,

Appendix 6-5

Draft Russian River Watershed Projection Selection Memorandum

Draft Russian River Watershed Projection Selection Memorandum

Russian River Watershed Resilience Plan

Draft February 4, 2026

1. Introduction

The Russian River Watershed Resilience Pilot (RRWRP) aims to assess and enhance climate resilience within the study area and develop a watershed resilience plan that will address climate risks and support long-term water sustainability. This technical memorandum provides information on the selection of the climate projections from 41 individual climate model projections that can be used to support water quality, groundwater, and Forecast Informed Reservoir Operations (FIRO) modeling efforts. Figure 1 shows Russian River watershed and Groundwater sub-basins.

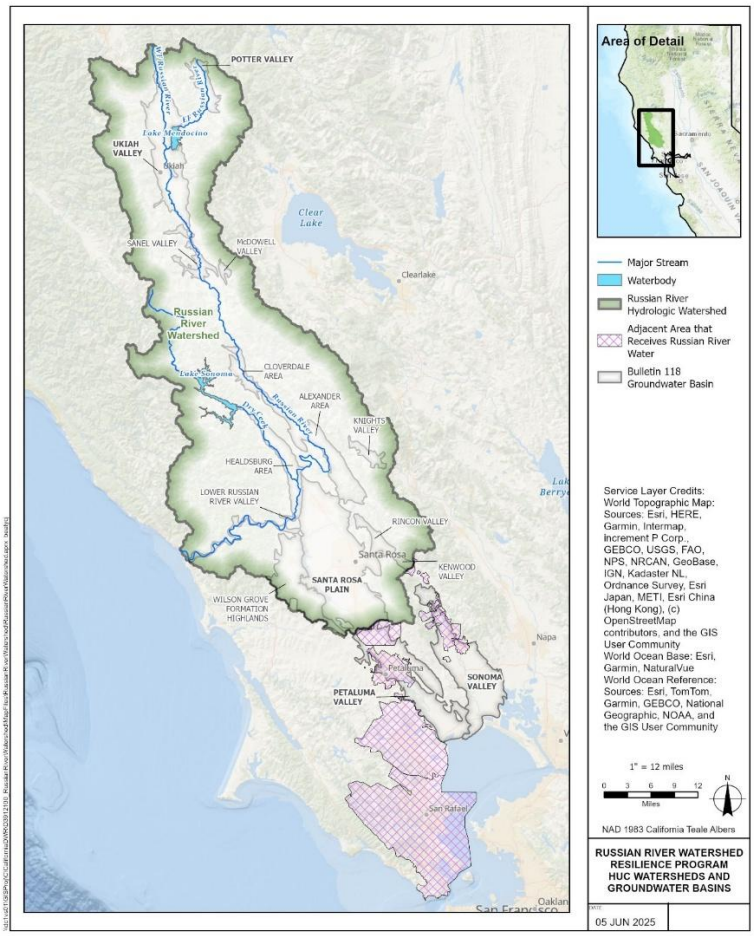

Figure 1. Russian River Watershed Resilience Pilot Study Area

2. Approach and Methods

2.1 CMIP6 climate model projections

The Coupled Model Intercomparison Project Phase 6 represents a significant advancement in climate modeling, building on the successes of previous phases. CMIP6 datasets used as input for the Sixth Assessment Report of the United Nations Intergovernmental Panel on Climate Change (IPCC AR6) (Intergovernmental Panel on Climate Change (IPCC), 2021). CMIP6 Global Climate Models (GCMs) feature higher spatial resolution with enhanced physical parameterizations, and improved representations of synoptic processes. Shared Socioeconomic Pathways (SSPs) are scenarios used in climate research to explore how global societal trends might influence future greenhouse gas emissions and climate change. The five main SSPs RCPs combination used in CMIP6 are SSP1-2.6, SSP2-4.5, SSP3-7.0, SSP4-6.0, and SSP5-8.5.

The Scripps Institution of Oceanography employs a hybrid-statistical downscaling method known as Localized Constructed Analogs version 2 Hybrid (LOCA2-Hybrid). This technique refines global climate model outputs to provide high-resolution regional climate projections, crucial for understanding localized climate impacts. LOCA2-Hybrid uses a hybrid downscaling scheme with a pattern library obtained from dynamically downscaled GCM-Weather Research Forecasting (WRF) runs that that were bias corrected to the ERA5-WRF-BC training data. The Hybrid-Statistical downscaling method has generated data for 15 General Circulation Models (GCMs) with a total of 199 ensemble runs. The details of the hybrid-statistical downscaling method (LOCA2-Hybrid) are available at LOCA (2025) and outlined in Pierce et al. (2023). The selection of the appropriate projection was performed from a pool of first ensemble members of the LOCA2-Hybrid climate model projections as listed in Table 1:

Table 1. List of first ensemble members of the CMIP6 downscaled datasets

S. No.	Model	Experiment	Variant	Alias used for Figure
1	ACCESS-CM2	SSP2-4.5	r1i1p1f1	ACC245
2	ACCESS-CM2	SSP3-7.0	r1i1p1f1	ACC370
3	ACCESS-CM2	SSP5-8.5	r1i1p1f1	ACC548
4	CESM2-LENS	SSP3-7.0	r1i1p1f1	CESM370
5	CNRM-ESM2-1	SSP2-4.5	r1i1p1f2	CNRM245
6	CNRM-ESM2-1	SSP3-7.0	r1i1p1f2	CNRM370
7	CNRM-ESM2-1	SSP5-8.5	r1i1p1f2	CNRM585
8	EC-Earth3	SSP2-4.5	r1i1p1f1	ECE245
9	EC-Earth3	SSP3-7.0	r1i1p1f1	ECE370
10	EC-Earth3	SSP5-8.5	r1i1p1f1	ECE585
11	EC-Earth3-Veg	SSP2-4.5	r1i1p1f1	ECVEG245
12	EC-Earth3-Veg	SSP3-7.0	r1i1p1f1	ECVEG370
13	EC-Earth3-Veg	SSP5-8.5	r1i1p1f1	ECVEG585
14	FGOALS-g3	SSP2-4.5	r1i1p1f1	FGOAL245
15	FGOALS-g3	SSP3-7.0	r1i1p1f1	FGOAL370
16	FGOALS-g3	SSP5-8.5	r1i1p1f1	FGOAL585
17	GFDL-ESM4	SSP2-4.5	r1i1p1f1	GFDL245

S. No.	Model	Experiment	Variant	Alias used for Figure
18	GFDL-ESM4	SSP3-7.0	r1i1p1f1	GFDL370
19	GFDL-ESM4	SSP5-8.5	r1i1p1f1	GFDL585
20	HadGEM3-GC31-LL	SSP2-4.5	r1i1p1f3	HADGEM245
21	HadGEM3-GC31-LL	SSP5-8.5	r1i1p1f3	HADGEM585
22	INM-CM5-0	SSP2-4.5	r1i1p1f1	INM245
23	INM-CM5-0	SSP3-7.0	r1i1p1f1	INM370
24	INM-CM5-0	SSP5-8.5	r1i1p1f1	INM585
25	IPSL-CM6A-LR	SSP2-4.5	r1i1p1f1	IPSL245
26	IPSL-CM6A-LR	SSP3-7.0	r1i1p1f1	IPSL370
27	IPSL-CM6A-LR	SSP5-8.5	r1i1p1f1	IPSL585
28	KACE-1-0-G	SSP2-4.5	r1i1p1f1	KACE245
29	KACE-1-0-G	SSP3-7.0	r1i1p1f1	KACE370
30	KACE-1-0-G	SSP5-8.5	r1i1p1f1	KACE585
31	MIROC6	SSP2-4.5	r1i1p1f1	MIROC245
32	MIROC6	SSP3-7.0	r1i1p1f1	MIROC370
33	MIROC6	SSP5-8.5	r1i1p1f1	MIROC585
34	MPI-ESM1-2-HR	SSP2-4.5	r1i1p1f1	MPI245
35	MPI-ESM1-2-HR	SSP3-7.0	r1i1p1f1	MPI370
36	MPI-ESM1-2-HR	SSP5-8.5	r1i1p1f1	MPI585
37	MRI-ESM2-0	SSP2-4.5	r1i1p1f1	MRI245
38	MRI-ESM2-0	SSP3-7.0	r1i1p1f1	MRI370
39	MRI-ESM2-0	SSP5-8.5	r1i1p1f1	MRI585
40	TaiESM1	SSP2-4.5	r1i1p1f1	TAI245
41	TaiESM1	SSP3-7.0	r1i1p1f1	TAI370

2.2 Climate and Hydrologic metrics

The selection of the projection was based on the ability to replicate the changes in climate and hydrological metrics from the 41 climate projections. The projected changes in the metrics are estimated for the future period (2026-2100) with respect to the historical period (1981-2010). Additionally, changes were also estimated for two 30-years future periods defined as mid-future period (2041-2070), and late-future period (2071-2100). The climate metrics were estimated to understand the projected change in temperature and precipitation over Russian River watershed, while the hydrologic metrics evaluated the change in flows at Russian River and Dry Creek confluence location. The details of the climate and hydrologic metrics are as follows:

- Annual Temperature (ΔTavg): Projected change in annual average temperature over Russian River watershed (°F). Daily average temperature values were used to calculate annual average temperature for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these water-year averaged temperature, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The absolute change in the annual temperature for the future period was then computed with respect to the historical reference period.

- Annual Precipitation (ΔP): Projected change in annual precipitation over Russian River watershed (%). Daily precipitation values were used to calculate annual total precipitation for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these

water-year precipitation, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the annual precipitation for the future period was then computed with respect to the historical reference period.

- Annual Flow (ΔQ Annual): Projected change in annual total flow at the Russian River and Dry Creek confluence location (%). Daily flow values were used to calculate annual total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these water-year annual flows, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the annual average flow for the future period was then computed with respect to the historical reference period.

- Fall Flow (ΔQ Fall): Projected change in total flow at the Russian River and Dry Creek confluence location during fall season (October to December) (%). Daily flow values were used to calculate fall season total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these water-year fall season flows, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the fall season average flow for the future period was then computed with respect to the historical reference period.

- Winter Flow (ΔQ Winter): Projected change in total flow at the Russian River and Dry Creek confluence location during winter season (January to March) (%). Daily flow values were used to calculate winter season total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these water-year winter season flows, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the winter season average flow for the future period was then computed with respect to the historical reference period.

- Rainy Season Flow (ΔQ Rainy): Projected change in total flow at the Russian River and Dry Creek confluence location during rainy season (November to April) (%). Daily flow values were used to calculate rainy season total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these water-year rainy season flows, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the rainy season average flow for the future period was then computed with respect to the historical reference period.

- Spring Flow (ΔQ Spring): Projected change in total flow at the Russian River and Dry Creek confluence location during spring season (April to June) (%). Daily flow values were used to calculate spring season total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these water-year spring season flows, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the spring season average flow for the future period was then computed with respect to the historical reference period.

- 1-day Flood: Projected changes in 99th percentile flows based on daily unimpaired flow at the Russian River and Dry Creek confluence location (%). Daily maximum flow values were calculated for each water year within the historical reference period (1981–2010) and the future period (2026–2100). From these annual maxima, the 99th percentiles were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the 99th-percentile flow for the future period was then computed with respect to the historical reference period.

- 2-day Flood: Projected changes in 99th percentile flows based on 2-day unimpaired flow at the Russian River and Dry Creek confluence location (%). A 2-day moving-average flow series was computed from the daily flow values. The maximum values from 2-day flow series were calculated for each water year within the historical reference period (1981–2010) and the future period

(2026–2100). From these annual maxima, the 99th percentiles were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the 99th-percentile flow for the future period was then computed with respect to the historical reference period.

- 3-day Flood: Projected changes in 99th percentile flows based on 3-day unimpaired flow at the Russian River and Dry Creek confluence location (%). A 3-day moving-average flow series was computed from the daily flow values. The maximum values from 2-day flow series were calculated for each water year within the historical reference period (1981–2010) and the future period (2026–2100). From these annual maxima, the 99th percentiles were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the 99th-percentile flow for the future period was then computed with respect to the historical reference period.

- Annual Flow Coefficient of Variance (CV Annual Flow): Coefficient of variance of the annual total flow at the Russian River and Dry Creek confluence location. Daily flow values were used to calculate annual total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). From these water-year annual flows, the coefficient of variance were derived using the 30 values from the historical period and the 75 values from the future period.

- 5-year Flow (ΔQ 5-Year): Projected change in 5-year average annual total flow at the Russian River and Dry Creek confluence location (%). Daily flow values were used to calculate annual total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). A 5-year moving-average flow series was computed from the water year annual flow values. From these 5-year averaged flows, the averages were derived using the 30 values from the historical period and the 75 values from the future period. The relative change in the 5-year averaged total flow for the future period was then computed with respect to the historical reference period.

- 5-year Flow Coefficient of Variance (CV 5-Year Flow): Coefficient of variance of the in 5-year average annual total flow at the Russian River and Dry Creek confluence location. Daily flow values were used to calculate annual total flow for each water year for the historical reference period (1981–2010) and the future period (2026–2100). A 5-year moving-average flow series was computed from the water year annual flow values. From these 5-year averaged flows, the coefficient of variance were derived using the 30 values from the historical period and the 75 values from the future period.

3. Results

The projected changes in the climate and hydrologic metrics for the future period (2026-2100) with respect to the historical period (1981-2010) was used for the selection of the projections for water quality, groundwater, and FIRO modeling efforts. Specifically, the projected changes in average temperature and annual precipitation were analyzed to characterize the meteorological signal. To assess the hydrological response, projected changes in annual, seasonal, and 5-year streamflow were evaluated. Additionally, changes in 1-day, 2-day, and 3-day peak flow events were examined to understand potential future extreme flow conditions. Evaluating multiple temporal scales also helps identify potential sensitivities in watershed behavior that may not be apparent from annual averages alone. The selection of representative climate projections was based on their ability to reproduce the combined effects of projected changes in climate and hydrologic metrics across the full ensemble of 41 climate projections. To support the selection process, three future scenarios were developed to characterize distinct ranges of projected hydroclimatic conditions. For the Central Tendency scenario, the 50th percentile of projected changes in average temperature, flow, and flood metrics for the future period was used. For the Hot–Dry scenario, the 75th percentile of temperature change and the 25th percentile of flow and flood changes were applied. Conversely, the Warm–Wet scenario used the 25th percentile of temperature change and the 75th percentile of flow and flood changes.

3.1 Projected Changes in Precipitation and Temperature

Projected changes in the annual precipitation and average temperature were estimated from the 41 climate projections for the future period (2026-2100) with the historical reference period (1981-2010). Figure 2 shows projected changes in annual precipitation and average temperature for Russian River Watershed Resilience Pilot Study Area. The multi-model ensemble projections indicate a consistent warming trend across all climate projections and scenarios, with estimated increases in average annual temperature ranging from roughly 1.9°F to 8.3°F. In contrast, projected changes in annual precipitation exhibit substantially greater variability, spanning from approximately –7% to +19%. While many projections cluster near small to moderate increases in precipitation, several project declines, highlighting the uncertainty in future hydroclimatic conditions. Overall, the projected changes demonstrate robust agreement among projections on future warming, while precipitation outcomes remain more model-dependent, underscoring the need to consider a wide range of plausible futures in planning and adaptation assessments.

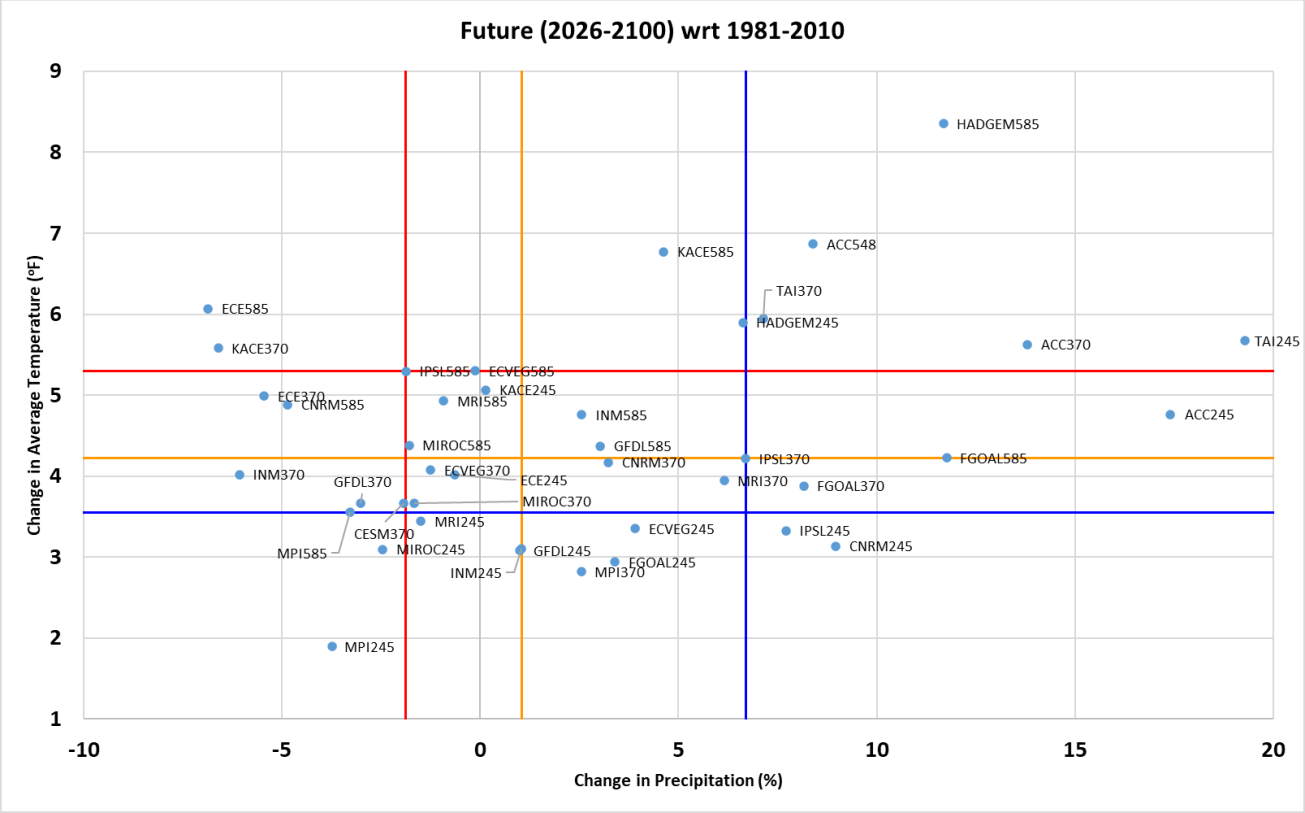

Figure 2. Projected Change in Annual Precipitation and Average Temperature for Russian River Watershed Resilience Pilot Study Area. Orange lines represent the Central Tendency Scenario, red lines represent the Hot-Dry Scenario, and blue lines represent the Warm-Wet Scenario.

3.2 Projected Changes in Annual and 5-year Streamflow

Projected changes in the annual flow and 5-year averaged flow were estimated from the 41 climate projections for the future period (2026-2100) with the historical reference period (1981-2010). Figure 3 shows projected changes in annual flow at the Russian River and Dry Creek confluence and average temperature for Russian River Watershed Resilience Pilot Study Area. The projected changes indicate a consistent warming trend across all climate projections, with increases in mean annual temperature ranging from approximately 1.9°F to more than 8.3°F. In contrast, projected changes in annual streamflow exhibit considerable variability among climate projections, spanning from decreases of more than 10% to increases

exceeding 20%. The projected changes in the 5-year flow range from -15% to 22%. Most projections results cluster around modest reductions or small increases in annual flow, highlighting substantial hydrologic uncertainty even as warming remains robust and uniform across projections. The broad spread in annual flow outcomes reflects differences in how projections represent future precipitation, evapotranspiration responses to warming, and watershed hydrologic processes. Overall, the ensemble indicates high confidence in future warming and lower confidence in the direction and magnitude of annual flow changes.

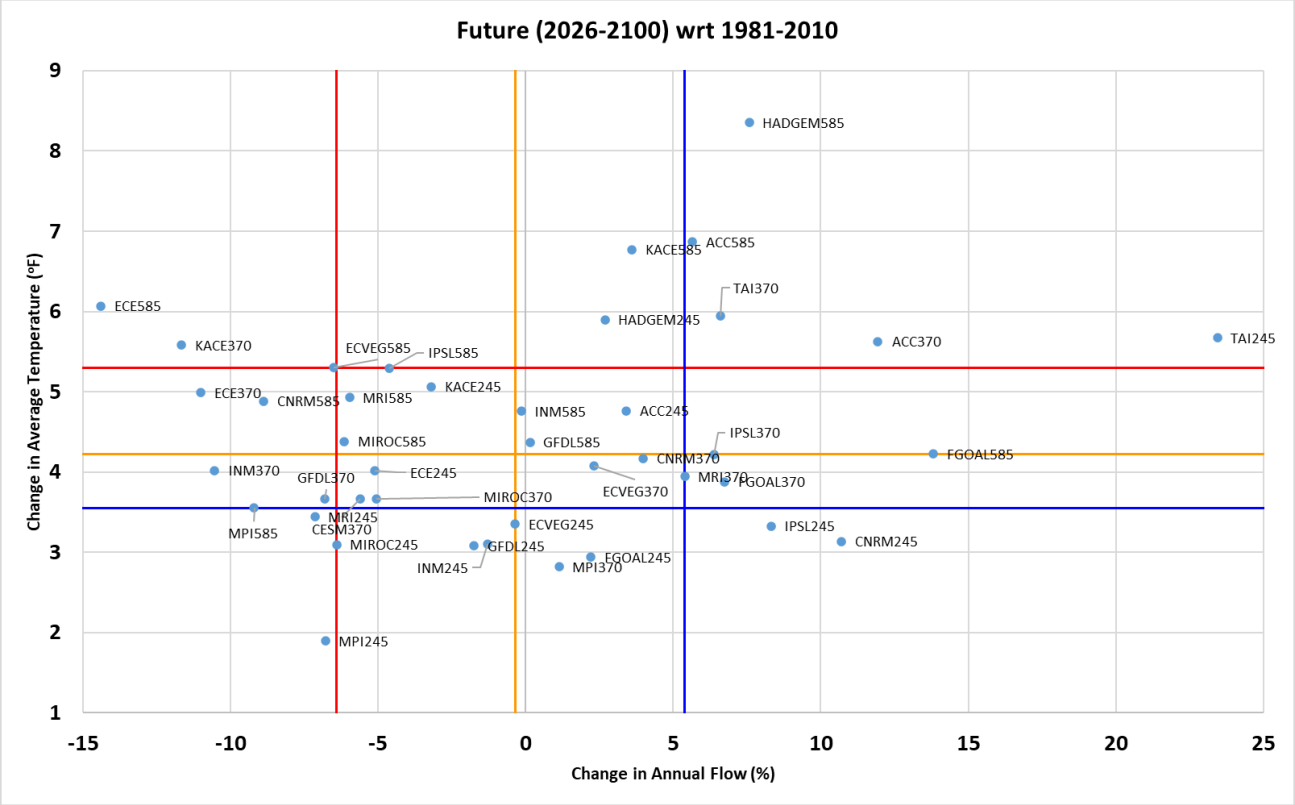

Figure 3. Projected Change in Annual flow at the Russian River and Dry Creek confluence and Average Temperature for Russian River Watershed Resilience Pilot Study Area. Orange lines represent the Central Tendency Scenario, red lines represent the Hot-Dry Scenario, and blue lines represent the Warm-Wet Scenario.

3.3 Projected Changes in Fall and Spring Streamflow

Projected changes in the fall, spring, winter, and rainy season flow were estimated from the 41 climate projections for the future period (2026-2100) with the historical reference period (1981-2010). Figure 4 shows projected changes in seasonal flow at the Russian River and Dry Creek confluence. Across most projections, fall flows tend to decrease, with many results showing reductions on the order of 10–40% and several exceeding –50%, though a few projections show small increases. Spring flows generally increase, commonly by 10–40% and in some cases by more than 50%, while a minority of projections project slight decreases. Winter flows show modest increases in many projections (ranges from -9% to 24%), and changes during the rainy season are comparatively small and centered near zero (often within ±10% and up to 24%). Collectively, the results point to a shift in runoff timing, higher winter–spring and lower fall flows, consistent with warming-related changes in precipitation phase and evapotranspiration.

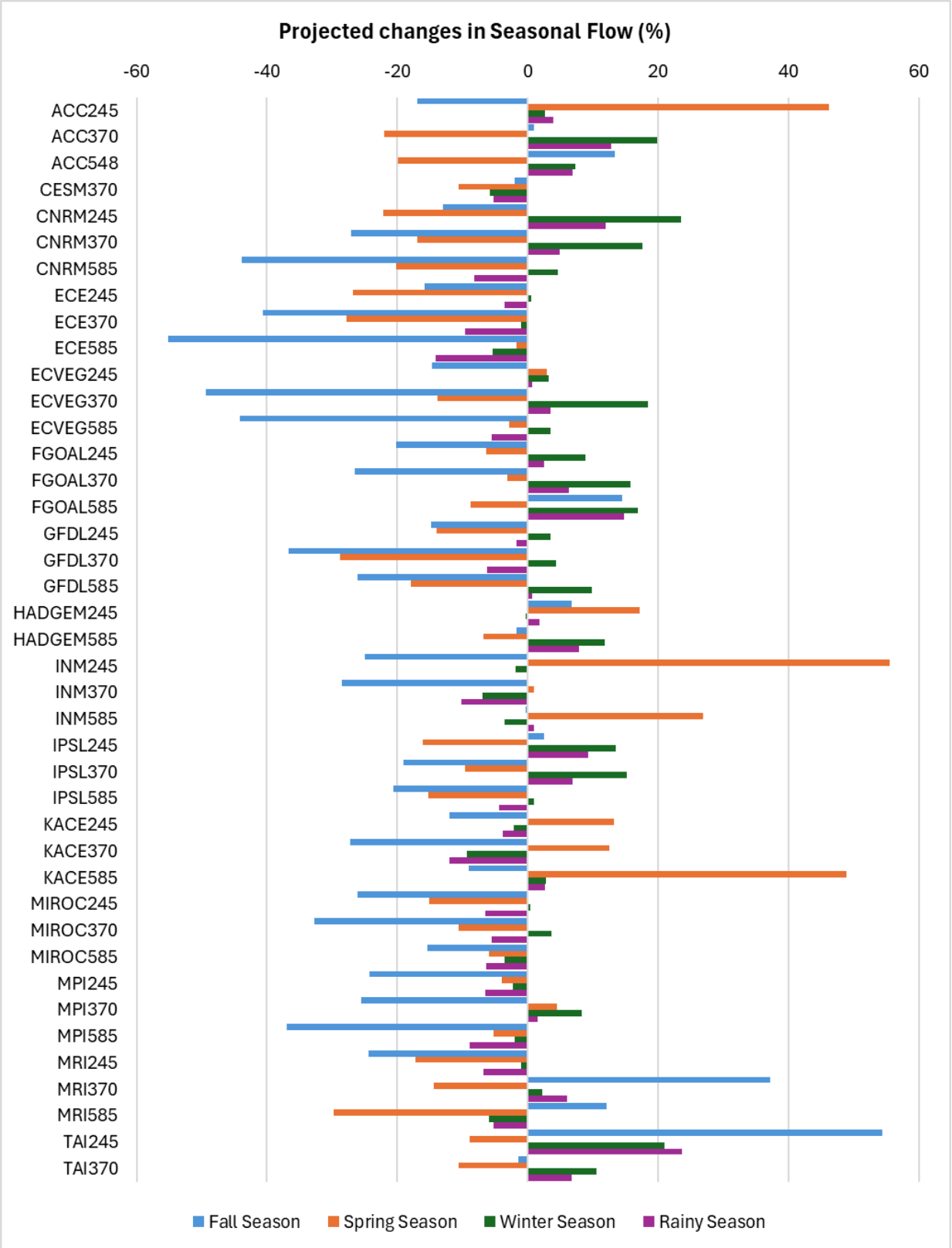

Figure 4. Projected Change in Fall season, Spring season, Winter season, and Rainy season flows at the Russian River and Dry Creek confluence.

3.4 Projected Changes in Flood

Projected changes in the 1-day flood, 2-day flood, and 3-day flood events were estimated from the 41 climate projections using the daily flow at the Russian River and Dry Creek confluence for the future period (2026-2100) with the historical reference period (1981-2010). Figures 5 and 6 show the projected changes in 1-day flood and 3-day flood events, respectively. For 1-Day floods, most projections plot to the right of the zero line, with a broad cluster showing positive changes of roughly 0–30%, and many exceeding a +5% threshold; a smaller subset surpasses +20%, including an outlier near +85%. Decreases are present but less common, generally on the order of 0 to –20% with a few larger negatives. The projected changes in the 2-day floods range from -40% to 68% (Figure A1). 3-day floods also tend to increase, but their central tendency appears slightly larger and the spread somewhat broader than for 1-day peaks. For 3-day floods, most projections indicate more frequent increases than decreases, with many projections clustering around 0–30% increases and a few showing large increases (40–60%); a smaller subset indicates declines (generally within about 10–30%). The joint patterns suggest that short-duration peak flows are more sensitive to warming, consistent with intensification of heavy precipitation, while multi-day floods reflect additional controls, resulting in more moderate but still positive changes on average.

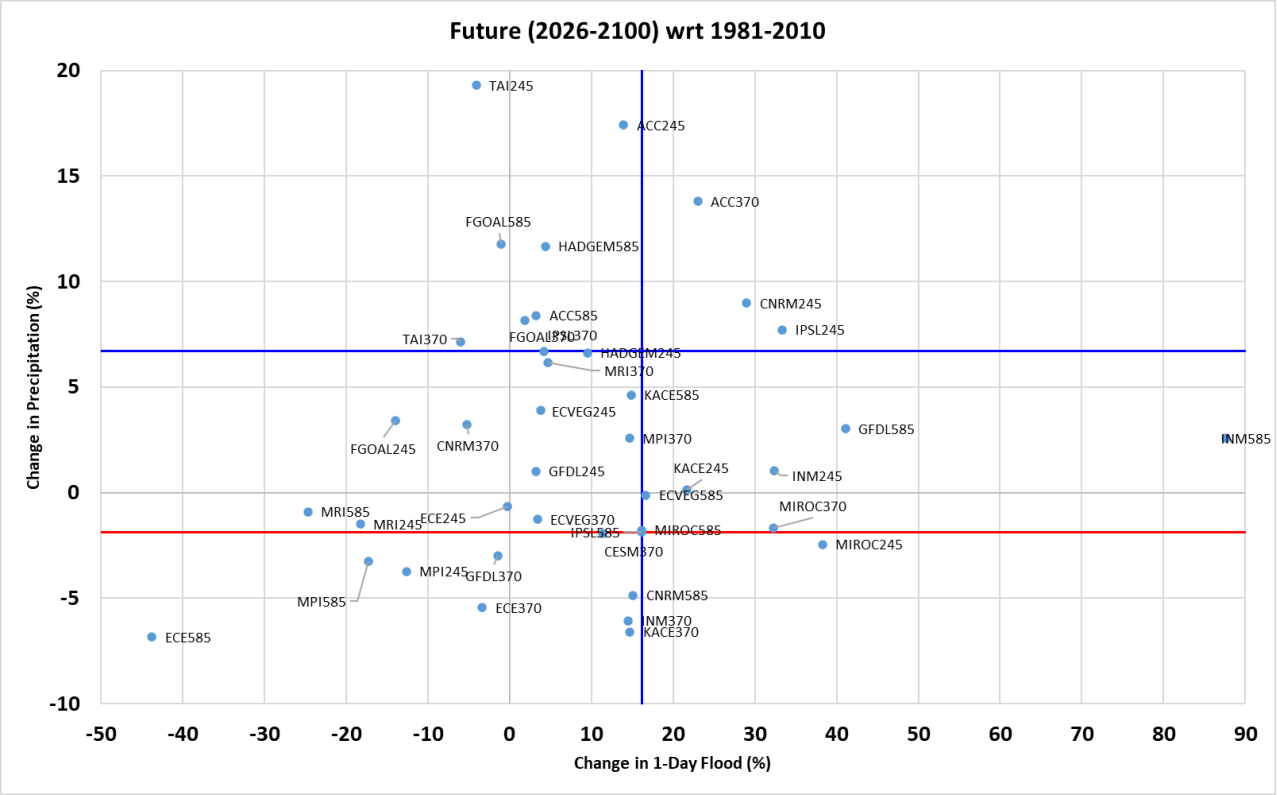

Figure 5. Projected Change in 1-Day Flood events and Annual Precipitation for Russian River Watershed Resilience Pilot Study Area. Red line represents the Hot-Dry Scenario, and blue lines represent the Warm-Wet Scenario.

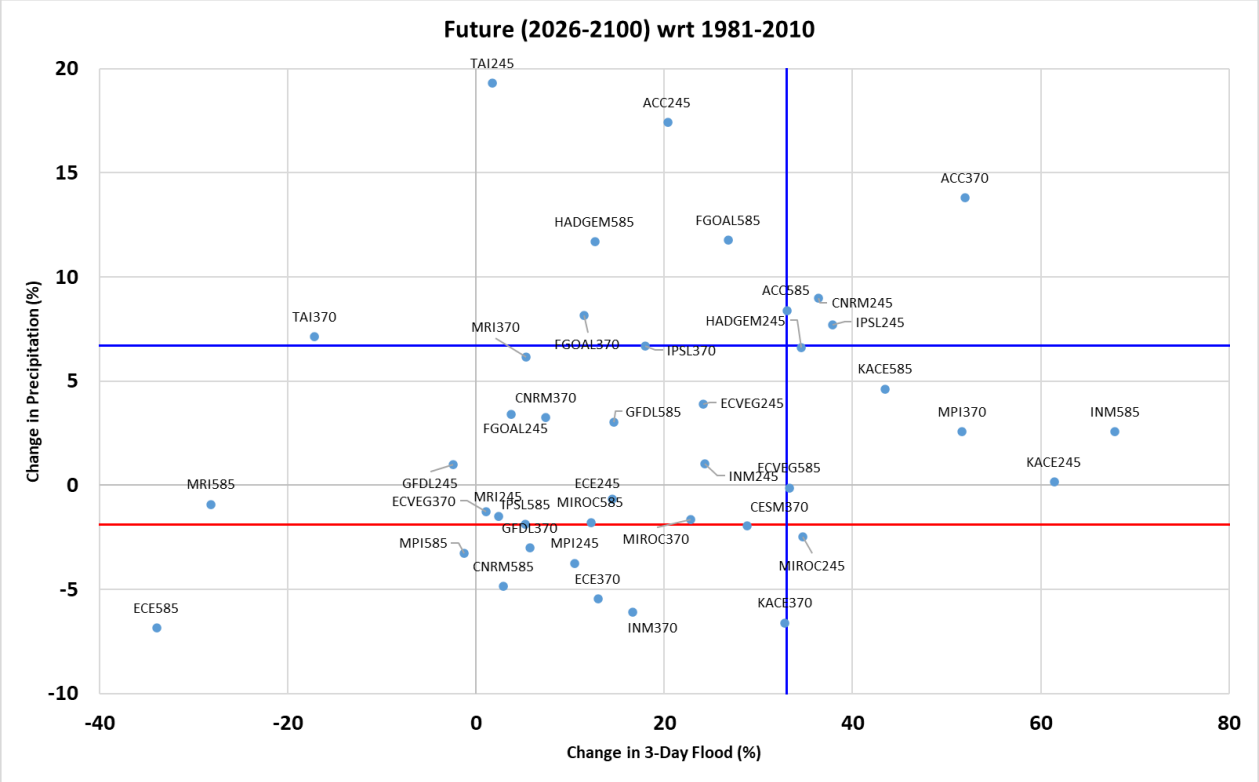

Figure 6. Projected Change in 3-Day Flood events and Annual Precipitation for Russian River Watershed Resilience Pilot Study Area. Red line represents the Hot-Dry Scenario, and blue lines represent the Warm-Wet Scenario.

4. Scenario Rankings

The selection of representative climate projections was based on their ability to reproduce the combined effects of projected changes in climate and hydrologic metrics across the full ensemble of 41 climate projections. Target values for each metric were defined separately for each scenario for the projection selection for water quality and groundwater modeling. To support the selection process, three future scenarios were developed to characterize distinct ranges of projected hydroclimatic conditions, namely Central Tendency, Warm-Wet, and Hot-Dry.

The projections for the FIRO modeling were selected based on their ability to represent the wet conditions in future. Accordingly, the target values for the FIRO modeling were considered primarily from the Warm-Wet Scenario with supplemental consideration of average temperature changes from Hot-Dry Scenario.

Table 2 presents the target values for the climate and hydrologic metrics used in selecting projections for water quality, groundwater, and FIRO modeling. Metrics marked with superscript 1 were used for the projection selection for water quality and groundwater, while those marked with superscript 2 were used for the projection selection for FIRO modeling

Table 2. Statistics of the 41 climate projections for the climate and hydrologic metrics

S. No.	Metrics	Central Tendency Scenario	Hot-Dry Scenario	Warm-Wet Scenario
1[1,2]	Change in Average Temperature, ΔTavg (°F)	4.2	5.3	3.6
2[1,2]	Change in Annual Precipitation, ΔP (%)	1.0	-1.9	6.7
3[1,2]	Change in Annual Flow, ΔQ Annual (%)	-0.4	-6.4	5.4
4[1,2]	Change in Fall Season Flow, ΔQ Fall (%)	-19.0	-27.1	-1.7
5[1,2]	Change in Spring Season Flow, ΔQ Spring (%)	-9.6	-16.9	-1.8
6[1,2]	Change in 5-year Flow, ΔQ 5-Year (%)	-2.1	-5.5	4.7
7[1]	Annual Flow Coefficient of Variance, CV Annual Flow	0.50	0.47	0.54
8[1]	5-year Flow Coefficient of Variance, CV 5-Year Flow	0.21	0.20	0.23
9[2]	Change in Winter Season Flow, ΔQ Winter (%)	NA	NA	10.6
10[2]	Change in Rainy Season Flow, ΔQ Rainy (%)	NA	NA	6.0
11[2]	Change in 1-Day Flood (%)	NA	NA	16.2
12[2]	Change in 2-Day Flood (%)	NA	NA	27.1
13[2]	Change in 3-Day Flood (%)	NA	NA	33.0

1 = Metrics used for the projection selection for Water Quality and Groundwater Modeling

2 = Metrics used for the projection selection for FIRO Modeling

NA = Not Applicable

For each scenario, all 41 projections were ranked according to their deviation from the scenario-specific target values. The projection closest to the target value received Rank 1, and the farthest received Rank 41. A combined rank for each projection was then calculated by averaging its ranks across all metrics. Although the lowest combined rank generally indicates the most suitable projection, a qualitative assessment was conducted before final selection.

4.1 Projections for Water Quality and Groundwater Modeling

The primary metrics used for the selection of climate projections for the water quality and groundwater modeling are projected change in average temperature and flow metrics including annual, seasonal, and 5-year flow. Given the large number of flow metrics, the highest-ranking projections were examined in detail to evaluate tradeoffs in their ability to reproduce different hydrologic characteristics. Tradeoffs in ranking were considered acceptable when lower performance occurred in less critical metrics. Scatter plots, average temperature versus annual flow (Figure 3) and average temperature versus precipitation (Figure 2) were developed to support this qualitative evaluation. Key strengths and limitations of the candidate projections were documented and discussed, after which the final projection was selected. Table 3, A1, and A2 show the ranks assigned to the individual projections for the metrics based on the ability to replicate the target values for Central Tendency, Hot-Dry, and Warm-Wet Scenarios shown in Table 2.

Table 3. Ranks assigned to the climate projections for the climate and hydrological metrics used for water quality and groundwater modeling for Central Tendency Scenario

Projection	ΔP (%)	ΔTavg (°F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Spring (%)	CV Annual Flow	ΔQ 5-Year (%)	CV 5-Year Flow
ACCESS-CM2 SSP2-4.5	40	12	11	4	39	20	18	31
ACCESS-CM2 SSP3-7.0	39	33	38	29	27	12	37	39
ACCESS-CM2 SSP5-8.5	33	40	21	37	24	15	24	1
CESM2-LENS SSP3-7.0	18	15	17	23	4	29	14	10
CNRM-ESM2-1 SSP2-4.5	36	26	36	12	28	18	39	17
CNRM-ESM2-1 SSP3-7.0	10	3	14	18	20	11	26	22
CNRM-ESM2-1 SSP5-8.5	27	17	31	32	25	25	22	40

Projection	ΔP (%)	ΔTavg (°F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Spring (%)	CV Annual Flow	ΔQ 5-Year (%)	CV 5-Year Flow
EC-Earth3 SSP2-4.5	7	8	16	5	31	4	9	20
EC-Earth3 SSP3-7.0	29	19	35	31	32	41	34	27
EC-Earth3 SSP5-8.5	35	37	39	39	22	38	38	35
EC-Earth3-Veg SSP2-4.5	16	22	1	8	29	23	4	3
EC-Earth3-Veg SSP3-7.0	11	4	8	35	10	1	8	8
EC-Earth3-Veg SSP5-8.5	4	25	23	33	19	14	23	36
FGOALS-g3 SSP2-4.5	12	30	7	2	8	30	17	4
FGOALS-g3 SSP3-7.0	32	10	29	17	18	37	32	33
FGOALS-g3 SSP5-8.5	38	2	40	38	5	40	40	6
GFDL-ESM4 SSP2-4.5	2	29	5	7	11	6	6	19
GFDL-ESM4 SSP3-7.0	21	14	25	26	33	5	25	25
GFDL-ESM4 SSP5-8.5	9	5	3	15	23	31	3	12
HadGEM3-GC31-LL SSP2-4.5	25	35	10	34	37	7	20	21
HadGEM3-GC31-LL SSP5-8.5	37	41	30	24	7	35	36	28
INM-CM5-0 SSP2-4.5	1	27	4	11	41	20	5	31
INM-CM5-0 SSP3-7.0	31	7	34	20	26	3	35	38
INM-CM5-0 SSP5-8.5	5	11	2	28	38	19	1	7
IPSL-CM6A-LR SSP2-4.5	30	23	32	30	17	16	33	26
IPSL-CM6A-LR SSP3-7.0	26	1	26	1	1	8	31	15
IPSL-CM6A-LR SSP5-8.5	17	24	13	3	15	39	7	18
KACE-1-0-G SSP2-4.5	3	21	9	14	36	22	2	41
KACE-1-0-G SSP3-7.0	34	31	37	19	35	13	30	14
KACE-1-0-G SSP5-8.5	20	39	12	21	40	36	29	2
MIROC6 SSP2-4.5	19	28	22	16	14	26	16	5
MIROC6 SSP3-7.0	14	13	15	22	3	9	13	30
MIROC6 SSP5-8.5	15	6	20	6	9	34	12	16
MPI-ESM1-2-HR SSP2-4.5	23	38	24	9	16	32	10	23
MPI-ESM1-2-HR SSP3-7.0	6	32	6	13	30	28	21	24
MPI-ESM1-2-HR SSP5-8.5	22	16	33	27	12	17	19	11
MRI-ESM2-0 SSP2-4.5	13	20	27	10	21	2	11	37
MRI-ESM2-0 SSP3-7.0	24	9	19	40	13	10	28	9
MRI-ESM2-0 SSP5-8.5	8	18	18	36	34	24	15	34
TaiESM1 SSP2-4.5	41	34	41	41	2	33	41	13
TaiESM1 SSP3-7.0	28	36	28	25	6	27	27	29

4.2 Projections for FIRO Modeling

The primary metrics used for the selection of climate projections for the FIRO modeling are projected changes in average temperature and flood event metrics including 1-day flood, 2-day flood, and 3-day flood events. The projected changes in the annual, seasonal, and 5-year flow were also considered for the selection of the climate projections. Given the large number of flow and flood metrics, the highest-ranking projections were examined in detail to evaluate tradeoffs in their ability to reproduce different hydrologic characteristics. Tradeoffs in ranking were considered acceptable when lower performance occurred in less

critical metrics. Various scatter plots, such as average temperature versus annual flow (Figure 3) and 1-day flood (Figure 5), 2-day flood (Figure A-1), and 3-day flood (Figure 6) versus annual precipitation, were developed to support this qualitative evaluation. Key strengths and limitations of the candidate projections were documented and discussed, after which the final projection was selected. Table 4 shows the ranks assigned to the individual projections for the metrics based on the ability to replicate the target values shown in Table 2. The target values for the FIRO modeling were considered primarily from the Warm-Wet Scenario with supplemental consideration of average temperature changes from Hot-Dry Scenario.

Table 4. Ranks assigned to the climate projections for the climate and hydrological metrics used for FIRO modeling

Projection	ΔP (%)	ΔTavg Warm (deg F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Winter (%)	ΔQ Rainy (%)	ΔQ Spring (%)	ΔQ 5-Year (%)	1-Day Flood	2-Day Flood	3-Day Flood	ΔTavg Hot (deg F)
ACCESS-CM2 SSP2-4.5	35	25	8	17	20	8	39	9	9	6	14	10
ACCESS-CM2 SSP3-7.0	22	34	19	5	22	20	32	15	13	26	20	6
ACCESS-CM2 SSP5-8.5	7	40	2	16	7	4	29	4	21	2	1	26
CESM2-LENS SSP3-7.0	30	2	27	3	38	27	16	30	10	11	7	29
CNRM-ESM2-1 SSP2-4.5	9	10	16	10	34	18	33	22	19	5	6	34
CNRM-ESM2-1 SSP3-7.0	12	18	6	29	15	6	26	2	31	32	26	19
CNRM-ESM2-1 SSP5-8.5	36	26	35	37	10	35	30	34	4	31	32	9
EC-Earth3 SSP2-4.5	23	13	26	15	24	23	34	25	25	30	18	22
EC-Earth3 SSP3-7.0	37	28	38	36	29	37	35	38	29	22	21	5
EC-Earth3 SSP5-8.5	41	38	41	40	37	41	1	41	40	41	41	14
EC-Earth3-Veg SSP2-4.5	10	6	18	11	17	16	9	19	17	17	11	32
EC-Earth3-Veg SSP3-7.0	25	16	12	39	19	9	18	13	18	28	35	20
EC-Earth3-Veg SSP5-8.5	21	32	31	38	16	28	2	35	3	8	3	2
FGOALS-g3 SSP2-4.5	11	17	13	20	4	12	8	10	36	25	31	38
FGOALS-g3 SSP3-7.0	6	8	5	28	9	2	3	11	22	15	24	24
FGOALS-g3 SSP5-8.5	17	20	22	18	12	22	12	24	27	10	9	17
GFDL-ESM4 SSP2-4.5	19	15	21	12	14	21	19	21	20	37	38	37
GFDL-ESM4 SSP3-7.0	32	3	33	33	11	30	36	36	28	34	27	28
GFDL-ESM4 SSP5-8.5	13	22	15	26	2	17	28	16	34	12	17	16
HadGEM3-GC31-LL SSP2-4.5	2	36	10	8	27	13	31	7	12	16	4	12
HadGEM3-GC31-LL SSP5-8.5	16	41	9	1	3	7	10	14	15	27	22	40
INM-CM5-0 SSP2-4.5	18	11	20	24	30	19	41	20	24	13	10	35
INM-CM5-0 SSP3-7.0	39	14	37	31	40	38	5	40	8	18	16	21
INM-CM5-0 SSP5-8.5	15	24	17	4	36	15	38	18	41	38	37	11
IPSL-CM6A-LR SSP2-4.5	5	7	11	6	6	10	24	12	26	1	8	33
IPSL-CM6A-LR SSP3-7.0	1	19	3	19	8	5	14	8	16	19	15	18
IPSL-CM6A-LR SSP5-8.5	29	31	24	21	23	25	22	23	2	29	29	1
KACE-1-0-G SSP2-4.5	20	29	23	9	32	24	25	17	11	24	30	3
KACE-1-0-G SSP3-7.0	40	33	39	30	41	40	23	37	7	3	2	4
KACE-1-0-G SSP5-8.5	8	39	7	7	18	11	40	5	5	14	13	25
MIROC6 SSP2-4.5	31	12	30	27	25	33	21	32	33	4	5	36

Projection	ΔP (%)	ΔTavg Warm (deg F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Winter (%)	ΔQ Rainy (%)	ΔQ Spring (%)	ΔQ 5-Year (%)	1-Day Flood	2-Day Flood	3-Day Flood	ΔTavg Hot (deg F)
MIROC6 SSP3-7.0	27	5	25	32	13	29	15	29	23	9	12	27
MIROC6 SSP5-8.5	28	23	29	13	35	31	7	28	1	21	23	15
MPI-ESM1-2-HR SSP2-4.5	34	30	32	22	33	32	4	26	35	23	25	41
MPI-ESM1-2-HR SSP3-7.0	14	21	14	25	5	14	11	6	6	7	19	39
MPI-ESM1-2-HR SSP5-8.5	33	1	36	34	31	36	6	33	37	35	36	30
MRI-ESM2-0 SSP2-4.5	26	4	34	23	28	34	27	27	38	36	33	31
MRI-ESM2-0 SSP3-7.0	4	9	1	35	21	1	20	3	14	20	28	23
MRI-ESM2-0 SSP5-8.5	24	27	28	14	39	26	37	31	39	40	40	7
TaiESM1 SSP2-4.5	38	35	40	41	26	39	13	39	30	33	34	8
TaiESM1 SSP3-7.0	3	37	4	2	1	3	17	1	32	39	39	13

5. Summary and Recommendations

This assessment of projected climate scenarios reviewed important climatic and hydrologic metrics that would be used to evaluate the relative performance of individual GCM projections within the Russian River watershed. The recommended list of the climate projections was developed for the water quality, groundwater modeling, and FIRO modeling. The selection of the projection was based on the ability to replicate the changes in climate and hydrological metrics from the 41 climate projections. The projected changes in the metrics are estimated for the future period (2026-2100) with respect to the historical period (1981-2010). The selection of the projection for the water quality and groundwater modeling is primarily based on the ability to replicate projected changes in temperature and flow, while the projections for FIRO modeling are based on the projected changes in flow and flood events.

Recommended climate projections for Water Quality and Groundwater Modeling:

For the Central Tendency Scenario, the EC-Earth3-Veg SSP3-7.0 projection is recommended for water quality and groundwater modeling because it provides the strongest overall alignment with temperature and flow metrics. This projection consistently performs well under drought conditions as well and falls within the 25th–75th percentile range of 41 future climate projections. Its strong ranking supports its reliability as it ranks 4th in replicating the average temperature, 8th in annual flow, and 1st for capturing annual flow variability. EC-Earth3-Veg SSP3-7.0 projection offers robust physical realism suitable for central tendency scenario future climate assessments. The other projections that can be considered for representing the Central Tendency Scenario are GFDL-ESM4 SSP2-4.5 and INM-CM5-0 SSP5-8.5.

For the Hot-Dry Scenario, EC-Earth3-Veg SSP5-8.5 is identified as the most appropriate projection for water quality and groundwater modeling due to its strong performance across precipitation, temperature, and flow metrics under increasingly extreme dry-warming conditions. It ranks 6th in combined metrics for the Hot-Dry Scenario and 2nd when focusing specifically on precipitation and temperature. The projection remains within the interquartile range of future projections and performs particularly well for temperature and annual flow, ranking 2nd for both. Its ability to also best represent late-century (2071-2100) Hot-Dry conditions further supports its selection for high-warming environments. In addition to EC-Earth3-Veg SSP5-8.5, MIROC6 SSP5-8.5 can also be considered for representing Hot-Dry Scenario.

For the Warm-Wet Scenario, the MRI-ESM2-0 SSP3-7.0 projection is recommended for water quality and groundwater modeling based on its strong multi-metric performance under wetter and warmer future conditions. The projection ranks 4th in representing combined precipitation, temperature, and flow behaviors, and 2nd when focusing on precipitation and temperature alone. It also remains within the 25th–

75th percentile range of 41 projections and demonstrates exceptional hydrologic skill, ranking 1st in replicating the annual flow and 3rd in capturing 5-year flow extremes. MRI-ESM2-0 SSP3-7.0 projection provides a reliable foundation for evaluating warm-wet climate futures. The other projections that can be considered for representing the Warm-Wet Scenario are IPSL-CM6A-LR SSP3-7.0 and FGOALS-g3 SSP3-7.0.

Recommended climate projections for FIRO Modeling:

The IPSL-CM6A-LR SSP2-4.5 projection is recommended for FIRO modeling because it provides one of the most balanced representations of both climatic and hydrologic conditions relevant to Warm-Wet future conditions. Climatically, the projection demonstrates strong skill in reproducing combined temperature and precipitation patterns, ranking 5th in precipitation and 7th in temperature, indicating reliable performance in capturing the primary drivers of watershed response. Hydrologically, IPSL-CM6A-LR exhibits consistent mid-range performance across multiple flow metrics, ranking 11th in annual flow, 6th in fall and winter flows, 10th in rainy-season flow, and 12th in the 5-year flow, suggesting a stable representation of seasonal hydrologic variability. For flood behavior, the projection shows valuable performance with best representation of 2-day flood, ranking 26th for 1-day floods and 8th for 3-day floods, making it particularly suitable for applications emphasizing prolonged storm sequences. Collectively, these attributes make IPSL-CM6A-LR SSP2-4.5 an appropriate and justified choice for analyzing warm-wet future scenarios and able to capture events exceeding 75th percentile of annual precipitation, 1-day, 2-day, and 3-day floods.

The ACCESS-CM2 SSP3-7.0 is recommended for FIRO to represent the Hot-Wet future conditions due to its strong performance in capturing the key climatic drivers associated with this scenario. The projection provides a good representation of combined temperature and precipitation characteristics, ranking 6th in capturing 75th percentile average temperature change in future. Its hydrologic performance is moderate but reliable, with rankings of 19th for annual flow, 5th for fall flow, and 15th for the 5-year flow, indicating acceptable skill in reproducing both seasonal and long-term flow variability under warmer and wetter conditions. For flood behavior, ACCESS-CM2 demonstrates mid-range performance across short-duration events, ranking 13th for 1-day floods, 26th for 2-day floods, and 20th for 3-day floods, providing a balanced characterization of peak flow response without extreme bias toward specific event durations. Collectively, these characteristics make ACCESS-CM2 SSP3-7.0 an appropriate projection choice for representing hot-wet futures in climate and able to capture events exceeding 75th percentile of annual precipitation, 1-day, 2-day, and 3-day floods.

Another recommended projection for the FIRO modeling representing Warm-Wet future conditions is CNRM-ESM2-1 SSP2-4.5 due to its balanced and credible performance across key climate and flood metrics. The projection demonstrates a good overall representation of combined temperature and precipitation characteristics, ranking 9th in precipitation and 10th in temperature in representing warm-wet scenarios. Its hydrologic rankings further support its suitability, with mid-range performance in annual flow (16th) and fall flow (10th), reflecting reasonable fidelity in baseline and seasonal streamflow behavior. For flood metrics, CNRM-ESM2-1 performs particularly well for multi-day events, ranking 5th in 2-day floods and 6th in 3-day floods, while maintaining moderate accuracy for 1-day floods (19th). This combination of strong multi-day flood representation and stable climate and flow performance make CNRM-ESM2-1 SSP2-4.5 a valuable supplementary projection for characterizing Warm and Wet future conditions and capturing events exceeding 75th percentile of annual precipitation, 1-day, 2-day, and 3-day floods.

The climate projections selected for the water-quality, groundwater, and FIRO-modeling analyses fall within the 68% confidence interval of temperature and precipitation changes, except ACCESS-CM2 SSP3-7.0 shown in Figure 7. The ACCESS-CM2 SSP3-7.0 projection was selected to represent extreme future conditions characterized by high temperatures and elevated flood flows, positioning this projection near the upper (approximately 95th-percentile) likelihood bound of the ensemble. As illustrated, the selected projections cluster near the densest region of the ensemble, representing moderate increases in temperature (approximately 3–5°F) and a range of modest precipitation changes. These projections lie well inside the inner elliptical contour (labeled 0.68), which denotes the region where most projection results are concentrated. The recommended climate model projections for FIRO analysis cover the range in

projected change in precipitation of 7.7% to 13.8%, average temperature by 3.1°F to 5.6°F, annual flow by 8% to 12%, 1-day flood of 23% to 33%, 2-day flood of 27% to 50%, 3-day flood of 36% to 52%. By selecting projections within this interval, the modeling framework captures climate futures that are both plausible and statistically representative of the broader ensemble.

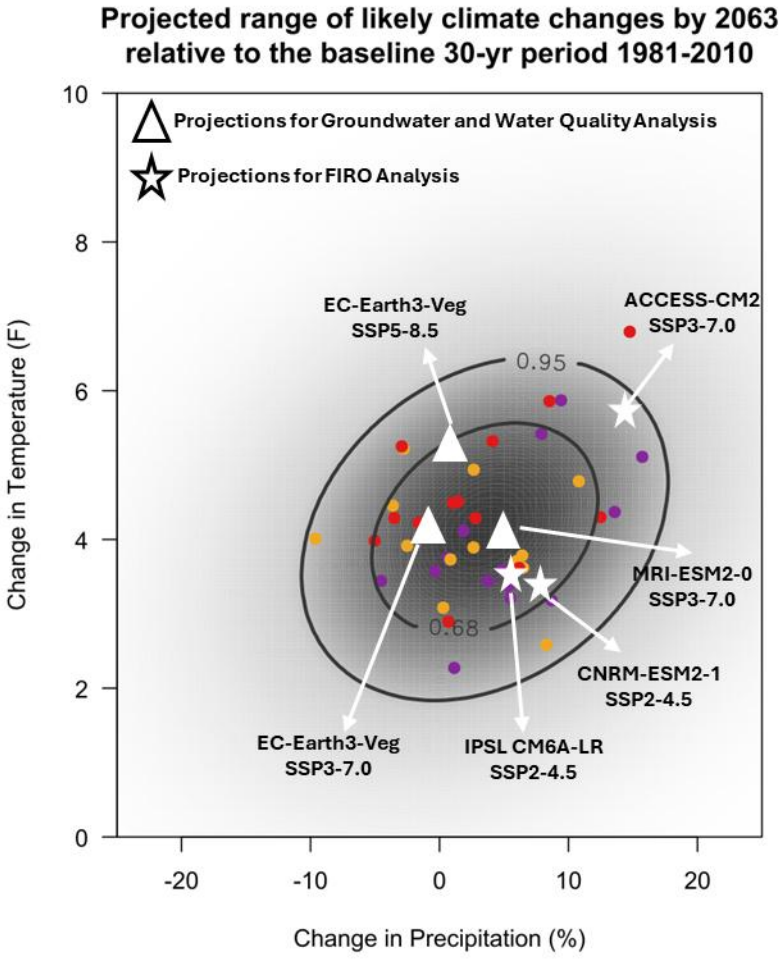

Figure 7. Likelihood contours of the projected Change in Annual precipitation and Average Temperature for Russian River Watershed Resilience Pilot Study Area estimated by 41 climate projections.

6. References

IPCC, 2021: Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change[Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

LOCA. 2025. What is LOCA? What is LOCA? – LOCA Statistical Downscaling (Localized Constructed Analogs)

Pierce, D. W., D. R. Cayan, S. Rahimi, and J. Kalansky, 2023: LOCA version 2 Hybrid Downscaling. Data Justification Memo for EPC-20-006 Development of Climate Projections for California and Identification of General Use Projections. https://www.energy.ca.gov/sites/default/files/2024-03/04_HybridDownscaling_DataJustificationMemo_Pierce_Adopted_ada.pdf

7. Appendix

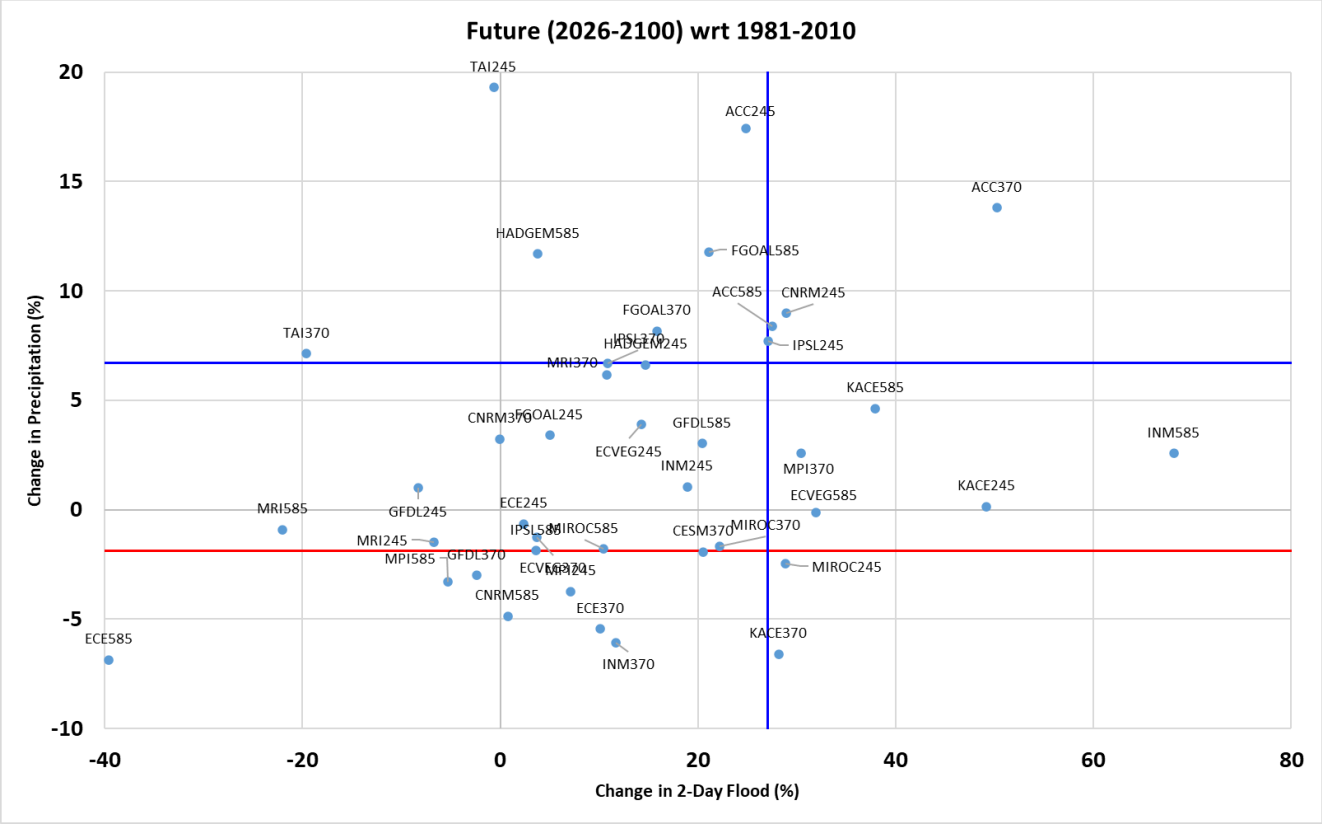

Figure A1. Projected Change in 2-Day Flood events and Annual Precipitation for Russian River Watershed Resilience Pilot Study Area. Red line represents the Hot-Dry Scenario, and blue lines represent the Warm-Wet Scenario.

Table A1. Ranks assigned to the climate projections for the climate and hydrological metrics used for water quality and groundwater modeling for Hot-Dry Scenario

Projection	ΔP (%)	ΔTavg (°F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Spring (%)	CV Annual Flow	ΔQ 5-Year (%)	CV 5-Year Flow
ACCESS-CM2 SSP2-4.5	40	10	28	17	22	2	25	20
ACCESS-CM2 SSP3-7.0	39	6	39	33	36	24	38	39
ACCESS-CM2 SSP5-8.5	35	26	32	38	33	27	29	14
CESM2-LENS SSP3-7.0	2	29	8	29	20	35	1	19
CNRM-ESM2-1 SSP2-4.5	36	34	38	23	37	28	39	24
CNRM-ESM2-1 SSP3-7.0	25	19	30	1	30	23	30	28
CNRM-ESM2-1 SSP5-8.5	17	9	12	25	34	31	12	40
EC-Earth3 SSP2-4.5	10	22	9	18	38	15	8	26
EC-Earth3 SSP3-7.0	18	5	16	22	39	41	22	33
EC-Earth3 SSP5-8.5	24	14	24	34	8	39	28	37
EC-Earth3-Veg SSP2-4.5	27	32	20	21	6	30	14	13
EC-Earth3-Veg SSP3-7.0	7	20	26	28	23	18	21	17
EC-Earth3-Veg SSP5-8.5	12	2	2	26	9	26	15	31
FGOALS-g3 SSP2-4.5	26	38	25	13	14	9	24	12
FGOALS-g3 SSP3-7.0	34	24	35	3	10	25	35	22
FGOALS-g3 SSP5-8.5	38	17	40	39	16	33	40	10
GFDL-ESM4 SSP2-4.5	15	37	17	20	24	13	11	5
GFDL-ESM4 SSP3-7.0	9	28	5	15	40	14	16	30
GFDL-ESM4 SSP5-8.5	23	16	22	5	32	10	19	4
HadGEM3-GC31-LL SSP2-4.5	30	12	27	36	1	12	26	27
HadGEM3-GC31-LL SSP5-8.5	37	40	36	30	15	38	37	34
INM-CM5-0 SSP2-4.5	16	35	18	8	35	2	13	20
INM-CM5-0 SSP3-7.0	19	21	15	6	7	16	23	38
INM-CM5-0 SSP5-8.5	20	11	21	32	4	1	17	9
IPSL-CM6A-LR SSP2-4.5	33	33	37	35	29	5	36	16
IPSL-CM6A-LR SSP3-7.0	31	18	33	14	18	19	34	23
IPSL-CM6A-LR SSP5-8.5	1	1	11	12	28	40	9	25
KACE-1-0-G SSP2-4.5	14	3	14	24	2	29	18	41
KACE-1-0-G SSP3-7.0	22	4	19	2	3	7	20	2
KACE-1-0-G SSP5-8.5	28	25	29	27	26	21	33	15
MIROC6 SSP2-4.5	6	36	1	4	27	32	7	11
MIROC6 SSP3-7.0	4	27	10	11	19	20	2	36
MIROC6 SSP5-8.5	3	15	3	19	13	37	3	1

Projection	ΔP (%)	ΔTavg (°F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Spring (%)	CV Annual Flow	ΔQ 5-Year (%)	CV 5-Year Flow
MPI-ESM1-2-HR SSP2-4.5	13	41	4	10	11	11	6	7
MPI-ESM1-2-HR SSP3-7.0	21	39	23	7	5	8	27	8
MPI-ESM1-2-HR SSP5-8.5	11	30	13	16	12	4	10	6
MRI-ESM2-0 SSP2-4.5	5	31	7	9	31	17	5	32
MRI-ESM2-0 SSP3-7.0	29	23	31	40	25	22	32	18
MRI-ESM2-0 SSP5-8.5	8	7	6	37	41	6	4	29
TaiESM1 SSP2-4.5	41	8	41	41	17	36	41	3
TaiESM1 SSP3-7.0	32	13	34	31	21	34	31	35

Table A2. Ranks assigned to the climate projections for the climate and hydrological metrics used for water quality and groundwater modeling for Warm-Wet Scenario

Projection	ΔP (%)	ΔTavg (°F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Spring (%)	CV Annual Flow	ΔQ 5-Year (%)	CV 5-Year Flow
ACCESS-CM2 SSP2-4.5	35	25	8	17	39	31	9	34
ACCESS-CM2 SSP3-7.0	22	34	19	5	32	10	15	33
ACCESS-CM2 SSP5-8.5	7	40	2	16	29	8	4	16
CESM2-LENS SSP3-7.0	30	2	27	3	16	7	30	8
CNRM-ESM2-1 SSP2-4.5	9	10	16	10	33	6	22	5
CNRM-ESM2-1 SSP3-7.0	12	18	6	29	26	11	2	1
CNRM-ESM2-1 SSP5-8.5	36	26	35	37	30	3	34	38
EC-Earth3 SSP2-4.5	23	13	26	15	34	21	25	3
EC-Earth3 SSP3-7.0	37	28	38	36	35	34	38	9
EC-Earth3 SSP5-8.5	41	38	41	40	1	25	41	23
EC-Earth3-Veg SSP2-4.5	10	6	18	11	9	1	19	17
EC-Earth3-Veg SSP3-7.0	25	16	12	39	18	17	13	11
EC-Earth3-Veg SSP5-8.5	21	32	31	38	2	9	35	40
FGOALS-g3 SSP2-4.5	11	17	13	20	8	36	10	18
FGOALS-g3 SSP3-7.0	6	8	5	28	3	40	11	36
FGOALS-g3 SSP5-8.5	17	20	22	18	12	41	24	20
GFDL-ESM4 SSP2-4.5	19	15	21	12	19	23	21	28
GFDL-ESM4 SSP3-7.0	32	3	33	33	36	22	36	7
GFDL-ESM4 SSP5-8.5	13	22	15	26	28	37	16	24
HadGEM3-GC31-LL SSP2-4.5	2	36	10	8	31	24	7	2
HadGEM3-GC31-LL SSP5-8.5	16	41	9	1	10	20	14	12
INM-CM5-0 SSP2-4.5	18	11	20	24	41	31	20	34
INM-CM5-0 SSP3-7.0	39	14	37	31	5	19	40	31

Projection	ΔP (%)	ΔTavg (°F)	ΔQ Annual (%)	ΔQ Fall (%)	ΔQ Spring (%)	CV Annual Flow	ΔQ 5-Year (%)	CV 5-Year Flow
INM-CM5-0 SSP5-8.5	15	24	17	4	38	30	18	21
IPSL-CM6A-LR SSP2-4.5	5	7	11	6	24	27	12	32
IPSL-CM6A-LR SSP3-7.0	1	19	3	19	14	15	8	6
IPSL-CM6A-LR SSP5-8.5	29	31	24	21	22	29	23	4
KACE-1-0-G SSP2-4.5	20	29	23	9	25	2	17	39
KACE-1-0-G SSP3-7.0	40	33	39	30	23	26	37	26
KACE-1-0-G SSP5-8.5	8	39	7	7	40	39	5	15
MIROC6 SSP2-4.5	31	12	30	27	21	4	32	19
MIROC6 SSP3-7.0	27	5	25	32	15	14	29	14
MIROC6 SSP5-8.5	28	23	29	13	7	16	28	27
MPI-ESM1-2-HR SSP2-4.5	34	30	32	22	4	38	26	29
MPI-ESM1-2-HR SSP3-7.0	14	21	14	25	11	35	6	30
MPI-ESM1-2-HR SSP5-8.5	33	1	36	34	6	28	33	22
MRI-ESM2-0 SSP2-4.5	26	4	34	23	27	18	27	41
MRI-ESM2-0 SSP3-7.0	4	9	1	35	20	12	3	10
MRI-ESM2-0 SSP5-8.5	24	27	28	14	37	33	31	37
TaiESM1 SSP2-4.5	38	35	40	41	13	13	39	25
TaiESM1 SSP3-7.0	3	37	4	2	17	5	1	13