin River Flow Rate At-latitude of Vernalis for Selected CVHS Flood Events

3.3.4 Upstream Boundary Flow Allocations

As shown in Figure 7, upstream boundary flows for RMA Bay-Delta model include: (1) total Sacramento River flows at-latitude of the city of Sacramento, (2) total San Joaquin River flow at-latitude of Vernalis, (3) eastern river inflows, including Mokelumne River, Cosumnes River, and Calaveras River, and (4) Central Valley Project and State Water Project exports at 4,000 cubic feet per second each. It was assumed there was no diversion for North Bay Aqueduct, Contra Costa Water District, and Delta Island consumptive use because of turbidity concerns.

3.3.4.1 Total Sacramento River Flows At-latitude of City of Sacramento

For each of the 10 selected flood-scaled event patterns in Table 2, Central Valley Floodplain Evaluation and Delineation hydraulic models flow-rate outputs that represent total Sacramento River flows at the latitude of the city of Sacramento (including Yolo Bypass flow, Sacramento Deep Water Channel, Sacramento River downstream of the confluence with American River, and overbank flows from the left bank of American River) were post-processed into eight flow hydrographs. These eight flow hydrographs were then assigned at eight locations as boundary inflows for RMA Bay-Delta model (shown with arrows in Figure 17).

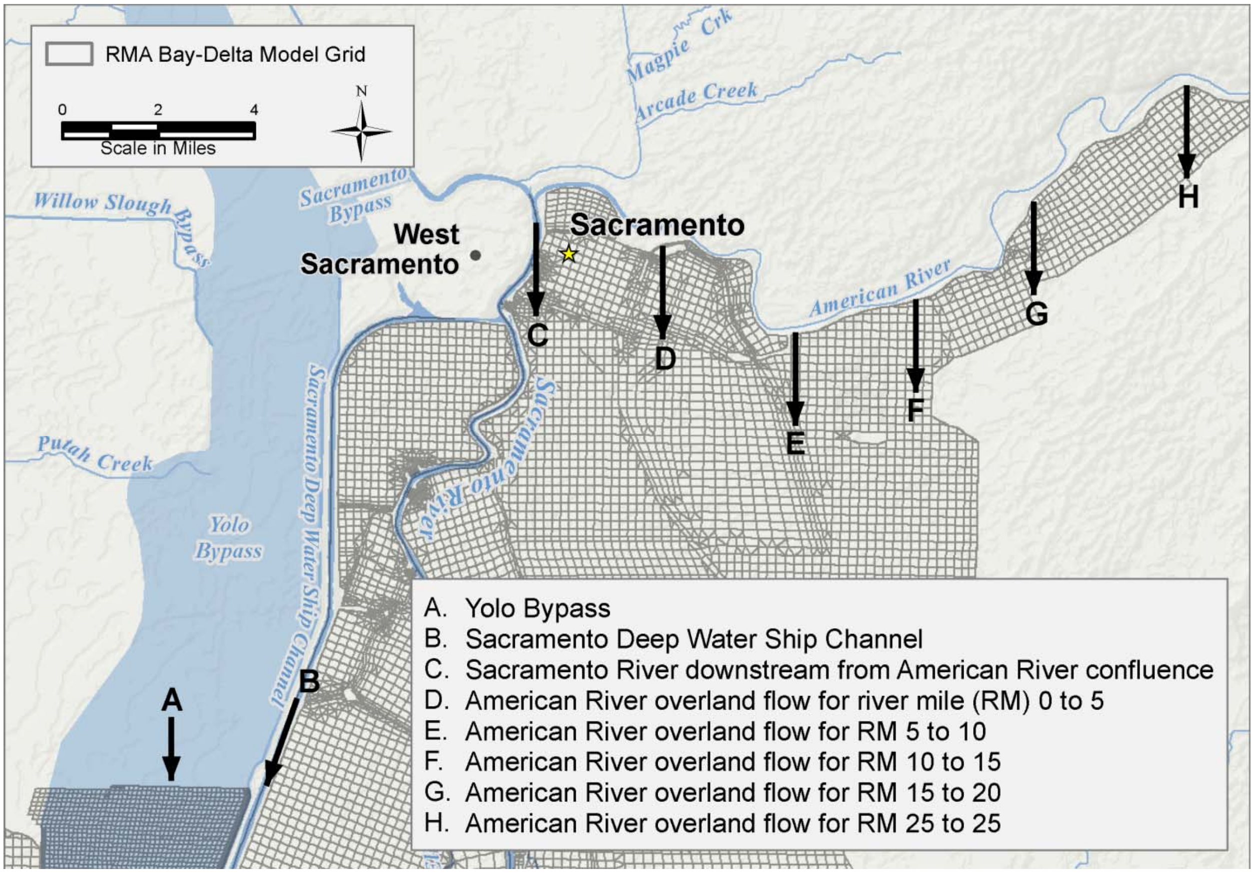


Figure 17: Boundary Flow Allocation for Total Sacramento River Flows At-latitude of the City of Sacramento

3.3.4.2 Total San Joaquin River Flows At-latitude near Vernalis

For each of the 10 selected flood-scaled event patterns in Table 2, Central Valley Floodplain Evaluation and Delineation hydraulic models flow-rate outputs that represent total San Joaquin River flows at-latitude of Vernalis (including San Joaquin River at Vernalis, overbank flows from the San Joaquin River, and overbank flows from the right bank of the Stanislaus River) were post-processed into seven flow hydrographs. These seven flow hydrographs were then assigned at seven locations as boundary inflows for RMA Bay-Delta model (shown with arrows in Figure 18).

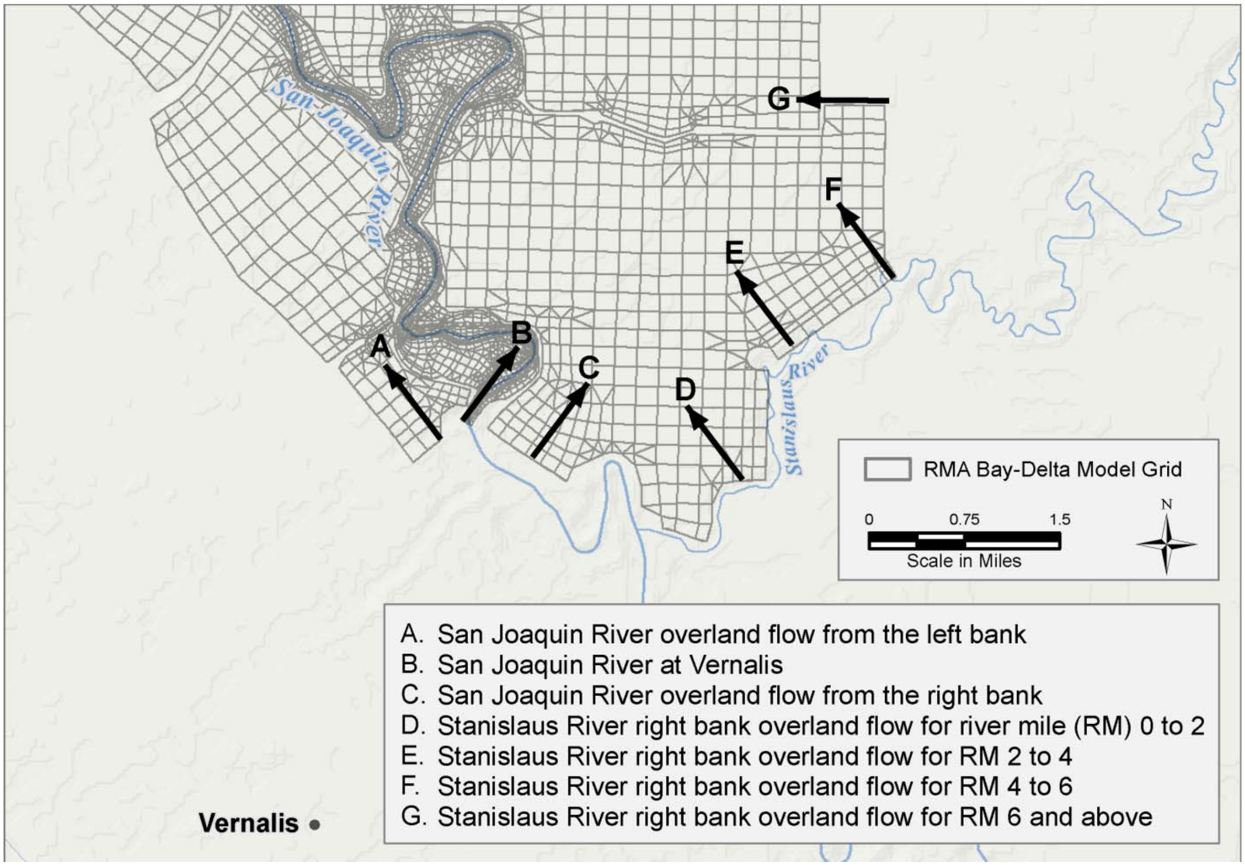


Figure 18: Boundary Flow Allocation for Total San Joaquin River Flows At-latitude of Vernalis

3.3.4.3 Eastside River Inflows

Calaveras River, Cosumnes River, and Mokelumne River were represented in the CVHS Hydrologic Engineering Center Reservoir System Simulation (HEC-ResSim) model for the San Joaquin River Basin.

For the Calaveras River, the 10 selected flood-scaled event patterns in Table 2 were collected from CVHS and applied into the RMA Bay-Delta model.

For the Cosumnes and Mokelumne rivers, the CVHS HEC-ResSim model assumptions were not reviewed after calibration at the same level as the remaining basins, creating some doubt on the validity in using those rivers' hydrology from CVHS. As a result, the DWR's Dayflow time-series of Cosumnes and Mokelumne river flows for the 1956, 1986, and 1997 flood events were used instead as inflows into the RMA Bay-Delta model. Because the Cosumnes River is an unregulated river, Dayflow hydrographs were scaled up and down in accordance with the selected flood event patterns in Table 2. The Mokelumne River is a regulated river; no scaling was performed because this is inappropriate without reservoir simulations.

3.3.5 Golden Gate Bridge Tidal Assumptions

Figure 19 presents the tidal conditions during the January 1997 flood events. In this figure, the relationship between predicted tide, storm tide, and storm surge can be seen. The storm surge residual for this specific event was 1.32 feet on January 1.

In Figure 19, the 1997 flood event contribution from the Sacramento and San Joaquin river basins in the Delta is presented under unregulated and regulated conditions. These flow hydrographs were simulated with the CVHS hydrology data.

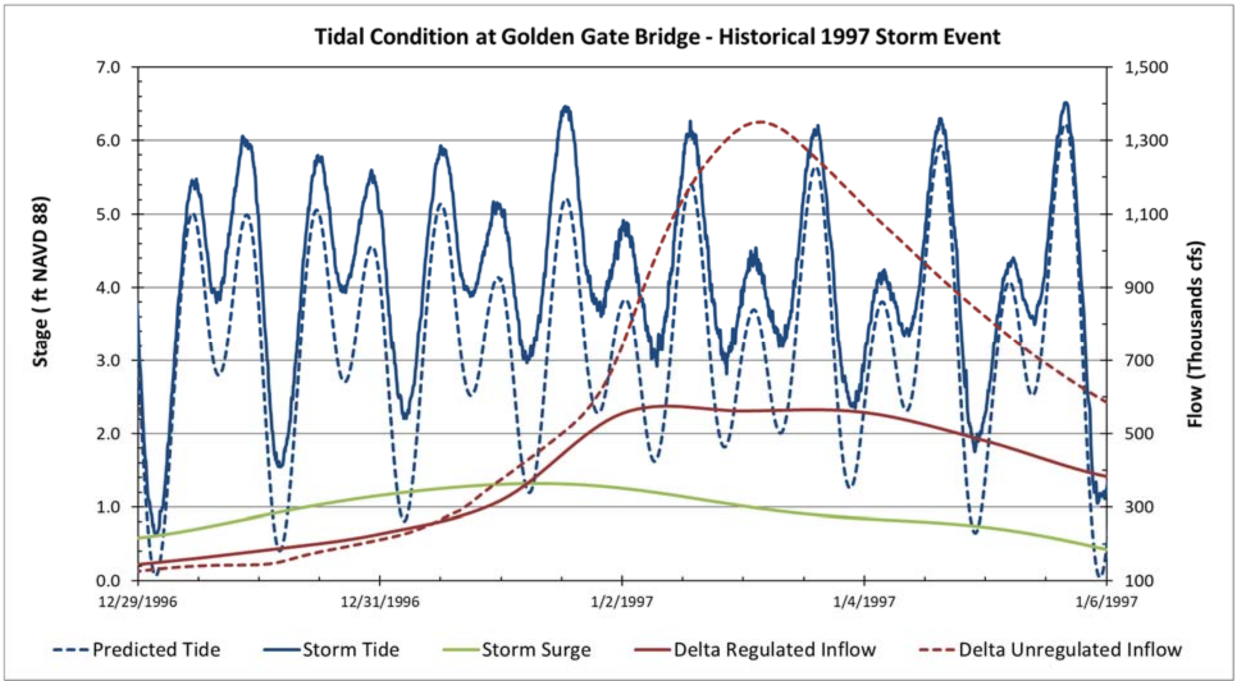


Figure 19: Tidal Conditions at the Golden Gate Bridge during the January 1997 Flood Events with Delta Regulated and Unregulated Flow.

There have been few efforts to correlate tides at the Golden Gate Bridge to the Central Valley flood events. Bromirski et al., (2008) showed that a relationship exists between non-tidal conditions at the Golden Gate Bridge and total daily flow in the Delta. However, the article did not provide regression applicable to determine the non-tidal conditions at the Golden Gate Bridge as a function of flow into the Delta.

For this study, DWR used historical data to develop a correlation between storm surges and flood events. It also established a reasonable representation of the Golden Gate Bridge storm tide that is a combination of storm surge and predicted tide. The following section provides detailed development of tidal assumptions for the Golden Gate Bridge as follows:

1. Determine the 99 percent AEP (1-year return period flood) mean sea level hydrograph with predicted tide.
2. Define the storm surge through:

A. Shape (independent of the size of flood events).

B. Timing (75 hours lag, independent of the size of flood events).

C. Magnitude (dependent and varied with the size of flood events).

3. Define the Golden Gate Bridge deterministic tidal hydrograph as the summation of the mean sea level, the predicted tide, and the storm surge.

4. Repeat Steps 2 and 3 for all 10 selected CVHS flood events to generate a deterministic tidal hydrograph at the Golden Gate Bridge for RMA Bay-Delta model simulation.

3.3.5.1 Mean Sea Level with Predicted Tide

For small flood events (storms with an AEP of 50 percent or more), tidal conditions at the Golden Gate Bridge are the dominating factor for water surface elevation in the Delta because flood flows are not large enough to override tidal effects. A historical predicted tide with an AEP equal to 99 percent (i.e., water levels at Golden Gate Bridge that has a 99% chance of occurring in any given year) was selected to represent the predicted tide for all flood events. National Oceanic and Atmospheric Administration (NOAA) provides the annual highest water levels for an AEP from 99 percent through 1 percent relative to the mean higher high-water (MHHW) after the mean sea level trend was removed for San Francisco (NOAA station 9414290, see Figure 20). For AEP of 99 percent, NOAA indicated the water level would be about 6.82 feet in NAVD 88 at the Golden Gate Bridge using the following calculation:

1. MHHW from NOAA at Golden Gate Bridge Station data = 11.82 feet.

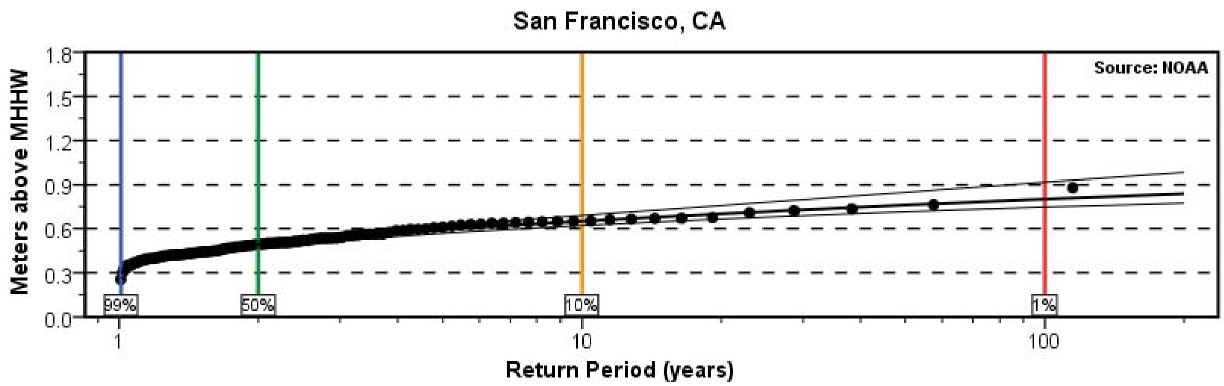
2. NAVD88 from NOAA at Golden Gate Bridge Station data = 5.92 feet.

3. NOAA's estimated 99 percent AEP water level above MHHW = 0.28 meter.

4. Convert NOAA's estimated 99 percent AEP water level from meters to feet,
   0.28 meter × 3.28 feet/meter = 0.92 feet above MHHW.

5. Mean sea level with predicted tide adjusted for data,
   11.82 feet + 0.92 feet - 5.92 feet = 6.82 feet in NAVD 88.

The peak predicted water level for Water Year 2011 (i.e., October 1, 2010 through September 30, 2011) at NOAA station 9414290 is 6.78 feet in NAVD 88 on January 19, 2011 at 18:18 hours (GMT) (see Figure 21). As a result, DWR selected Water Year 2011 and the predicted water level for NOAA station 9414290 to represent the mean sea level with predicted tide for the Golden Gate Bridge. This 2011 sea level hydrograph was shifted to align the timing of the peak predicted water level with the timing of peak storm surge as described in the following section.



Source: National Oceanic and Atmospheric Administration (NOAA) 2015

Figure 20: NOAA's Inverse Annual Exceedance Probability (1/AEP) or Annual Return Period Curve with 95 Percent Confidence Intervals for the Highest Water Levels at San Francisco (Station 9414290) MHHW Datum

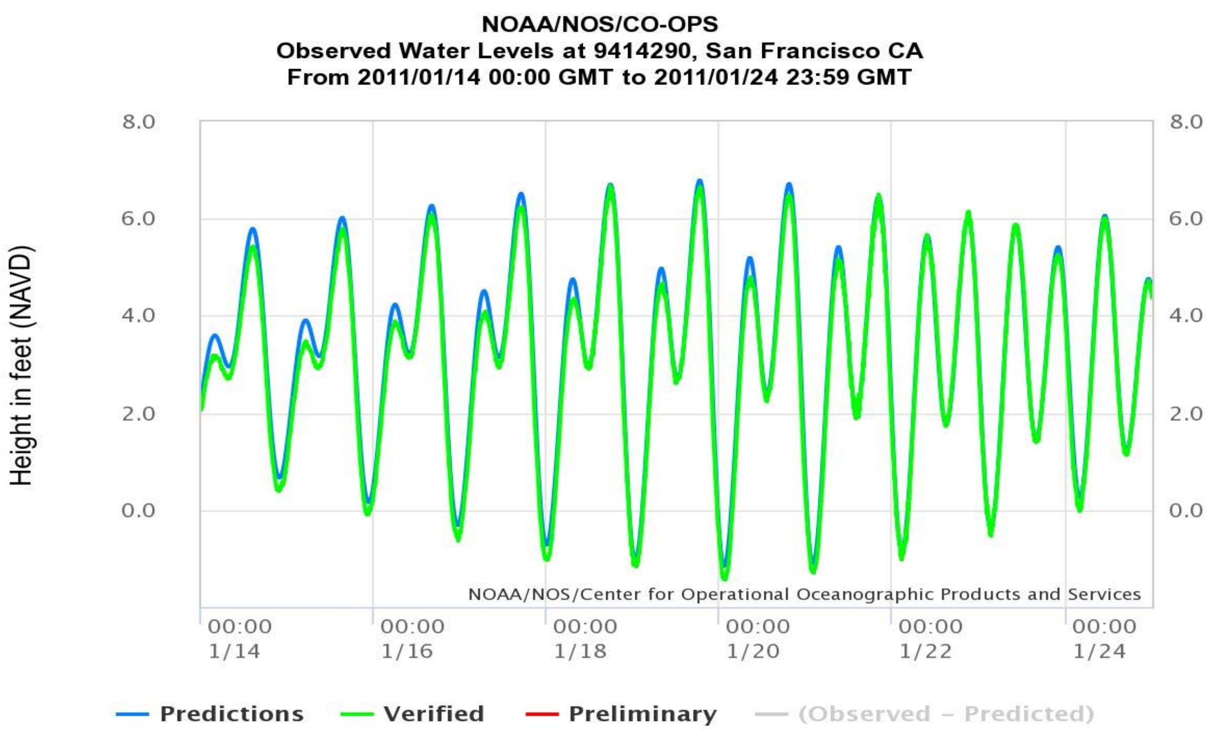


Figure 21: NOAA's Water Level Records from January 14 through 24, 2011 at San Francisco (Station 9414290) Relative to the Mean Lower Low Water Datum

3.3.5.2 Timing of Peak Storm Surge

Because "unregulated" refers to a condition of the system absent of reservoir and floodplain storage, the unregulated flow is a better representation of the natural hydrologic cycle that correlates with the occurrence of storm surge. Note that even though regulated flows that reflect reservoir operations and floodplain storage were used for the study evaluations, they were not used to establish peak storm surge because flood control system operations have a poor correlation with the occurrence of storm surge caused by an anthropogenic effect. During a flood event, the Sacramento and San Joaquin rivers are the two dominating inflows into the Delta. The total of their unregulated flows at-latitude of Sacramento and Vernalis was used to develop a correlation with the storm surge based on the CVHS for Water Years 1921–2008.

For the wet season (November through April) of Water Years 1921–2008, the time lapse between the historical peak storm surge and peak unregulated flow for each storm event was evaluated through lag-correlation, also known as cross-correlation. The lag-correlation uses an auto correlation function (ACF) to measure the similarity of two series as a function of the lag of one relative to the other. Figure 22 shows this relationship for 500 time steps, with each time step equal to one hour. There is a strong correlation of the peak total unregulated flows lagging 75 hours behind the peak storm surge at the Golden Gate Bridge. Individual lag will vary greatly with the storm centering location. For example, peak flood flows from a storm centering at Shasta Lake would take about four days to reach the Delta; for storm centering at the American River, it would take about two days to reach the Delta (as examples, see the January 1997 flood events depicted in Figure 19). In this study, for simplification, it is assumed the peak storm surge would occur 75 hours before the peak of total unregulated flows at-latitudes of Sacramento and Vernalis.

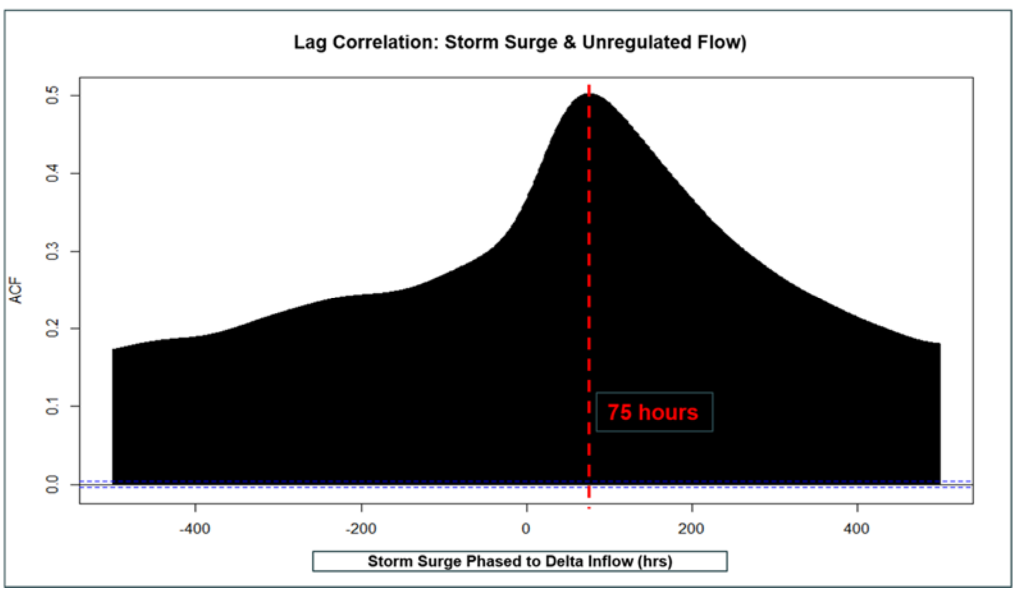


Figure 22: Lag-correlation between the Historical Peak Storm Surge and Peak Unregulated Flow from 1921 to 2008

3.3.5.3 Magnitude of Storm Surge

Using the peak storm surge and peak unregulated flow data from Water Years 1921–2008, a scatter plot of peak storm surge and peak unregulated flow was developed (Figure 23). A local regression, using 500 points in the moving regression, was developed using Visual Basic for Applications (Cleveland and al. 1988 and Peltier 2009) and is shown as the series red square boxes. In general, as the unregulated flow increases, the lower bound of the storm surge increases. The upper bound of the storm surge is constant at 1.5 feet (except for some outlier events such as 1998, an El Niño year with more than usual storm surge). This regression was applied to estimate the peak storm surge from the peak total unregulated flows at-latitude of Sacramento and Vernalis. This estimated peak storm surge was then used to scale the storm surge shape developed in the next section.

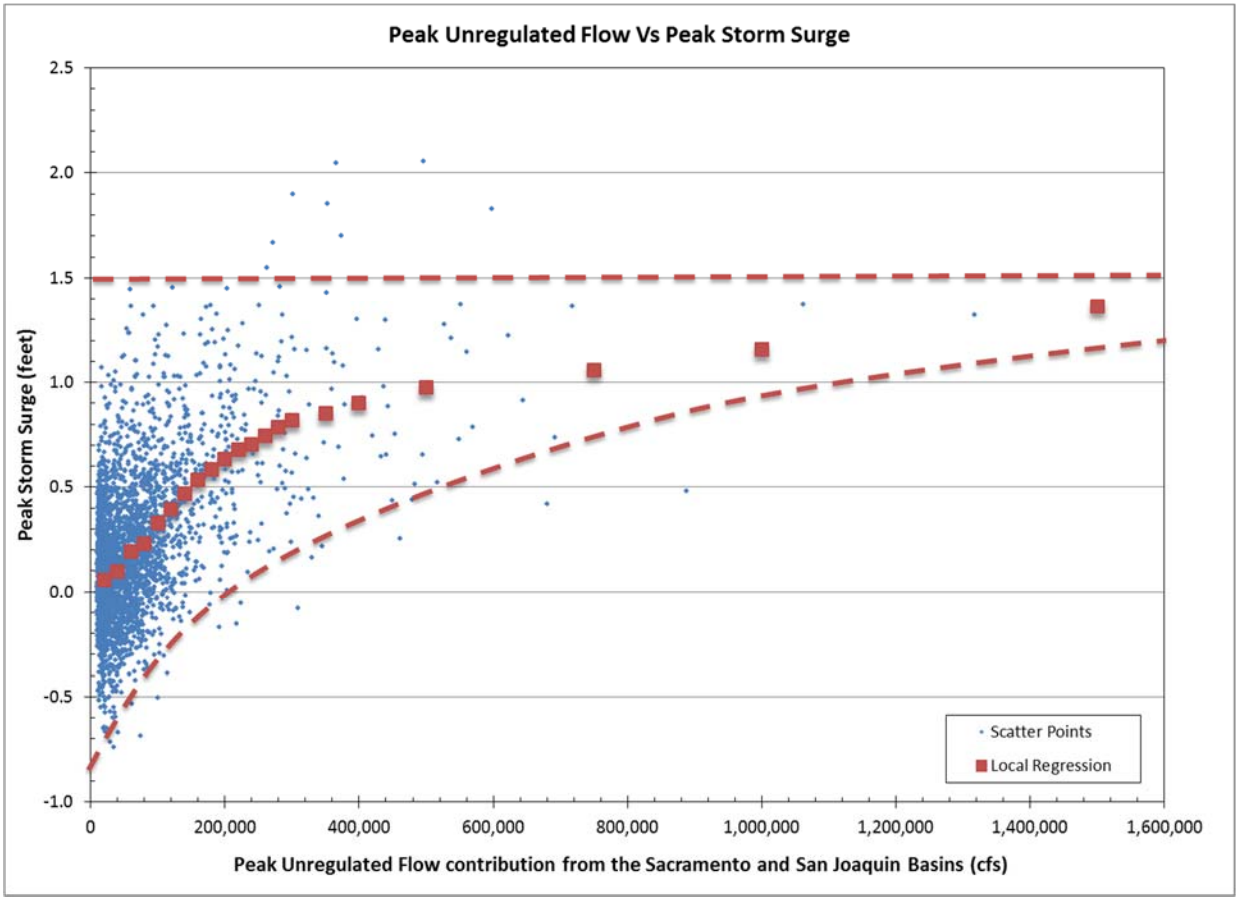


Figure 23: Historical Peak Storm Surge Adjusted for Sea Level Rise and Peak CVHS Unregulated Flow from Sacramento and San Joaquin Rivers for Water Years 1921 through 2008

3.3.5.4 Shape of Storm Surge

The shape of the storm surge (which is observed tide minus predicted tide, after eliminating the gravitational effects and sea level rise), varies with storms. Figure 24 compares historical Golden Gate Bridge storm surge during flood events in 1951, 1956, 1965, 1986, 1997, and 1998, with their peak aligned on day 32. The first five storms were selected as representative flood events in the CVSH. The 1998 storm surge was the largest in 80 years of record. For each time step, the average of these six storm surges was calculated to develop the average storm surge (red line in Figure 24). This average storm surge was then scaled uniformly by correlating the peak storm surge to the size of the storm, as described in the following section.

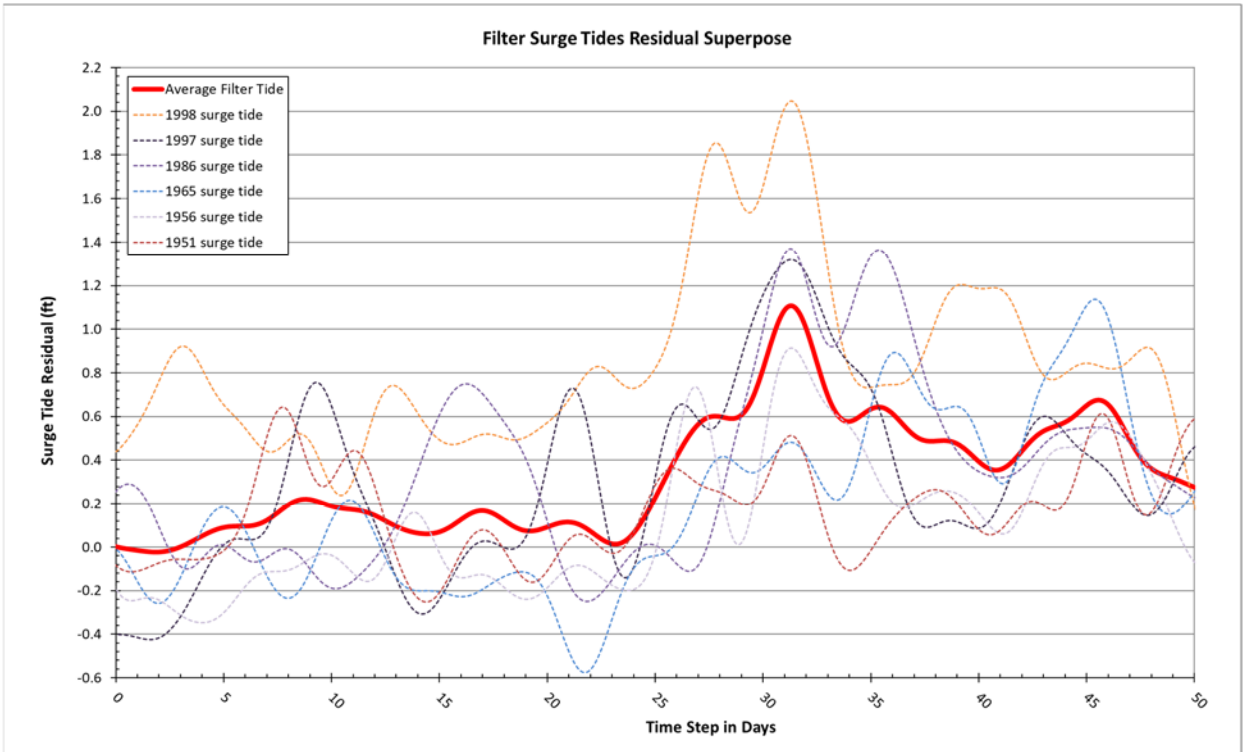


Figure 24: Historical Storm Surge at the National Oceanic and Atmospheric Administration Station 9414290 in San Francisco

3.3.6 Projected Sea Level Rise at the Golden Gate Bridge

Tidal gauges show that global sea level has risen approximately 7 inches during the 20th century, and recent satellite data show that the rate of sea level rise is accelerating. Figure 9 shows the relative sea level trend for the Golden Gate Bridge. As the earth warms, sea levels are rising mainly because ocean water expands as it warms, and water from melting glaciers and ice sheets is flowing into the ocean. Sea level rise poses enormous risks to the valuable infrastructure, development, and wetlands that line much of the 1,600-mile shoreline of California, Oregon, and Washington. As those states seek to incorporate projections of sea level rise into coastal planning, they asked the National Research Council (NRC) of the National Academies to make independent projections of sea level rise along their coasts for the years 2030, 2050, and 2100, taking into account regional factors that affect sea level. NRC's committee on Sea Level Rise in California, Oregon, and Washington led this study, which was supported by DWR, NOAA, USACE, and the U.S. Geological Survey.

In 2012, the NRC released its findings in *Sea-Level Rise for the Coasts of California, Oregon, and Washington: Past, Present, and Future* (National Research Council 2012). This report explains that sea level along the United States' West Coast differs from global mean sea level rise because of local steric (primarily thermosteric) contributions, dynamic height differences caused primarily by changes in winds, the gravitational and deformational effects of modern land ice melting, and vertical land motions along the coast. NRC projected the contributions of these components to sea level rise off the California, Oregon, and Washington coasts for the years 2030, 2050, and 2100, relative to year 2000. DWR used NRC's late-century low bound projection for San

Francisco. This late-century low bound projection corresponds approximatively to a mid-century mean projection around year 2062 with a projected sea level rise of 1.27 feet (Table 3). The projected 1.27 feet of sea level rise was added to the deterministic tide hydrographs of the Golden Gate Bridge as the downstream boundary conditions for the RMA Bay Delta model.

Table 3: National Research Council's Estimated Value of Future Sea Level Rise at the Golden Gate Bridge, California

Year	Range: Low Bound	Projection (Mean Only)	Range: High-Bound
2030	4.3 cm	14.4 cm	29.7 cm
2050	12.3 cm	28.0 cm	60.8 cm
2062[a]	18.5 cm (0.61 foot)	38.8 cm (1.27 feet)	83.1 cm (2.73 feet)
2100	42.4 cm	91.9 cm	166.4 cm

Source: National Research Council 2012
Notes: cm = centimeters
[a] Interpolation from third order of polynomial to National Research Council estimate.

3.3.7 Simulated Estuarine Boundary Conditions

Following the procedures outlined in the previous sections, 20 deterministic tide hydrographs (10 without sea level rise and 10 with sea level rise) were created for the 10 selected CVHS scaled event patterns. Figure 25 shows an example of a deterministic tide hydrograph at the Golden Gate Bridge for the CVHS 1997 1.15 scaled event. Using the shape of the storm surge outlined in section 3.3.5.2, the magnitude of the storm surge was sized based on the peak unregulated flow of the scaled event (section 3.3.5.3) and the timing of the tide hydrograph stage peak is phased to 75 hours before the peak of total unregulated flows from the Sacramento and San Joaquin rivers (section 3.3.5.4). This deterministic tide hydrograph was then applied as the downstream boundary condition in RMA Bay-Delta model for this specific CVHS flood event.

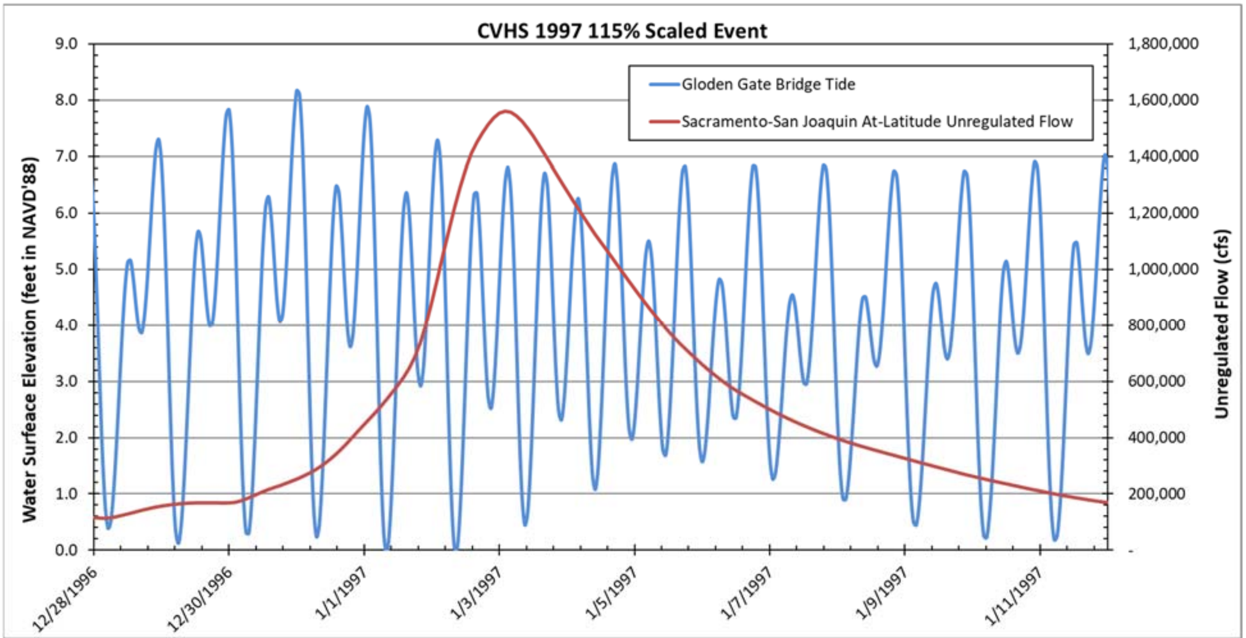


Figure 25: Deterministic Tide Hydrograph at Golden Gate Bridge for CVHS 1997 1.15 Scaled Event as Downstream Boundary Condition of RMA Bay-Delta Model

The RMA Bay-Delta model then generated stage hydrographs at the appropriate physical locations which are then used as downstream boundaries of the CVFED trimmed hydraulic models (Figure 26). In the San Joaquin CVFED trimmed hydraulic models, these boundaries are located near the intersection of Grant Line Canal (GLC) and Old River (ODR); by the intersection of Middle River and Victoria Canal (MDR), and downstream of Stockton for the San Joaquin River (SJR) and Burns Cutoff (BCO). In the Sacramento CVFED trimmed hydraulic models, these boundaries are located near Collinsville for the Sacramento River (CSE); by the intersection of Georgiana Slough and Mokelumne River (GSM), and by the intersection of Three Mile Slough and San Joaquin River (TSL).

Figure 27 shows the stage hydrographs of CVHS 1997 1.15 scaled event for the Sacramento River at Collinsville, which is one of the downstream boundary locations for the Sacramento River CVFED hydraulic model. Figure 28 shows the stage hydrographs of CVHS 1997 1.15 scaled event for the San Joaquin River at the Port of Stockton, which is one of the downstream boundary locations for the San Joaquin River CVFED hydraulic model.

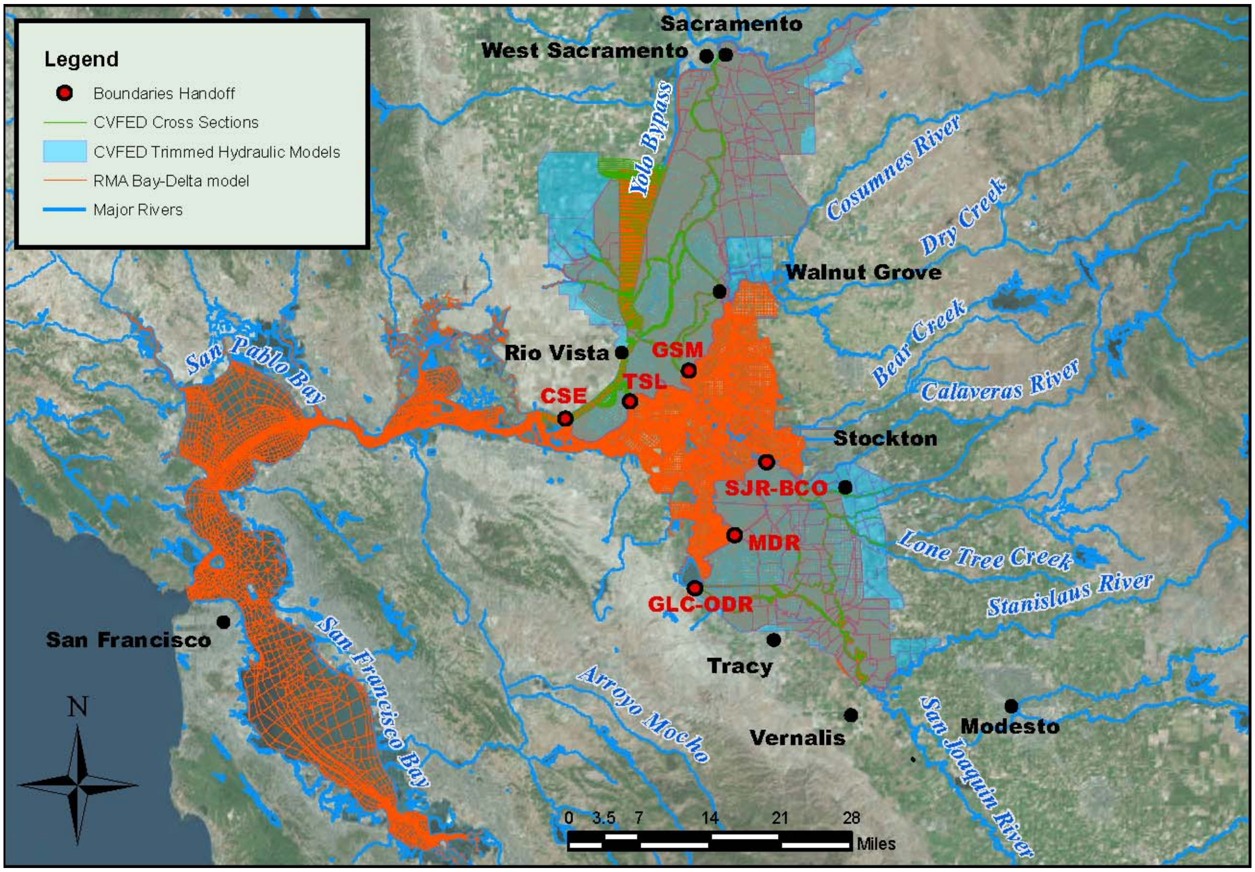


Figure 26: RMA Bay Delta Model, Central Valley Floodplain Evaluation and Delineation (CVFED) Trimmed Hydraulic Models and Downstream Boundary Conditions Locations Handoff

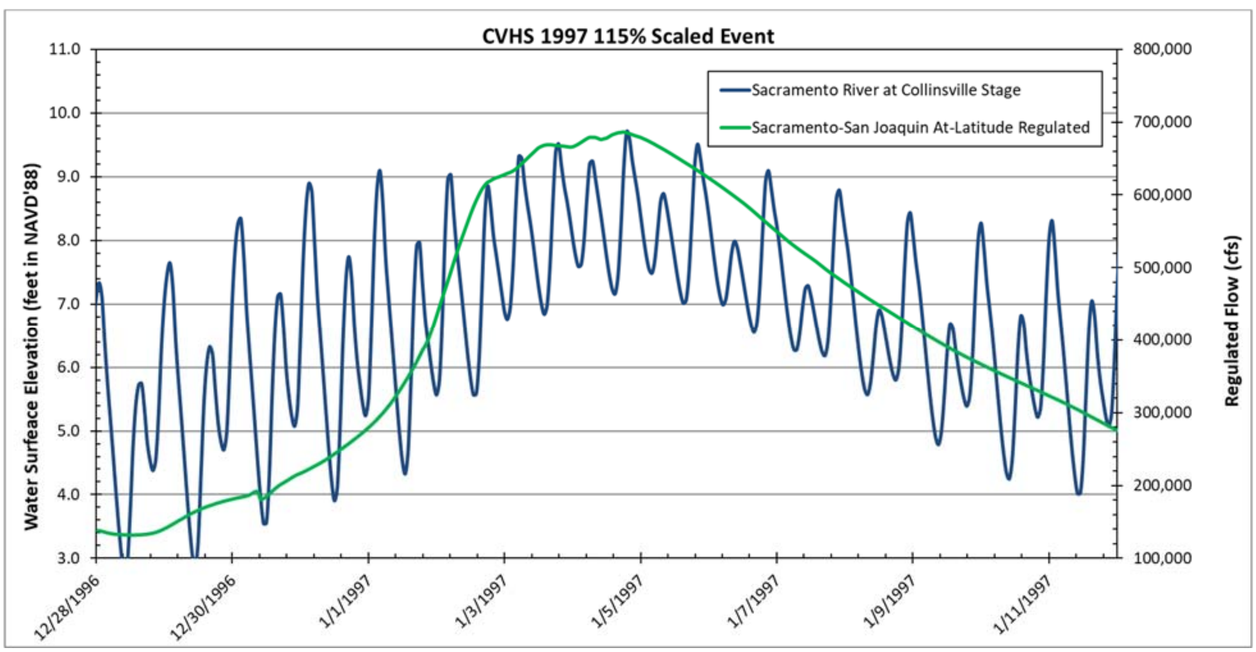


Figure 27: RMA Bay-Delta Model Simulated Stage Hydrograph for CVHS 1997 1.15 Scaled Event for the Sacramento River at Collinsville

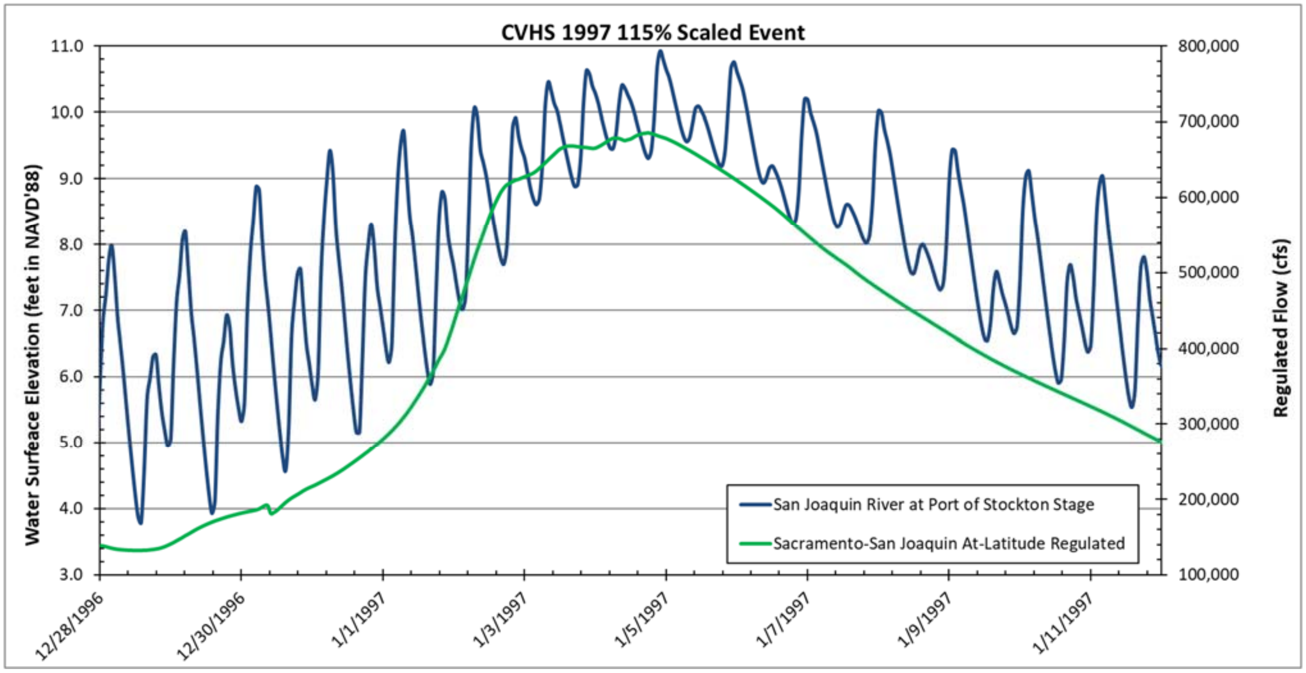


Figure 28: RMA Bay-Delta Model Simulated Stage Hydrograph for CVHS 1997 1.15 Scaled Event for the San Joaquin River at the Port of Stockton

3.3.8 Stage Discharge Rating Curves

By routing flood scaled event patterns listed in Table 2 through the RMA Bay-Delta model, stage hydrographs were developed and applied to the CVFED hydraulic trimmed models' downstream boundary locations (Figure 26). The CVFED trimmed hydraulic models were then run with these updated boundary conditions to develop tidal-influenced stage hydrographs at the index point locations. Here, the stage hydrographs were used from the CVFED trimmed hydraulic models instead of the RMA Bay-Delta model results to be consistent with the CVFPP 2017 Update technical work. The upstream boundary conditions of the CVFED trimmed hydraulic models match the CVFED hydraulic models output to develop at-latitude flow frequency curves.

The stage discharge rating curves at each index point location were created by matching the peak stage from the CVFED trimmed hydraulic models to the peak at-latitude flow for each of the 10 selected flood-scaled event patterns. The matches were done for with and without sea level rise. In total, 84 stage discharge rating curves were created for 54 index point locations. Twelve index points are situated at the same geo-location.

Figures 29 and 30 show three stage discharge rating curves along the Sacramento and San Joaquin rivers, going downstream from the top of the rivers. The locations of these curves can be found on Figure 31. At the entry of the Delta (IP SAC42 and SJ28), sea level rise has no or little effect on the curves because of higher ground. As the stage discharge rating curves approach the center of the Delta, sea level rise has a greater effect on the curves. Even for the largest flows, 1.27 feet of sea level rise at the Golden Gate Bridge corresponds to approximately 0.5 foot of sea level rise at IP SAC58 and SJ54-55.

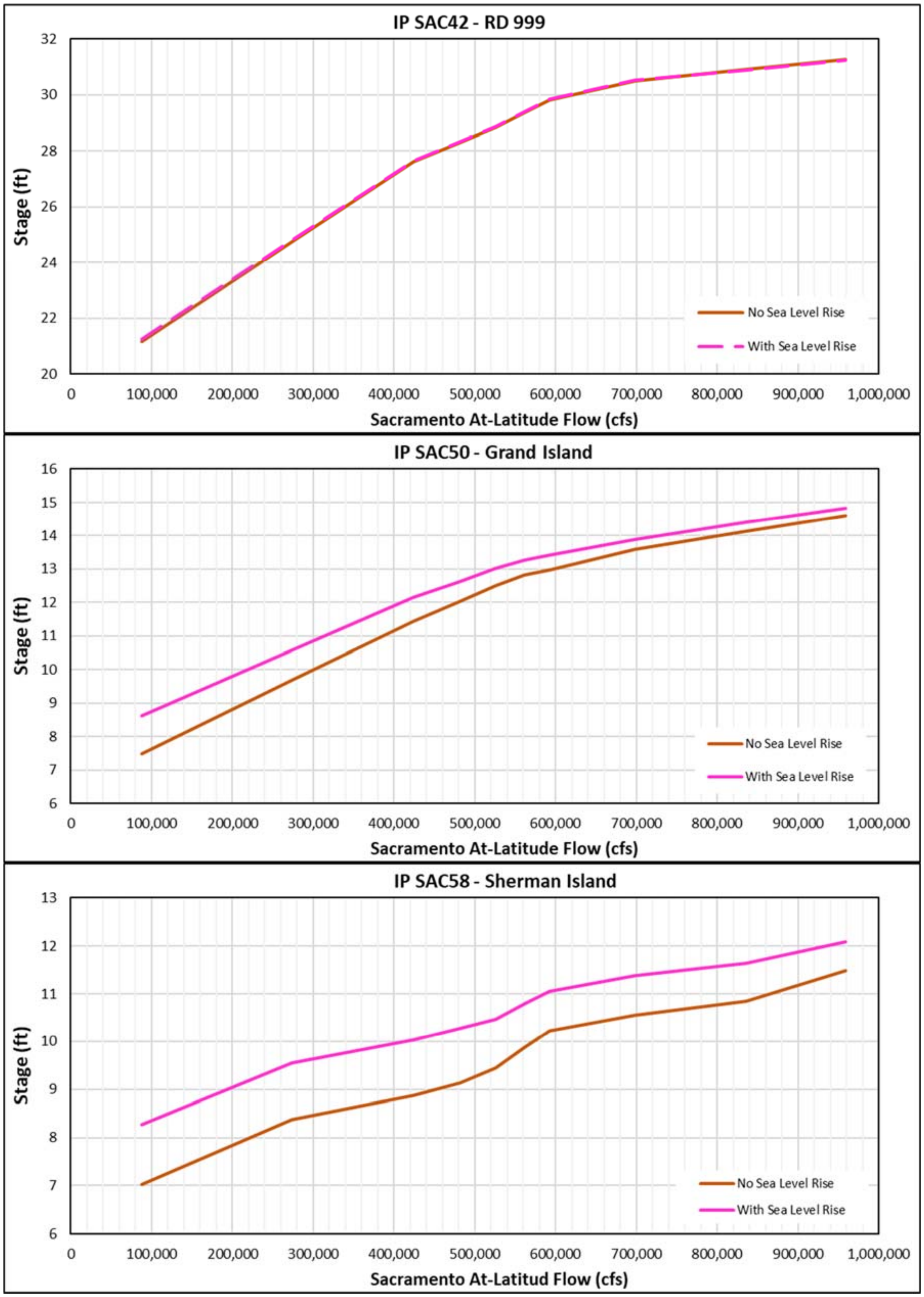


Figure 29: Stage Discharge Rating Curves for Conditions With and Without Sea Level Rise for 3 Index Points (IP) along the Sacramento River Basin

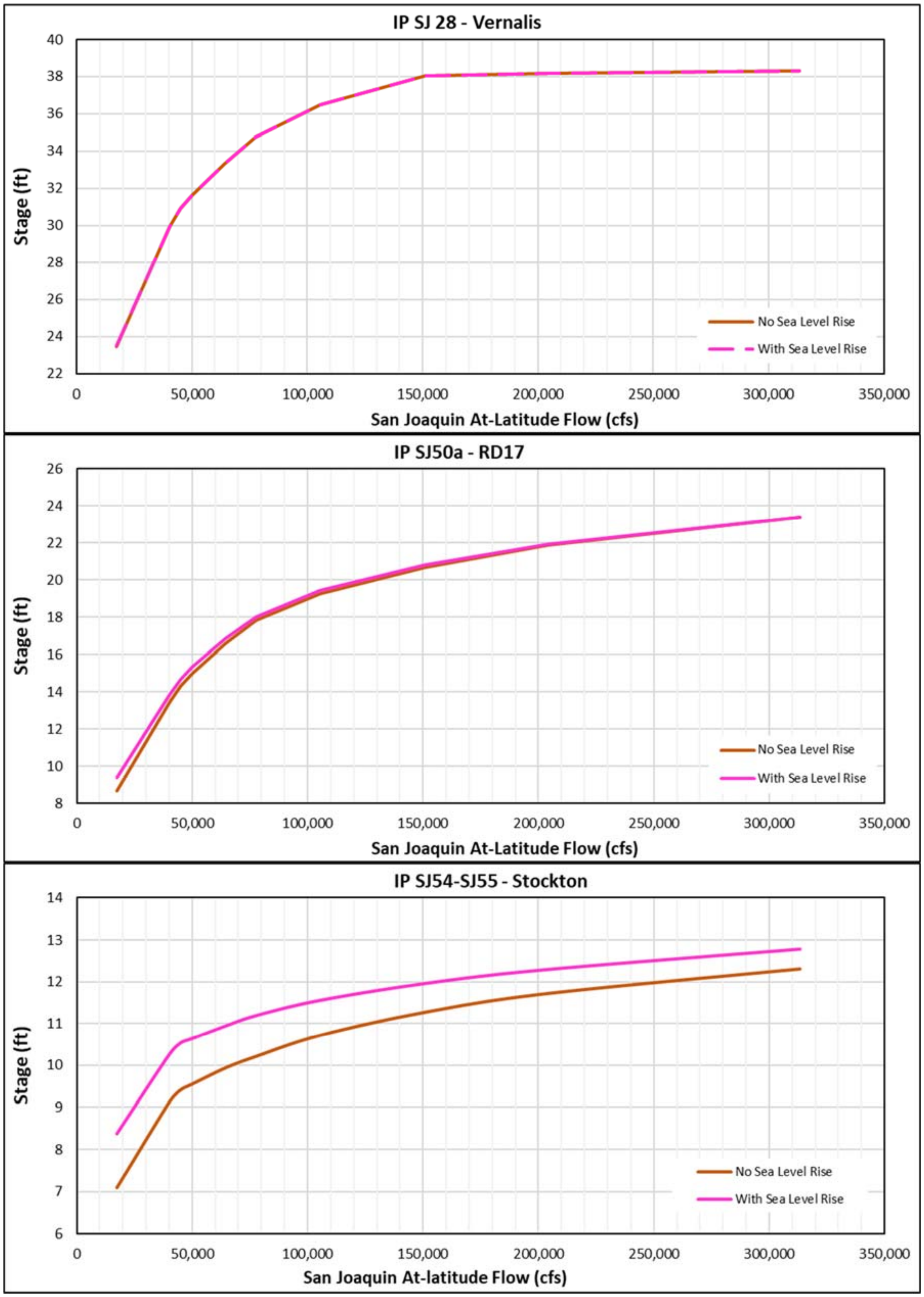


Figure 30: Stage Discharge Rating Curves for Conditions With and Without Sea Level Rise for 3 Index Points (IP) along the San Joaquin River Basin

3.3.9 Stage Frequency Curves

The last step of the method is to combine the at-latitude flow frequency curve (Section 3.3.1) to the stage discharge rating curves (Section 3.3.8) by matching at-latitude flows from the two curves, as depicted in Figure 4.

Table 4 shows the combination between at-latitude flow frequency curves and stage discharge rating curves to develop stage frequency curves for current hydrology, current hydrology with sea level rise, and climate change hydrology with sea level rise.

Table 4: Combination Between At-Latitude Flow Frequency curves and Stage Frequency Curves to Develop Stage Frequency Curves

At-Latitude Flow Frequency Curve	Stage Discharge Rating Curves	Stage Frequency Curves
Current Hydrology	Without Sea Level Rise	Current Hydrology
Current Hydrology	With Sea Level Rise	Current Hydrology with Sea Level Rise
Climate Change Hydrology	With Sea Level Rise	Climate Change Hydrology with Sea Level Rise

These resulting stage-frequency curves are discussed in detail in the next section and were applied into the risk assessment of the CVFPP 2017 Update.

4: Results and Discussions

Stage-frequency curves for current hydrology, current hydrology with sea level rise, and late-century climate change hydrology with sea level rise were developed for multiple index points (IPs). An index point is a specific location that is representative of a river reach with consistent hydrologic, hydraulic, and geotechnical characteristics. Flood risk is analyzed by evaluating its effect on an impact area. An impact area is the delineation of a specific portion of the floodplain that is vulnerable to a flood hazard from the reach associated with the index point locations. Figure 31 shows 54 index point locations where the method presented in Section 3.3 has been used to develop 126 stage-frequency curves presented in Appendix A. Twelve index point are situated at the same geo-location.

This chapter validates the method by comparing current hydrology stage-frequency curves to results from previous studies results at key index point locations. That is followed by a discussion on the change in stage-frequency curves between current hydrology, current hydrology with sea level rise, and climate change hydrology with sea level rise. Finally, the chapter presents water surface elevation profiles along the Sacramento and San Joaquin rivers for various magnitudes of flood events compared to the top of levee elevations.

Both stage-frequency curves and water surface elevation profiles provide important information to decision makers regarding the vulnerability of levee overtopping for specific flood events as well as annual exceedance probability of water surface elevation along the Delta levee system. For example, the stage-frequency curves developed in the Central Valley Flood Protection Plan (CVFPP) 2017 Update were used to evaluate flood damage (expected annual damage) and life risk (expected annual life loss) for the Central Valley.

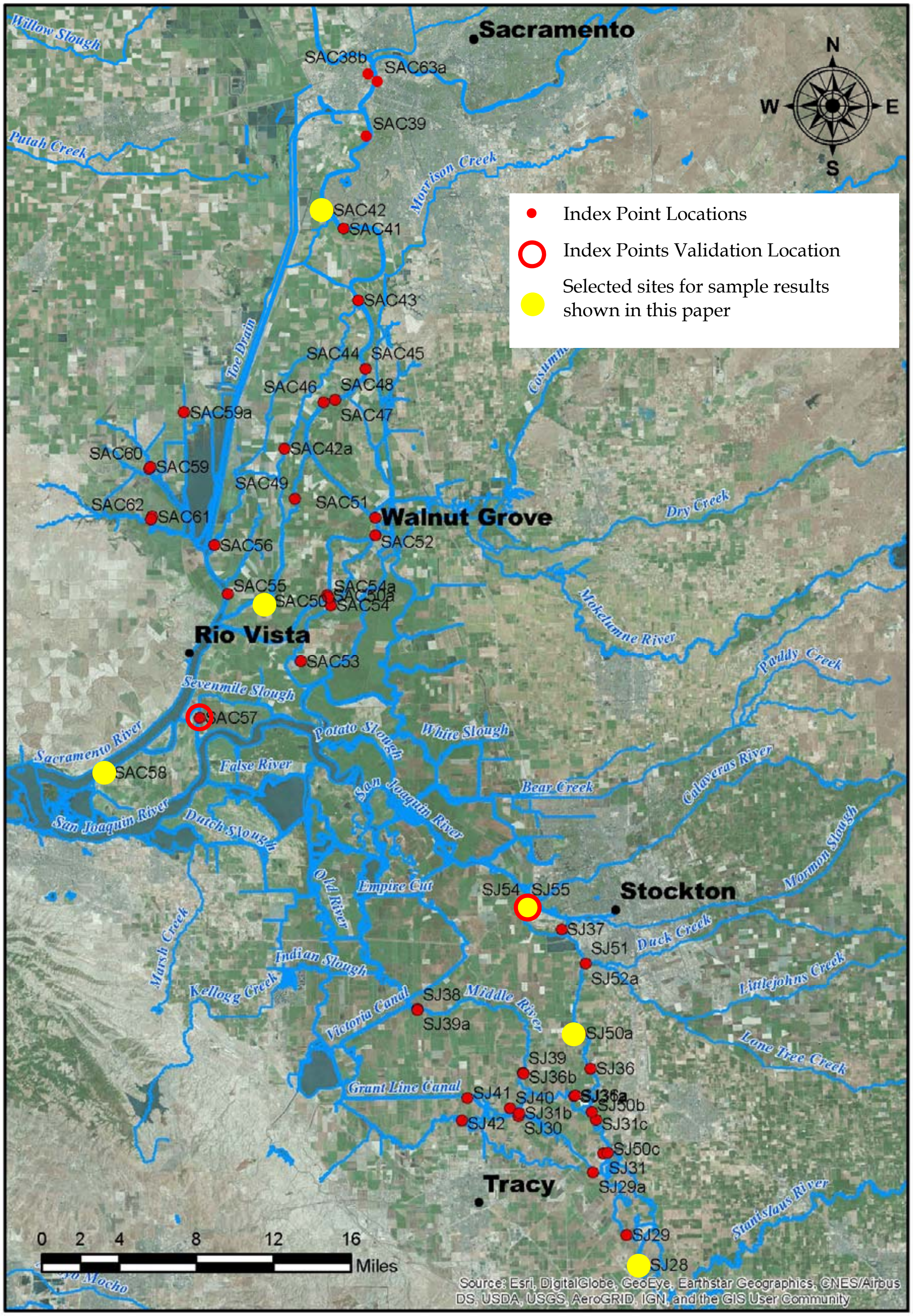


Figure 31: Analysis Locations (also called Index Points or IP) in the Delta

4.1 Stage-Frequency Curve Validation

For the purpose of validating the method, two stage-frequency curves were compared to previous studies. Figure 32 shows the stage-frequency relationship at Burns Cutoff in the San Joaquin River Basin near Stockton (IP SJ54_55) for the U.S. Army Corps of Engineers (USACE) 1992 and 2014 and the CVFPP 2017 Update studies. The 1992 and 2014 USACE stage-frequency curves coincide with the CVFPP 2017 Update curve up to a 100-year return period flood.

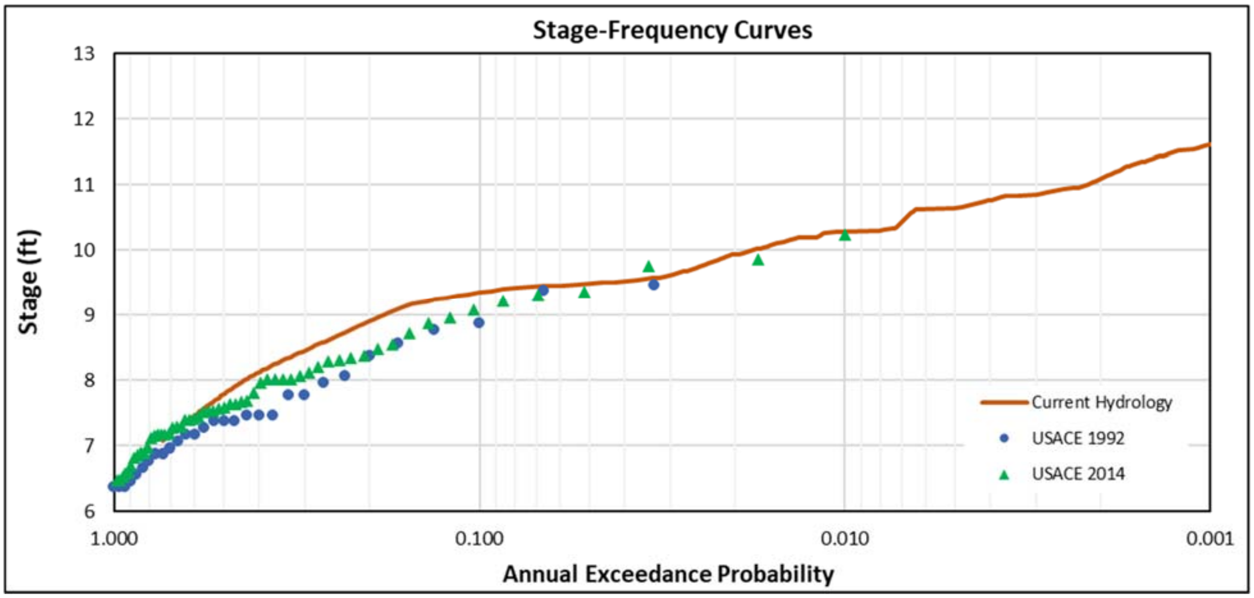


Figure 32: Stage-Frequency Curve Relationship for Current Hydrology at San Joaquin River – Burns Cutoff from the USACE (1992 and 2014) and the CVFPP 2017 Update

The USACE 1992 study used 30 years of recorded data. The USACE 2014 study used 57 years of recorded data and extrapolated the stage-frequency curve for larger flood events (more than 60-year return period) by using hydraulic model simulations of the San Joaquin River system. USACE 2014 describes in detail the method used. One limitation of the hydraulic model used in the USACE 2014 study is that it assumes that a vertical wall on each side of the channel can contain channel flows indefinitely. As a result, levee overtopping is not represented, and creates a steep slope in the curve for larger events. The method used in this study allowed to represent larger flood events with levee overtopping.

Figure 33 shows the stage-frequency relationship at Three Mile Slough in the Sacramento River Basin (near IP SAC57) for the USACE 1992 and the CVFPP 2017 Update studies. The 1992 USACE stage-frequency curve coincides with the CVFPP 2017 Update curve, up to a 12-year return period flood.

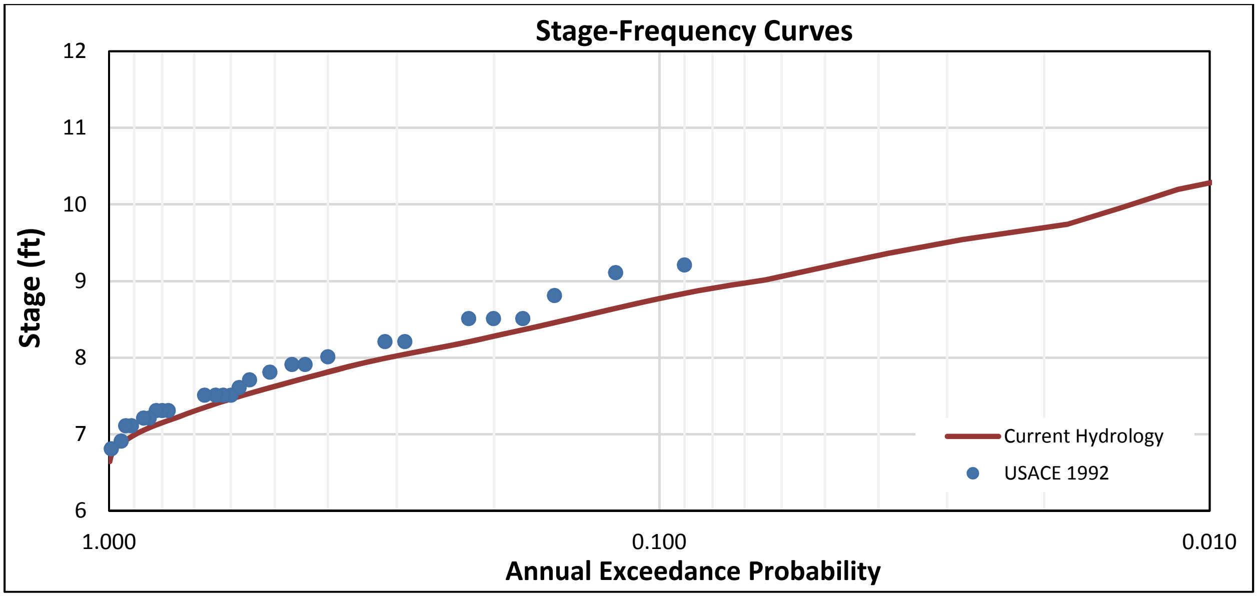


Figure 33: Stage-Frequency Curve Relationship for Current Hydrology at Sacramento River – Three Mile Slough from the USACE (1987 and 1992) and the CVFPP 2017 Update

4.2 Change in Stage-Frequency Curve under Future Conditions

Figure 34 presents the stage-frequency curve for current hydrology, current hydrology with sea level rise, and climate change hydrology with sea level rise at index point (IP) location SJ54_SJ55 near Stockton (see map in Figure 31).

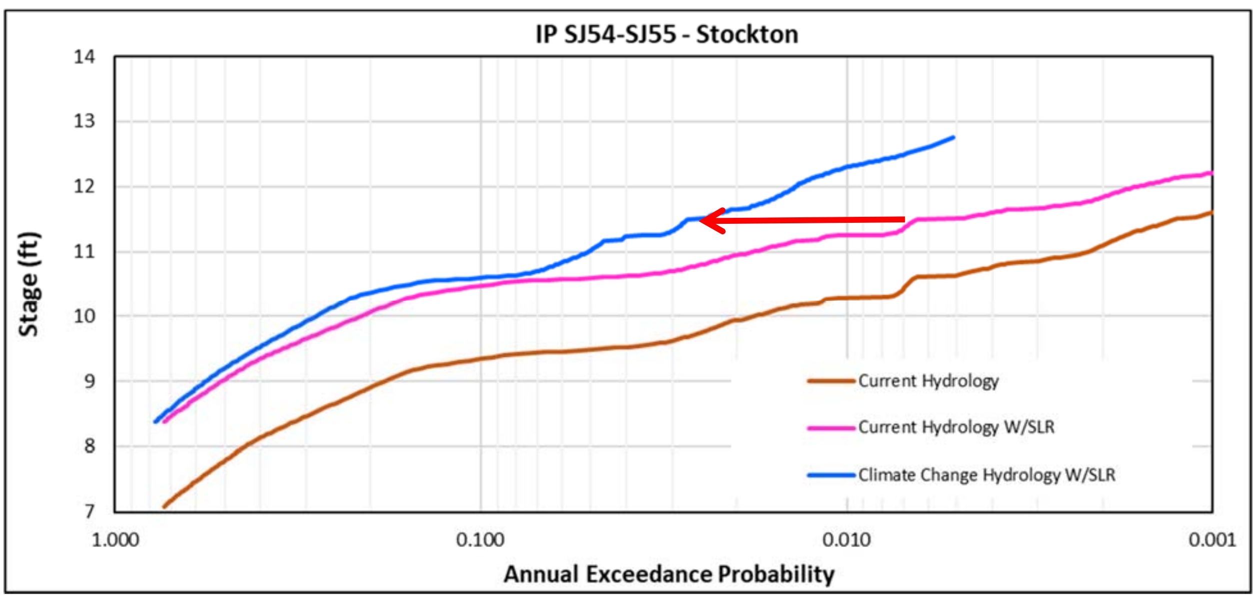


Figure 34: Stage-Frequency Curve for the San Joaquin River Basin near Stockton

The vertical arrow shows change in stage for a given annual exceedance probability (AEP) with sea level rise. The horizontal arrow shows the decrease in AEP that would be expected for the same stage value with sea level rise and climate change hydrology.

Figure 35 and 36 show how stage-frequency curves for current hydrology, current hydrology with sea level rise, and climate change hydrology with sea level rise changes while going downstream of the Sacramento River (Figure 35) and San Joaquin River (Figure 36) basins. At the highest elevation of the Delta (IP locations SJ28 and SAC42), the current hydrology, and current hydrology with sea level rise stage-frequency curves, match one another. Sea level rise has little effect on the upstream index point locations, while climate change hydrology has the biggest effect. Moving downstream, toward the center of the Delta, sea level rise has a larger impact on the stage-frequency curves (IP locations SJ54-SJ55 and SAC58). Although only these six stage-frequency curves are included in this discussion, curves for all 45 locations analyses (see Figure 31) can be found in Appendix A.

The stage increases to 1.27 feet at index point location SJ54-55 in Stockton, and to 1.29 feet at index point location SAC58 on Sherman Island, for an AEP of 0.1, or 10-year return period flood. These stage increases reflect the 1.24 feet of sea level rise at the Golden Gate Bridge. For an AEP of 0.05, or 200-year return period flood, the same sea level rise at the Golden Gate Bridge at those locations produced a 1.01 feet stage increase at index point location SJ64-55, and a 0.8-foot stage increase at index point location SAC58. The effect of sea level rise diminishes with larger flood events because the flood flow drives the water surface elevation.

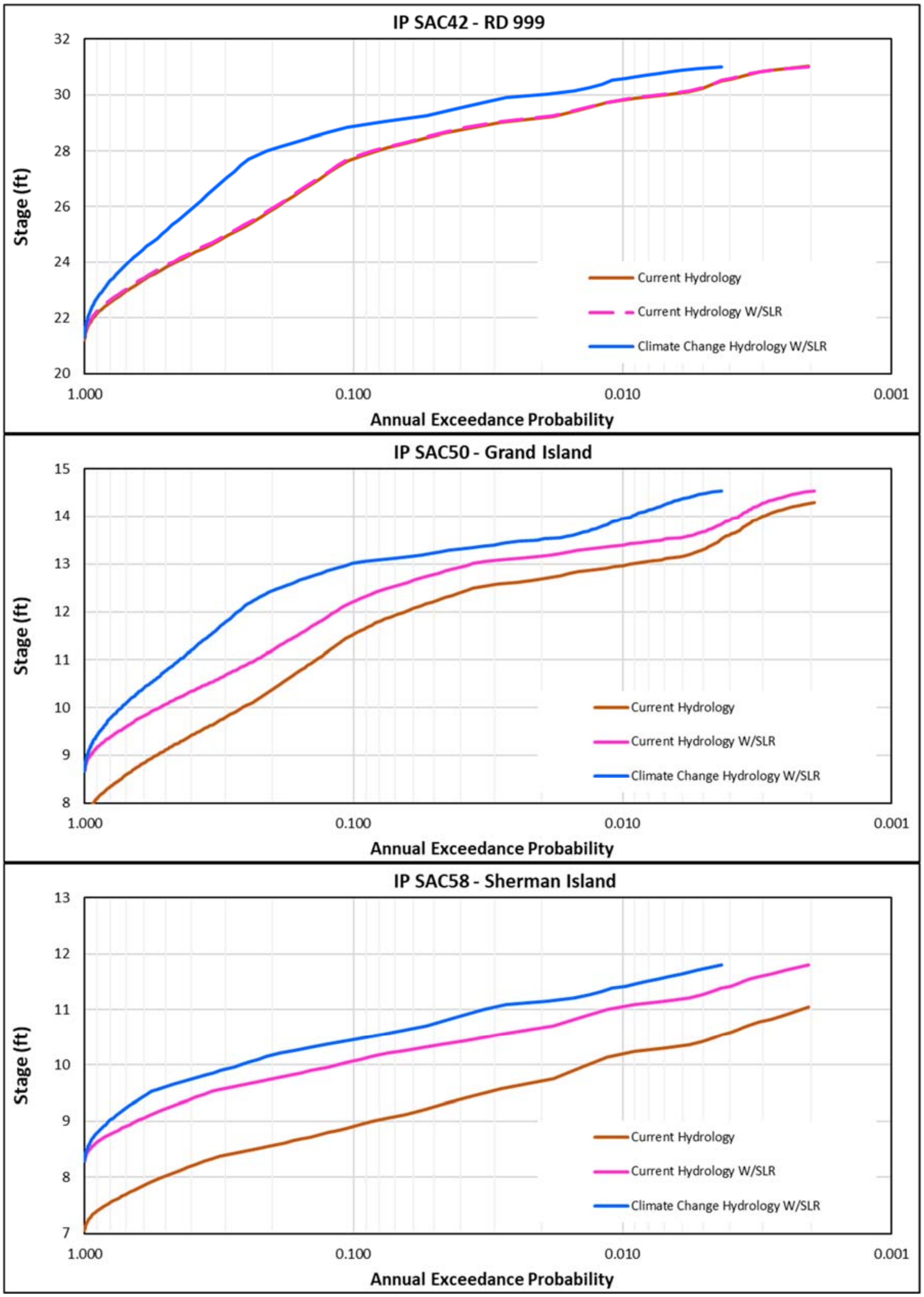


Figure 35: Stage-Frequency Curves for Current Hydrology, Current Hydrology with Sea Level Rise and Climate Change Hydrology with Sea Level Rise for 3 Index Points (IP) along the Sacramento River Basin

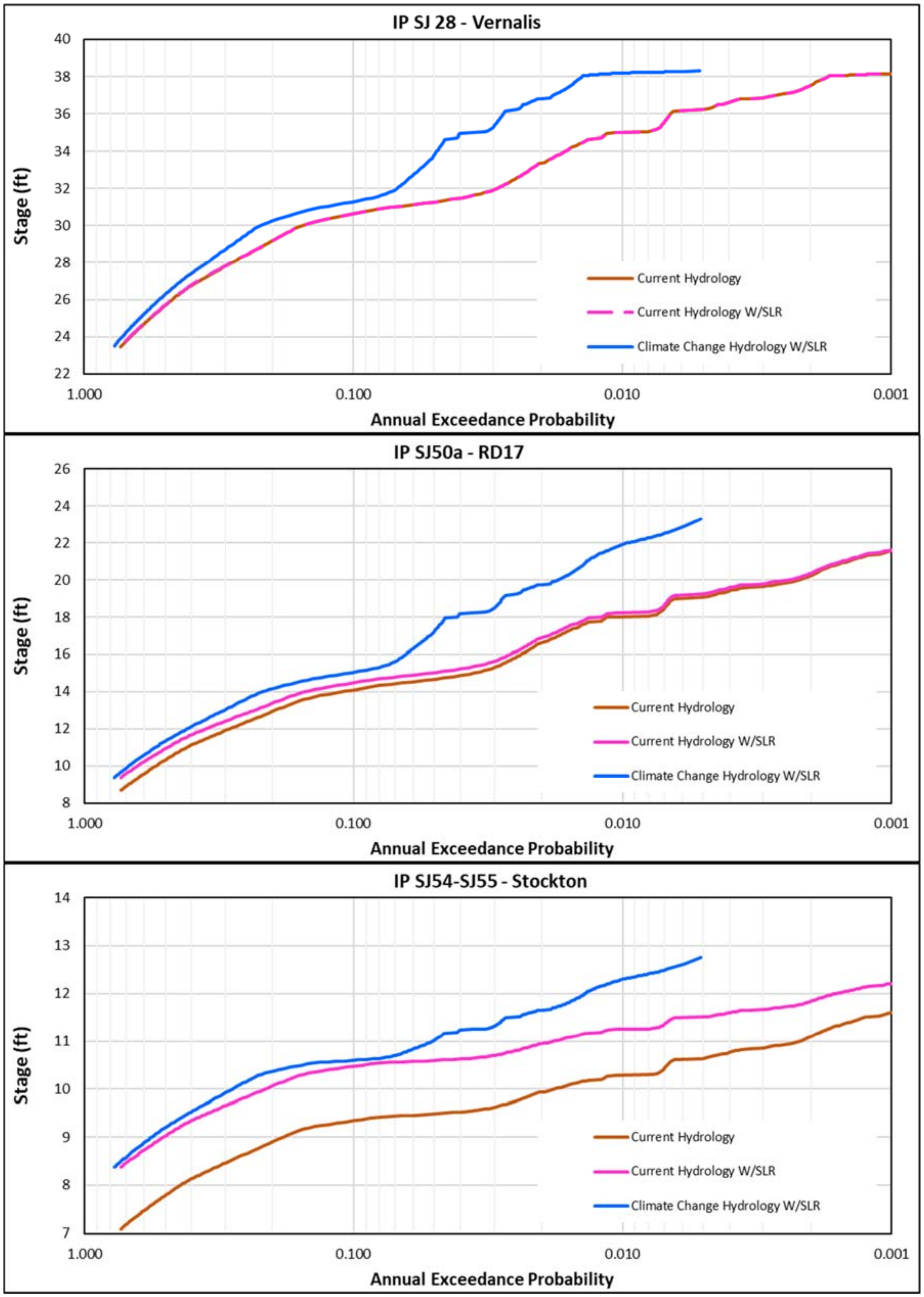


Figure 36: Stage-Frequency Curves for Current Hydrology, Current Hydrology with Sea Level Rise and Climate Change Hydrology with Sea Level Rise for 3 Index Points (IP) along the San Joaquin River Basin

4.3 Water Surface Elevation Profiles

As described in Section 3.3.1, the stage-frequency curves at each index point location in the Delta, along with results of the hydraulic modeling, were used to choose scaled event patterns that are close to the depths and flows of key return periods (e.g., 1/AEP of 10-, 50-, 100-, and 200-year return flood). Figures 37 and 38 show the water surface elevation profiles of scaled events meant to represent the 10-year and 200-year flood events, with and without climate change hydrology, on the Sacramento and San Joaquin rivers respectively. These events were run with and without the sea level rise assumption at the downstream boundaries. The stage-frequency curves and long profiles show that sea level rise has a larger effect on water surface elevation in locations closer to the center of the Delta toward the San Francisco Bay. This is because of two major reasons: the decrease in gradient of the channel bottoms and increase in amplitude of the tide.

In the Sacramento profile, under the 200-year return period flood, the sea level rise has an effect approximately 32 miles upstream of Collinsville (near River Station 150,000 feet on Figure 37). Near Clarksburg, the effect of climate change hydrology is more pronounced than sea level rise and, near the confluence with the American River, climate change hydrology is projected to raise the water surface elevation by 1.8 feet. On the San Joaquin River, under the 200-year return period flood, sea level rise is projected to increase the water surface elevation by 0.8 foot at Burns Cut Off. The impact of sea level rise dissipates to zero by 8.5 miles upstream of Burns Cut Off (near River Station 45,000 feet on Figure 38). Climate change hydrology plus sea level rise causes more than a 7-foot increase in water surface elevation above existing conditions upstream of the confluence with French Camp Slough. This is because of significantly more flow in the system under climate change hydrology in the San Joaquin River system, which is exacerbated by a change in flood-flow routing with the higher flows.

Figure 37: Sacramento River Profiles of Scaled Events Meant to Represent the 10-Year and 200-Year Return Period Flood for Current Hydrology, Current Hydrology with Sea Level Rise and Climate Change Hydrology with Sea Level Rise

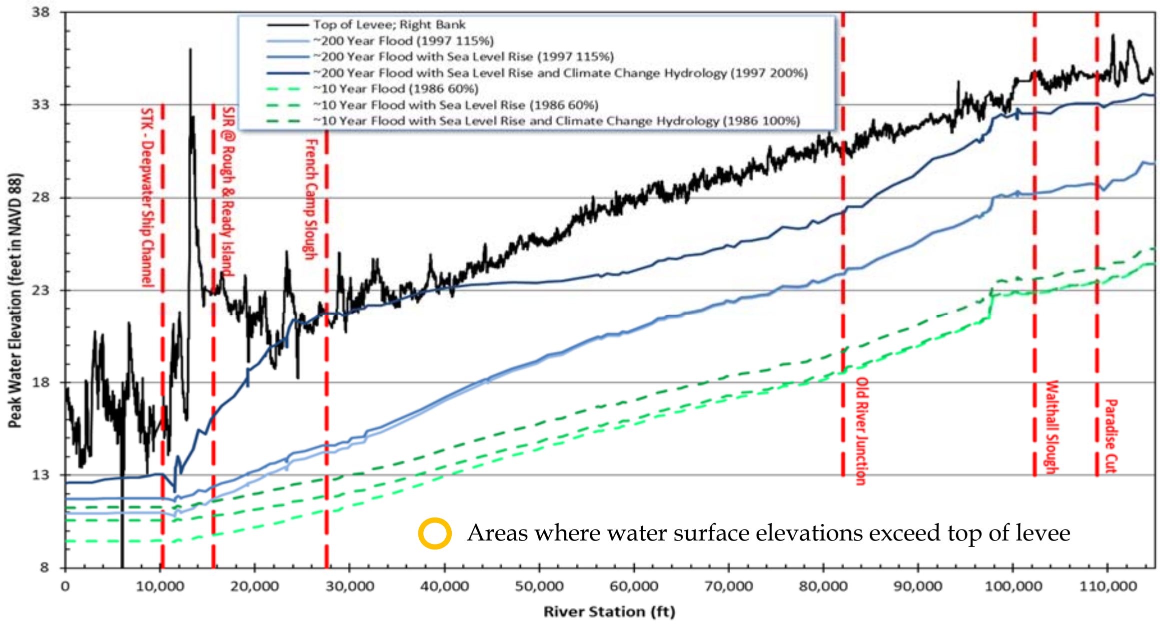


Figure 38: San Joaquin River Profiles of Scaled Events Meant to Represent the 10-Year and 200-Year Return Period Flood for Current Hydrology, Current Hydrology with Sea Level Rise and Climate Change Hydrology with Sea Level Rise

4.4 Limitations and Recommendations

One limitation in this study is the usage of a subset of the Central Valley Hydrology Study flood events (10 flood events) instead of the full range of events. The 10 flood events were used to create stage-discharge rating curves. Using more than 10 events would have provided a more refined stage-discharge relationship and reduced the uncertainty with any of the 10 selected events.

The study calculated stage-frequency curves in the Sacramento and San Joaquin rivers independently. Flows at-latitude of the city of Sacramento help develop the regulated flow frequency curve for the Sacramento River portion of the Delta. Correspondingly, the flows at-latitude of Vernalis help develop the regulated flow frequency curve for the San Joaquin River portion of the Delta. The flows of the Sacramento River, being approximatively one order of magnitude larger than the San Joaquin River, will create some effect on the water surface elevation near Stockton. Future studies should incorporate both flows (Sacramento and San Joaquin rivers) to evaluate stage-frequency curves, especially in the southern portion of the Delta.

This study created deterministic tidal conditions for specific storm events. This method provides a first look at understanding the complex relationship between storm surge and flood flows by defining the storm surge through shape, timing, and magnitude. But by fixing the predicted tidal condition to a 1-year exceedance probability at the Golden Gate Bridge, there is no consideration for the bivariate joint distribution between predicted tides without the effect of storm surge and Delta inflow from the Sacramento and San Joaquin rivers. For example, does the water surface elevation of the joint probability between a tidal condition with a 10-year exceedance probability and a 10-year return period flood equal the water surface elevation of a 1-year exceedance probability tidal condition with a 100-year return period flood in the Delta?

Another limitation is related to the sea level rise and climate change hydrology. In this study, a median projection for these future conditions was used. Picking the median provides a good estimate of potential future conditions by discarding the uncertainty behind those projections. For example, Tables 3 presents a range of sea level rise projections which could be as low as 0.61 foot and as much as 2.73 feet, by 2062. Consideration should be given to higher-bound as much as lower-bound projections when planning for future risk. Similar consideration should be given to the climate change factors.

Finally, this study used the NRC 2012 rise projection to predict sea level rise for 2062, which was available at the time of the CVFPP 2017 Update preparation. More recent studies have reported new sea level rise projection. For example, the California Ocean Protection Council Science provided new projections (Griggs et. al. 2017). Using the same method described in Section 3.3.5, median sea level rise projections from this study are estimated to range between 1.17 feet and 1.23 feet for Resource Concentration Pathways (RCP) 4.5 and 8.5, respectively. This is slightly less than the 1.27 feet used for this study. Similarly, the California Fourth Climate Change Assessment recommended the use of RCP 4.5 and 8.5 for sea level rise projection beyond 2060. The projections for 2062 range from 0.98 foot to 1.28 feet. The 1.27 feet used in this study fall in this range but does not provide information on potentially larger sea level rise effects on stage frequency curves. These extreme sea level rise projections would overwhelm the Delta even more during periods of large floods.

In conclusion, more studies need to take place to refine stage-frequency curves in the Sacramento-San Joaquin Delta for current hydrology, sea level rise, and sea level rise with climate change hydrology, beginning with the recommendations in this section.

5: Summary and Conclusions

Developing stage-frequency curves where tidal conditions meet river flows is challenging because of the complex hydrodynamic conditions that affect water surface elevations. This section summarizes the method used for this study and findings.

Using up-to-date tools and models developed in the Sacramento and San Joaquin river basins, this study presented a method to create stage-frequency curves for current hydrology, current hydrology with sea level rise, and climate change hydrology with sea level rise in the Delta to inform the Central Valley Flood Protection Plan 2017 Update. The study used two sets of hydraulic models, the Central Valley Floodplain Evaluation and Delineation (CVFED) hydraulic models, and RMA Bay Delta model, which are used in concert. Three sets of data, the Central Valley Hydrology Study (CVHS) hydrology, eastside river inflows, and tides and storm surge at the Golden Gate Bridge were used as input for those models.

The California Department of Water Resources developed and used the following method to estimate estuarine stages and develop stage-frequency curves for risk assessment:

1. Develop at-latitude flow frequency curves for the Sacramento River and San Joaquin River using the CVHS procedure.
2. Develop climate change factors to represent climate change hydrology for late-century projection. These climate change factors are applied to the historical unregulated volume-frequency curves and alter the regulated flow-frequency curves.
3. Select 10 CVHS flood events, scaled from historical events, to encompass the range of annual exceedance probability of flood from 99% to 0.025%.
4. Define the upstream boundary flow handoff locations from the CVFED hydraulic models to the RMA Bay-Delta model for Sacramento River and San Joaquin River.
5. Develop deterministic time-varying Golden Gate Bridge tidal conditions for the 10 selected flood events.
6. Incorporate sea level rise, medium projection value, for year 2062 from National Research Council Report estimate.
7. Run RMA Bay-Delta model with the 10 selected flood events and deterministic tides, with and without sea level rise, at the Golden Gate Bridge, and create a new set of tidal influenced boundary conditions for the CVFED trimmed hydraulic models.
8. Run the CVFED trimmed hydraulic models with the 10 selected flood events and the tidal influenced boundary conditions from the RMA Bay-Delta model to determine stage discharge rating curves for each index point.
9. Create stage-frequency curves following CVHS hydrology procedure using the CVFED hydraulic models stage discharge rating curves and at-latitude flow frequency curves.

Once the method is applied and validated, 126 stage-frequency curves are developed and analyzed for current hydrology, current hydrology with sea level rise, and climate change hydrology with sea level rise for 54 index point locations in the Delta (Appendix A). Twelve index points are situated at the same geo-location.

With these results, the California Department of Water Resources is able to analyze the consequences of sea level rise and climate change hydrology on water surface elevation for specific return period floods. Sea level rise has a larger effect on water surface elevation in locations closer to the center of the Delta, toward the San Francisco Bay. As you move upstream to the riverine system, sea level rise has a smaller effect on water surface elevation, because the channel bottom's slope increases while amplitude of the tide decreases For larger flood events, the effect of sea level rise diminishes because flood-flow drives the water surface elevation. Climate change hydrology shifts the stage-frequency curve to more frequent, larger flood events. The climate change hydrology has a greater impact on water surface elevation in the San Joaquin River with stage increase of as much as 7 feet for the 200-year return period flood event, which would overtop the levee near the city of Stockton.

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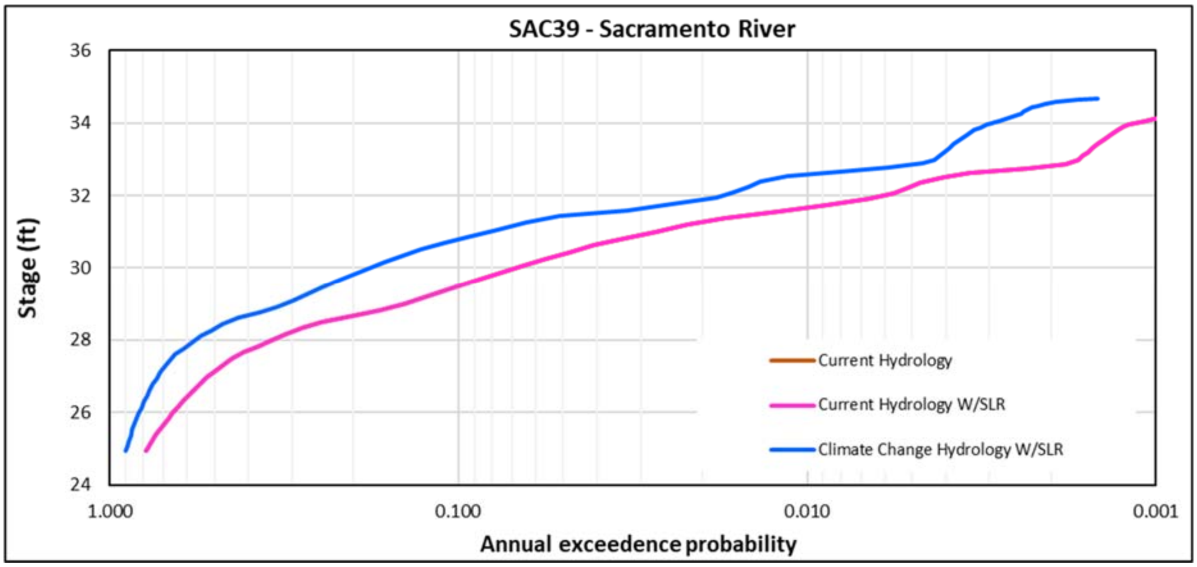
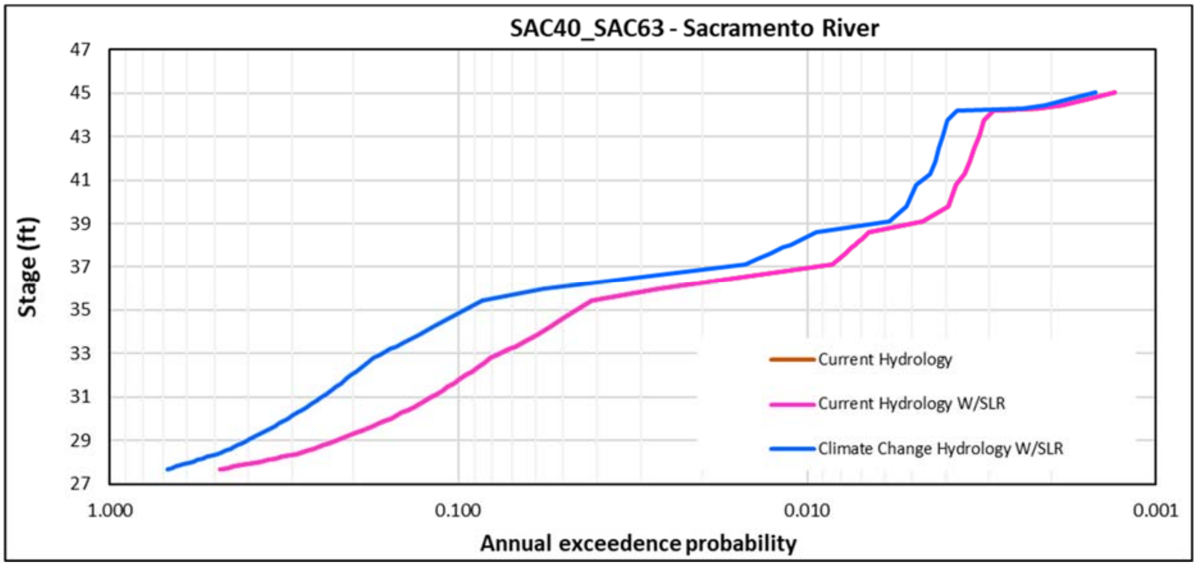
APPENDIX A: Stage-frequency Curves Developed for 42 Locations in the Delta

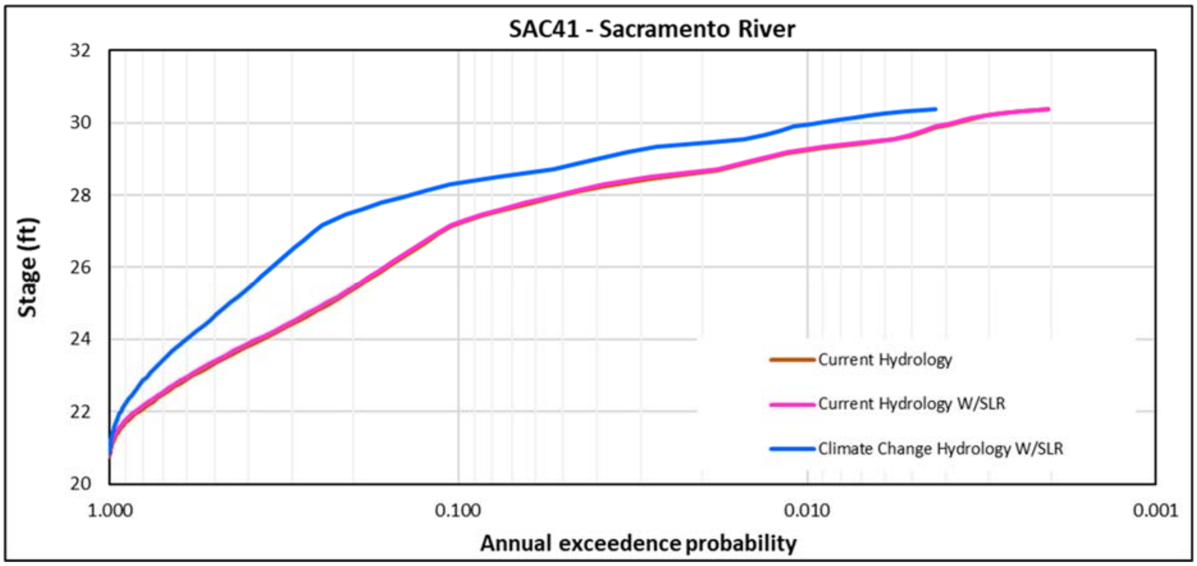
For each index point location analyzed in this study, three stage-frequency curves were generated:

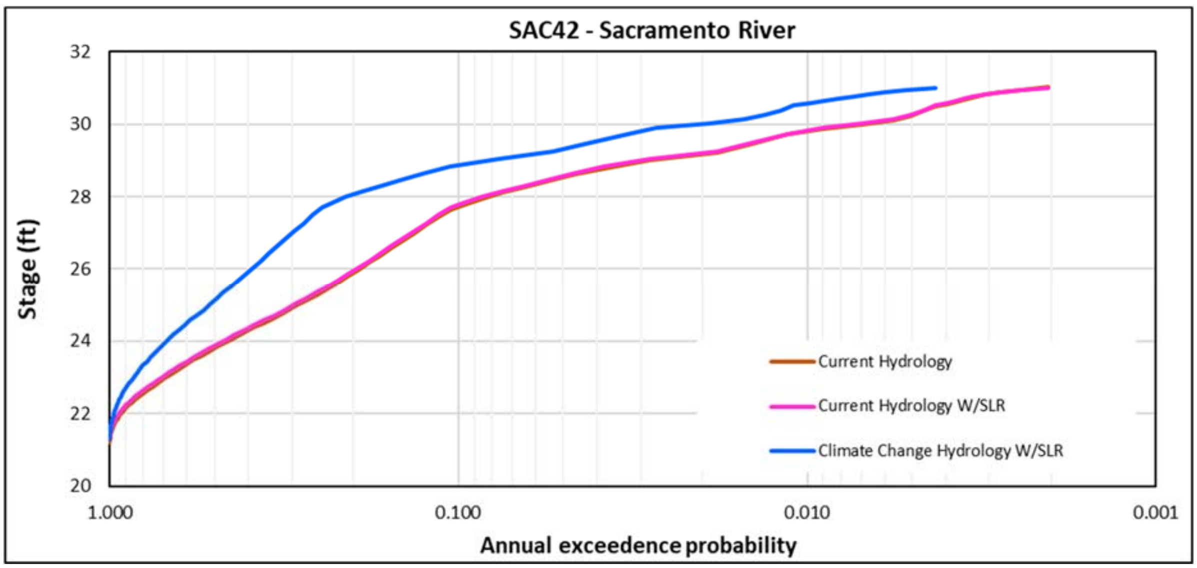
- Current hydrology.
- Current hydrology with sea level rise.
- Climate change hydrology with sea level rise.

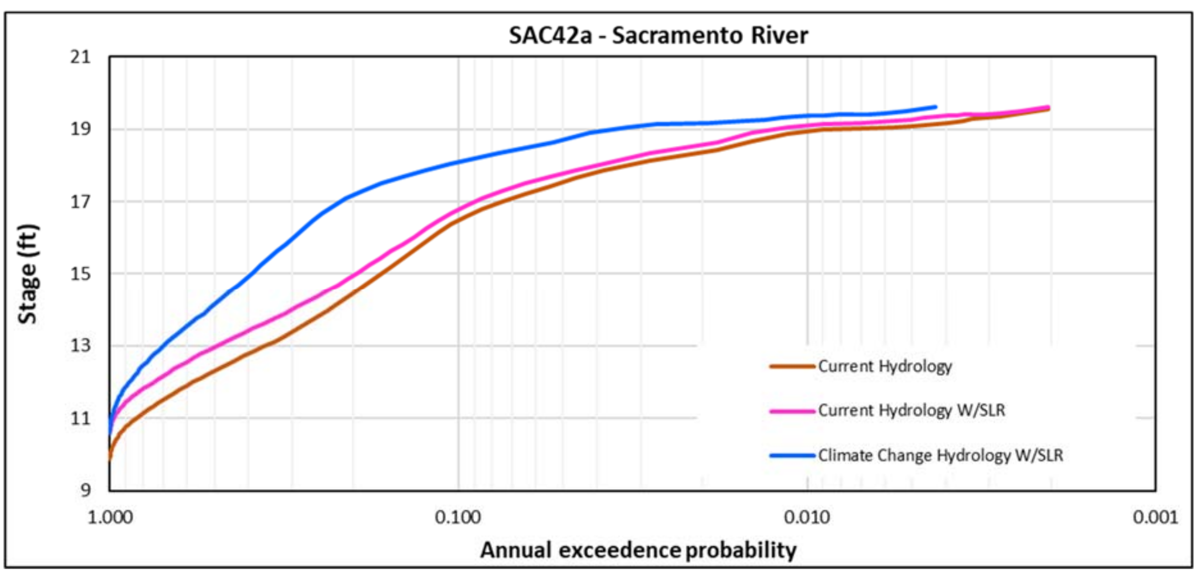
Figure 31 in the main document shows 54 index point locations where the method presented in Section 3.3 has been used to develop 126 stage-frequency curves. Twelve index points are situated at the same geo-location. The 126 stage-frequency curves are presented below.

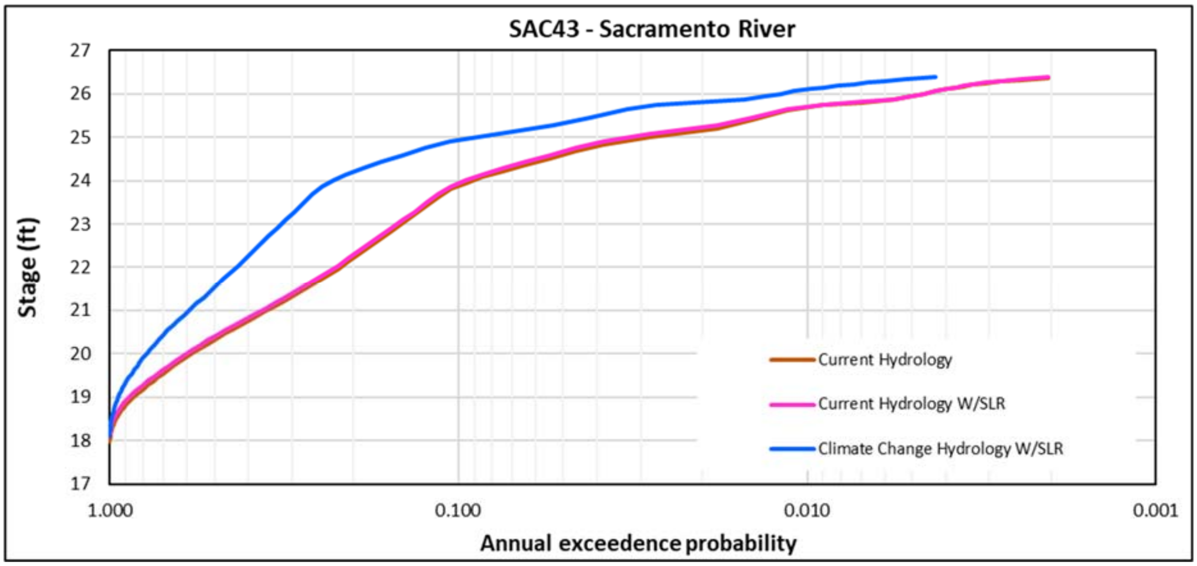


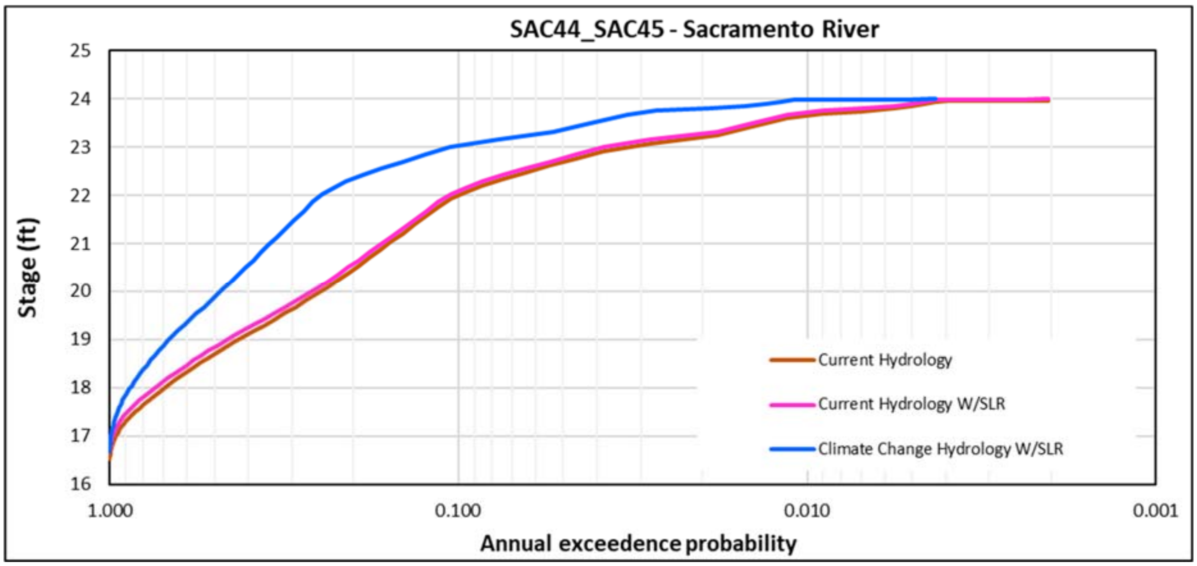


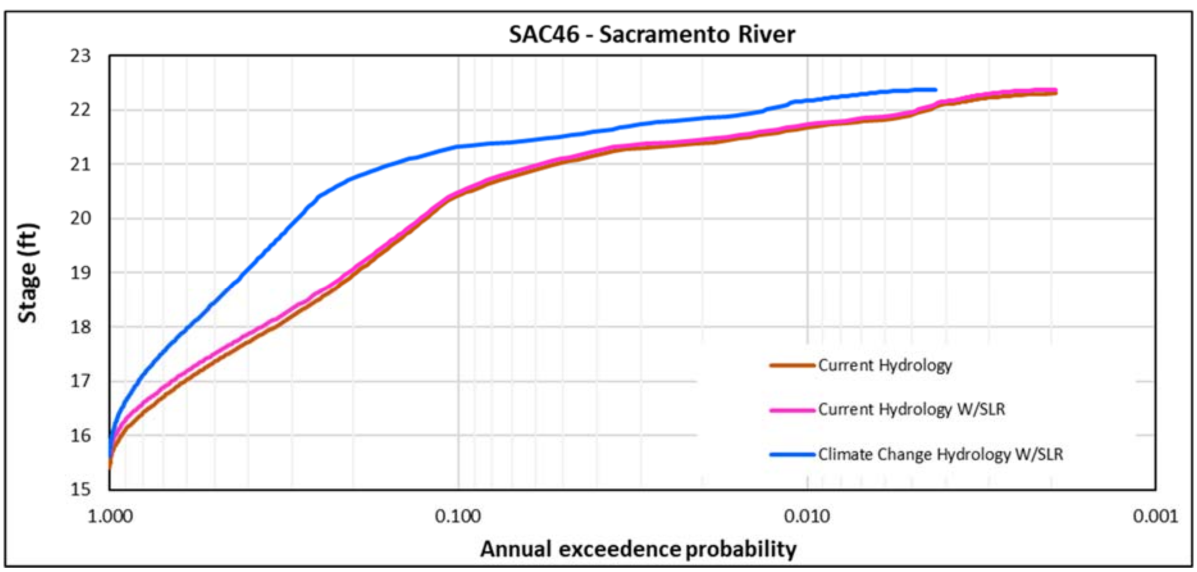

SAC41 - Sacramento River
Stage (ft)
32
30
28
26
24
22
20
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

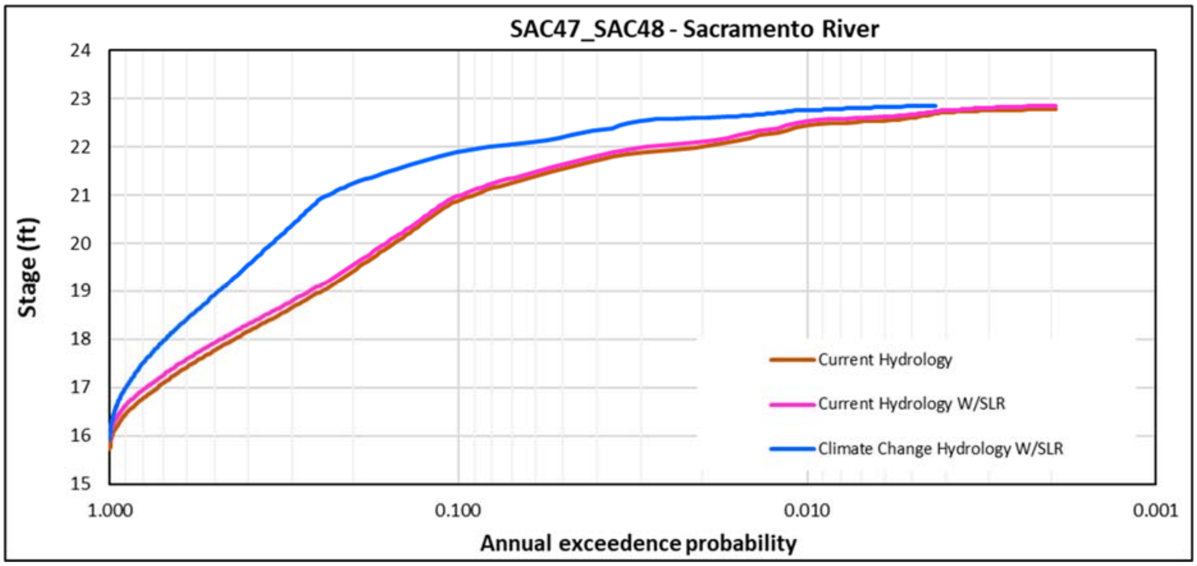

SAC42 - Sacramento River
Stage (ft)
32
30
28
26
24
22
20
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

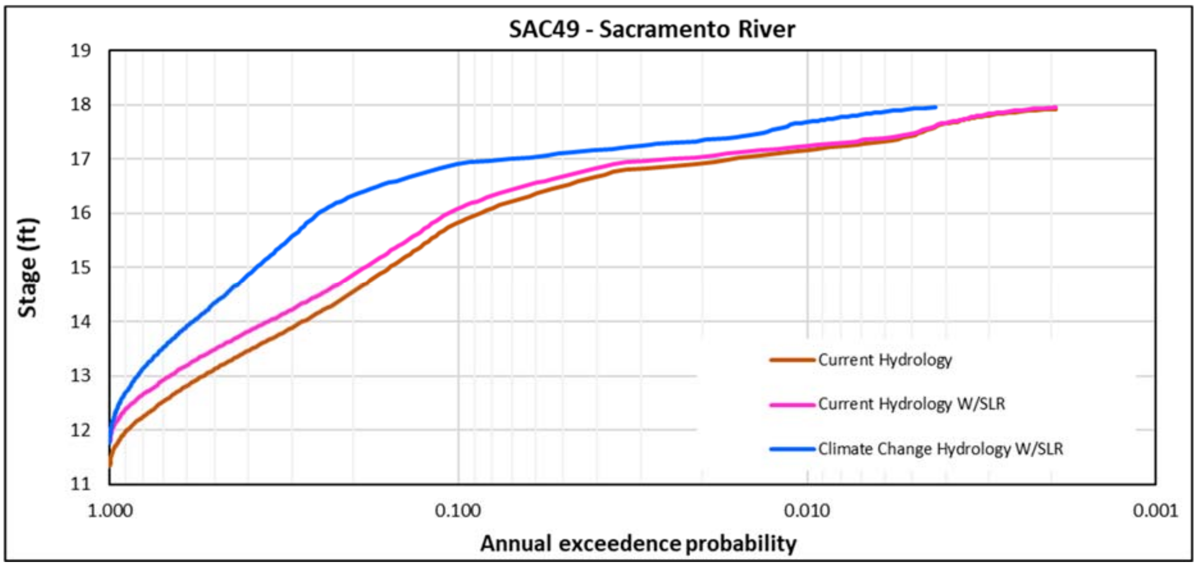

SAC42a - Sacramento River
Stage (ft)
21
19
17
15
13
11
9
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

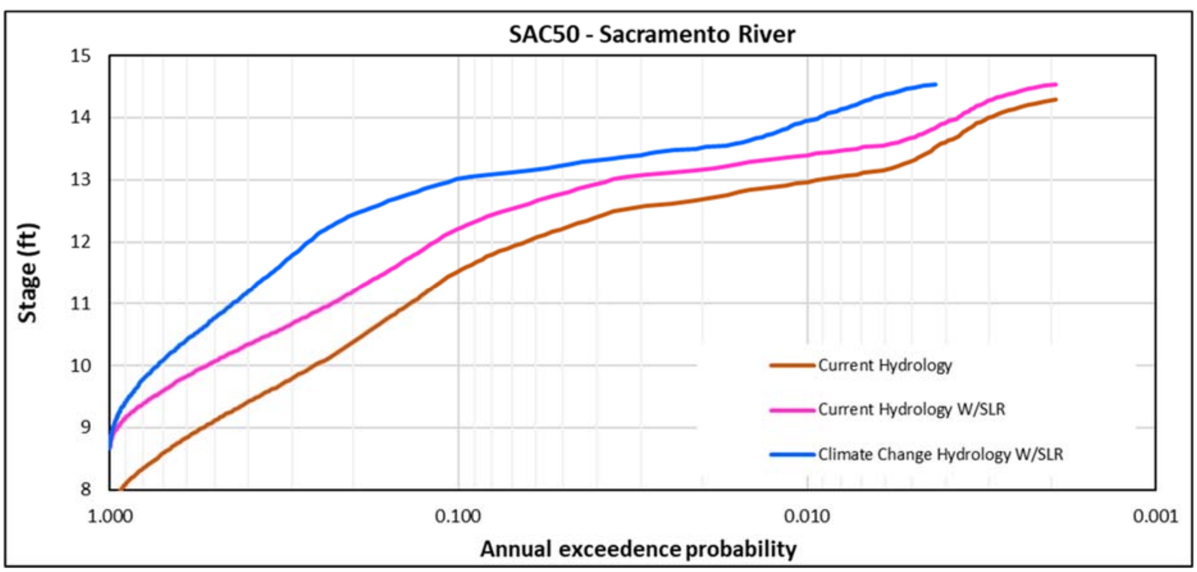

SAC43 - Sacramento River
Stage (ft)
27
26
25
24
23
22
21
20
19
18
17
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

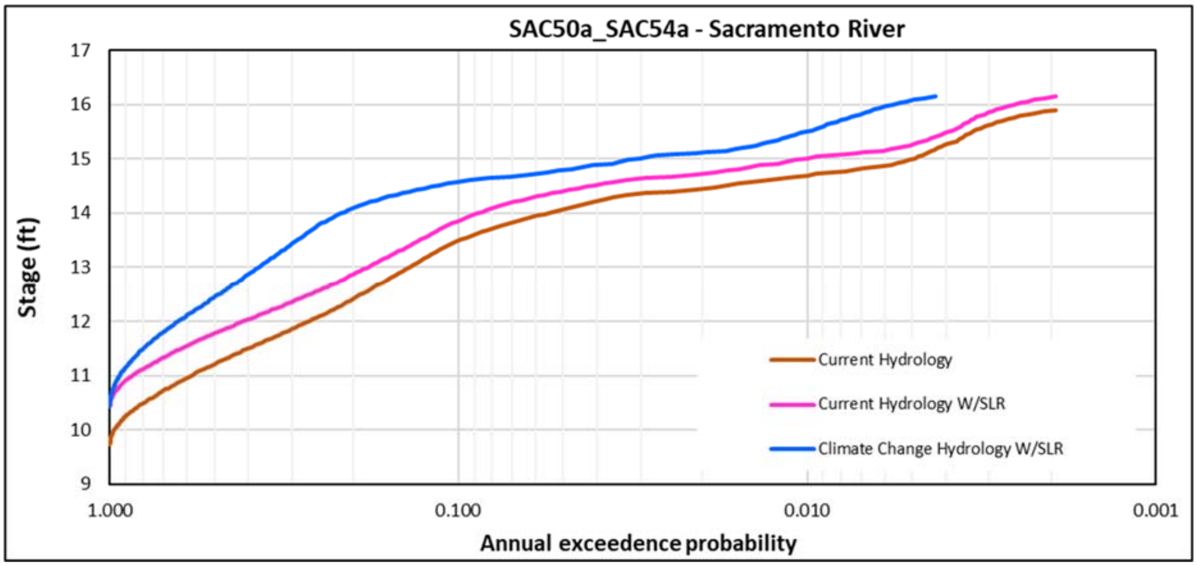

SAC44_SAC45 - Sacramento River
Stage (ft)
25
24
23
22
21
20
19
18
17
16
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

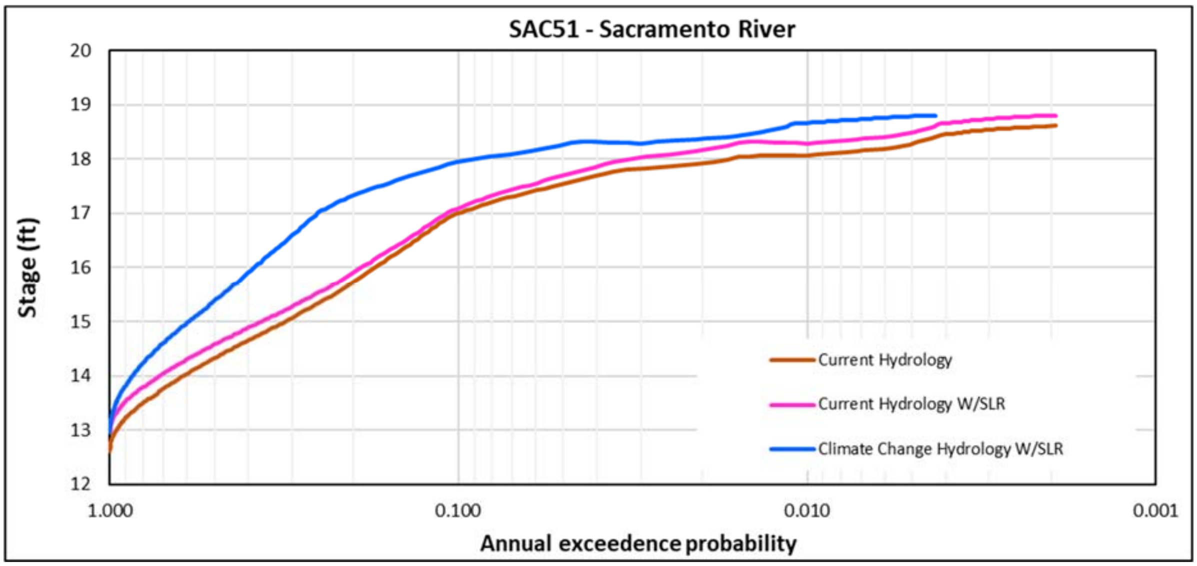

SAC46 - Sacramento River
Stage (ft)
23
22
21
20
19
18
17
16
15
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

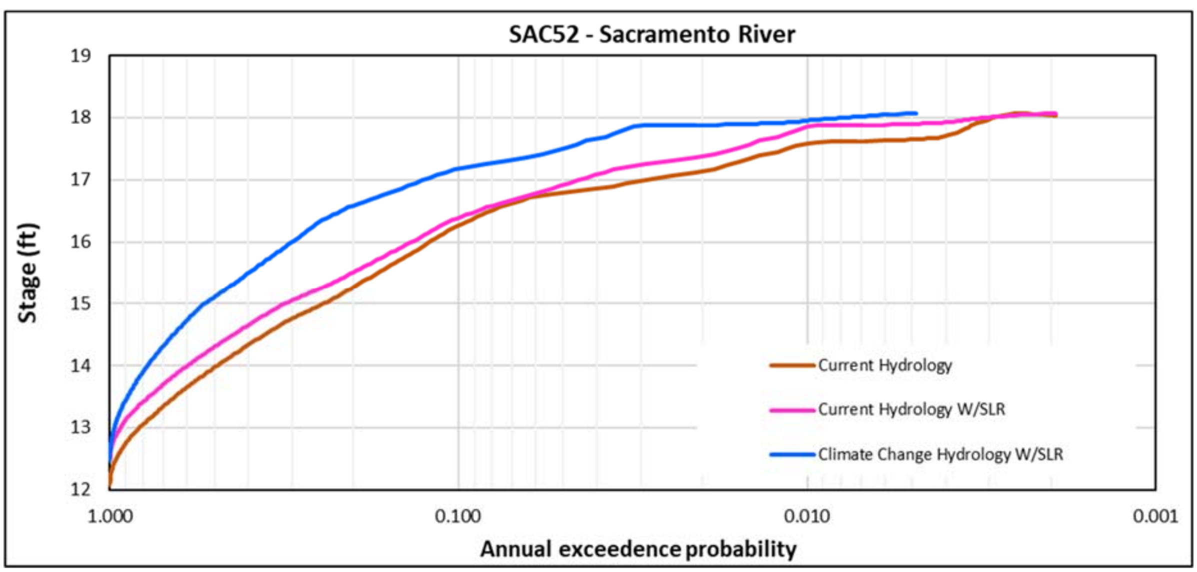

SAC47_SAC48 - Sacramento River
Stage (ft)
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR
24
23
22
21
20
19
18
17
16
15
1.000
0.100
0.010
0.001

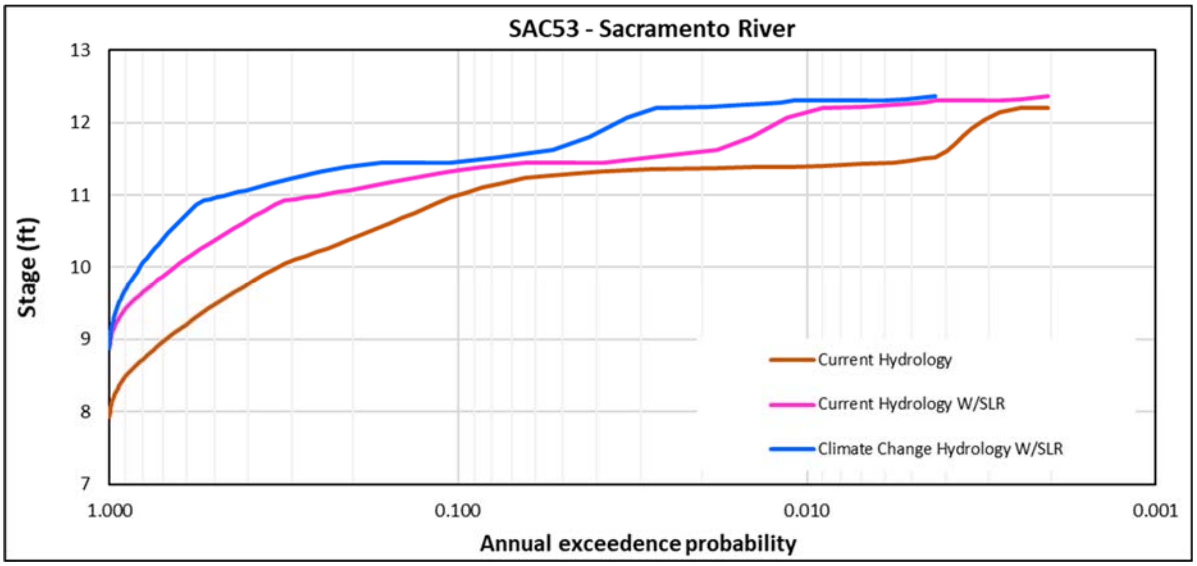

SAC49 - Sacramento River
Stage (ft)
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR
19
18
17
16
15
14
13
12
11
1.000
0.100
0.010
0.001

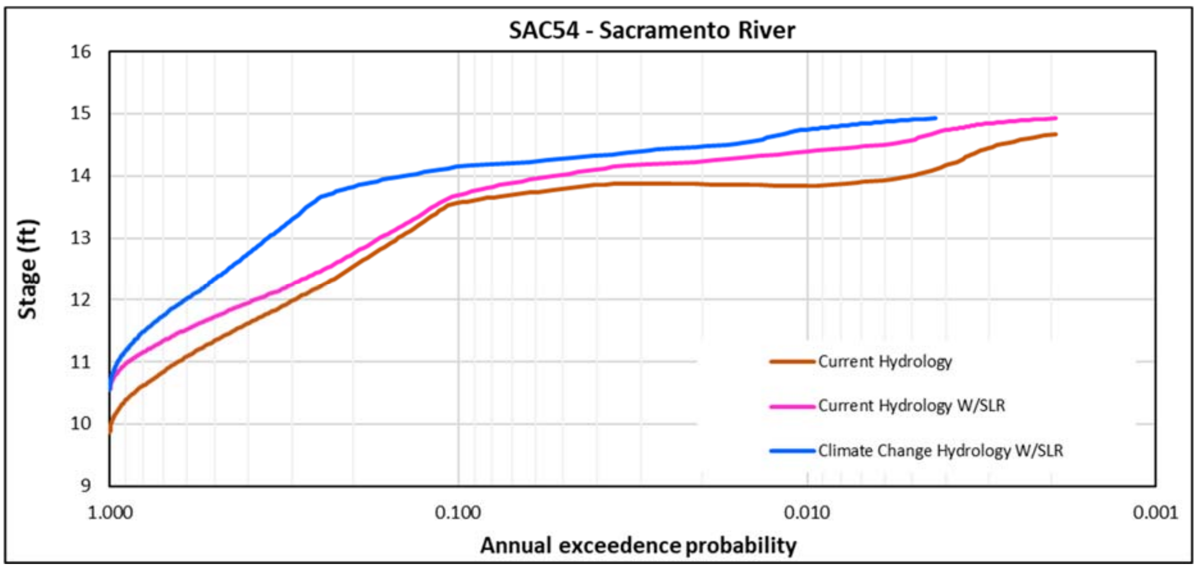

SAC50 - Sacramento River
Stage (ft)
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR
15
14
13
12
11
10
9
8
1.000
0.100
0.010
0.001

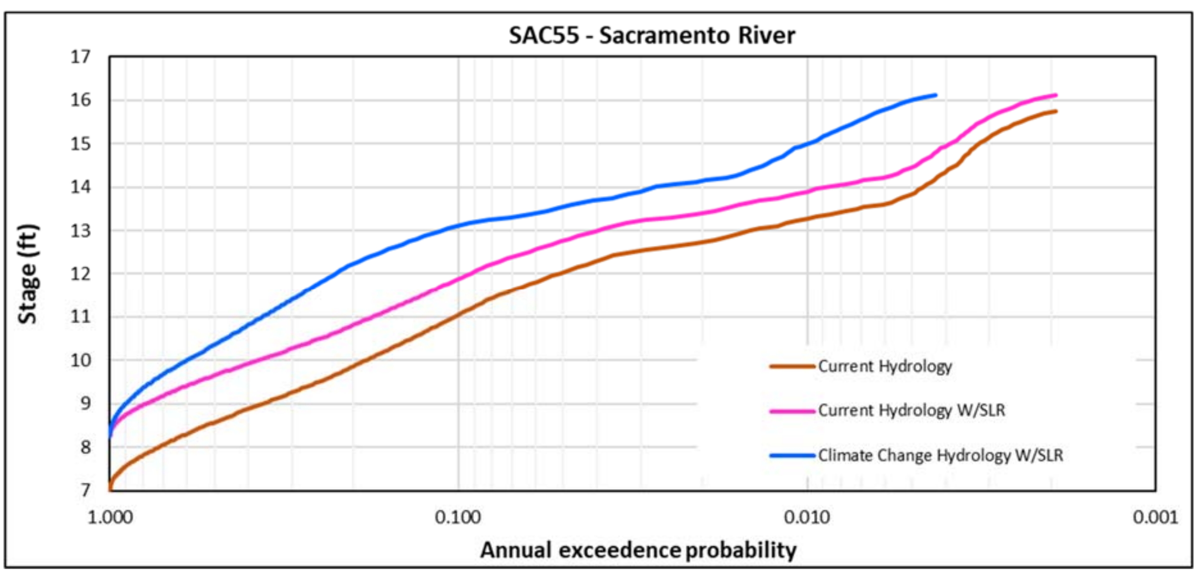

SAC50a_SAC54a - Sacramento River
Stage (ft)
17
16
15
14
13
12
11
10
9
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

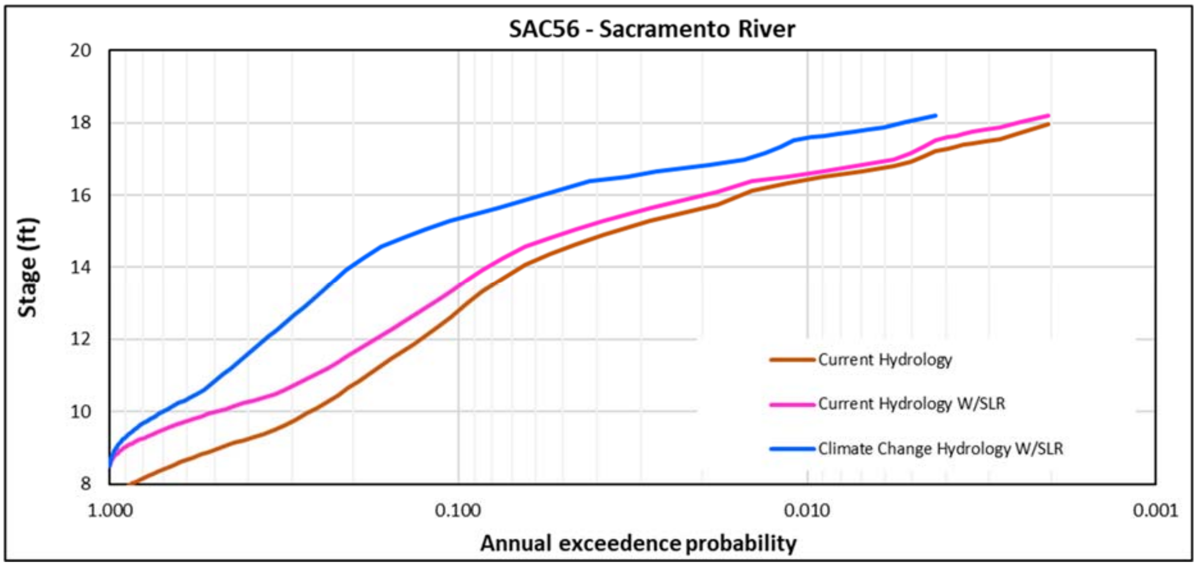

SAC51 - Sacramento River
Stage (ft)
20
19
18
17
16
15
14
13
12
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

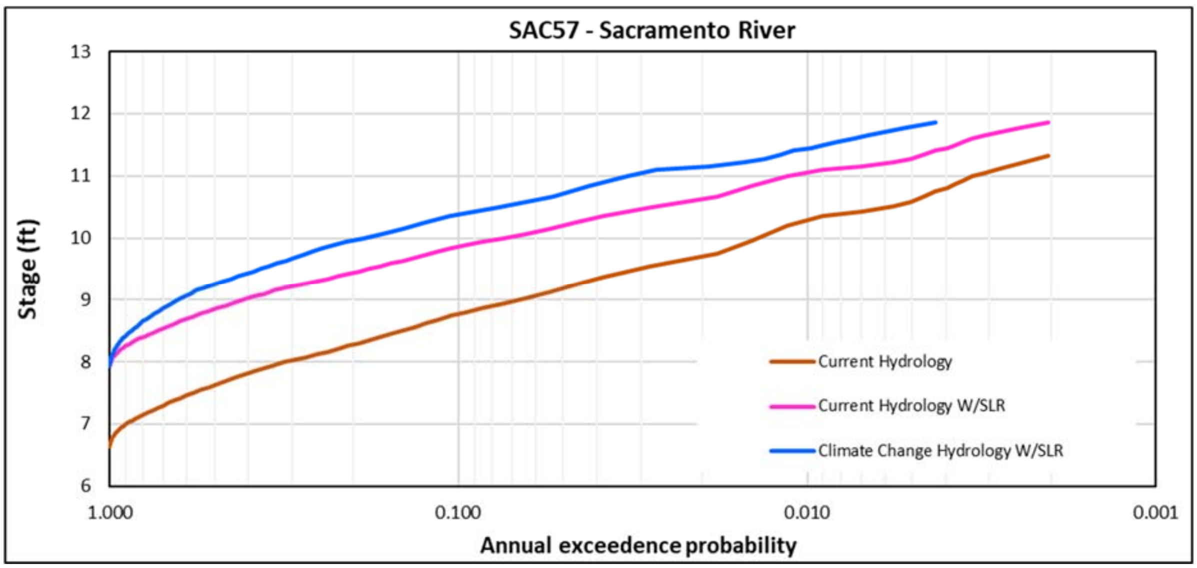

SAC52 - Sacramento River
Stage (ft)
19
18
17
16
15
14
13
12
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

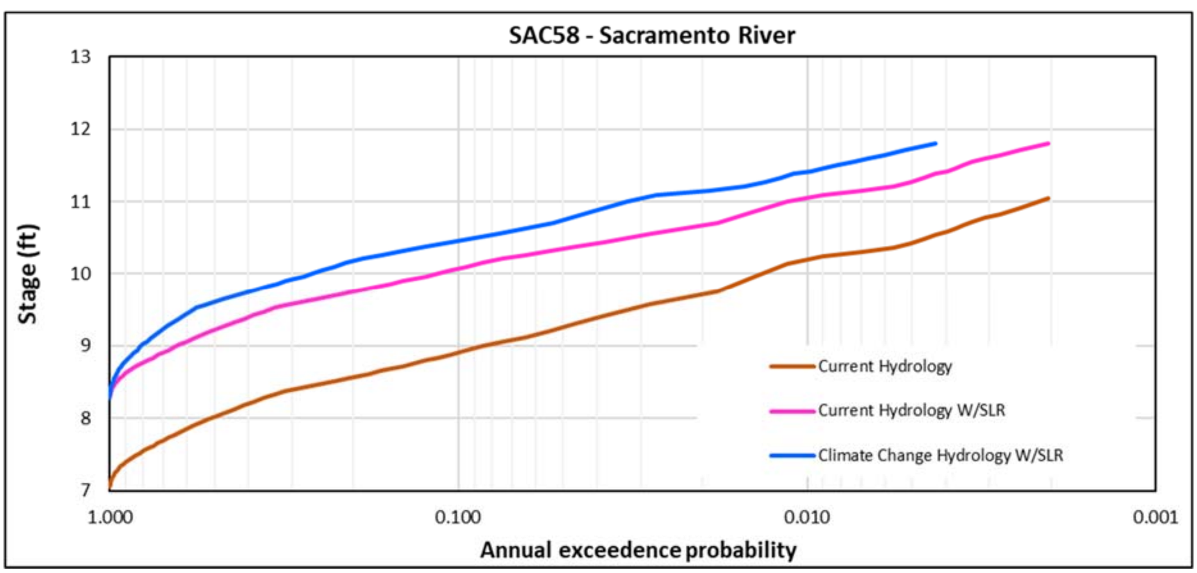

SAC53 - Sacramento River
Stage (ft)
13
12
11
10
9
8
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

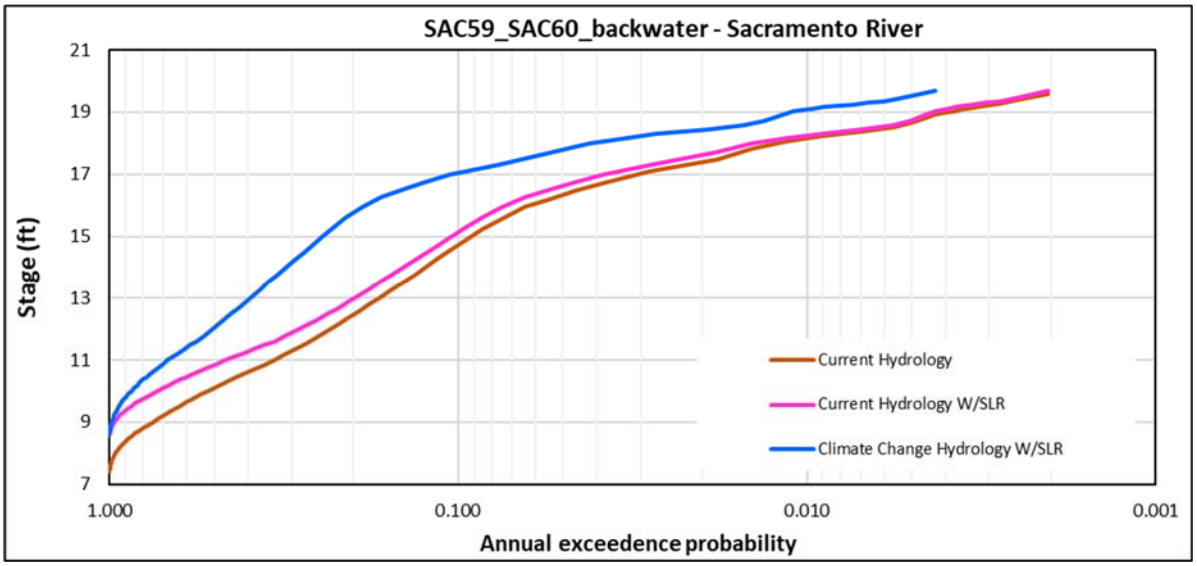

SAC54 - Sacramento River
Stage (ft)
16
15
14
13
12
11
10
9
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR


SAC55 - Sacramento River
Stage (ft)
17
16
15
14
13
12
11
10
9
8
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

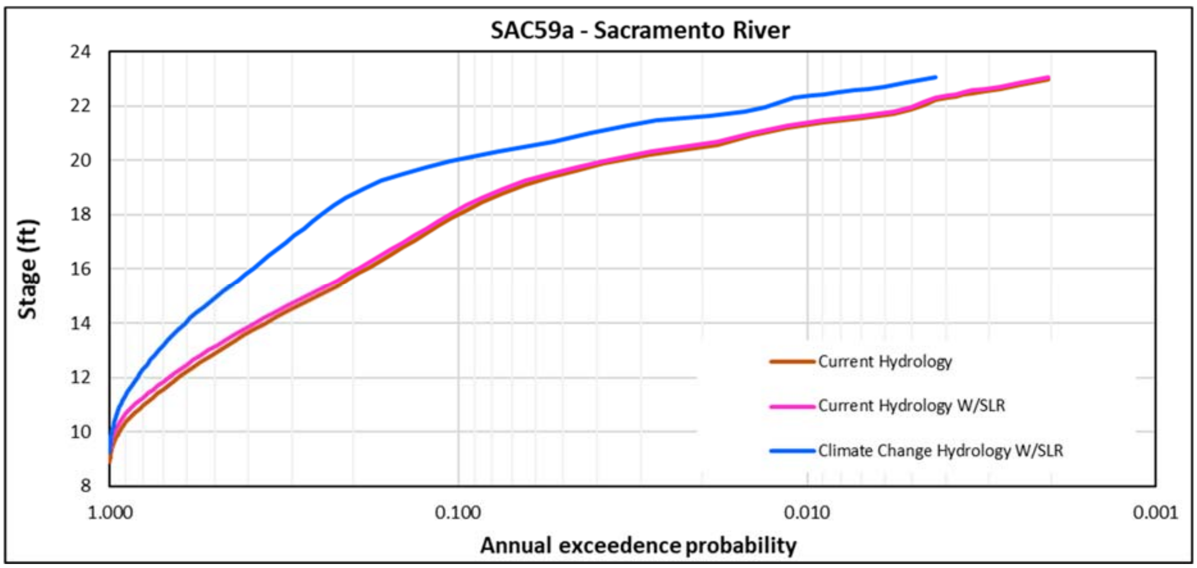

SAC56 - Sacramento River
Stage (ft)
20
18
16
14
12
10
8
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR


SAC57 - Sacramento River
Stage (ft)
13
12
11
10
9
8
7
6
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

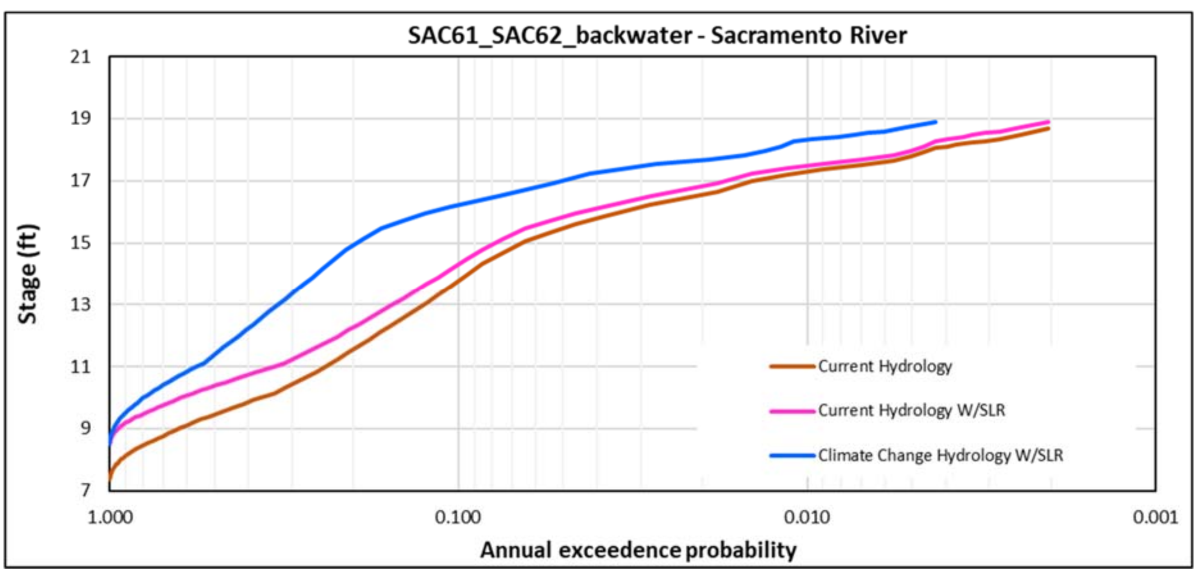

SAC58 - Sacramento River
Stage (ft)
13
12
11
10
9
8
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR



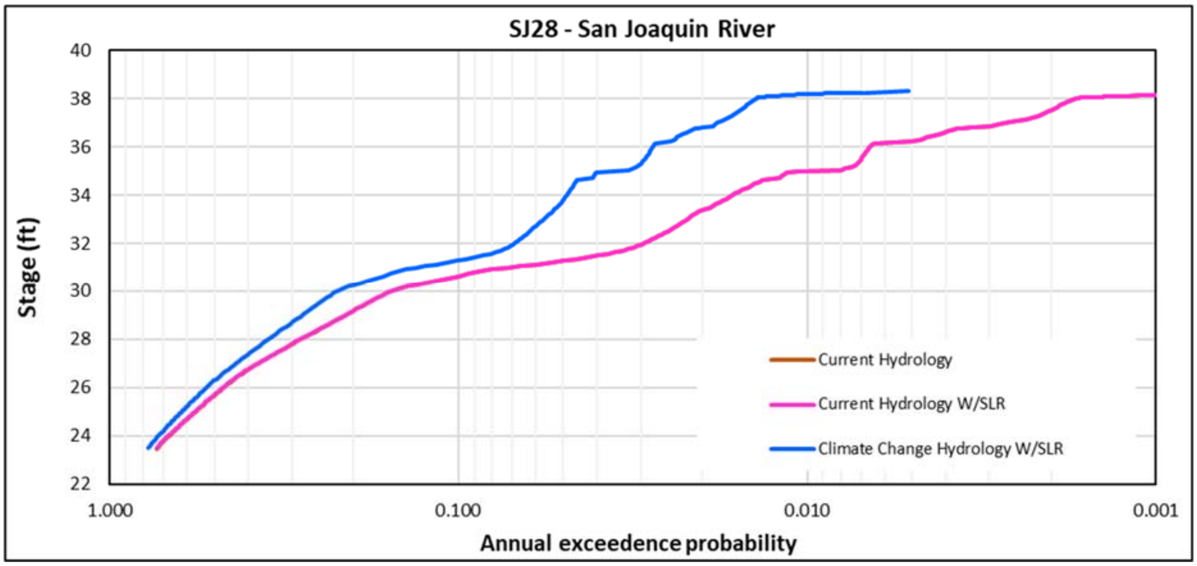
SAC59_SAC60_backwater - Sacramento River
Stage (ft)
Annual exceedence probability
21
19
17
15
13
11
9
7
1.000
0.100
0.010
0.001
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

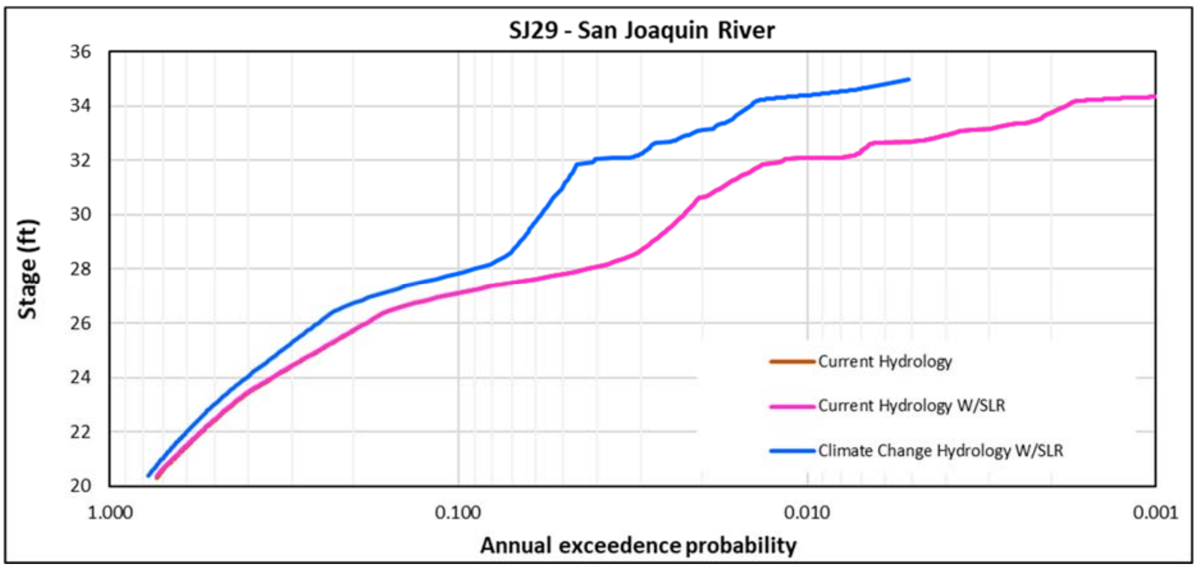


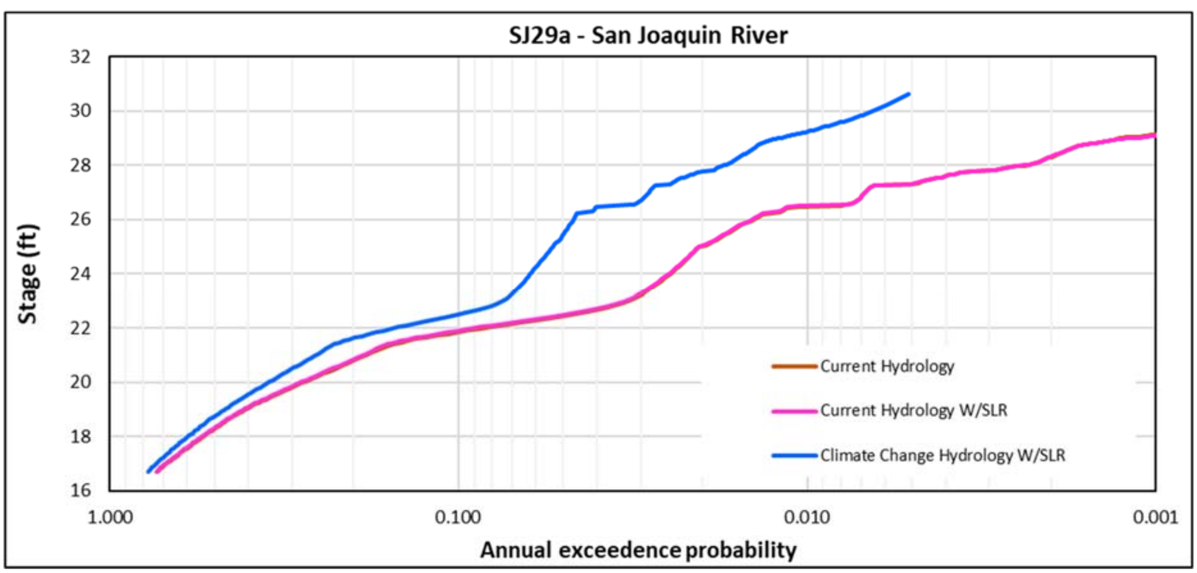
SAC59a - Sacramento River
Stage (ft)
Annual exceedence probability
24
22
20
18
16
14
12
10
8
1.000
0.100
0.010
0.001
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

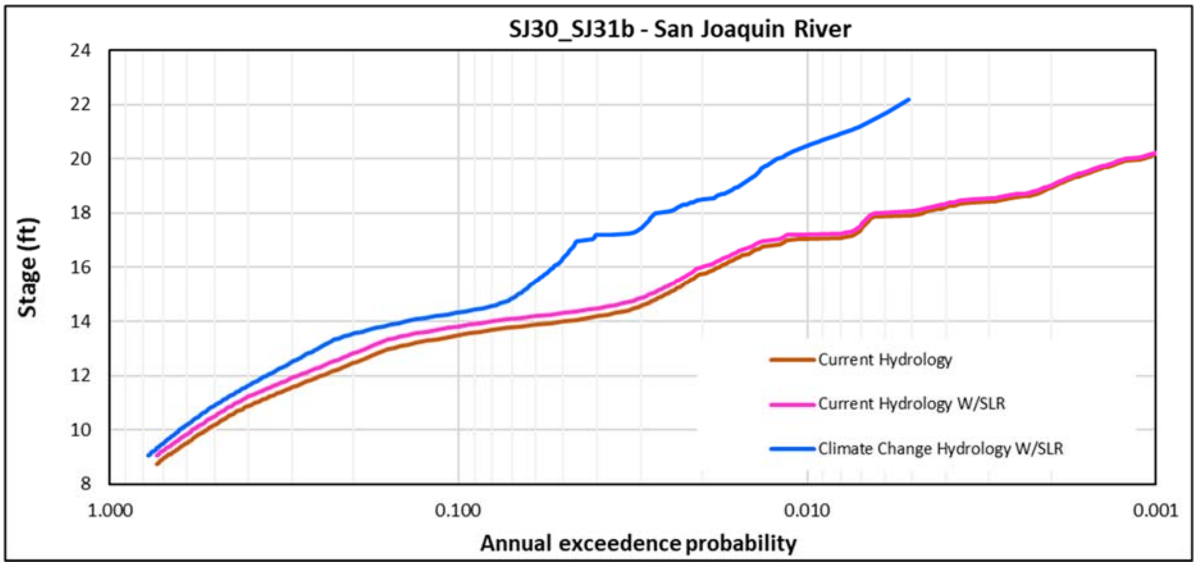


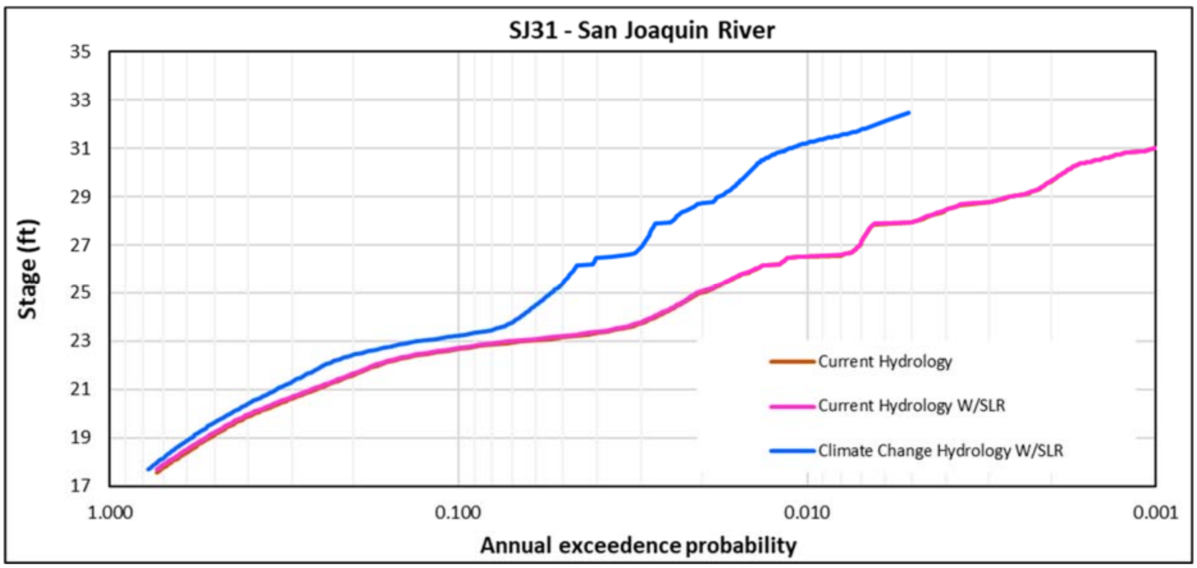
SAC61_SAC62_backwater - Sacramento River
Stage (ft)
Annual exceedence probability
21
19
17
15
13
11
9
7
1.000
0.100
0.010
0.001
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

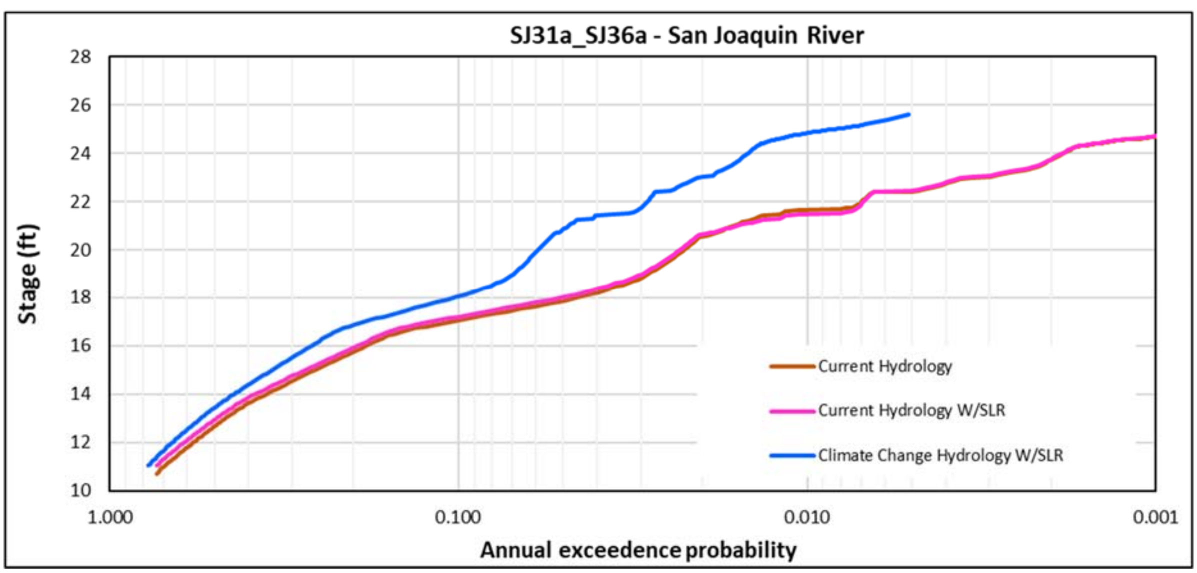

SJ28 - San Joaquin River
Stage (ft)
40
38
36
34
32
30
28
26
24
22
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

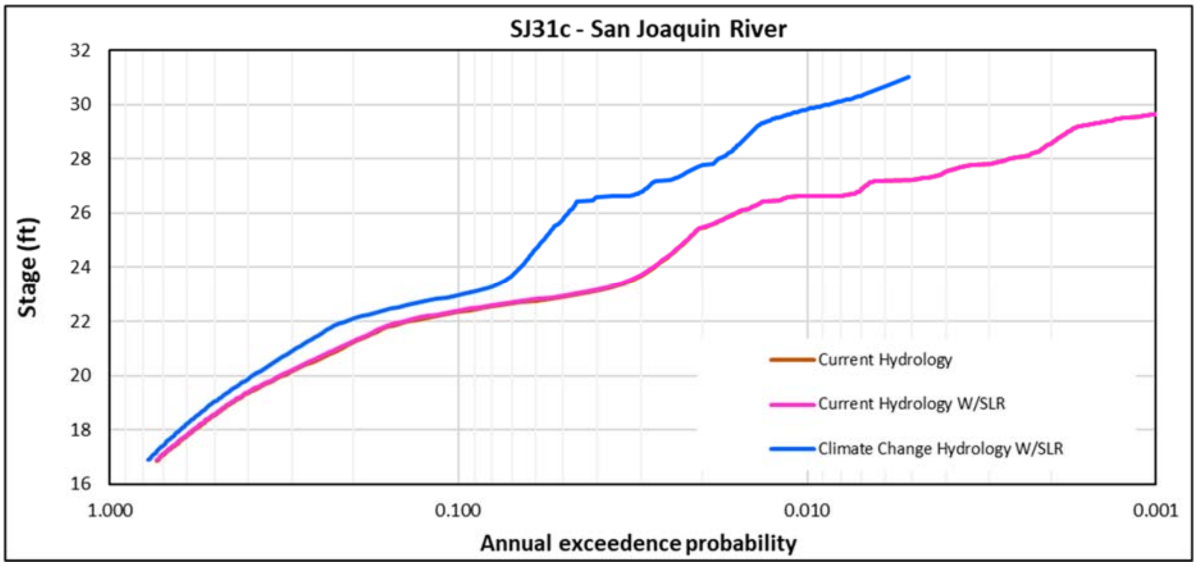

SJ29 - San Joaquin River
Stage (ft)
36
34
32
30
28
26
24
22
20
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

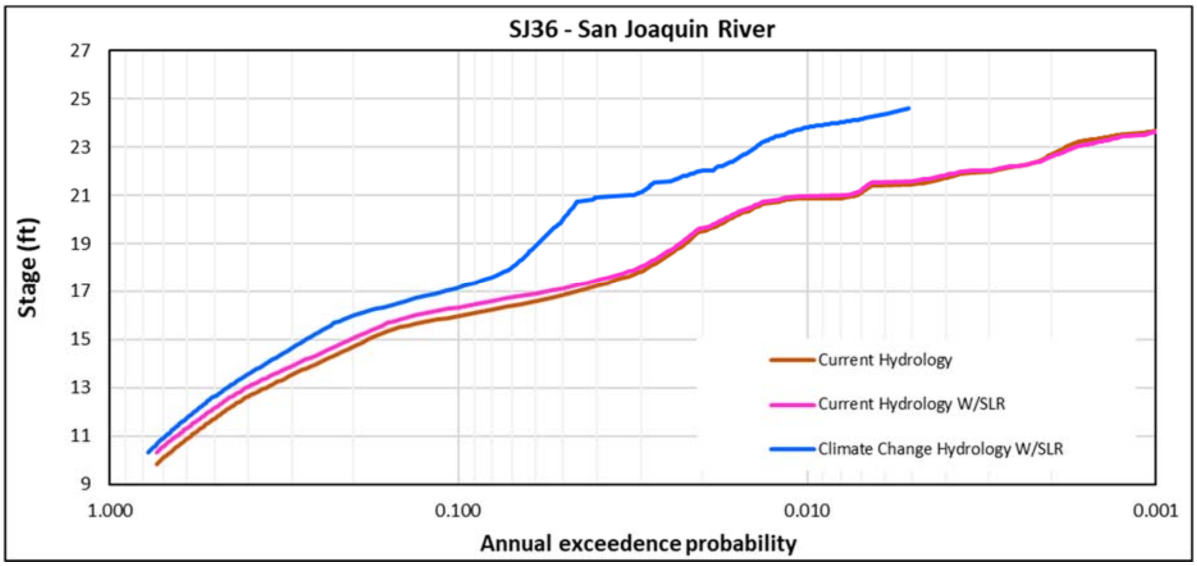

SJ29a - San Joaquin River
Stage (ft)
32
30
28
26
24
22
20
18
16
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

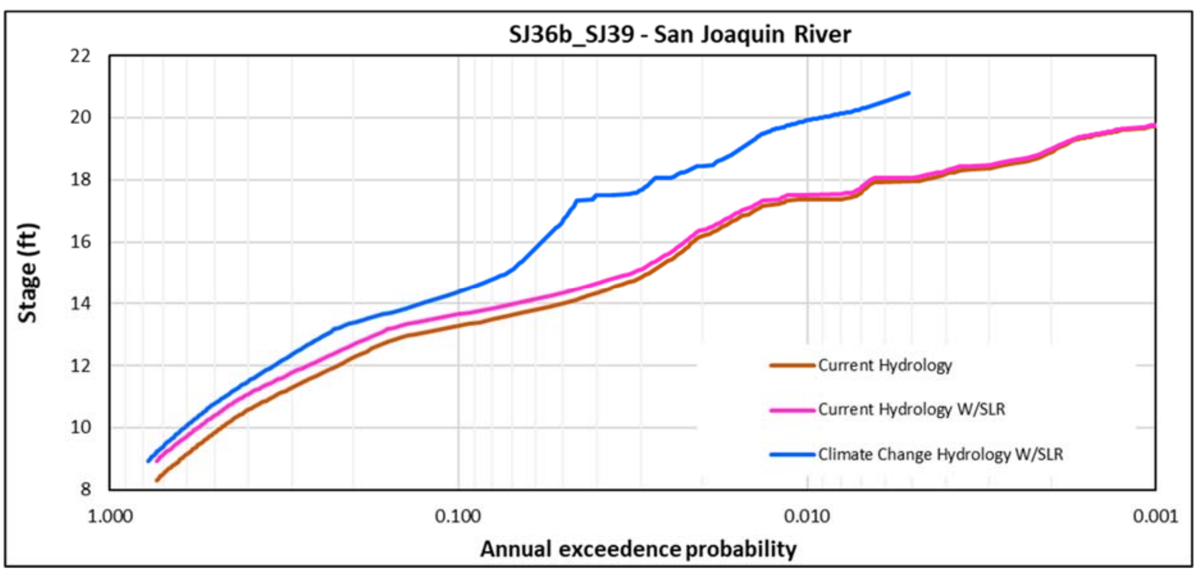

SJ30_SJ31b - San Joaquin River
Stage (ft)
24
22
20
18
16
14
12
10
8
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

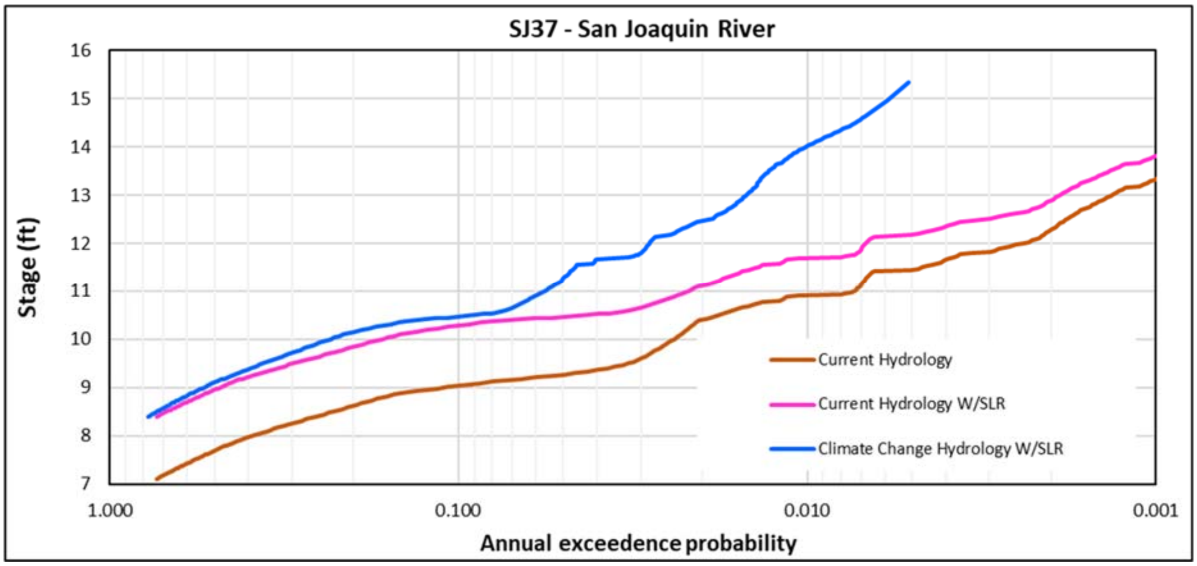

SJ31 - San Joaquin River
Stage (ft)
35
33
31
29
27
25
23
21
19
17
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

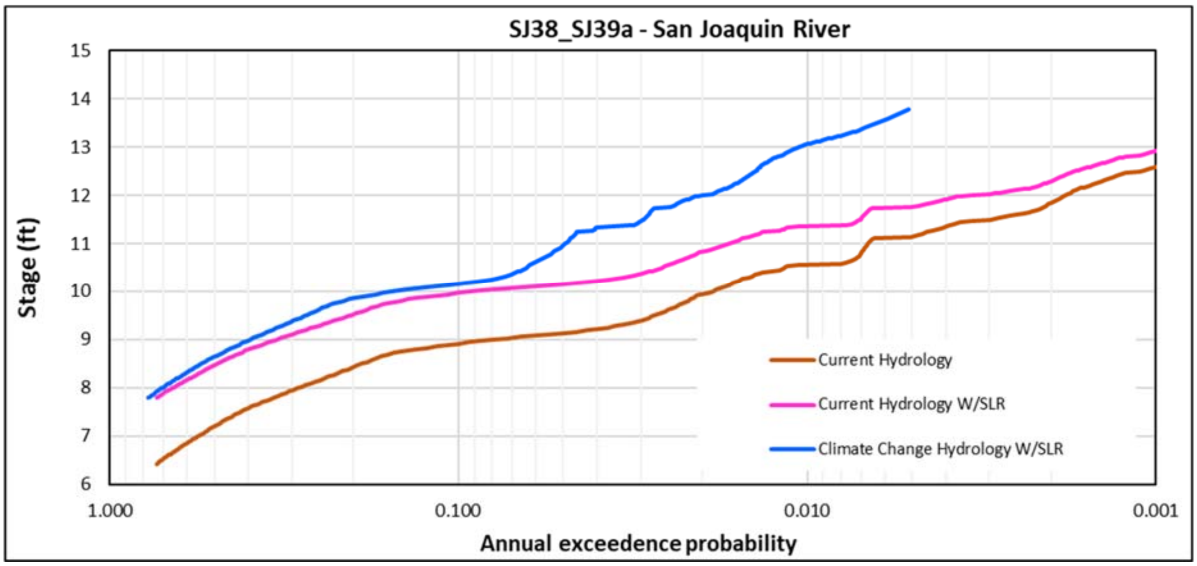

SJ31a_SJ36a - San Joaquin River
Stage (ft)
28
26
24
22
20
18
16
14
12
10
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

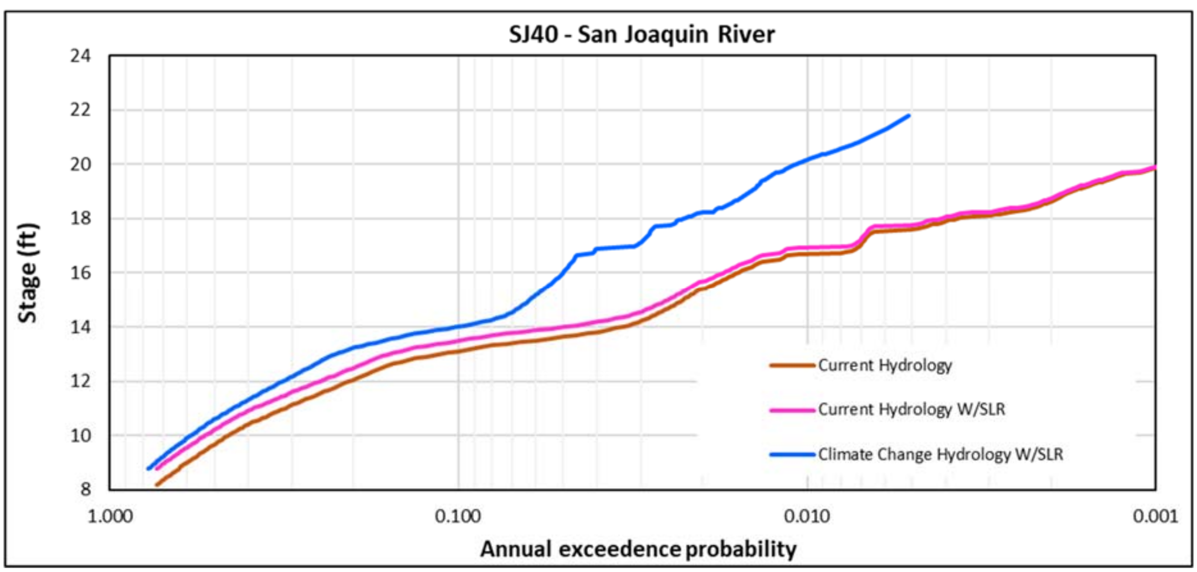

SJ31c - San Joaquin River
Stage (ft)
32
30
28
26
24
22
20
18
16
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

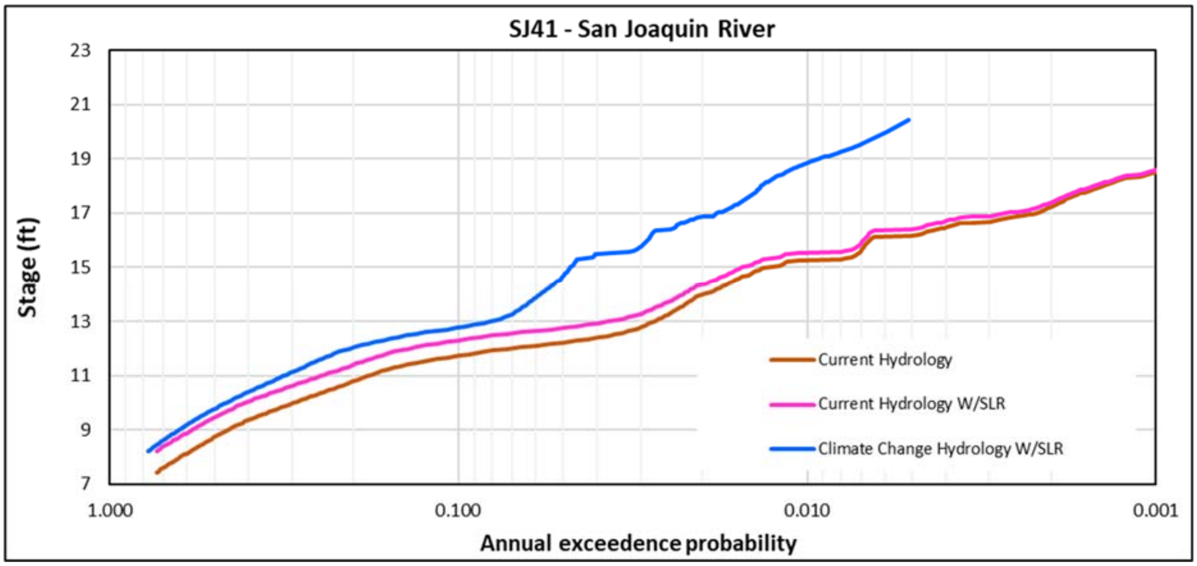

SJ36 - San Joaquin River
Stage (ft)
27
25
23
21
19
17
15
13
11
9
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

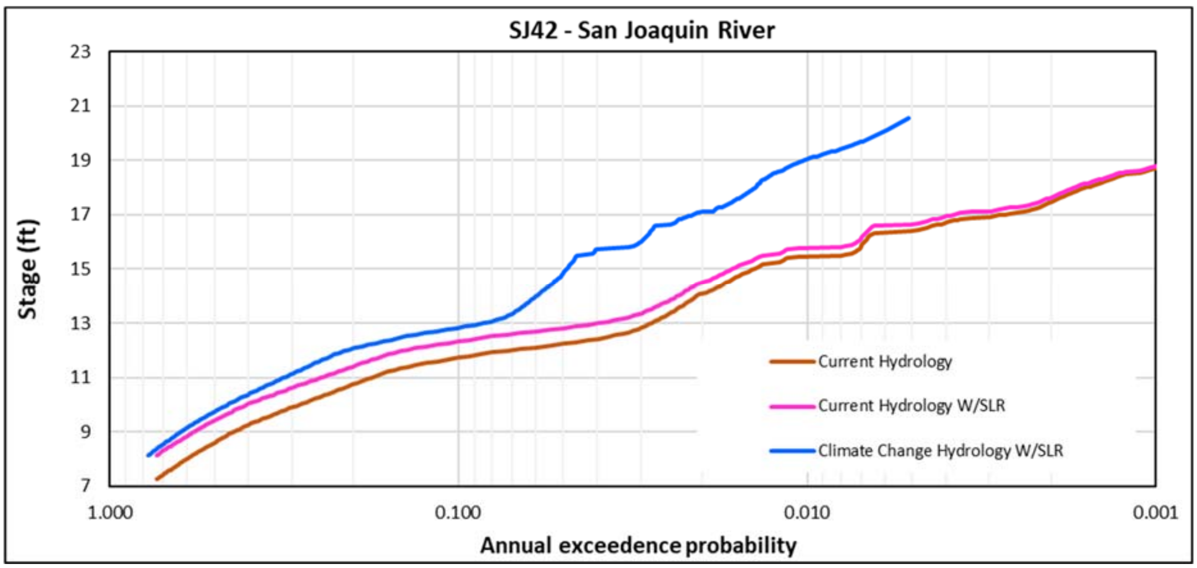

SJ36b_SJ39 - San Joaquin River
Stage (ft)
22
20
18
16
14
12
10
8
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

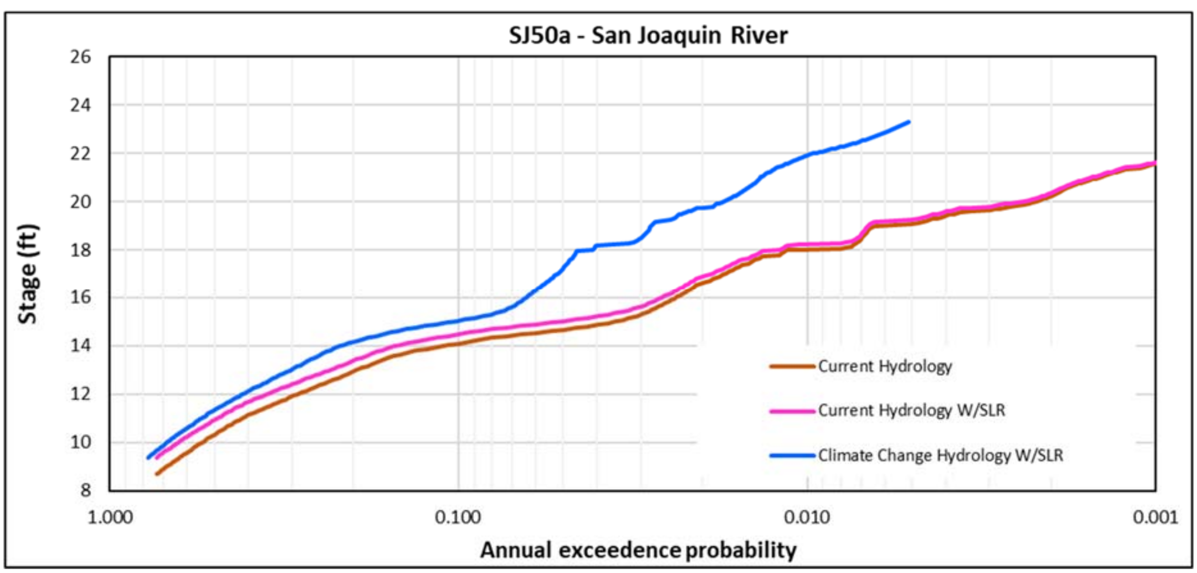

SJ37 - San Joaquin River
Stage (ft)
16
15
14
13
12
11
10
9
8
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

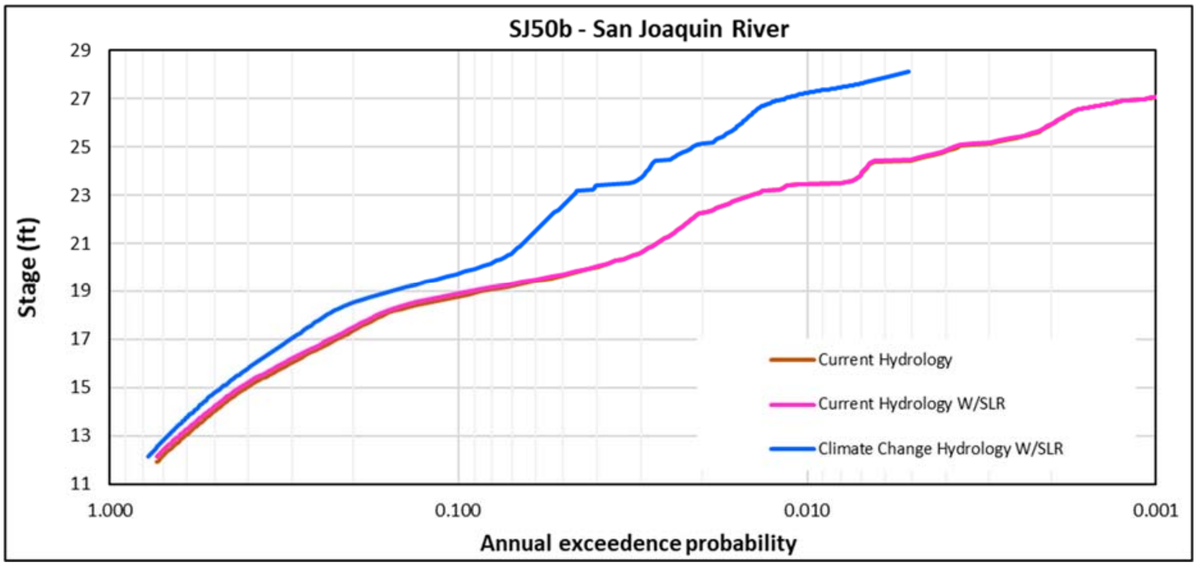

SJ38_SJ39a - San Joaquin River
Stage (ft)
15
14
13
12
11
10
9
8
7
6
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

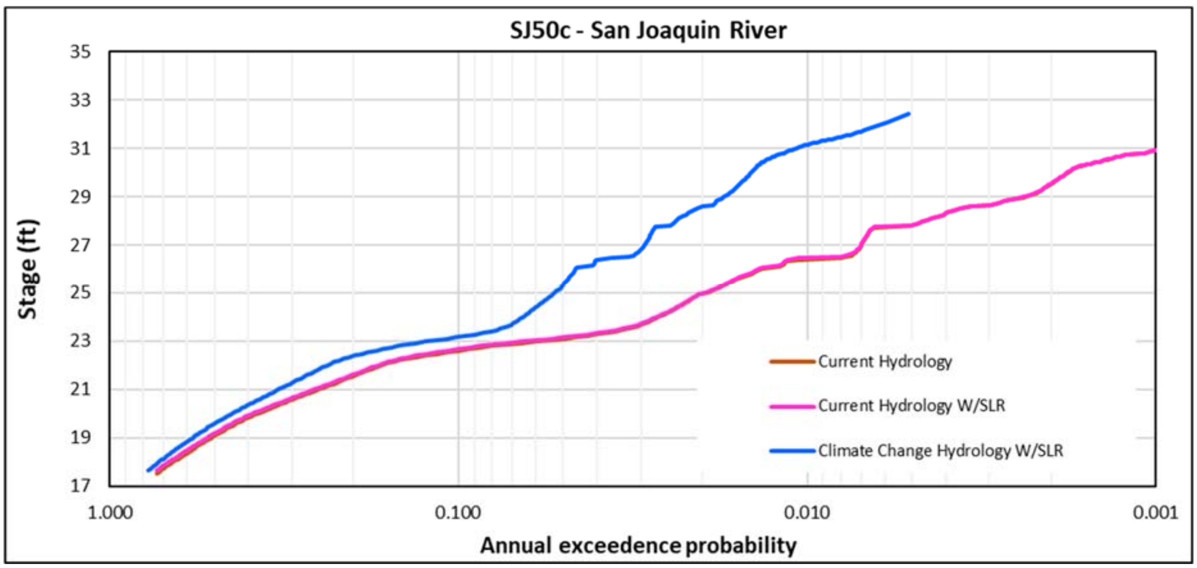

SJ40 - San Joaquin River
Stage (ft)
24
22
20
18
16
14
12
10
8
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

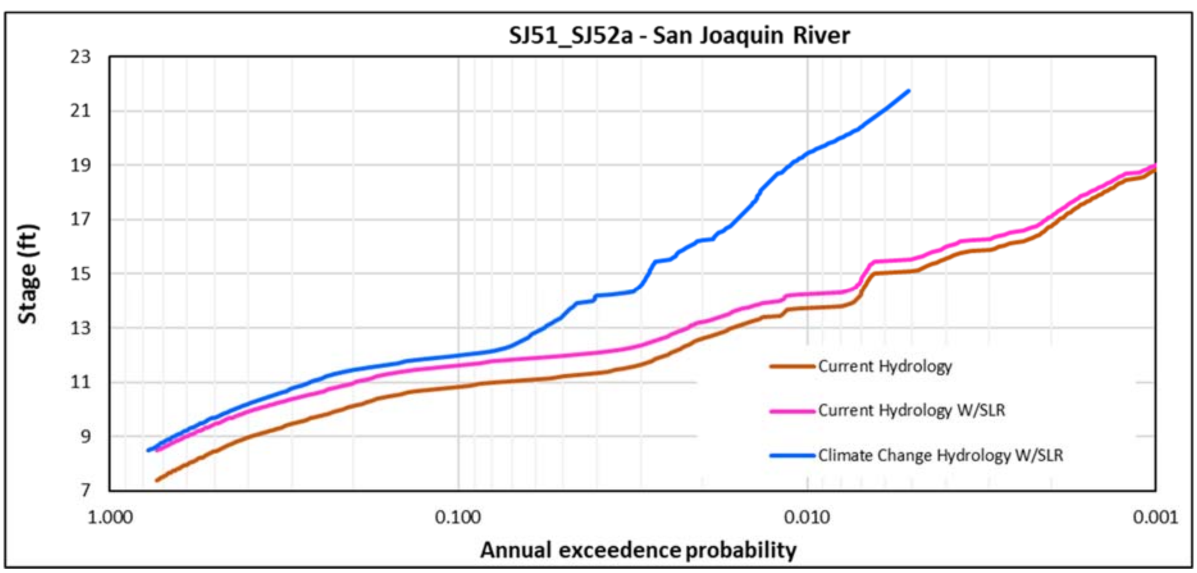

SJ41 - San Joaquin River
Stage (ft)
23
21
19
17
15
13
11
9
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR

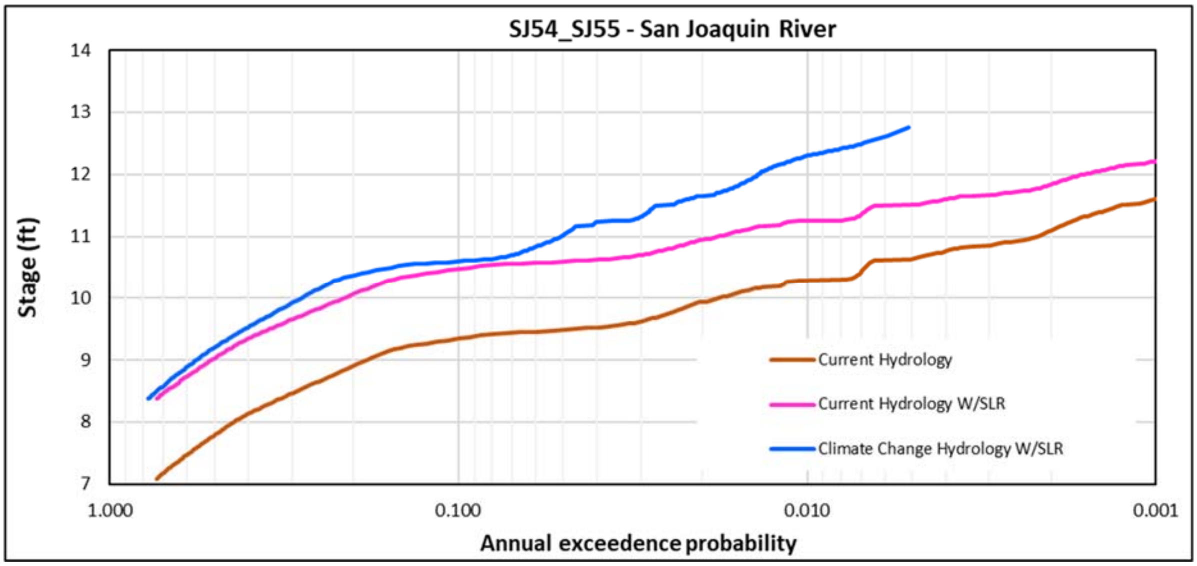

SJ42 - San Joaquin River
Stage (ft)
23
21
19
17
15
13
11
9
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR


SJ50a - San Joaquin River
Stage (ft)
26
24
22
20
18
16
14
12
10
8
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR


SJ50b - San Joaquin River
Stage (ft)
29
27
25
23
21
19
17
15
13
11
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR


SJ50c - San Joaquin River
Stage (ft)
35
33
31
29
27
25
23
21
19
17
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR


SJ51_SJ52a - San Joaquin River
Stage (ft)
23
21
19
17
15
13
11
9
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR


SJ54_SJ55 - San Joaquin River
Stage (ft)
14
13
12
11
10
9
8
7
1.000
0.100
0.010
0.001
Annual exceedence probability
Current Hydrology
Current Hydrology W/SLR
Climate Change Hydrology W/SLR