Sonoma Water

Final Report

Appendix C. Risk Assessment Special Studies

October 2021

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Contents

Tables

Figures

SECTION 1

Risk Assessment Special Studies

1.1 Introduction

Following the vulnerability assessment findings and workshops with the Climate Adaptation Plan (CAP) team, several areas of uncertainty with respect the magnitude of risk were identified. Specific modeling and technical analyses were developed to gain further insight into the climate vulnerabilities and risks for these areas. Five areas were identified as needing further information to support the quantitative assessment. These included the climate impacts for the following:

1. Russian River hydrologic impacts on water supply management and operations
2. Fire risk and water quality impacts to the water supply system
3. Russian River flooding impacts
4. Santa Rosa Creek flooding impacts
5. Sediment loading impacts on flood system operations

Detailed descriptions of these assessments are included in this section.

1.2 Climate and Sea Level Change Scenarios

In order to consider the range of available Coupled Model Intercomparison Project - Phase 5 (CMIP5) climate projections, a total of 20 individual daily downscaled climate projections were analyzed for the quantitative aspects of the risk analysis. These climate projections were statistically downscaled using the LOCA statistical daily downscaling method (Pierce et al., 2014) from 10 General Circulation Models (GCMs) at approximately 6 kilometers spatial resolution by the researchers at Scripps Institution of Oceanography (Pierce et al., 2014). A list of the GCMs utilized in this study is included in Table C-1. The climate projections reflect the use of these GCMs and two representative concentration pathways (RCPs) (i.e., RCP 4.5 and RCP 8.5) in the IPCC's CMIP5 model data set (Taylor et al., 2012), and are recommended for use by the California DWR Climate Change Technical Advisory Group (DWR CCTAG, 2015). LOCA downscaled climate model projections were collected from the Scripps Institution of Oceanography.

Table C-1. GCMs Downscaled by LOCA

Model Number	Model Name	Model Institution	Model Resolution
1	ACCESS-1.0	Commonwealth Scientific and Industrial Research Organization and Bureau of Meteorology	192 by 145 (165 kilometers)
2	CCSM4	National Center for Atmospheric Research	288 by 192 (110 kilometers)
3	CESM1-BGC	National Science Foundation, Department of Energy, National Center for Atmospheric Research	288 by 192 (110 kilometers)
4	CMCC-CMS	Centro Euro-Mediterraneo per I Cambiamenti Climatici	192 by 96 (165 kilometers)
5	CNRM-CM5	Centre National de Recherches Météorologiques, Centre Européen de Recherche et Formation Avancées en Calcul Scientifique	256 by 128 (123 kilometers)
6	CanESM2	Canadian Centre for Climate Modeling and Analysis	128 by 64 (247 kilometers)
7	GFDL-CM3	Geophysical Fluid Dynamics Laboratory	144 by 90 (219 kilometers)
8	HadGEM2-CC	Met Office Hadley Centre	192 by 145 (165 kilometers)
9	HadGEM2-ES	Met Office Hadley Centre; additional HadGEM2-ES realizations contributed by Instituto Nacional de Pesquisas Espaciais	192 by 145 (165 kilometers)
10	MIROC5	Atmosphere and Ocean Research Institute at the University of Tokyo, National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	256 by 128 (123 kilometers)

Note: models are listed alphabetically; and size of the model's atmospheric grid (number of longitudes by number of latitudes)

Based on these projections, specific climate change scenarios were developed to support water supply, flood management, and sanitation system assessments. When quantitative analyses permitted, all 20 climate projections were utilized. However, for many assessments, such as flood modeling, specific scenarios derived from the projections were used to represent the range of projections.

Specific scenarios were developed for flood modeling analyses, depicting increases in precipitation based on downscaled results from the set of 20 global climate model simulations. Climate model simulated 24-hour precipitation total was processed to develop a scaling factor relative to a baseline period for 19 different watersheds presented in the Russian River Basin HEC-HMS model for three future time periods over early (2016-2045), mid (2046-2075), and late (2070-2099) century. Similar scaling factors were also developed for the watersheds presented in the Santa Rosa Creek HEC-HMS model. These factors were developed for a range of return interval events ranging from about 1-year through 100-years using the L-moments method, which is consistent with NOAA Atlas 14.

The precipitation frequency statistical analysis procedure includes the following 5 main steps as described in the following steps:

1. Compute spatial average daily precipitation for each watershed using 20 individual daily downscaled climate projections using the Localized Constructed Analogs (LOCA) statistical daily downscaling method (Pierce et al., 2014) at 1/16th degree (approximately 6 kilometers) (3.75 mile) spatial resolution over the period 1950 through 2099

2. 20 individual daily downscaled precipitation projections from 10 general circulation models (GCMs) under 2 Representative Concentration Pathways (RCPs) from the Coupled Model Intercomparison Project Phase 5 (CMIP5) recommended for use by the DWR Climate Change Technical Advisory Group (CCTAG) (DWR CCTAG, 2015)

3. Compute annual daily maximum precipitation for each water year over the period WY 1951 through WY 2099 from 20 individual daily downscaled climate projections.

4. Fit the Generalized Extreme Value (GEV) distributions to the annual maximum precipitation using the L-moments method which is consistent with NOAA Atlas 14

5. Compute precipitation frequency changes by comparing frequency curves over the reference period WY 1981 through WY 2010 and early (2016-2045), mid (2046-2075), and late (2070-2099) future periods from 20 individual daily downscaled precipitation projections.

Sea level rise scenarios were developed based on Kopp et al (2014) and are consistent with those included in the State of California's Ocean Protection Council (OPC) sea level rise guidance (OPC 2018). Polynomial regressions were developed for the RCP 8.5 and RCP 4.5 scenarios using the Kopp et al (2014) published percentile data for San Francisco centered on 2030, 2060, and 2085 future periods.

Table C-2 shows the projected changes in temperature, precipitation, and mean sea level based on likelihood for the mid-century period, while Table C-3 shows the projected changes for the late-century period.

Table C-2. Projected Climate Change Parameters by Likelihood of Exceedance for 2046-2075 Period Compared to the 1981-2010 Period

Change in Parameter	Very Likely (90% of projections exceed)	Likely (66% of projections exceed)	Moderate (50% of projections exceed)	Unlikely (33% of projections exceed)	Very Unlikely (10% of projections exceed)
Annual Average Temperature (degrees C)	1.4	2.0	2.1	2.3	3.1
Annual Average Precipitation (%)	-6.0%	-1.3%	5.7%	10.1%	30.8%
2-year 24-hour Precipitation Total (%)	-2.5%	1.7%	6.0%	11.5%	22.3%
5-year 24-hour Precipitation Total (%)	-2.4%	1.8%	6.1%	11.5%	22.4%
10-year 24-hour Precipitation Total (%)	-2.7%	1.5%	5.8%	11.2%	22.0%
25-year 24-hour Precipitation Total (%)	-3.2%	1.0%	5.2%	10.7%	21.4%
50-year 24-hour Precipitation Total (%)	-3.6%	0.5%	4.8%	10.2%	20.9%
100-year 24-hour Precipitation Total (%)	-4.1%	0.1%	4.3%	9.6%	20.3%
Mean Sea Level (centimeter) – 2060	22.2	29.3	33.2	36.7	44.8

Table C-3. Projected Climate Change Parameters by Likelihood of Exceedance for 2070-2099 Period Compared to the 1981-2010 Period

Change in Parameter	Very Likely (90% of projections exceed)	Likely (66% of projections exceed)	Moderate (50% of projections exceed)	Unlikely (33% of projections exceed)	Very Unlikely (10% of projections exceed)
Annual Average Temperature (degrees Celsius)	1.7	2.4	2.9	3.2	4.6
Annual Average Precipitation (%)	-3.0%	2.1%	7.9%	12.6%	34.2%
2-year 24-hour Precipitation Total (%)	-0.8%	4.6%	9.5%	24.9%	31.9%
5-year 24-hour Precipitation Total (%)	0.0%	5.4%	10.3%	25.9%	32.8%
10-year 24-hour Precipitation Total (%)	0.2%	5.6%	10.5%	26.1%	33.1%
25-year 24-hour Precipitation Total (%)	0.2%	5.7%	10.6%	26.2%	33.2%
50-year 24-hour Precipitation Total (%)	0.2%	5.7%	10.5%	26.2%	33.2%
100-year 24-hour Precipitation Total (%)	0.1%	5.6%	10.5%	26.1%	33.0%
Mean Sea Level (centimeter) – 2085	34.6	46.6	53.1	60.1	75.5

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SECTION 2

Russian River Water Supply Modeling

2.1 Purpose

The goal of this analysis was to conduct water supply modeling of the Potter Valley Project (PVP) and Russian River System to quantify impacts of climate change on this integrated water system. Hydrological information based on the 20 downscaled climate projections were selected from available (USGS) Basin Characterization Model (BCM) hydrological model results. These climate and hydrologic projections were used to adjust inflow time series and to adjust water demands in the PVP Fortran Model ER2.5 and Russian River HEC-ResSim model. The models used in this assessment are identical to those used by Sonoma Water in the Fish Habitat Flows and Water Rights Project Draft EIR (SCWA, 2016).

2.2 Methodology

Hydrological adjustments to reflect future climate change consisted of routed streamflows for 10 locations that are required as input to the Russian River Basin HEC-ResSim model and two locations in the Eel River Basin that are used for the PVP operations model. Twenty downscaled GCM projections were selected from ten different GCMs and two different Representative Concentration Pathways, RCP4.5 and RCP8.5. These ten GCMs were chosen by the DWR Climate Change Technical Advisory Group (CCTAG) based on a regional evaluation of climate model ability to reproduce a range of historical climate conditions. Two locations in the Eel River Basin were used for the PVP operations model.

Due to inherent limitations in the downscaling methods, meteorological inputs, and BCM model, the resulting streamflows were adjusted to remove historical bias before being applied for future simulations in the models.

Adjustment factors were also applied to historical consumptive use estimates to reflect future changes in potential evapotranspiration and open water surface evaporation. Existing Variable Infiltration Model (VIC) model results for potential evapotranspiration (using short grass as a reference crop) and open water surface evaporation were used to develop these demand and evaporation adjustment factors. In addition, due to the significance of frost days on water depletions on Russian River, a method was developed to translate projected changes in frost days to increases in river demand. Frost day frequency was computed for selected LOCA grid cells in areas historically affected by frost-associated water loss (Calpella, Hopland, Cloverdale, Healdsburg, Dry Creek).

PVP Fortran Model ER2.5 and Russian River HEC-ResSim model simulations were developed for a historical baseline and for future climate change conditions. PVP and Russian River HEC-ResSim model simulations were evaluated and summarized for the historical simulations and climate change conditions, and results of model simulations under historical and climate change conditions across the key locations over the Russian River were documented.

2.3 Results

Climate projection outcomes were assessed for two future periods. In order to capture variability in precipitation and streamflow a period of sufficient length was required. For this assessment, the mid-century period is defined as the period of 2006-2060 and late-century is the period of 2045-2099 and results are compared to the historical period of 1951-2005. Each of these periods includes 55-years of variability, and the historical period represents the same period for which BCM streamflow results were bias-corrected. For climate information (temperature and precipitation change), we also present changes for shorter 30-year periods in addition to the longer 55-year periods for comparison. These additional periods are 2035-2065 for mid-century and 2070-2099 for late-century compared to the historical period of 1976-2005 and are those presented in Pierce et al. (2018), a report prepared for the California Fourth Climate Change Assessment.

Figure C-1 shows the annual natural streamflow exceedance probability curves for historical and future scenarios at the Russian River downstream of the Dry Creek confluence for the period of 2006-2060. The results indicate the potential for streamflow reductions, particularly during the drier years (lower percentiles) and potential increases during wetter years (higher percentiles).

Figure C-1. Projected Changes in Russian River Annual Streamflow for Period of 2006-2060.

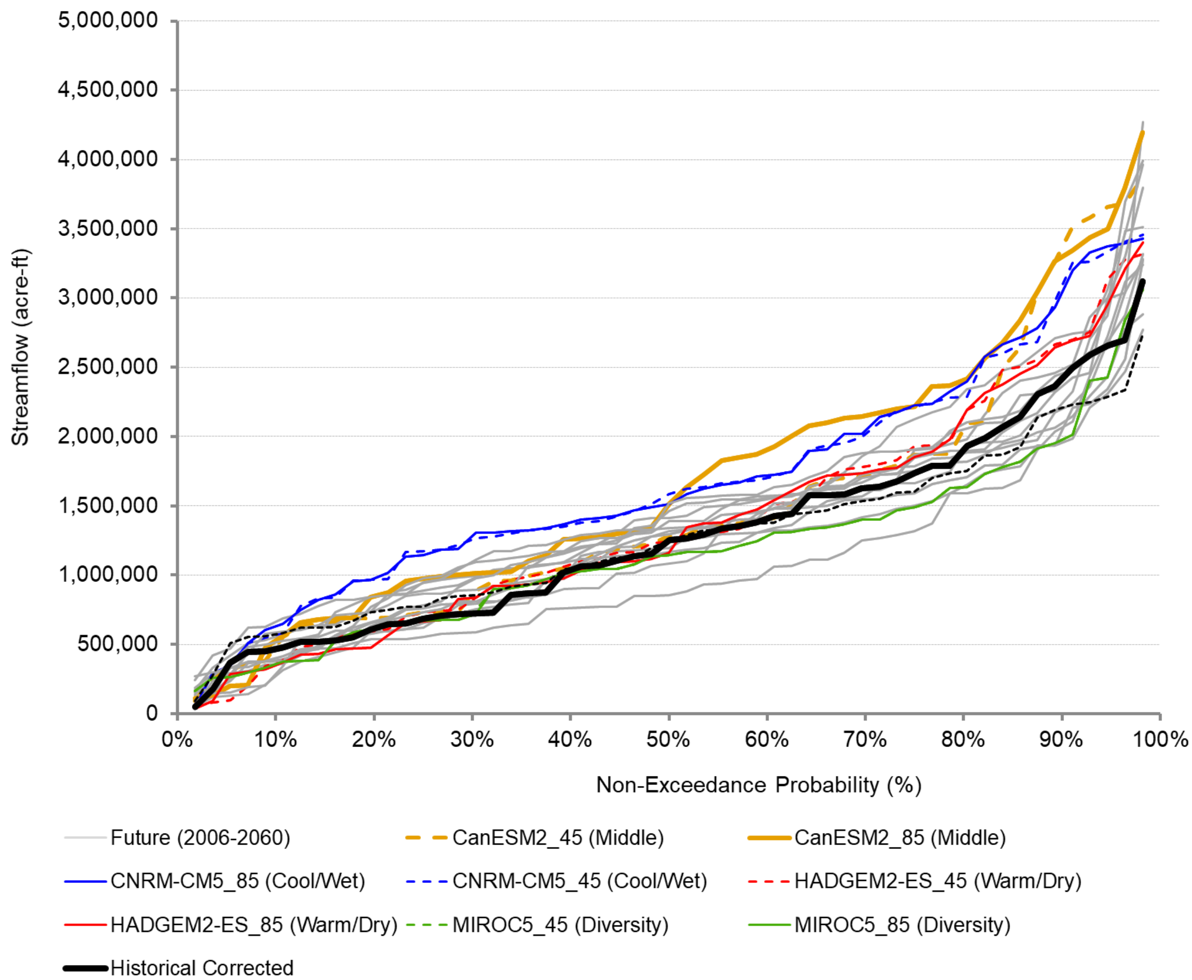


Figure C-2 shows the 3-year annual natural streamflow exceedance probability curves for historical and future scenarios at the Russian River downstream of the Dry Creek confluence for the period of 2006-2060. The results indicate an expansion in variability for the moderate to wet periods but only modest changes in variability for the driest periods. The “cool/wet” and “middle” projections show the largest increases in 3-year streamflow, while the “diversity” and “warm/dry” projections indicate the greatest reductions in 3-year streamflow. The “diversity” projection continues to exhibit the lowest 3-year annual streamflow. While not well simulated in GCMs, some projections suggest future droughts through mid-century up to 20% more severe than historical droughts.

Figure C-2. Projected Changes in Russian River 3-Year Annual Streamflow for Period of 2006-2060.

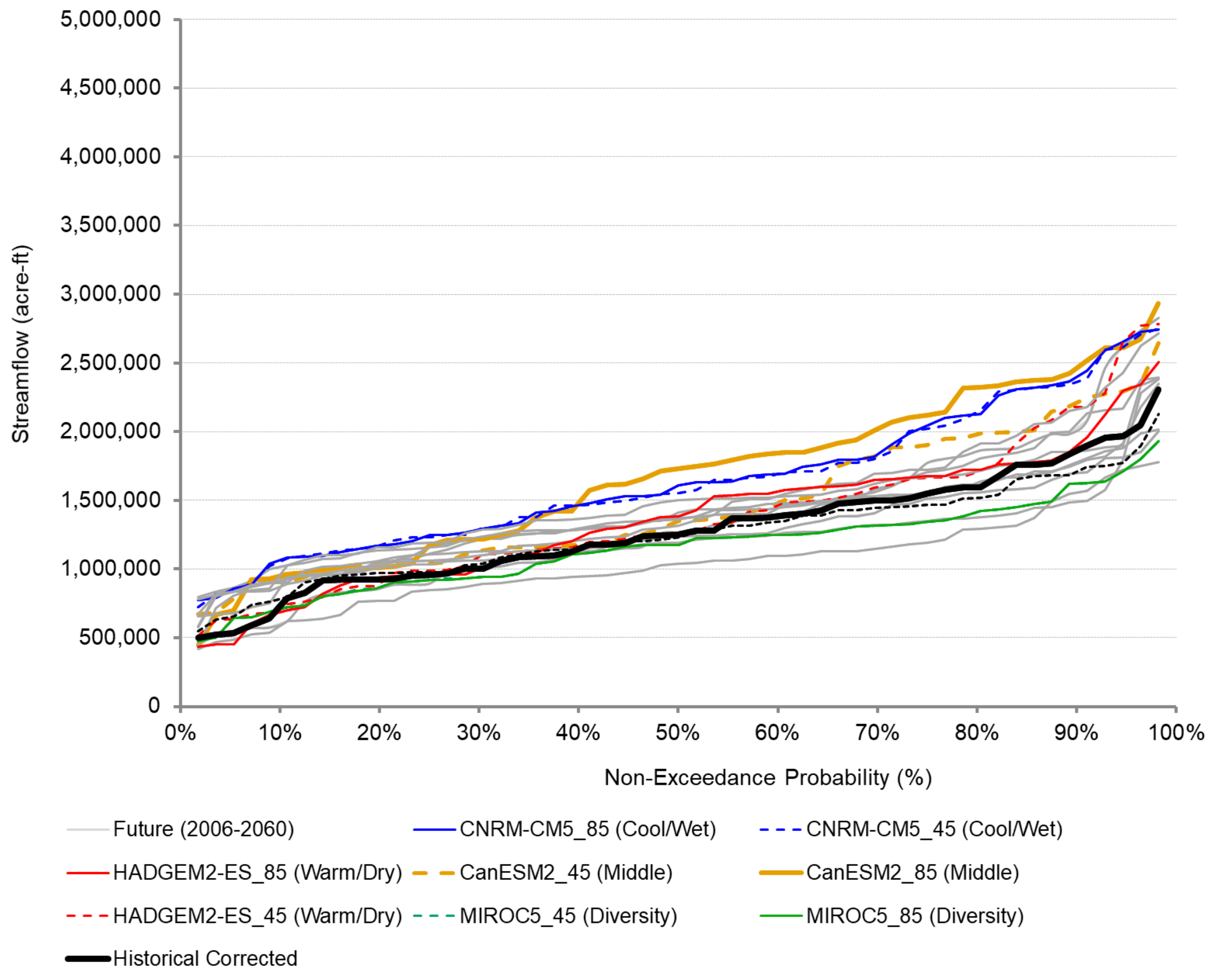


Figure C-3 shows the end-of-September storage exceedance probability curves for baseline and future scenarios at Lake Sonoma for the period of 2006-2060. Most future projections project decreases in storage across all exceedance values due to the projected increase in water demand in the basin and by Sonoma Water contractors. Note that the historical projections and "current operations" assume historical water demands. The range of outcomes for the lowest 30-40% of years is driven by the climate projections. Some projections suggest lower storage conditions than that projected under historical operations and indicate a few extreme challenging years.

Figure C-3. Projected End-of-September Lake Sonoma Storage for Period of 2006-2060.

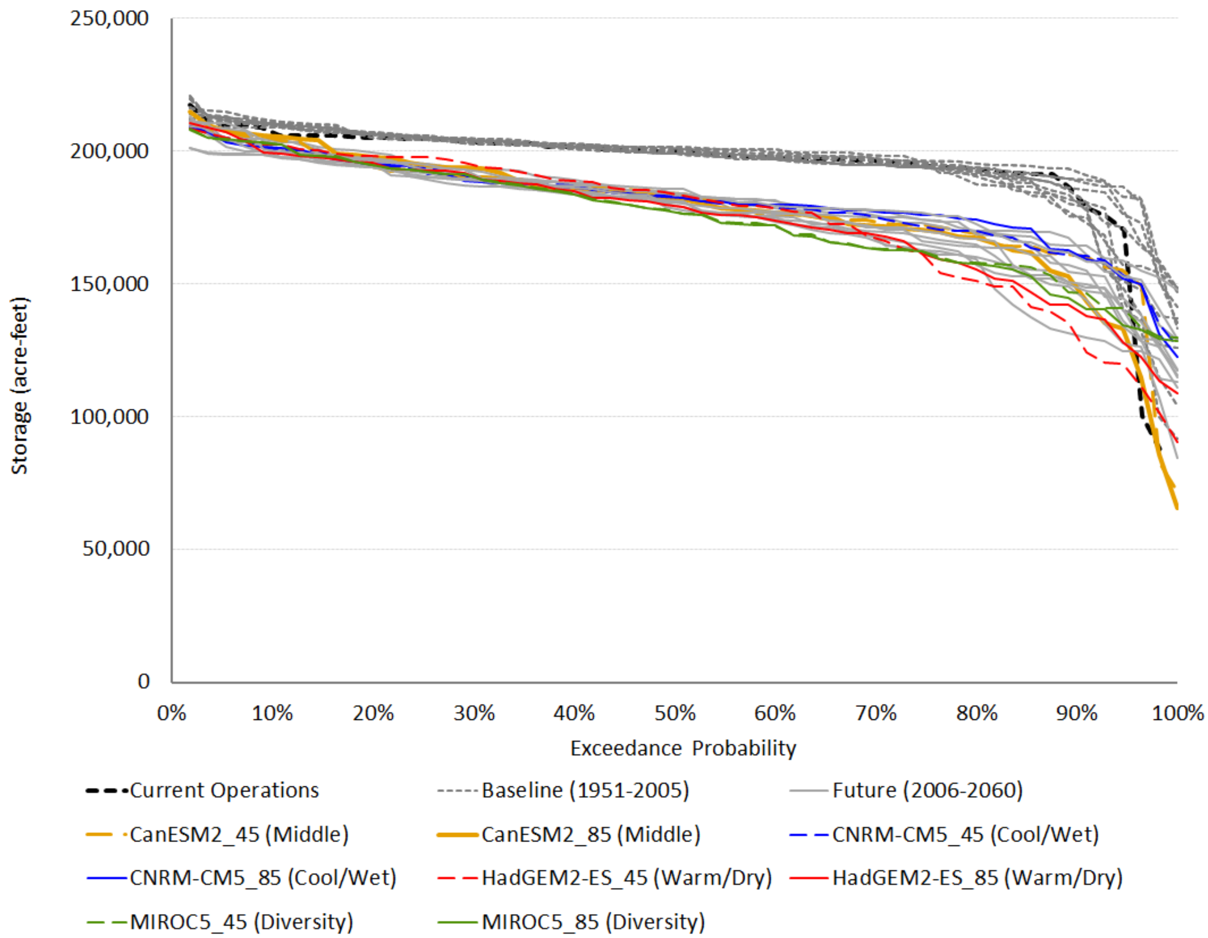
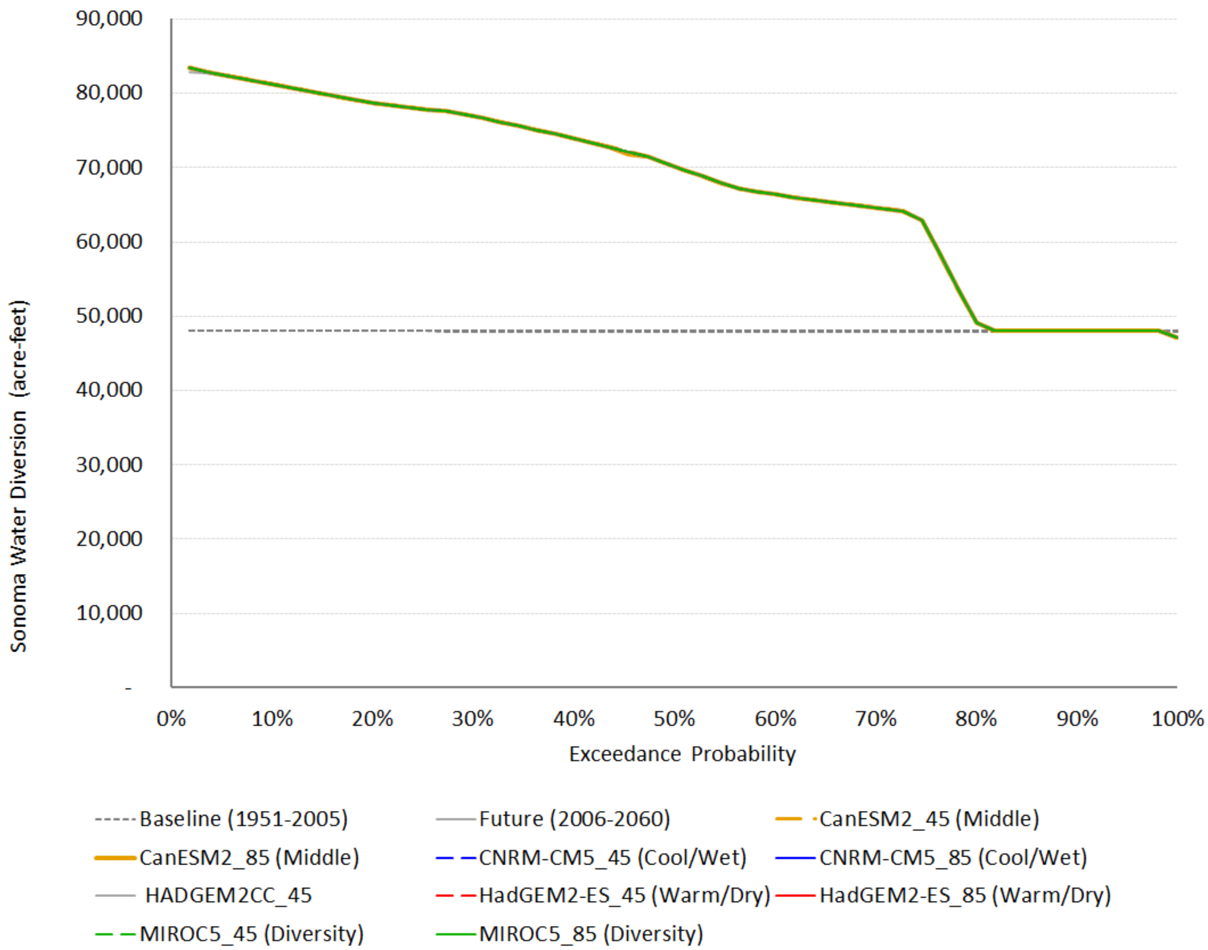


Figure C-4 shows the exceedance probability curves for annual Sonoma Water diversion (acre-feet) under both baseline and future conditions. Due to increase in water demand, the Sonoma Water diversion is increased in all simulations. In general, HEC-ResSim simulations suggest nearly identical results for all GCM model projections which indicates similar delivery capability. The Sonoma Water system appears to be able to adapt to the climate and hydrologic changes projected in the scenarios.

Figure C-4. Projected Sonoma Water Annual Diversion Capability for Period of 2006-2060.



In summary, modeling results were evaluated for changes in future streamflow, reservoir storage, and water delivery as compared to a no climate change condition. Based on these modeling results the following findings are relevant:

- Annual and 3-year streamflow on the Russian River downstream of the Dry Creek confluence is projected to become even more variable in the future with climate change. The results indicate the potential for both lower streamflows during the drier years (lower percentiles) and higher streamflows during wetter years (higher percentiles). While most projections indicate potential increases in streamflow, several projections suggest conditions drier than historical record for the lowest 10 percent of years.
- Most future projections project decreases in Lake Sonoma end-of-September storage across all exceedance values due to projected increases in water demand in the basin and by Sonoma Water contractors. However, changes in the lowest 30 to 40% of years are largely driven by climate change and some projections suggest lower storage conditions than that under historical hydrology. All projections indicate an incidence of Lake Sonoma end-of-September storage less than 150,000 acre feet and five projections indicate storage lower than 100,000 acre feet.

Sonoma Water diversion under both baseline and future conditions appears relatively robust in the face of changing climate and hydrology. Due to increases in water demand, the Sonoma Water diversion is increased in all simulations. However, simulations indicate similar delivery capability (meeting contractor demand). The Sonoma Water system appears to be able to adapt to the climate and hydrologic changes projected in the scenarios.

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SECTION 3

Fire Risk and Water Quality Risk Modeling

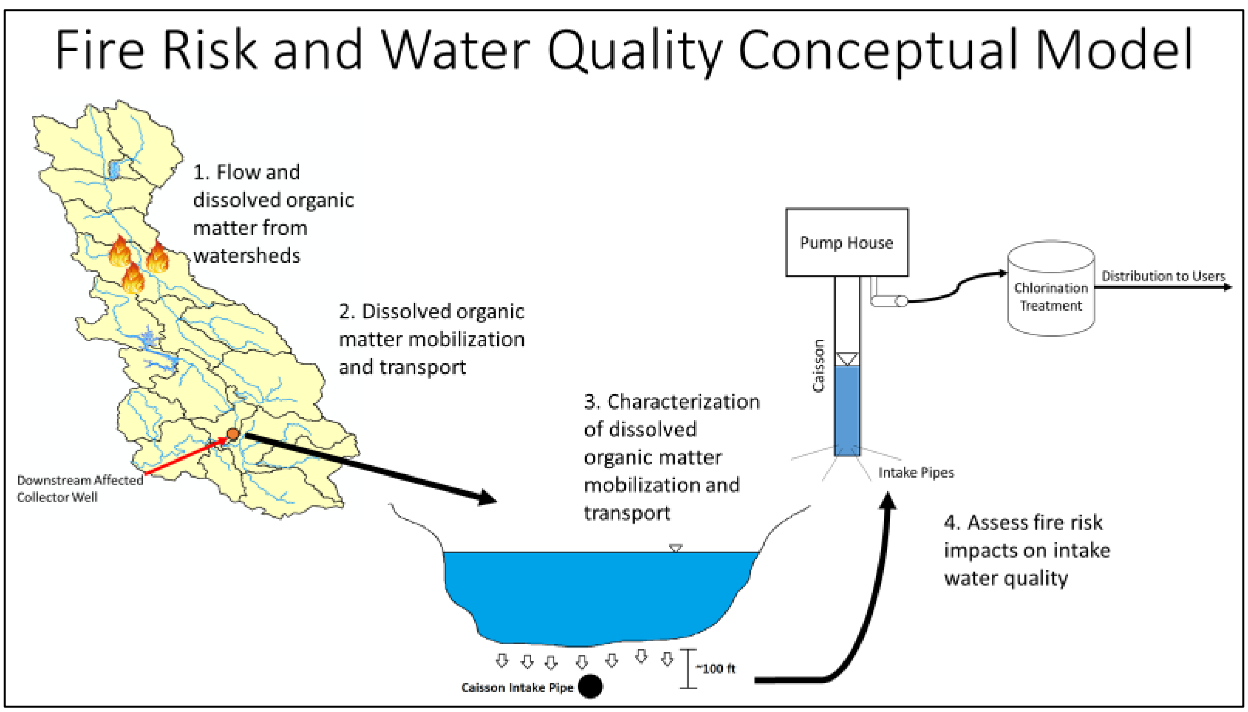
3.1 Purpose

The role of increasing fire risk and its impacts on river and intake water quality was identified as a need for the improved quantitative information. An innovative analysis was developed to better understand the probability, location, and extent of fire risk; and to assess impacts on intake water quality. This analysis integrates fire risk modeling, hydrologic modeling, and water quality estimates (primarily organic carbon) to assess impacts to water supply operations. The HEC-HMS model and landscape-scale fire modeling has been used to assess to fire risk and water quality risk.

3.2 Methodology

The workflow of the methodology is presented in four major steps shown graphically in Figure C-5 and described in the following sections.

Figure C-5 Fire Risk and Water Quality Conceptual Model Steps



Daily runoff volumes in each of the 19 study area watersheds were simulated by HEC-HMS under baseline and early, mid, and late future climate conditions. Potential future fires of low, medium, and high severity in each climate scenario were represented by the fraction of watershed area burned. Geographic specification of future fire severity by watershed was accomplished using change in area burned in wildfire scenario projections from Cal Adapt (Cal Adapt Wildfire Tool, 2018). Percent difference in area burned between historical and future periods for eight climate projections for nine HUC-10 watersheds that covered the study area were used to develop change factors to apply to baseline burn severities to include the effect of climate change. For each future time period, climate change factors were considered to be uniform for low, medium, and high burn severities. Pre-fire flows in each watershed were translated to post-fire flows using severity of the potential future fires based on the USGS Regression Methodology (Foltz, Robichaud, and Rhee, 2009).

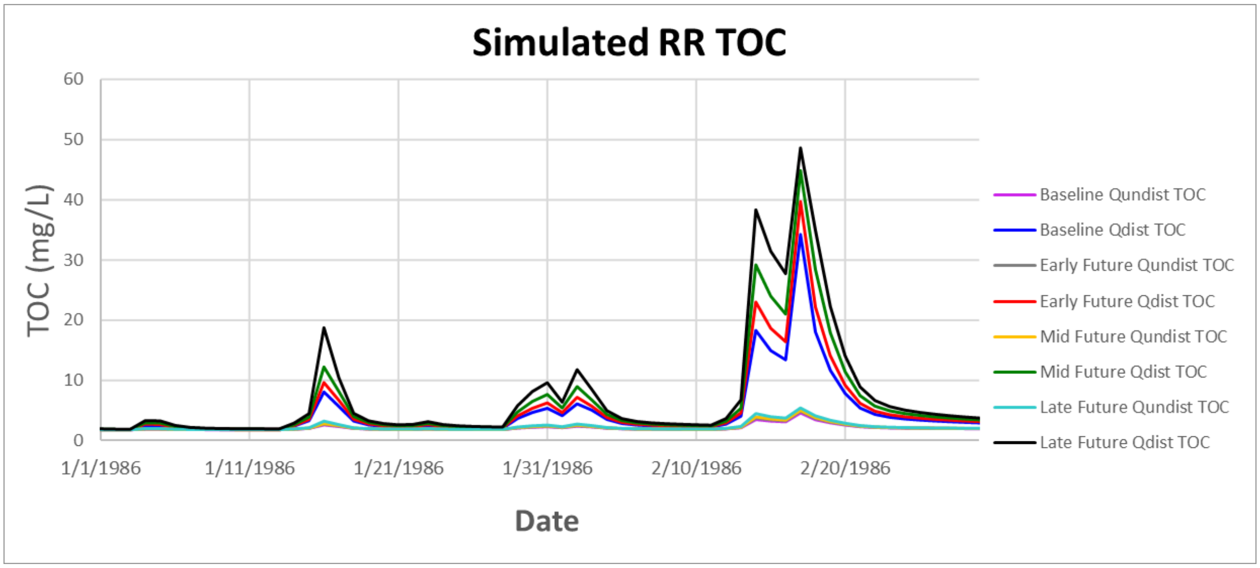
The sediment and organic carbon (DOC and TOC) relationship with hydrology and watershed changes post-fire was characterized. The hydrologic and sediment/carbon response to climate/land disturbance conditions were also developed. The organic carbon loading at the Russian River water supply intakes was estimated under historical and future conditions. The carbon loading (TOC and DOC) in each watershed was calculated from streamflow and concentration relationships developed based on observed data, and then summed to create system-wide loading at the Russian River Diversion. Russian River organic carbon was related to caisson organic carbon with appropriate attenuation and filtration based on historical relationships. Results of potential changes in fire frequency, hydrologic conditions, and organic carbon at water supply intakes were documented, and the potential for significant water supply impacts due to water quality were estimated.

3.3 Results

Using HEC-HMS, flow in each of the 19 watersheds in Sonoma County was simulated under four climate conditions, baseline, early future, mid future, and late future. Pre-fire flows in each watershed were translated to post-fire flows using severity of the potential future fires based on the USGS Regression Methodology (Foltz, Robichaud, and Rhee, 2009).

Carbon loading (TOC and DOC) in each watershed was calculated from streamflow and concentration relationships developed based on observed data, and then summed to create system-wide loading at the Russian River Diversion. Figure C-6 shows daily simulated TOC and DOC concentrations at the Russian River Diversion for baseline and three climate scenarios under both undisturbed and disturbed conditions.

Figure C-6. Russian River Diversion Daily TOC and DOC Concentrations under Climate and Fire Conditions



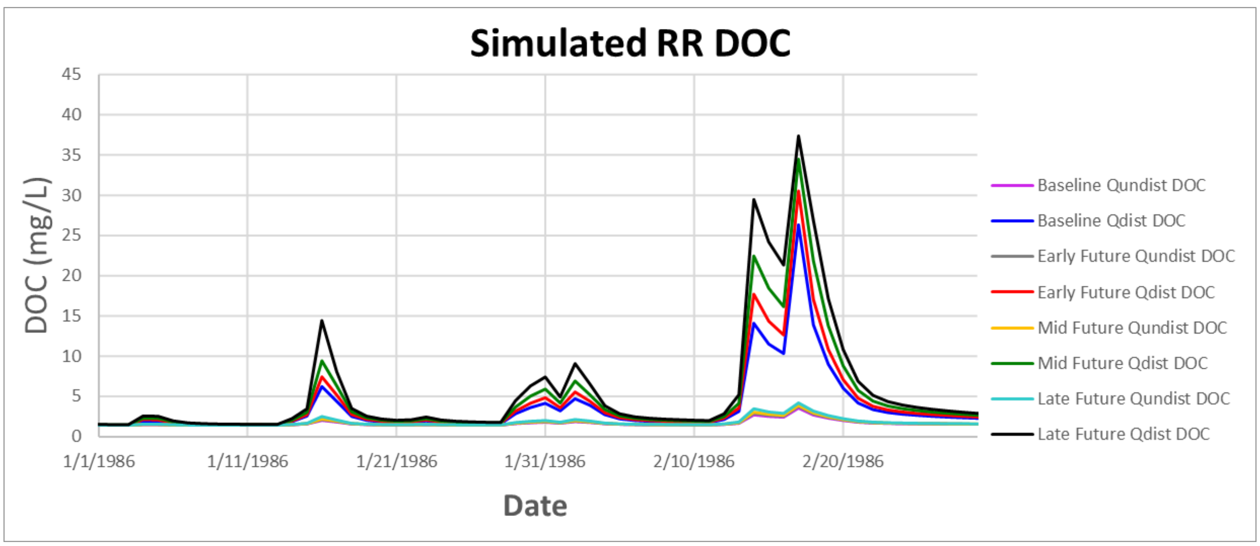
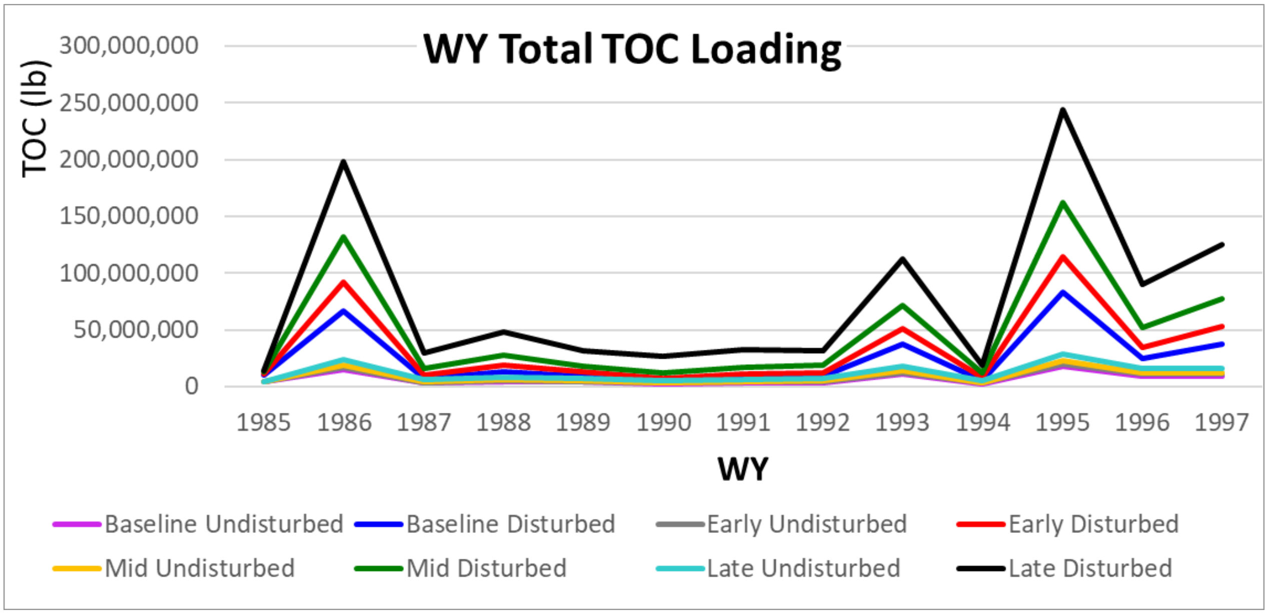
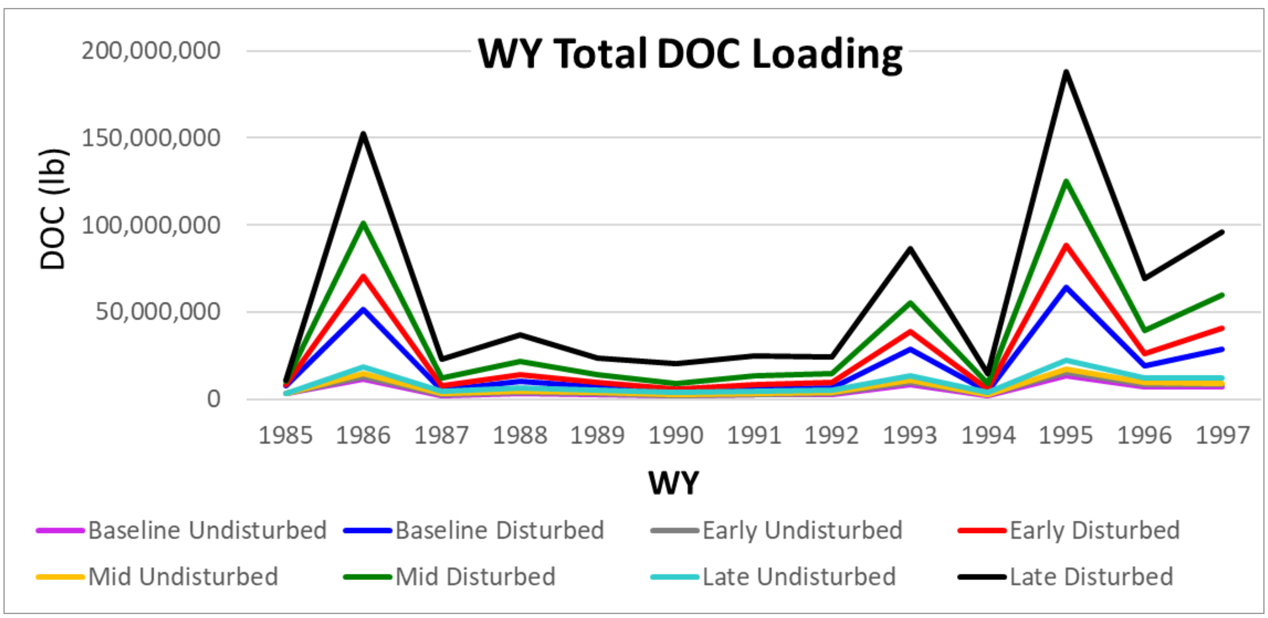


Figure C-7 in the following section shows WY total magnitude of TOC and DOC carbon loading for baseline and three climate scenarios under both undisturbed and disturbed conditions.

Figure C-7. Russian River Diversion WY Total TOC and DOC Loadings under Climate and Fire Conditions





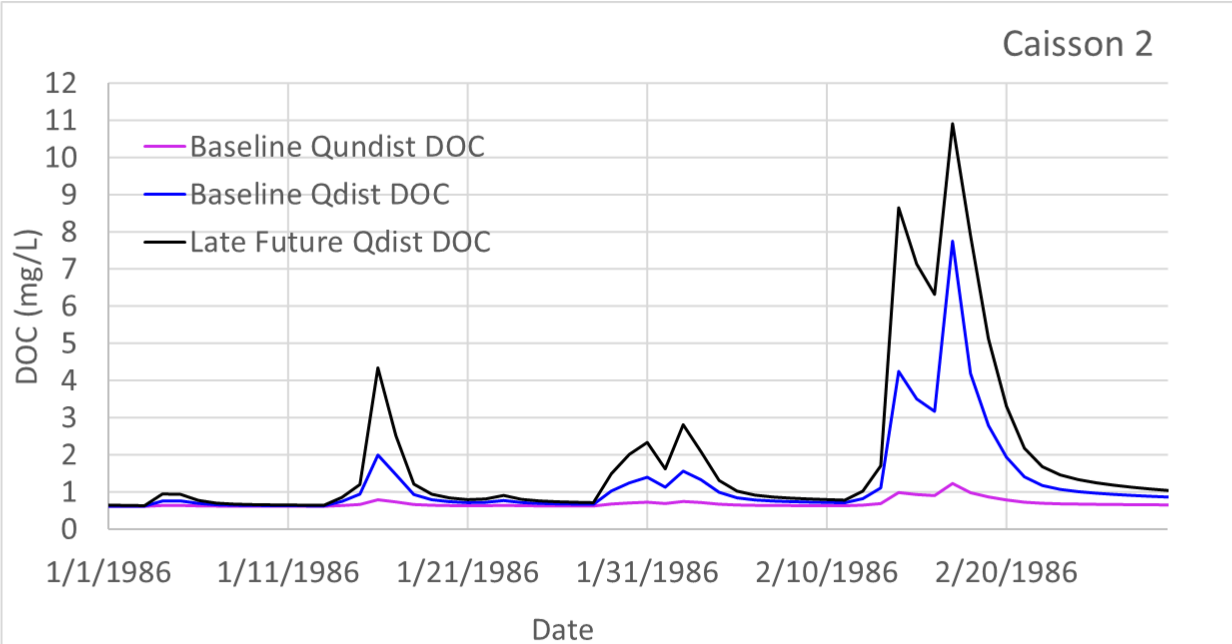
At the Russian River diversion point, river water filters through the streambed into the caisson intake pipes. The linear equations that describe relationships between river and caisson TOC and DOC can be seen in the following section in Table C-4. These linear regression models are used to capture the very complicated effect of the aquifer natural filtration and thus contain much uncertainty. The coefficient of correlation for the linear models at all caissons was less than 0.5.

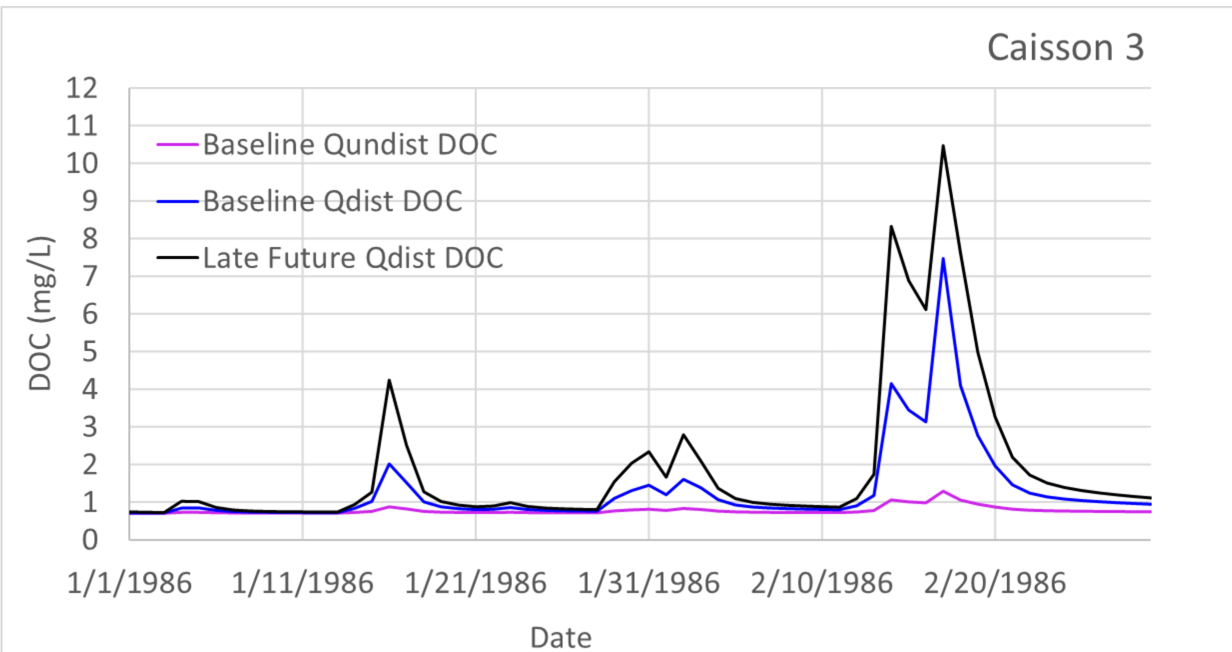
Table C-4. Organic Carbon Models

Caisson No.	TOC	DOC
1	$TOC^{C} = 0.333 * TOC^{RR} + 0.118$	$DOC^{C} = 0.360 * DOC^{RR} + 0.053$
2	$TOC^{C} = 0.168 * TOC^{RR} + 0.321$	$DOC^{C} = 0.203 * DOC^{RR} + 0.283$
3	$TOC^{C} = 0.197 * TOC^{RR} + 0.399$	$DOC^{C} = 0.308 * DOC^{RR} + 0.249$
4	$TOC^{C} = 0.229 * TOC^{RR} + 0.288$	$DOC^{C} = 0.295 * DOC^{RR} + 0.218$
5	$TOC^{C} = 0.170 * TOC^{RR} + 0.277$	$DOC^{C} = 0.280 * DOC^{RR} + 0.180$
6	$TOC^{C} = 0.164 * TOC^{RR} + 0.312$	$DOC^{C} = 0.215 * DOC^{RR} + 0.267$

FigureB C-8 shows the change from undisturbed and disturbed flows under baseline and future conditions for Caisson 2 and 3. Both show significant increases in DOC concentrations in disturbed conditions.

Figure C-8. Caisson 2 and 3 DOC Concentrations





While this modeling analysis should be considered only approximate at this point in the development, it did suggest important findings that should be considered in both current and future climate risks. The following observations are drawn from this quantitative analysis:

- Wildfire risks are found to be increasing throughout the contributing watersheds to the Russian River. Both the extent and severity of wildfire burn is expected to increase under future climate change associated with earlier drying of the watershed, extended dry season length, and substantial combustible fuel in the predominantly privately-owned lands.

- Post-wildfire extreme precipitation events (flood-after-fire) have the ability to substantially increase sediment and carbon runoff from the disturbed watershed lands. Total and dissolved organic carbon in the Russian River post-fire may increase by more than 10 times the concentration under an undisturbed (non-fire) condition.
- The alluvial aquifer underlying the Russian River transmits water to the Mirabel and Wohler collectors and substantially reduces the organic carbon in the water supply. Following the Walbridge Fire of 2020, Sonoma Water conducted a robust water quality monitoring program. Some changes were noted in surface water quality, but no impacts were detected in the collector well water. However, water year 2020 was dry and no significant runoff events followed. The analysis included here suggests that under more severe hydrologic conditions water quality could be challenged. The analysis suggests that DOC at the collectors may increase by up to five times during large post-fire runoff events. Several simulated post-fire runoff events produced estimated DOC concentrations greater than the disinfection byproducts threshold (~ 2 mg/L) for chlorination. While this condition has not yet been experienced after recent wildfires, this analysis suggests that the flood-after-fire risk is high depending on the location and timing of coincident wildfire and extreme precipitation.

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SECTION 4

Santa Rosa Creek Flood Modeling

4.1 Purpose

Flooding management operations on Santa Rosa Creek were assessed to be highly vulnerable to climate change. To better understand climate-flood related vulnerabilities along the Santa Rosa Creek flood management system, a modeling study was performed covering the extent of the watershed, detention facilities, hydraulic control facilities, culverts, and flood channels.

4.2 Methodology

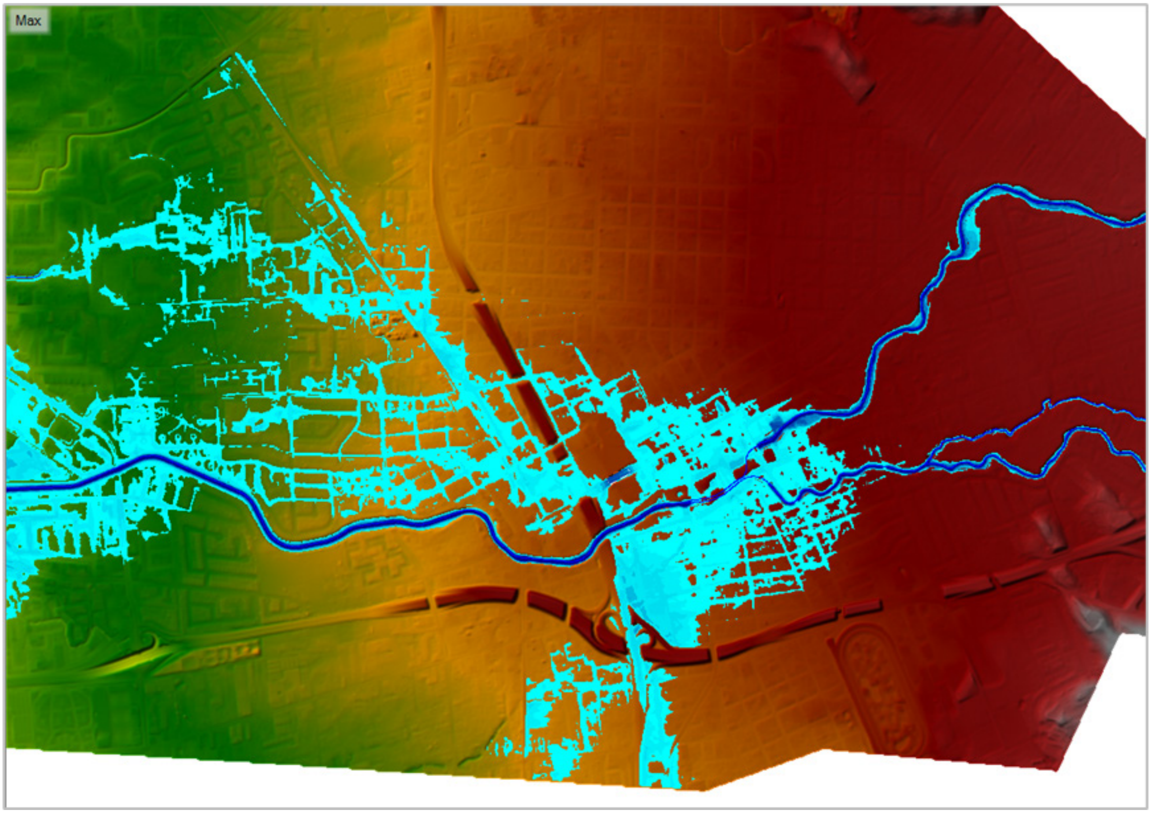
The flood modeling analysis on Santa Rosa Creek made use of existing HEC-HMS and HEC-RAS models. Precipitation time series for 69 HEC-HMS watersheds was developed to reflect future climate change. The climate and hydrologic projections were translated into modified design storms to reflect projected changes in extreme precipitation. HEC-HMS modeling using these modified design storms was also performed to investigate detention basin operations and vulnerability. Finally, two-dimensional HEC-RAS modeling, using the existing model developed by ESA, was employed to investigate flood flows and inundation throughout Santa Rosa Creek (SCWA, 2017).

4.3 Results

Flood conveyance channels along Santa Rosa Creek and its tributaries provide flood protection for downtown Santa Rosa. The triple box culverts along Santa Rosa Creek and Matanzas Creek, which route these two creeks through downtown Santa Rosa, are of particular concern for climate induced vulnerabilities. The primary hazard for these culverts is their inability to convey flood flows much larger than a 10-year event. High resolution hydraulic modeling conducted by ESA as part of the Santa Rosa Creek Hydrology and Hydraulics Study (SCWA 2017) indicate the inability of these culverts to pass flood flows above a certain return interval event between 10 and 25 years. These results are in stark contrast to assumptions made by FEMA in the development of local Flood Insurance Rate Maps.

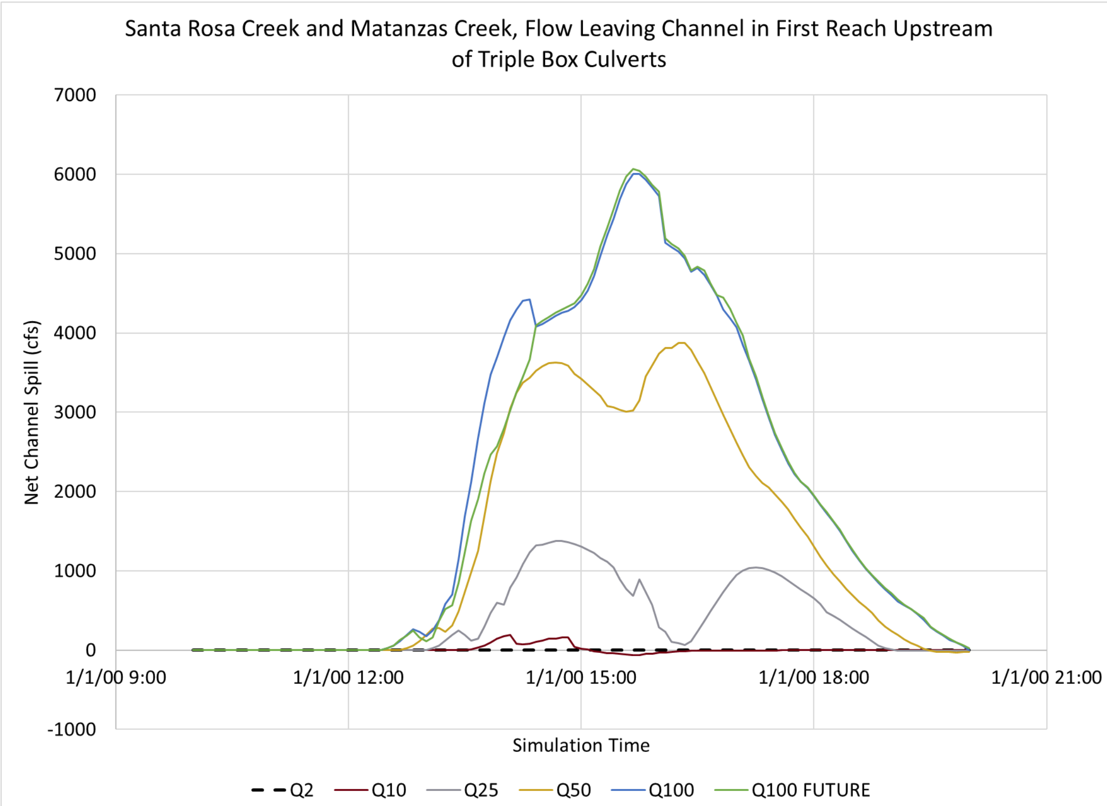
Figure C-9 presents results of the recent hydraulic modeling results for a simulated 25-year flow event, showing inundation depths throughout downtown Santa Rosa. Figure C-10 presents a time series plot of the total predicted overbank flow from Santa Rosa Creek between the Triple Box Culverts and Brush Creek, and from Matanzas Creek between the triple box culvert and Spring Creek, for each return interval model simulation. Note that overbank flow exceeding 1000 cubic feet per second (cfs) is predicted for the 25-year event, and overbank flows approaching 4000 cfs is shown for the 50-year event. The 100-year simulation had over 6,000 cfs leaving the creek banks upstream of the triple box culverts.

Figure C-9. Predicted Localized Flooding in Santa Rosa for a 25-year Event



Source: ESA

Figure C-10. Combined Overland Flow from Santa Rosa Creek and Matanzas Creek above Triple Box Culverts



Source: ESA

Tables C-5a and C-5b provides a quantitative overview of the frequency shift and projected changes in peak flow as well as the percent increase in peak flow for Santa Rosa Creek below Bush Creek. In the early future scenario, high frequency flows show a larger increase in peak flow than low frequency events. However, for the late future scenario, low frequency flows show larger increases in peak flow than the high frequency events.

Table C-5a. Peak Flow in Santa Rosa Creek below Bush Creek

Period	50 percent Peak Discharges (cfs)	20 percent Peak Discharges (cfs)	10 percent Peak Discharges (cfs)	4 percent Peak Discharges (cfs)	2 percent Peak Discharges (cfs)	1 percent Peak Discharges (cfs)
Baseline	3,319	4,862	6,239	8,111	9,483	10,599
Early Future	3,731	5,781	7,473	9,777	11,499	13,185
Mid Future	4,699	7,037	8,776	11,147	13,089	14,586
Late Future	6,409	8,986	10,982	13,775	15,763	17,280

Table C-5b. Percent Increase in Peak Flow in Santa Rosa Creek below Bush Creek

Period	Increase in 50 percent Peak Discharges (%)	Increase in 20 percent Peak Discharges (%)	Increase in 10 percent Peak Discharges (%)	Increase in 4 percent Peak Discharges (%)	Increase in 2 percent Peak Discharges (%)	Increase in 1 percent Peak Discharges (%)
Early Future	12	19	20	21	21	24
Mid Future	42	45	41	37	38	38
Late Future	93	85	76	70	66	63

Modeling results for simulations under historical and climate change conditions were evaluated at key locations Bin order to inform the risk assessment. The flood risk was found to be high in several areas of the watershed. The key findings are summarized in the following sections:

- Flood conveyance channels along Santa Rosa Creek and its tributaries provide flood protection for downtown Santa Rosa. The triple box culverts along Santa Rosa Creek and Matanzas Creek, which route these two creeks through downtown Santa Rosa, are of particular concern. The primary hazard for these culverts is their inability to convey flood flows much larger than a 10-year event. High resolution hydraulic modeling conducted by ESA as part of the Santa Rosa Creek Hydrology and Hydraulics Study (SCWA 2017) indicate the inability of these culverts to pass flood flows above a certain return interval event between 10 and 25 years. These results are in stark contrast to assumptions made by FEMA in the development of local Flood Insurance Rate Maps.
- Analysis of inundation depth results suggest substantial inundation throughout downtown Santa Rosa. Overbank flow is simulated from Santa Rosa Creek between the Triple Box Culverts and Brush Creek, and from Matanzas Creek between the triple box culvert and Spring Creek for each return period simulated. Overbank flow exceeding 1000 cfs is predicted for the 25-year event, nearly 4000 cfs for the 50-year event, and over 6,000 cfs for the 100-year event.
- Peak flow in Santa Rosa Creek below Brush Creek is projected to increase by about 40% under mid-century climate changes and over 60% by end of century changes. By late-century, the current 25-year event will be closer to a 5-year event, and the 100-year event will be best represented as a 10-year event.
- The nonlinear nature between flood flow and sediment transport could exacerbate future flood control channel maintenance, as expected increases in precipitation intensity drive increases in runoff and increases in sediment transport.
- Detention basins in the upper reaches of Santa Rosa Creek and tributaries will be substantially impacted by greater flow volumes associated with climate change. These reservoirs serve a vital role in reducing flood risk for the City of Santa Rosa by attenuating flows on the largest watersheds draining through Santa Rosa. The basins were designed for a 100-year event and are designed for passive operation. Increases in runoff events, sediment, and debris will reduce the effectiveness of these basins to attenuate peak flows

and could lead to overtopping of the dam. Matanzas Creek Reservoir is the most at risk due to its earthen embankment that serves as the emergency spillway.

Sedimentation is expected to increase under all future climate scenarios. The diversion structure on Santa Rosa Creek, the vortex drain structure under Montgomery Drive, and the diversion structure on Spring Creek and box culvert are all susceptible to sedimentation and/or woody debris reducing hydraulic performance.

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SECTION 5

Russian River Flood Modeling

5.1 Purpose

The goal of this analysis is to provide more refined assessments of Russian River flood impacts under future climate change. The primary objectives were to assess potential changes in Russian River flood frequencies at the Wohler and Mirabel water supply facilities and within the Russian River Sanitation Zone facilities.

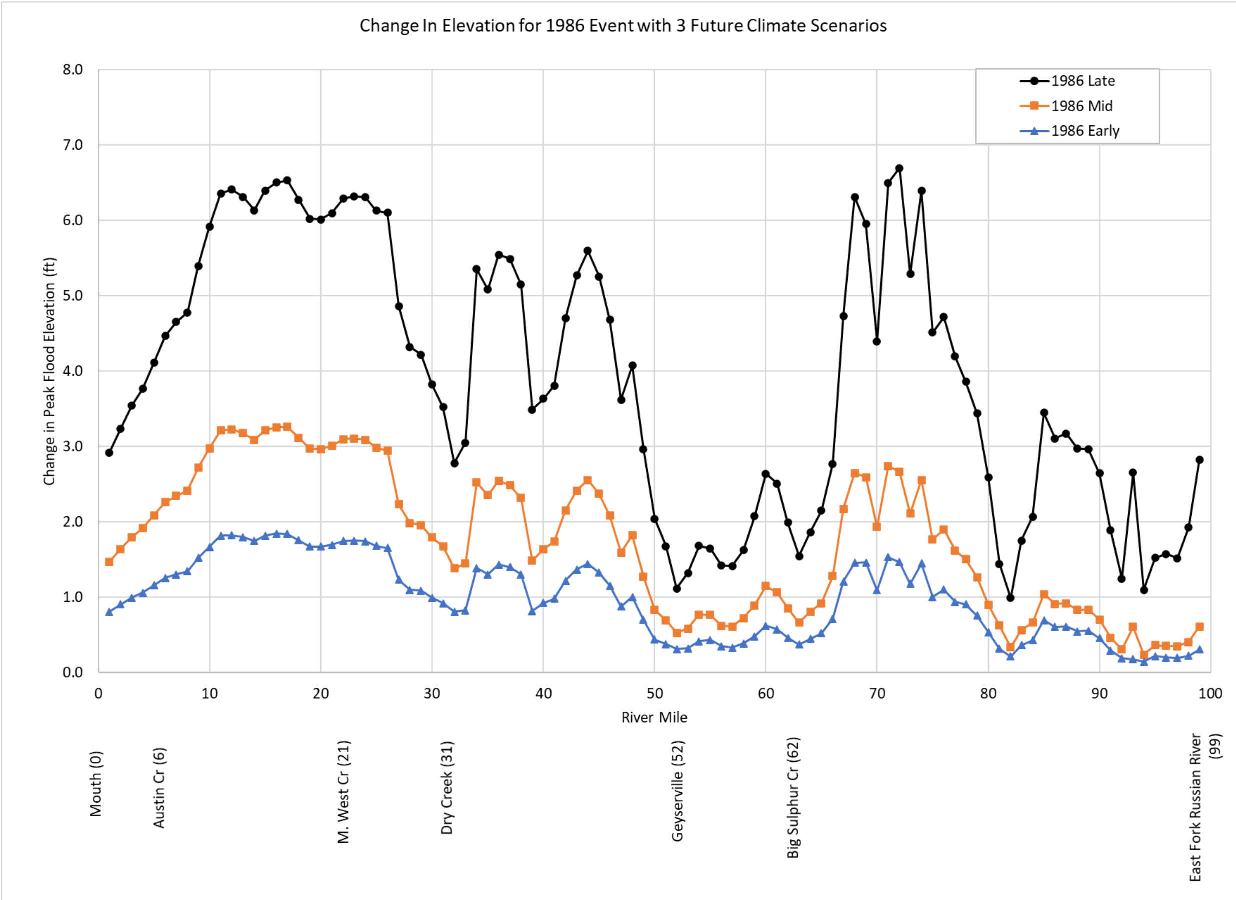
5.2 Methodology

Historical and future climate change hydrologic time series were developed for the existing Russian River HEC-RAS models for the lower Russian River. HEC-HMS and HEC-RAS models were used from the Analyzing Flood Risk for Forecast Informed Reservoir Operations in the Russian River Watershed using HEC-WAT (USACE, 2017). The downstream coastal boundary of the Russian River HEC-RAS was modified to reflect increases in mean sea level at the estuary. Changes in flood flow and stage frequencies were determined and impacts were then evaluated at the Mirabel and Wohler facilities. Additionally, changes were also evaluated for flood (flow and stage) frequencies and impacts at the Russian River Sanitation Zone.

5.3 Results

The change in elevation characterized by a future 1986-magnitude flood event under three future climate scenarios was examined along each river mile for the Russian River beginning with the mouth and ending with the East Fork of the Russian River. The simulated changes in Russian River flood stage with three future climate scenarios is shown in Figure C-11.

Figure C-11. Simulated Change in Russian River Flood Stage under Three Future Scenarios



Based on these modeling results, several observations were made and are summarized in the following sections:

- Under mid-century scenarios, changes in peak flood elevations greater than 3 feet occur in the lower Russian River, with the largest increases shown in the reach between the confluence with Mark West Creek and Austin Creek. Under the late-century scenarios, changes in peak flood elevation increase dramatically, with the largest magnitude of changes exceeding 6 feet. Across all scenarios, river miles between Geyserville and Big Sulphur Creek and between river mile 82 and the East Fork of the Russian River show the smallest magnitude of changes.
- Most infrastructure at the Wohler and Mirabel diversion facilities (e.g. collectors, access roads) will be experience substantial inundation under future climate change extreme events. All collector critical elevations will be exceeded under future extreme events and flooding may cause structural damage to facilities and will very likely flood the collectors through the access doors.
- The Russian River near Cloverdale is expected to exceed its channel capacity during the 100-year event. FEMA mapping of the 100-year and 500-year floodplains indicate that expected inundation extends over fields on the eastern bank and over light industrial areas, including the All-Coast property, and fields on the western bank. Sediment loading from Big Sulphur Creek is expected to increase and impact the riverbed significantly.

- Hazards to flood conveyance in Zone 5A include increased precipitation intensity and associated runoff, bank erosion and bank failure with higher runoff, and increased sediment transport in the Russian River and tributaries. Most populated areas in the lower Russian River are located in the 100-year floodplain, including communities of Guerneville, Monte Rio, Villa Grande, and Duncan Mills.
- Management of the freshwater lagoon in the estuary can be affected by changes in the timing and amount of runoff as well as sea level rise. Projected sea level rise and increased wave action will lead to changes in the beach profile and the effectiveness of the natural sand berm that currently closes the estuary on an annual cycle. Changes in flood stage in the lower river associated with sea level rise is most pronounced up to river mile 4 but decreases to nearly no change by river mile 10.

The 100-year Russian River floodplain will be enlarged under future climate scenarios with higher intensity rainfall events. Based on tabulated percent chance flood events shown in Table C-6, an increase of 26% in the peak flow value for the 10 percent flood event would equal the current 2 percent flood event, and an increase of 26% in the peak flow value for the current 2 percent event would equal the 1 percent event. Significant shifts in the recurrence intervals for given flood flows are expected under future climates.

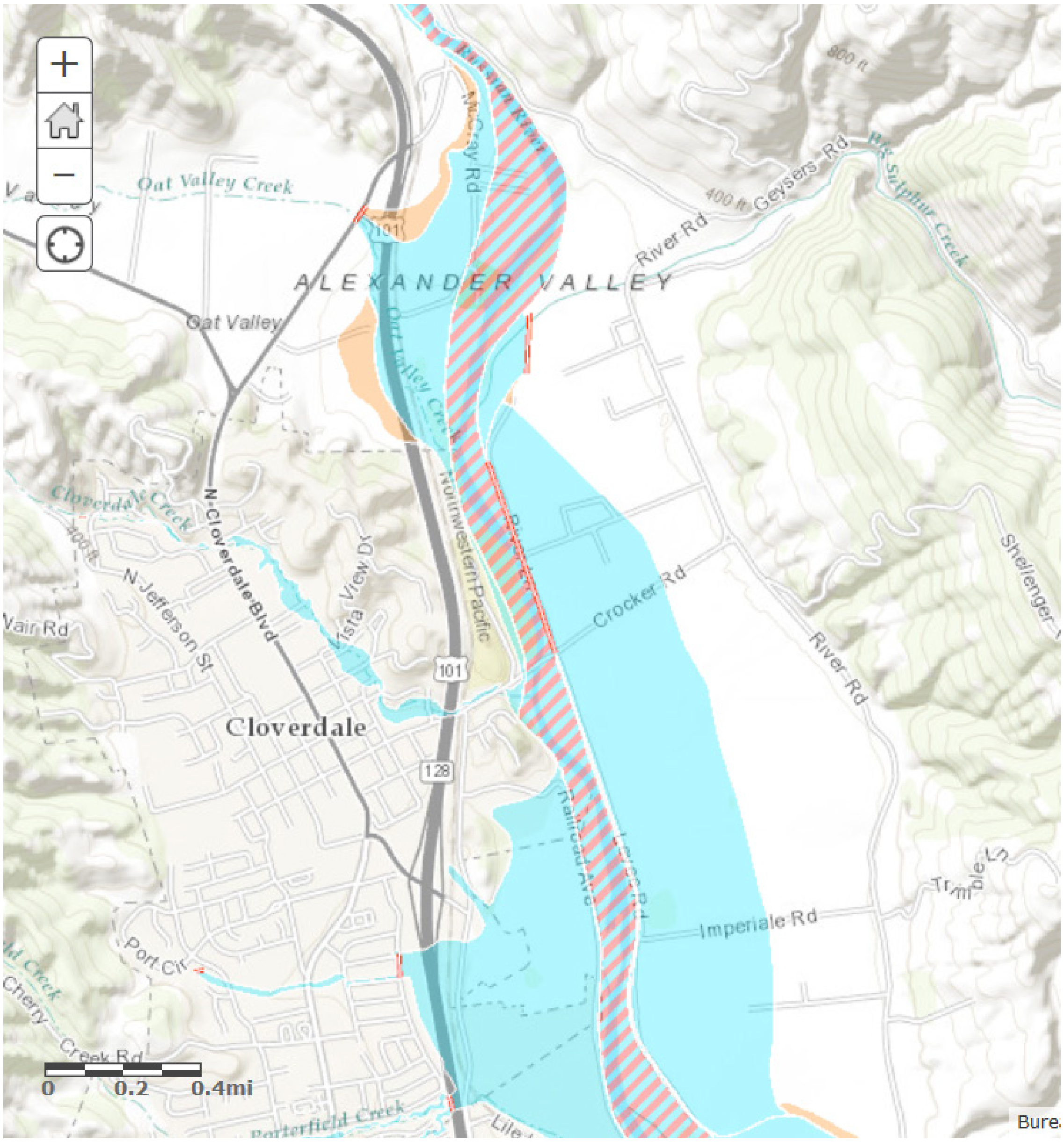
The current levees do not appear to provide 100-year flood protection based on the FEMA maps. Modifications to levees would be required to remove lands adjacent to the river from the 100-year floodplain.

Table C-6. Tabulation of Peak Discharges for Various Flood Events along the Russian River

Flooding Source and Location (Russian River)	Drainage Area (Square miles)	10 percent Peak Discharges (cfs)	2 percent Peak Discharges (cfs)	1 percent Peak Discharges (cfs)	0.2 percent Peak Discharges (cfs)
Upstream of confluence of Maacama Canal	707	51,000	73,000	82,000	115,000
Upstream of confluence of Sausal Creek	686	50,000	71,000	81,000	111,000
Upstream of confluence of Lytton Creek	678	50,000	70,000	80,000	110,000
Upstream of confluence of Miller Creek	654	48,000	68,000	79,000	106,000
Upstream of confluence of Gill Creek	642	47,000	67,000	76,000	105,000
Upstream of confluence of Big Sulphur Creek	520	46,000	58,000	73,000	100,000
Upstream of confluence of Oat Valley Creek	502	40,000	56,000	64,000	85,000

The Russian River 100-year floodplain in Cloverdale extends west to Highway 101 and the sediment contribution from Big Sulphur Creek can alter the riverbed significantly (Figure C-12).

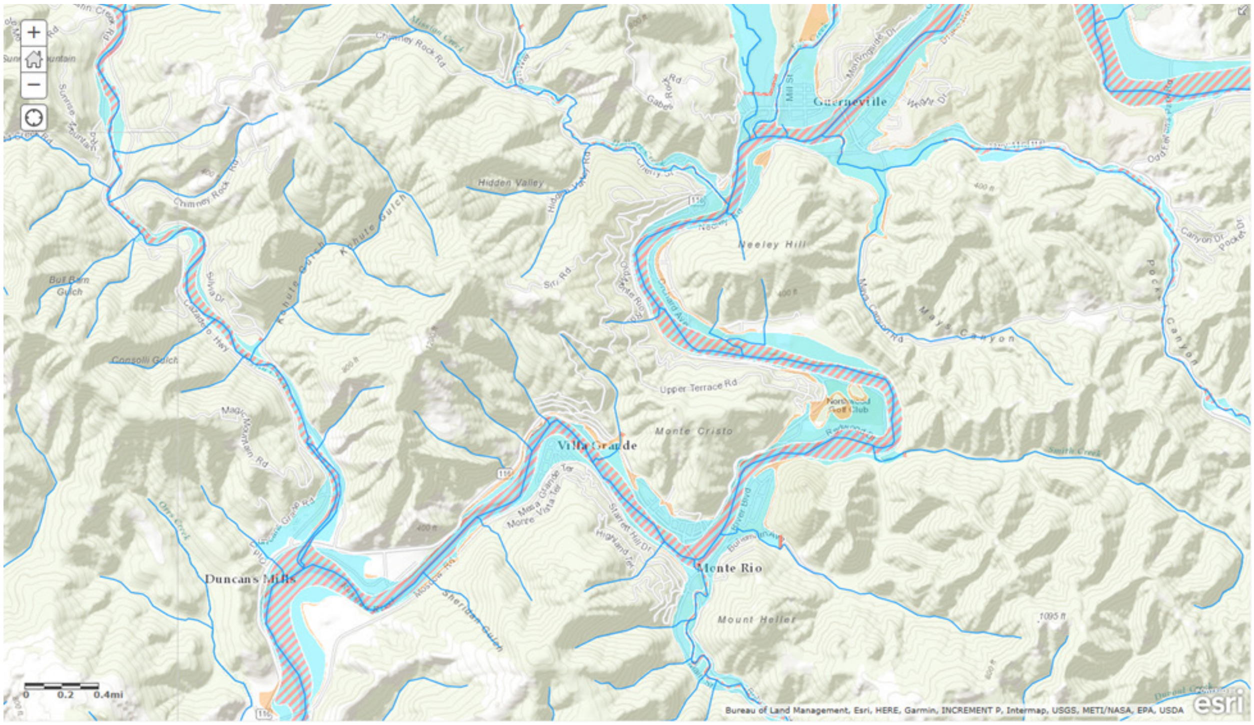
Figure C-12. 100-year Flood Hazard, Russian River near Cloverdale (Zone 4A)



Source: FEMA

Hazards to flood conveyance in Zone 5A include increased precipitation intensity and associated runoff, bank erosion and bank failure with higher runoff, and increased sediment transport in the Russian River and tributaries. Most populated areas in the lower Russian River are located in the 100-year floodplain, including communities of Guerneville, Monte Rio, Villa Grande, and Duncan Mills (Figure C-13).

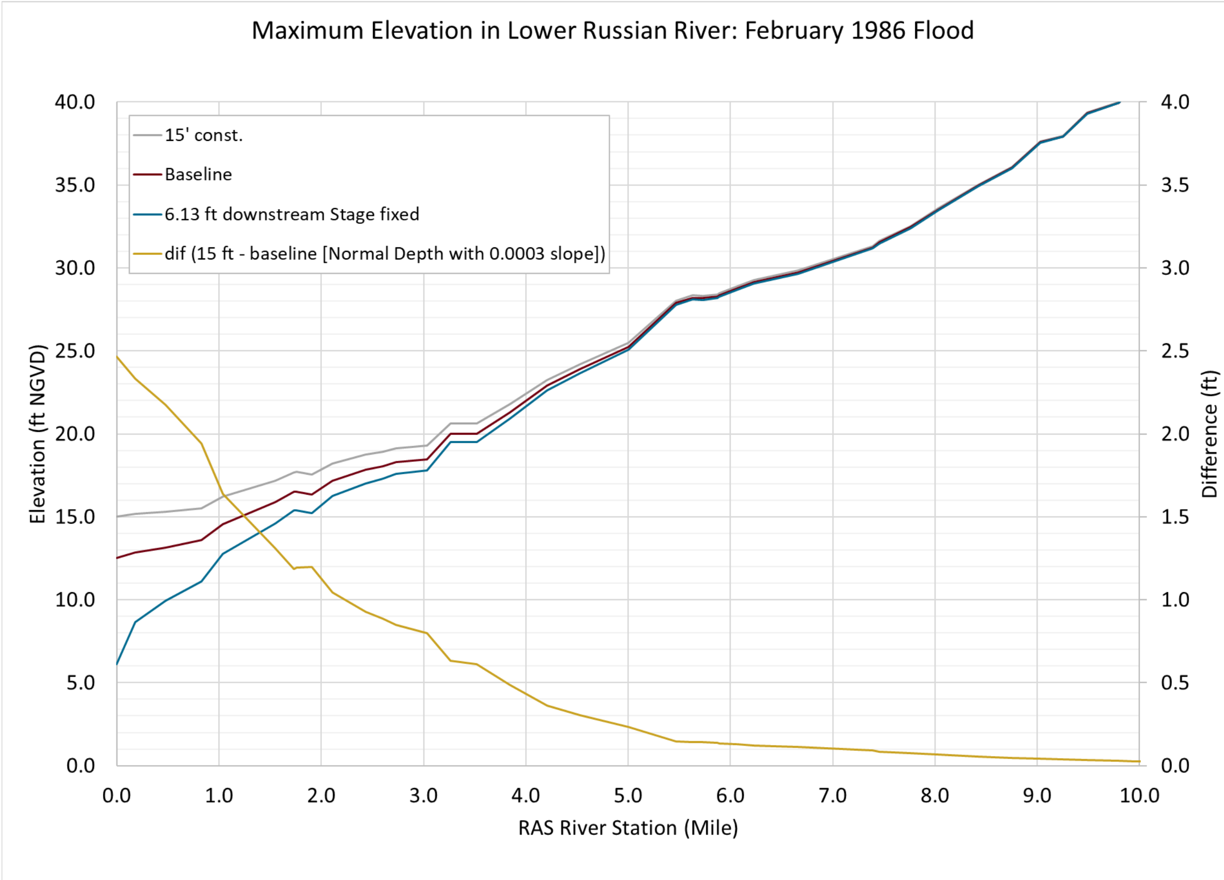
Figure C-13. 100-year Flood Hazard, Lower Russian River



Source: FEMA

Flood conveyance in Zone 5A is considered moderately sensitive to climate induced increases in river flow, as the system has current flood vulnerabilities that will occur more frequently under expected future climate scenarios. The management of the Russian River Estuary is sensitive to climate change as sea level rise will increase wave energy at the beach, requiring modifications to the management plan. Given the lack of demonstrable success of the natural berm in maintaining lagoon closure for the desired periods, future climate induced stressors acting against berm stability could further reduce the viability of this approach. Figure C-14 shows the elevation along HEC-RAS River Stations from the ocean to river mile 10 upstream. Differences are more pronounced up to river mile 4 but decrease to approximately 0 by river mile 10. Changes in flood stage in the lower river associated with sea level rise is most pronounced up to river mile 4 but decreases to nearly no change by river mile 10.

Figure C-14. Lower Russian River Sensitivity to Sea Level Rise



SECTION 6

Sediment Loading Estimates

6.1 Purpose

One of the major responsibilities of Sonoma Water Stream Maintenance Program is associated with sediment management in Zone 1A. The goal of this analysis was to improve understanding of the distribution of sediment load, and potential changes in sediment loading in this zone.

6.2 Methodology

Historical sediment transport was correlated to historical hydrology based on maintenance records and local stream gauges. A GIS analysis was also conducted to relate gauged to ungauged streams. To estimate future sediment transport volumes for normalized and future hydrology, HEC-RAS modeling results from analyses for Santa Rosa Creek were used. Flow return periods of 2-years and 10-years as well as Early, Mid, and Late Future climate scenarios were developed for this model.

To estimate sediment loading, the Bedload Assessment in Gravel-bedded Streams (BAGS) program was used from the U.S. Forest Service and STREAM System Technology Center. BAGS employs bedload transport equations based on channel geometry, reach-average slope, and bed material grain size (Pitlick et al., 2009). The BAGS data was used to develop bedload transport estimates within the Santa Rose Creek based on the HEC-RAS model output. The Parker (1990) and Wilcock and Crowe (2003) methods were applied within BAGS. The percent change in bedload sediment transport was estimated at 3 stations (cross-sections) within the Santa Rosa Creek for the future climate scenarios compared to the baseline historic climate scenario. Stations 11342 and 13677 are on Santa Rosa Creek downstream of Patterson Creek, and station 52535 is on Santa Rosa Creek just downstream of Brush Creek.

6.3 Results

The percent change from baseline conditions for the Early, Mid, and Late Future scenarios under each return interval is summarized in Table C-7 for the three cross-sections considered. Results vary based on the method and grain size considered. In general, the station on the Santa Rosa Creek (52535) shows the largest percent changes from baseline conditions, particularly under the late future scenario.

Figures C-15 and C-16 show the results for station 52535 in a graphical format for the 2-year and 10-year return intervals. For each of these return periods, the bedload transport increases for each of the future scenarios considered, with the largest increases being shown for the late future conditions. Compared to the 2-year return interval, the 10-year return interval shows higher bedload transport quantities across all methods used. These results help to inform yearly sediment management maintenance activities within the Sonoma Water Stream Maintenance Program.

Several key observations derived from this analysis are summarized in the following list:

- Results vary based on the method and grain size considered. However, bedload transport increases in across all methods used.
- Station on the Santa Rosa Creek downstream of Brush Creek (52535) generally shows the largest percent changes from baseline conditions. Station 11342 and 13677 are estimated to have less than half the loading of station 52535.
- Under the mid-century scenarios, bedload transport at station 52535 is projected to increase by up to 25-55% for the 2-year event and 41-76% for the 10-year event. Bedload transport could increase by more than 150% for the late-century 10-year event.
- Planning for substantial increases in sediment removal or management is necessary for sediment management maintenance activities within the Sonoma Water Stream Maintenance Program.

Table C-7. Percent Change from Baseline Conditions at for Each Cross-Section and Return Period

Section	Time Period	Change in 50 percent sediment loading 70/30[a] Parker (1990)	Change in 50 percent sediment loading 55/45[a] Parker (1990)	Change in 50 percent sediment loading 70/30[a] Wilcock and Crowe (2003)	Change in 50 percent sediment loading 55/45[a] Wilcock and Crowe (2003)	Change in 10 percent sediment loading 70/30[a] Parker (1990)	Change in 10 percent sediment loading 55/45[a] Parker (1990)	Change in 10 percent sediment loading 70/30[a] Wilcock and Crowe (2003)	Change in 10 percent sediment loading 55/45[a] Wilcock and Crowe (2003)
11342	Early	7%	4%	9%	10%	16%	14%	19%	18%
11342	Mid	21%	14%	28%	30%	32%	28%	34%	33%
11342	Late	51%	38%	64%	69%	41%	35%	45%	44%
13677	Early	6%	3%	-22%	-19%	18%	16%	46%	-13%
13677	Mid	11%	13%	-8%	-3%	27%	10%	2%	-2%
13677	Late	40%	37%	20%	28%	42%	18%	19%	13%
52535	Early	8%	9%	6%	7%	42%	33%	14%	15%
52535	Mid	52%	54%	24%	27%	76%	59%	41%	44%
52535	Late	129%	151%	66%	73%	182%	155%	83%	89%

[a] Gravel/Sand Distribution in Sediment

Figure C-15. Cross-Section 52535 Change in Bedload Sediment Transport for a 2-year Return Interval

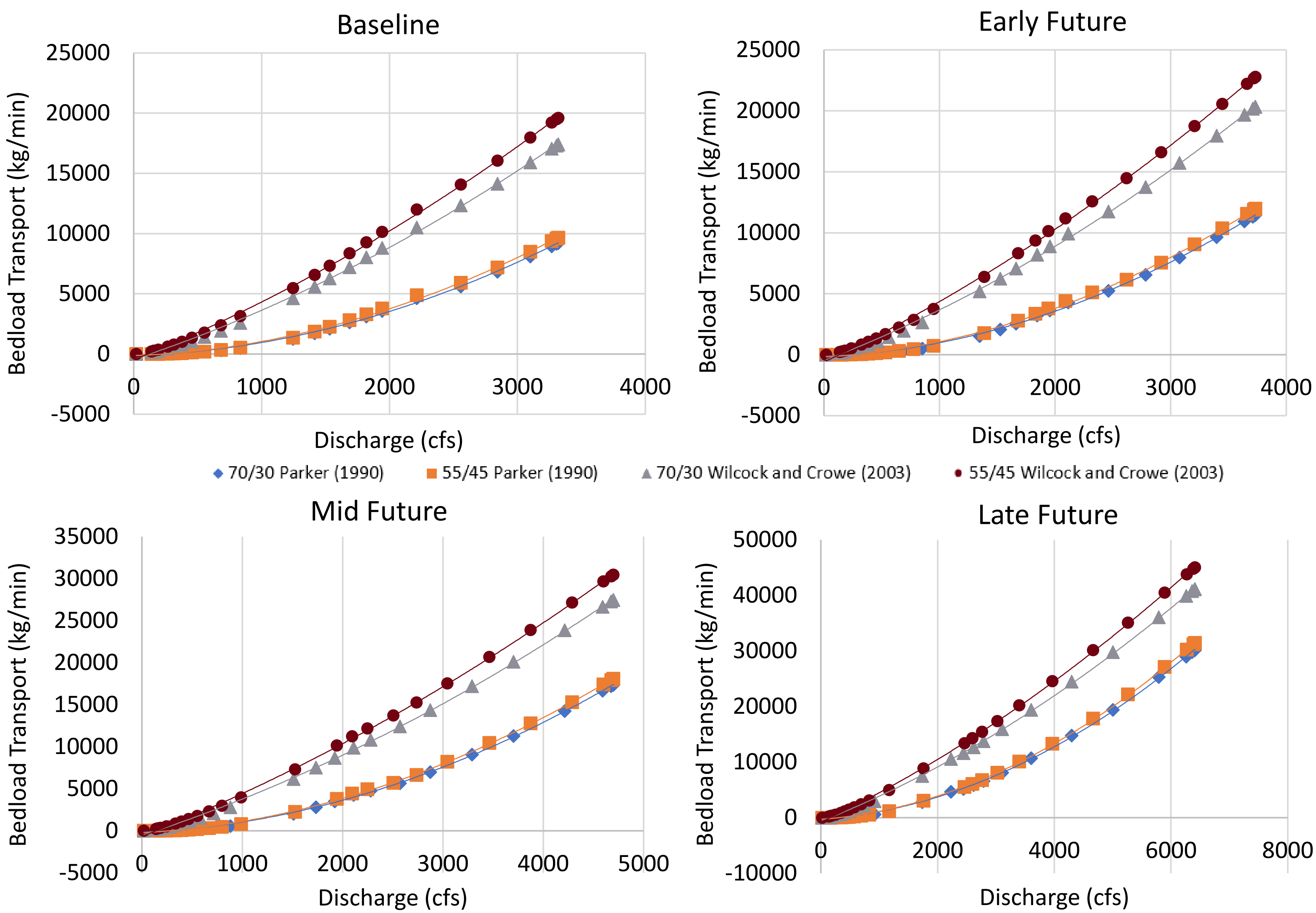
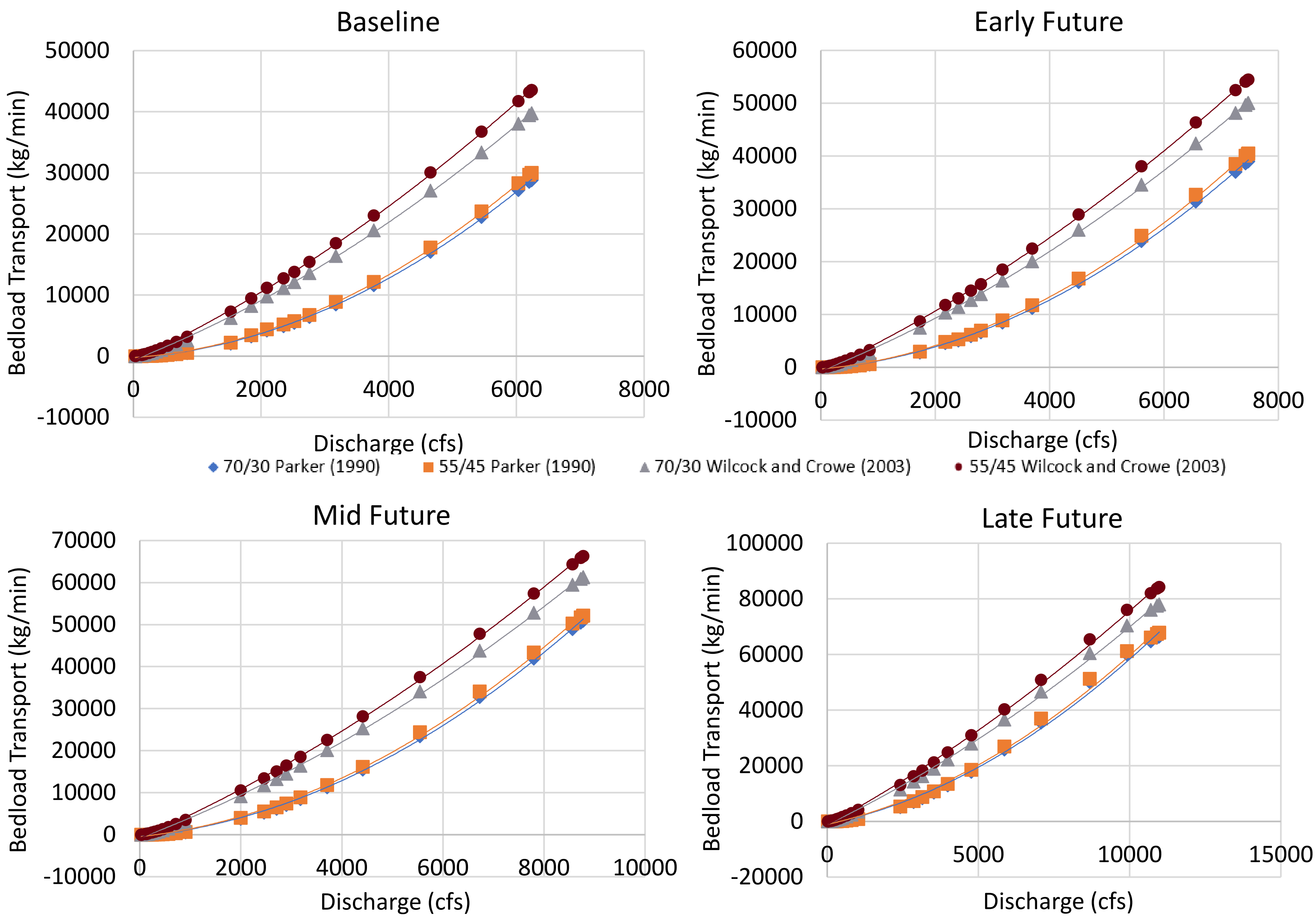


Figure C-16. Cross-Section 52535 Change in Bedload Sediment Transport for a 10-year Return Interval



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SECTION 7

References

California Department of Water Resources Climate Change Technical Advisory Group (CCTAG). 2015. Perspectives and guidance for climate change analysis. California Department of Water Resources Technical Information Record. p. 142.

Cal Adapt Wildfire Tool. 2018. http://cal-adapt.org/tools/wildfire

Foltz, R.B.; Robichaud, P.R.; Rhee, H. 2009. A synthesis of post-fire road treatments for BAER teams: methods, treatment effectiveness, and decision making tools for rehabilitation. Gen. Tech. Rep. RMRS-GTR-228. Fort Collins, CO. U.S.D.A., Forest Service, Rocky Mountain Research Station. 152 p.

Kopp, R. E., R. M. Horton, C. M. Little, J. X. Mitrovica, M. Oppenheimer, D. J. Rasmussen, B. H. Strauss, and C. Tebaldi (2014), Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites, Earth's Future, 2, 383–406,doi:10.1002/2014EF000239

Ocean Protection Council. 2018. State of California Sea-Level Rise Guidance 2018 Update. Retrieved from http://www.opc.ca.gov/webmaster/ftp/pdf/agenda_items/20180314/Item3_Exhibit-A_OPC_SLR_Guidance-rd3.pdf.

Parker, G. 1990. Surface-based bedload transport relation for gravel rivers. Journal of Hydraulic Research. 28: 417-436.

Pierce, David W., Daniel R. Cayan, and Bridget L. Thrasher. 2014. "Statistical Downscaling Using Localized Constructed Analogs (LOCA)." J. Hydrometeor. 15, 2558–2585.

Pierce, D. W., J. F. Kalansky, and D. R. Cayan, (Scripps Institution of Oceanography). 2018. Climate, Drought, and Sea Level Rise Scenarios for the Fourth California Climate Assessment. California's Fourth Climate Change Assessment, California Energy Commission. Publication Number: CNRA-CEC-2018-006.

Pitlick, John; Cui, Yantao; Wilcock, Peter. 2009. Manual for computing bed load transport using BAGS (Bedload Assessment for Gravel-bed Streams) Software. Gen. Tech. Rep. RMRS-GTR-223. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Research Station. 45 p.

Sonoma County Water Agency (SCWA). 2016. Russian River Hydrologic Modeling for the Fish Habitat Flows and Water Rights Project. August 2016.

Sonoma County Water Agency (SCWA). 2017. Santa Rosa Creek Hydrology and Hydraulics: Hydraulic Modeling Report. Prepared by ESA. D130851.00

Taylor, Karl E., Ronald J. Stouffer, Gerald A. Meehl. 2012. An Overview of CMIP5 and the Experiment Design. Bull. Amer. Meteor. Soc., 93, 485–498.

U.S. Army Corps of Engineers (USACE). 2017. Analyzing Flood Risk for Forecast Informed Reservoir Operations in the Russian River Watershed using HEC-WAT. HEC Project Report PR-100. Partial Draft. June 2017.

Wilcock, P.R. Crowe, J.C. 2003. Surface-based transport model for mixed-size sediment. Journal of Hydraulic Engineering. 129: 120-128.