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Comments

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California Drought Outlooks Based on Climate Change Models' Effects on Water Availability

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Abstract: Future streamflow in California is evaluated based on eight climate projections models and the effects on water availability. The unimpaired projected streamflow for eleven California rivers, collected from Cal-Adapt, are compared with unimpaired historical flows (1950–2015) using eight climate model projections (2020–2099) identified as representative as possible future scenarios; Warm Dry RCP 4.5, Average RCP 4.5, Cool Wet RCP 4.5, Other RCP 4.5, Warm Dry RCP 8.5, Average RCP 8.5, Cool Wet RCP 8.5, and Other RCP 8.5. Projected drought deficits (or magnitudes), durations, and intensities are statistically tested against historical values to determine significance of differences between past streamflow and future streamflow. The models show significant differences between historical and projected streamflow with all three drought categories (deficit, duration, intensity), using difference in means *t*-tests. Warm Dry and Other simulations are projected to have larger droughts (2–3 times larger) than the historical record. Average and Cool Wet simulations are projected to have fewer droughts than the historical period. Results are consistent for 4.5 and 8.5 RCP scenarios that represent two different greenhouse gas emission levels. Potential impacts of such streamflow variations are discussed.

Keywords: drought; climate; water; hydrology; streamflow

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1. Introduction

Southwestern United States drought persistence increases competition among various sectors of water use, affecting economic security. Continued dryness in the area is resulting in water level decline in various basins since 2000. Sustained dryness will result in water shortages not only for the immediate affected area, but other areas reliant on the basins for water. Local and state governments are implementing water conservation plans to allocate water usage [1]. For instance, the Colorado River basin will experience Tier 1 shortage in late 2021 and must implement drought contingency plans with lower basin states. As climate change continues, precipitation and temperature levels will be affected [2], thus there is a need to completely understand how water availability will be impacted.

Drought scenarios under climate change conditions at specific locations (Shasta Dam) have found changes in the drought frequency curves [3]. Expanded studies have looked at streamflow conditions at seven (7) locations in California under conditions forced from the coupled model intercomparison project (CMIP) in 2005 and highlighted changes in the seasonality of flows [4]. The distribution of streamflow under changing climate conditions was further evaluated in 2018 and identified a potential new normal of wetter winters and drier summers [5]. Pierce et al. predicted potential effects such as average annual temperature, precipitation, top level soil moisture, annual runoff, and snow water equivalent [6]. Piechota et al. studied water supply and drought duration, deficit (or magnitude) and severity in the Colorado River Basin to assess the deficit in relation to past paleo records [7]. However, there is a lack of information on the broad changes in California for water supply drought scenarios (e.g., duration, deficit and severity) under change climates.

The specific objectives of the current study are to first evaluate water supply drought scenarios (duration, deficit, severity) for various river basins in California. Secondly, we evaluate the changes in water supply drought scenarios under climate change scenarios commonly used in assessment studies. The study provides novel contributions to the understanding of how climate change will impact water supply drought scenarios under changing climate conditions. Previous studies have not focused on understanding the impacts that climate change will have on drought (in the form of water supply) for multiple California streamflow stations. Analysis of streamflow and water supply under changing climates, regarding these three drought related categories will be a significant contribution.

2. Materials and Methods

2.1. Data Used for Analysis

Historical yearly streamflow data (1950–2015) for eleven California rivers (Sacramento River, Feather River, Yuba River, Bear River, American River, Mokelumne River, Calaveras River, Stanislaus River, Tuolumne River, Merced River, and San Joaquin River) were collected from Cal-Adapt which is an online system to access data and information on climate impacts in California [8]. These eleven river stations were selected by Pierce et al. [6] who conducted climate impact assessment and identified these stations as locations in the variable infiltration capacity (VIC) hydrologic model as bias corrected to unimpaired flows that are common to the eleven stations used by California Department of Water Resources. These stations represent flows in the absence of human activities.

Future scenarios of climate (e.g., temperature and precipitation) have been downscaled from 100 km to 6 km resolution using the LOCA statistical downscaling method for California and Nevada to be used in climate assessments [9]. Pierce et al. [6] evaluated the possible effects of the changing climate on the eleven unimpaired streamflow under eight climate simulations representing four different climate models and two different climate scenarios. The eight projections include four generalized circulation model (GCM) simulations/models at two emission levels as representative concentration pathways (RCP) 4.5 and 8.5. The emission level of RCP 4.5 is an intermediate climate change scenario, which will occur if policy makers enact mitigative policies that will minimize greenhouse gas emissions [6]. The RCP 8.5 pathway incorporates the highest level of greenhouse gas emissions resulting from a large population with high energy needs devoid of climate change policies [10]. There is no greater likelihood of occurrence for RCP 4.5 or 8.5 [11]. The four simulations are from models representing different future conditions-HadGEM2-ES (Warm Dry), CNRM-CM5 (Cool Wet), CanESM2 (Average), MIROC5 (Other). The MIROC5 (Other) simulation is a model most unlike the first three to provide inclusion of as many different possibilities. These four models were identified in the Cal-Adapt study to best represent the climate in California. [6]. Eight future projected water flows (2020–2099) were collected from Cal-Adapt for each of the eleven streamflow stations (see Figure 1). Yearly streamflow data were transformed from ft^3/sec to million-acre feet of water per year (MAF) (Note: 1 MAF = 1233 million cubic meters MCM) to be used in the drought analysis.

State Outline data were obtained from ArcGIS Hub,
Statation coodiantes were obtained from National Water
Information System: Web Interface

National Geographic, Esri, Garmin, HERE, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, increment P Corp.

Figure 1. Map of California streamflow station locations used in this study. Map generated from ArcGIS Hub and station coordinate obtained from National Water Information System [12].

2.2. Description of Analyses

Various statistical analyses were conducted on three drought categories: deficit, duration, and intensity. As previously used for drought studies in the western United States [7], a drought is defined as two or more years in which the streamflow is below the historical average streamflow. To determine when a streamflow station experienced drought, historical volumetric values were averaged and each yearly streamflow value of the eight future projections was subtracted from the average historical streamflow. Yearly droughts were explored as this is appropriate for analysis of changes in water supply which is generated over a water year (October 1 to September 30 of next year) and meets various demands throughout the year. A positive difference between the long-term average and the yearly streamflow represents a deficit in the given year. If a streamflow deficit occurred in two or more consecutive years, a drought occurred. Three drought categories were used to conduct data analysis for all eleven streamflow stations: (1) drought deficit, (2) duration, and (3) intensity. Overall drought deficit was calculated by summing the deficit for each of the years in which the drought occurred. Drought duration was found by adding the years in which consecutive streamflow deficits occurred. Drought intensity was determined by dividing drought deficit by the drought duration.

The variability in streamflow across California rivers only permits analysis against the corresponding historical data. To accurately compare data among the rivers, drought deficit, duration, and intensity were standardized with a z-score based on the mean (u) and standard deviation (σ) for each streamflow station (both for the historical and projected drought quantities). Each drought measure (deficit, duration, and intensity) was transformed into a standardized z-score. The two tailed difference in means *t*-tests were conducted on the standardized data of aggregated streamflow drought measures, at a significance level of 0.05, comparing the projected values to historical values.

The variability for individual streamflow stations was also evaluated using a similar *t*-test analysis on the non-standardized streamflow values for all the three drought measures (deficit, duration and intensity) and presented for as box plots and as extreme values (largest drought).

3. Results

3.1. Aggregate Analysis of California Streamflow Stations

Table 1 represents the two tailed *t*-test results for each of the drought categories with the highlighted boxes significant at a level of 0.05. This summary is for all eleven stations aggregated into one composite standardized time series. The largest impacts are seen in the deficit and duration drought quantities. The Warm Dry model (for both RCP 4.5 and 8.5) produces larger drought deficits and duration. For RCP 4.5, the Average and Cool Wet scenarios produce lower drought conditions for deficit, intensity and duration. The largest impacts are seen in drought deficits and durations.

Table 1. Aggregated streamflow analysis using two tailed difference in means *t*-tests with a significant difference in drought categories. Highlighted boxes indicate a significant difference (at a 0.05 level) between historical (1950–2015) and model (2020–2099) projected means. Red represents a higher projected mean than historical. Blue represents a lower projected mean than historical.

	Deficit (MAF)	**Intensity (MAF/Year)**	**Duration (Years)**
Historical vs. Warm Dry RPC 4.5	🟥		🟥
Historical vs. Average RPC 4.5	🟦	🟦	
Historical vs. Cool Wet RPC 4.5	🟦	🟦	🟦
Historical vs. Other RPC 4.5	🟥		🟥
Historical vs. Warm Dry RPC 8.5	🟥		🟥
Historical vs. Average RPC 8.5			
Historical vs. Cool Wet RPC 8.5	🟦		🟦
Historical vs. Other RPC 8.5			

3.2. Analysis of Individual California Streamflow Stations

Table 2 uses the same statistical significance test as Table 1 except the analysis is performed for each individual streamflow station and the non-standardized data (raw streamflow data). Results are shown for the drought duration and deficit. The patterns of having significantly different Warm Dry and Other projected means (higher) from the historical mean, and Average and Cool Wet projected means lower than historical, still occur in the individual stations. For instance, the Warm Dry scenario produced higher drought durations and quantities at the Feather, Yuba, Mokelumne and American River stations. There were some instances where the Cool Wet and Average scenarios produced lower drought duration and deficit (i.e., wetter conditions). This occurred in the Feather, Tuolumne, Merced and San Joaquin River stations. This demonstrates some of the spatial variability (Figure 1) in the response to climate change and the sensitivity to local conditions that can change how a watershed may respond.

Table 2. Individual streamflow station two tailed difference in means *t*-tests for drought duration (Dur) and deficit (Def). Highlighted boxes indicate a significant difference (at a 0.05 level) between historical and model projected means. Red represents a higher projected mean than historical. Blue represents a lower projected mean than historical.

	Sacramento		**Feather**		**Yuba**		**Tuolumne**		**Stanislaus**		**Mokelumne**		**Calaveras**		**American**		**Bear**		**Merced**		**San Joaquin**	
	Dur	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**	**Dur**	**Def**
Warm Dry RPC 4.5					🟥	🟥					🟥	🟥			🟥							
Average RPC 4.5			🟦	🟦																		
Cool Wet RPC 4.5		🟦						🟦											🟦			🟦
Other RPC 4.5																						
Warm Dry RPC 8.5			🟥	🟥	🟥	🟥																
Average RPC 8.5																						
Cool Wet RPC 8.5																						
Other RPC 8.5																						

Fewer significant differences occurred in the data analysis when drought deficit is evaluated by individual stations as when aggregated by climate model projection (Table 1), due to the nature of *t*-testing and fewer observations in the Table 2 analysis reducing degrees of freedom. Regardless of more restrictive criteria for significance, the individual streamflow data followed the patterns found in Table 1, further suggesting they were not due to chance.

Figure 2 depicts yearly streamflow deficit for the historical period (1950–2015) and under the Warm Dry RCP 8.5 projection model (2020–2099) at one station, Yuba River. The height of the bar represents the drought deficit in MAF. The width of the bars represents the length of the drought period. Streamflow deficits are highlighted as becoming more frequent in the projected time period 2020–2099. For instance, the projected drought from 2060–2070 has a particularly large deficit and is 3–4 times larger in comparison with the historical record. The longest historical (from 1950–2015) drought was four years, while the largest future drought (2060–2070) is 11 years. The largest deficit historically was 24 MAF (29,592 MCM), while the projection is 73 MAF (90,009 MCM) for the 2060–2070 drought.

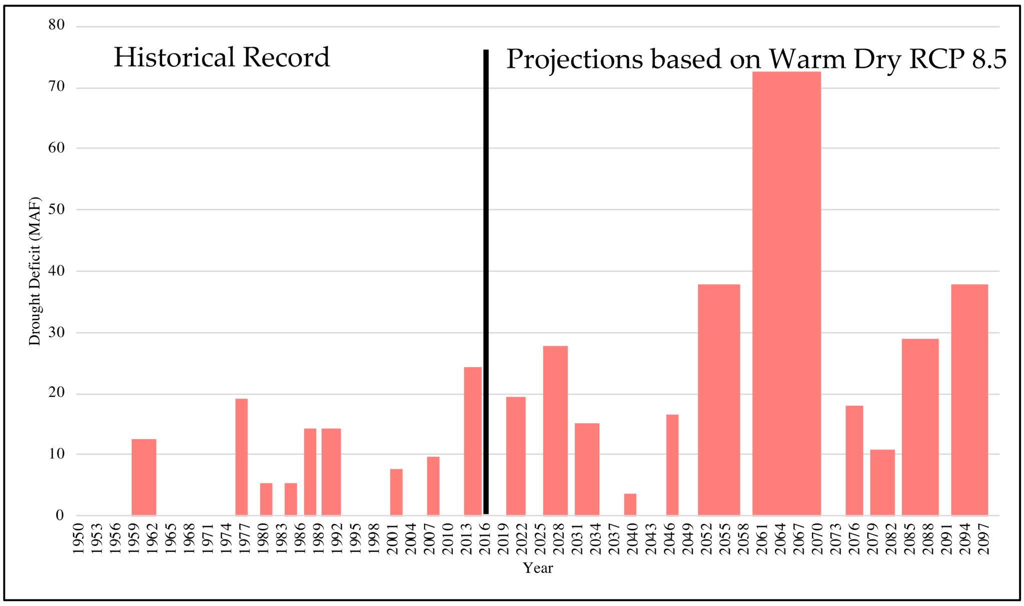

Figure 2. Yuba River drought deficit quantities for historical (1950–2015) and Warm Dry RCP 8.5 (2020–2099). The width of each bar represents the length of drought and the height of each bar represents the deficit (or magnitude) of the drought. (Note: 1 MAF = 1233 million cubic meters).

Figure 3 depicts yearly historical (1950–2015) and Cool Wet RCP 4.5 (2020–2099) streamflow deficit at San Joaquin River. It appears that the streamflow deficit during droughts becomes less frequent and intense in the future under this scenario. Drought frequency declines from eight historical droughts in the historical period to only six shorter and lower deficit droughts in the future period. The largest drought deficit in the historical record was 22 MAF and in the future period (2020–2099) it is 7 MAF.

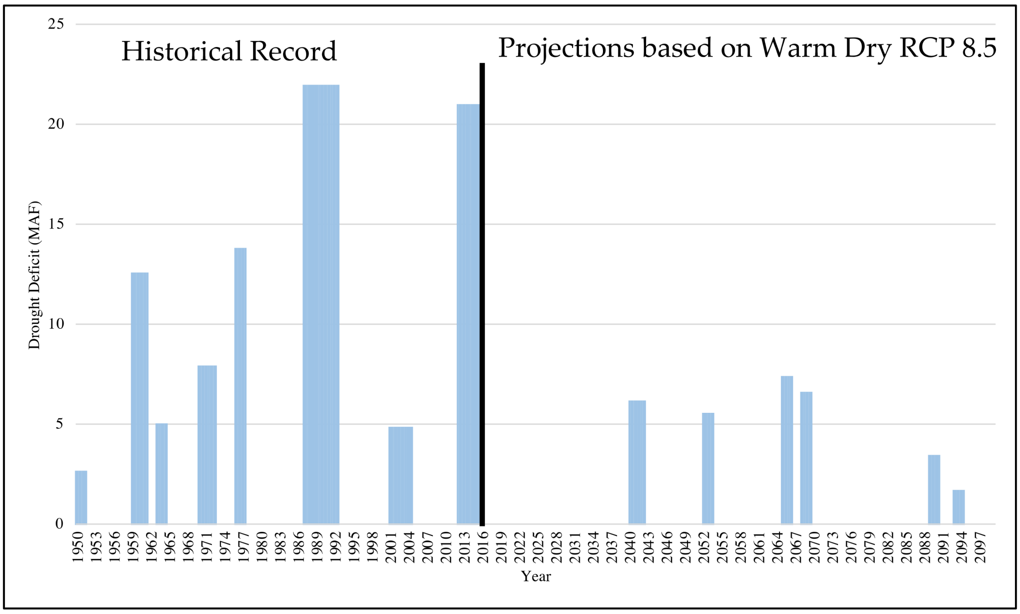

Figure 3. San Joaquin drought deficit quantities historical (1950–2015) and Cool Wet RCP 4.5 (2020–2099). The width of each bar represents the length of drought and the height of each bar represents the deficit (or magnitude) of the drought. (Note: 1 MAF = 1233 million cubic meters).

3.3. Analysis of Distributions for Individual California Streamflow Stations (Historical and Future)

Figures 4 and 5 depict the distribution of historical and projected drought deficit quantities for select stations (Yuba and San Juaquin), as compared to Figures 2 and 3 which show drought deficits over time. The median of Warm Dry and Other projection models at RCP 4.5 and 8.5, appear higher than historical. The median of Average and Cool Wet projections at RCP 4.5 and 8.5, appear to vary from being far above historical to slightly below. Outliers tend to be more extreme with Warm Dry and Other projection models than for Average and Cool Wet projection models. The ranges of drought deficit quantities vary across all projection models. For the Yuba River (Figure 4), only the Warm Dry RPC 4.5 and 8.5 scenarios have drought scenarios that are significantly different (i.e., larger deficits) from the historical distribution (as determined from the two tailed t-test at $p = 0.05$). For the San Joaquin River (Figure 5), only the Cool Wet RPC 4.5 scenario had a significantly different (i.e., smaller deficit) from the historical distribution.

Tables 3–5 display the largest deficit, longest duration, and highest intensity of each drought under historical conditions and under model scenarios. Out of all the droughts that were historically recorded or projected, this table displays the highest values of the three drought categories. Streamflow deficit (Table 3) increases by as much as three times larger than historical in the worst-case future scenario. For instance, in the American River, the largest drought deficit in the historical record is 30 MAF and the in the future scenario Warm Dry RCP 8.5 the drought deficit is 89 MAF.

Table 4 displays the duration (length) of droughts for each station and scenario. It is noteworthy that future droughts may increase in duration two to three times larger than historical. For instance, in the American River the largest drought duration in the historical record is 4 years and the in the future scenario Warm Dry RCP 8.5 the drought duration is 11 years.

Table 5 displays the intensity (deficit divided by duration) of droughts for each station and scenario. In general, there are fewer differences in drought intensity between the historical record and future period. This could be a result of droughts being longer in duration (see Table 4) and this would lead to less intense droughts in a given year. This is a limitation of the analysis as we are not evaluating the individual yearly deficits as isolated droughts and intensity is defined based on extended drought periods.

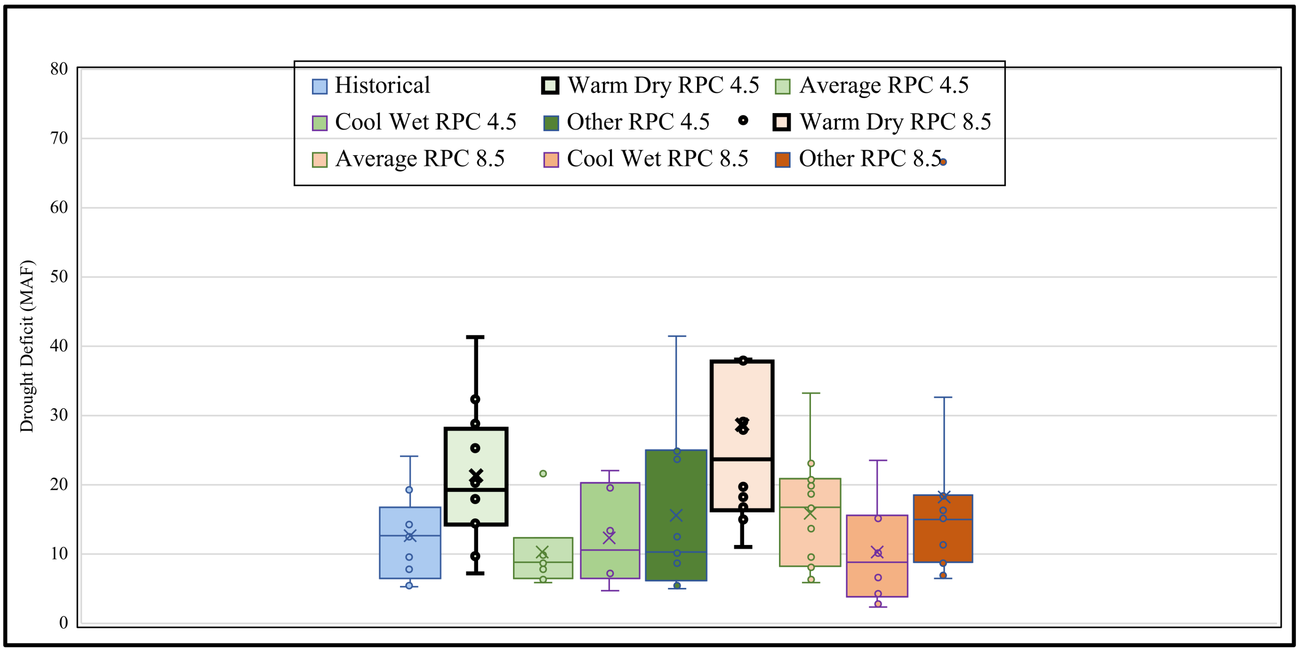

Figure 4. Box plot of Yuba River's drought deficit quantities historical (1950–2015) under all projected models (2020–2099). Bottom bar and top bars extended from the box represent the lowest and highest usable values. The line in the middle represents the median value in the data. Bottom half of the box represents the lower quartile, and the top half represents the upper quartile. The highlighted boxes are significant ($p = 0.05$) in terms of different from the historical distribution based on the *t*-test. (Note: 1 MAF = 1233 million cubic meters).

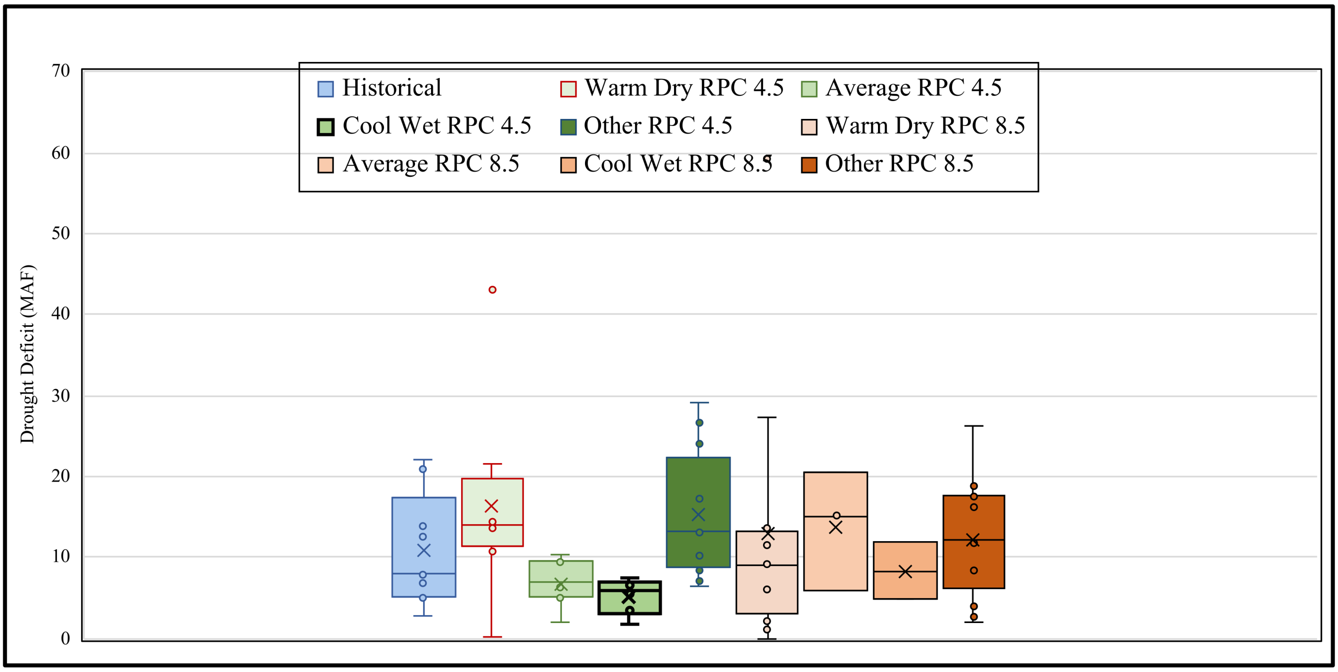

Figure 5. Box plot of San Joaquin River's drought deficit quantities historical (1950–2015) under all projected models (2020–2099). Bottom bar and top bars extended from the box represent the lowest and highest usable values. The line in the middle represents the median value in the data. Bottom half of the box represents the lower quartile, and the top half represents the upper quartile. The highlighted boxes are significant ($p = 0.05$) in terms of different from the historical distribution based on the *t*-test. (Note: 1 MAF = 1233 million cubic meters).

Table 3. Largest drought streamflow deficit (MAF) by projection model for each streamflow station. Each of the values represent the largest drought deficit out of all projected droughts under each climate scenario or historical records. Red highlighting indicates droughts with a larger deficit than historical. Blue highlighting indicates droughts with a smaller deficit than historical. Bold values are the largest projected deficit for each station. (Note: 1 MAF = 1233 million cubic meters).

Station	Historical	Warm Dry RCP 4.5	Average RCP 4.5	Cool Wet RCP 4.5	Other RCP 4.5	Warm Dry RCP 8.5	Average RCP 8.5	Cool Wet RCP 8.5	Other RCP 8.5
Sacramento River	22	43	10	7	29	**59**	20	12	26
Feather River	48	79	28	27	89	86	65	31	**111**
Yuba River	24	41	22	22	41	**73**	33	24	67
Tuolumne River	20	39	12	8	26	**58**	24	13	26
Stanislaus River	19	21	13	7	16	**39**	7	18	23
Mokelumne River	9	18	9	5	12	**28**	11	9	18
Calaveras River	3	5	5	2	5	**7**	3	3	6
American River	30	49	22	23	43	**89**	41	28	67
Bear River	3	4	3	3	6	**8**	4	3	6
Merced River	14	24	7	7	15	**33**	13	9	15
San Joaquin River	22	43	10	7	29	**59**	20	12	26

Table 4. Longest drought duration (years) by projection model for each streamflow station. Each of the values represent the longest drought out of all projected droughts under each climate scenario or historical records. Red highlighting indicates a longer drought than historical. Blue highlighting indicates a shorter drought than historical. Bold values are the longest projected drought for each station. (Note: 1 MAF = 1233 million cubic meters).

Station	Historical	Warm Dry RCP 4.5	Average RCP 4.5	Cool Wet RCP 4.5	Other RCP 4.5	Warm Dry RCP 8.5	Average RCP 8.5	Cool Wet RCP 8.5	Other RCP 8.5
Sacramento River	6	9	3	3	10	**11**	6	3	5
Feather River	4	7	3	3	10	7	5	3	**11**
Yuba River	4	8	7	5	**11**	**11**	6	5	**11**
Tuolumne River	6	10	4	3	7	**11**	6	3	5
Stanislaus River	6	10	8	3	5	**11**	3	4	8
Mokelumne River	4	10	8	3	6	**11**	4	3	8
Calaveras River	6	**11**	**11**	4	10	**11**	7	6	**11**
American River	4	7	4	5	**11**	**11**	5	3	8
Bear River	4	7	5	5	11	**12**	6	4	8
Merced River	6	10	5	3	9	**11**	6	3	5
San Joaquin River	6	9	3	3	10	**11**	6	3	5

Table 5. Highest drought intensity by projection model for each streamflow station (MAF/year). Each of the values represent the highest drought intensity out of all projected droughts under each climate scenario or historical records. Red highlighting indicates droughts with a higher intensity than historical. Blue highlighting indicates droughts with a lower intensity than historical. Bold values are the highest projected intensity for each station. (Note: 1 MAF = 1233 million cubic meters).

Station	Historical	Warm Dry RCP 4.5	Average RCP 4.5	Cool Wet RCP 4.5	Other RCP 4.5	Warm Dry RCP 8.5	Average RCP 8.5	Cool Wet RCP 8.5	Other RCP 8.5
Sacramento River	7	**7**	5	4	6	6	5	4	6
Feather River	18	**15**	14	12	12	**15**	13	12	13
Yuba River	10	7	6	7	6	**8**	7	**8**	**8**
Tuolumne River	7	8	6	4	6	7	6	4	6
Stanislaus River	5	**5**	**5**	3	4	4	3	4	4
Mokelumne River	3	2	**3**	2	2	**3**	**3**	**3**	**3**
Calaveras River	1	1	1	1	1	1	1	1	1
American River	12	**11**	10	8	8	10	8	9	10
Bear River	1	1	1	1	1	1	1	1	1
Merced River	4	**4**	**4**	3	3	3	3	3	3
San Joaquin River	7	**7**	5	4	6	6	5	4	6

4. Discussion

Climate change will likely result in greater precipitation and runoff, but also more years of drought [2], as reflected by the climate models used in this study. The results of this drought analysis indicate that under three of the four climate change model scenarios, there are increased streamflow deficits, greater intensity, and longer duration of droughts with both RCP conditions (4.5 and 8.5). Warm Dry and Other simulations are projected to have larger droughts (2–3 times larger) than the historical record. Recent studies propose that longer droughts may become more prevalent in future years [13], and the study presented here suggests this is most likely to occur under the Warm Dry or Other RCP 4.5 or 8.5 scenarios. A limitation in this analysis is the aggregation of the streamflow into a water year value which does not allow for the analysis of changes in seasonality of flows as was show might lead to higher winter flows and lower summer values [4]. This was also shown in monthly drought analyses at Shasta Dam [5]. Regardless, from a water supply and planning perspective, the analyses presented here allows for enhanced planning of drought scenarios. Based on this analysis of the eight projection models, future scenarios may be used for improved water management, including drought impacts on groundwater usage and flood potential.

5. Conclusions

It is commonly understood that with climate change, climate related events will become more extreme. Californians will need to adapt appropriately if this happens. In times of prolonged drought, the western United States tends to use groundwater reserves to fulfill water needs [14]. If drought deficit, duration, and intensity increase as the Warm Dry and Other models project, groundwater may become a more prevalent water source, resulting in potentially negative consequences. As groundwater is consumed, the level drops and wells must be dug deeper, consequently raising the cost of groundwater access [15]. Socio-economic issues, due to unequal groundwater access and the associated costs needed to dig deeper wells and purify lower quality water frequently found deeper in aquifers [14]. Aside from economic effects, seawater intrusion, wetland devastation, land surface abatement, spring bereavement [15], regional climate feedback-loops, and other unintended consequences [14] may occur. Appropriate investments in infrastructure may be needed to mitigate changes in future water availability. Analyses conducted in this paper intend to help California resource managers understand the implication of the projected climate models on future California river streamflow, allowing policy for preparation of the worst-case scenarios.

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Conflicts of Interest: The authors declare no conflict of interest.

List of Acronyms

CanESM2 CCCma	climate model from the Canadian Centre for Climate Modelling and Analysis, Victoria, BC, Canada
CMIP	Coupled Model Intercomparison Project
CNRM-CM5 CNRM	climate model from the Centre National de Recherches Meteorologiques, Meteo-France
GCM	generalized circulation model
HadGEM2-ES	climate model from the Met Office Hadley Centre
LOCA	localized constructed analogues
MAF	million-acre-ft
MCM	million cubic meters
MIROC5 JAMSTEC	climate model from the Japan Agency for Marine-Earth Science and Technology
RCP	representative concentration pathway
VIC	variable infiltration model

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