Salinity Controls in the San Francisco Bay and Delta under Future Climate Scenarios

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Abstract

As water demands continue to increase in California, droughts continue to threaten California's water supply. Water resource managers are challenged with meeting demands and sustaining important ecosystems and land use functions. Compounds hazards of drought and sea level rise could jeopardize our ability to meet water supply demands while maintaining a healthy ecosystem in the future. This analysis examines changes in salinity within the San Francisco Bay and Delta to understand the interrelationships between the salinity (X2), water levels, and outflows in Sacramento and San Joaquin Rivers. This is the first phase of research is to develop water resource management measures to plan for salinity changes in future uncertain climate conditions. The focus of this paper is to examine how X2 position responses to delta river outflows and tidal water levels and explores indicators to extreme conditions such as the relationship of X2 position to reservoir storage volumes. The results will provide an understanding of how X2 responds under various conditions to inform the next phase of research that will simulate X2 future climate conditions.

Key words: salinity control, drought, compound hazard, water resource management, planning under uncertainty

Introduction

Climate change poses a major threat to the sustainability of water systems. To better understand this threat, planners require future climate scenarios that are used to test the robustness of their system to different components of climate change. However, how these scenarios can be generated in an internally consistent and computationally efficient manner for risk-based water system studies remains an open question [1]. In the context of climate change, an increase in global temperatures is projected that will impact evapotranspiration and specific humidity of the air, affecting the ability of the atmosphere to store water, with direct effects on the magnitude, frequency, intensity and spatio-temporal distribution of precipitation. As a consequence, the frequency and severity of extreme events such as droughts and floods would increase, being droughts the slowest to develop, but the longest to last [2]. Climate change is expected to intensify the existing pressure on water availability and will affect agricultural systems particularly in semi-arid environments [3]. Coastal infrastructure planners at the federal and regional levels face numerous challenges in translating science into landscape-scale risk management actions. First, there remains significant uncertainty in the estimates and projections of the extreme events they must protect against, worsened by the compounding of riverine and coastal events [4]. This “deep uncertainty”, under which planners cannot identify a probability distribution to describe extreme events, prevents traditional cost-benefit analysis and can result in decision paralysis [5]. Second, the tools of water resource policy have not kept pace with evolving coastal risks due to climate change and human development [6]. While uncertainty is inevitable, infrastructure planners must still arrive at decisions which are often irreversible and contain multi-objective tradeoffs. These challenges demand interdisciplinary approaches and the participation of a diversity of actors and interests in decision-making processes [7]. The result is a coupled social-environmental problem which requires new understanding of the risks of compound coastal hazards as well as the science of decision making to support adaptation.

This paper will analyze changes in salinity within the San Francisco Bay and Delta to assess the ability for water resource managers to control salinity under extreme weather scenarios in the future.

Freshwater inflows have a direct influence on the salinity structure in estuaries. In the San Francisco Bay, the salinity structure has been related to the health of estuarine species in the Suisun Bay and the western Delta (Fig.1). In particular, the location or position of two parts per thousand (ppt) bottom salinity—hereafter referred to as X2—has been correlated with the abundance of several species [8, 9]. Figure 1 presents the X2 distance throughout the Bay and Delta.

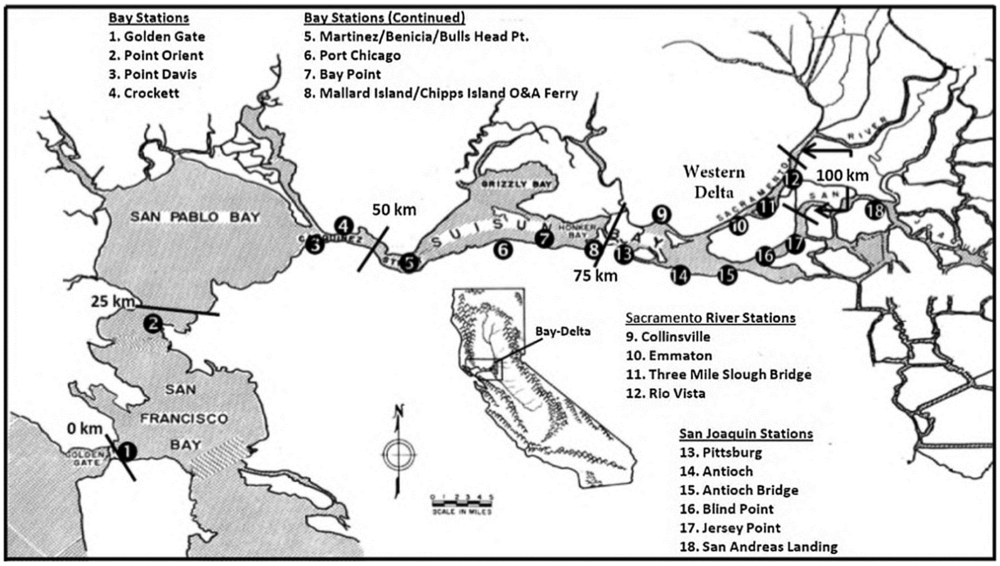


Figure 1: Locations of the X2 positions throughout the San Francisco Bay and Delta [8]

Objective

The primary objective of this overall research is to advance the science and practice of watershed and estuarian planning under uncertainty by (1) understanding the vulnerabilities to salinity changes for estuaries and bays to uncertain projected changes in future climate scenarios, and (2) and designing decision support processes to support adaptation over time as potential changes in extreme events are observed.

Research Questions: Q1) How will projected changes to salinity affect San Francisco Bay-Delta system, with associated uncertainty? Q2) Can significant increases to these risks be detected outside the range of natural variability over the next several decades? Q3) How can these scientific findings support decision making to develop dynamic water resource planning in response to evolving climate uncertainty?

For this paper, I will initiate the first phase of this study. My goal for this first phase is to synthesize observed X2 timeseries data in comparison to storage capacity for three major dams that influence the Delta outflows. I will analyze the interrelationships of X2, outflows from Sacramento and San Joaquin Rivers, water levels observed at the Golden Gate tide gauge, and storage capacities for the dams to determine the joint probability of changes in storage capacity to X2 positions. Analyzing these relationships will help assess our ability to control the X2 position under extreme future scenario conditions.

Hypothesis

I hypothesize that under drought conditions the X2 will increase (move further up into the Sacramento and San Joaquin Rivers) beyond the set control ranges regulated by EPA and California State Water Control Board. The inability to implement control measures in order to maintain the X2 position for suitable habitat for endangered species and water supply will worsen under future climate scenarios as we experience an increase in the frequency and intensity of prolonged drought conditions. This result will impact land use around the Bay Delta.

Data Sources

Data was collected for the following parameters.

- Outflows for the Sacramento and San Joaquin Rivers from California Data Exchange Center (CDEC) [10].
- X2 position time series data from CDEC [10].
- Shasta, Oroville, and Don Pedro Reservoirs monthly volumes from CDEC [10].
- Drought conditions for the X2 time series from the National Integrated Drought Information System [11].
- Water levels from Golden Gate Tide Gauge University of Hawaii, Sea Level Center [12].

Methods and Assumption

The method for this analysis was conducted using the following steps:

1. Collect existing data on the following parameters:

- Outflows for the Sacramento and San Joaquin Rivers
- X2 position time series data
- Water levels from Golden Gate Tide Gauge
- Shasta, Oroville, and Don Pedro Reservoirs monthly volumes
- Drought conditions for the X2 time series

2. Clean the data

- The tide gauge data was missing several hours of measurements in 2000 and 2012. I made the assumption that the water levels would be similar to the previous recorded hour of recorded data. I filled the missing data with the previously recorded hour to fill the missing data.

3. Find the mean X2 position from the daily time series data

- I found the mean from the daily X2 positions to determine a monthly mean in order to compare X2 data to the monthly reservoir storage data.

4. Calculated the X2 positions between 10km increments.

5. Calculated the frequency that storage capacity fell within the following incremental percentages of 0-25%, 25-40%, 40-60%, 60-75%, 75-85%, 85-90%, 90%-full capacity.

6. Calculated the frequency that X2 fell within the incremental percentages in each of the storage volume percentages.

7. Calculated the joint probability that X2 would occur within each of the incremental reservoir storage volumes. Then charted the joint probability for each reservoir

9. Created graphs of the data to compare the following:

- X2 position time series data vs. water levels from Golden Gate Tide Gauge
- Drought conditions for the X2 time series
- Outflows for the Sacramento and San Joaquin Rivers overlaid with X2 and water levels to understand the relationships between each of the parameters.

Calculation/Results

I calculated the frequency of X2 positions throughout the time series of 1997-2020. I then calculated the frequency of X2 positions (increments of 10km) that occurred at each of the increments of storage volumes, 0-25%, 25-40%, 40-60%, 60-75%, 75-85%, 85-90%, 90%-full capacity. I then calculated the probability that the X2 position would fall within each increment of storage volumes. The results are shown in *Table 1-3. Table 1* shows the results for Shasta reservoir, *Table 2* shows the results for Oroville reservoir, and *Table 3* for Don Pedro reservoir.

Table 1: Shasta Dam Storage Volumes and Frequency of X2 positions.

Capacity **1997-2021**

Shasta Dam = 4,552,000

X2 (Freq)

Volume	**Storage**	**Frequency**		**40-49**	**50-59**	**60-69**	**70-79**	**80-89**
0-1,138,000	Below 25% Capacity	**2**	**0.01**	0	0	0	0	2
1,138,001-1,816,248	25-40% capacity	**26**	**0.09**	0	0	0	0	26
1,816,249-2,731,200	40-60% Capacity	**56**	**0.20**	0	0	0	15	41
2,731,201-3,414,000	60-75% Capacity	**81**	**0.29**	0	0	6	45	30
3,414,001-3869,200	75-85% Capacity	**61**	**0.21**	2	7	18	32	2
3,869,201-4,096,800	85-90% Capacity	**22**	**0.08**	2	5	9	6	0
4,096,801-4,552,000	90%-Full Capacity	**36**	**0.13**	4	12	14	6	0

	X2 (Cond. Prob)				
	40-49	**50-59**	**60-69**	**70-79**	**80-89**
2	0.00	0.00	0.0000	0.00	1.00
26	0.00	0.00	0.00	0.00	1.00
56	0.00	0.00	0.00	0.27	0.73
81	0.00	0.00	0.07	0.56	0.37
61	0.03	0.11	0.30	0.52	0.03
22	0.09	0.23	0.41	0.27	0.00
36	0.11	0.33	0.39	0.17	0.00

X2 (joint Prob)

40-49	**50-59**	**60-69**	**70-79**	**80-89**
0.0000%	0.0000%	0.0000%	0.0000%	0.7042%
0.0000%	0.0000%	0.0000%	0.0000%	9.1549%
0.0000%	0.0000%	0.0000%	5.2817%	14.4366%
0.0000%	0.0000%	2.1127%	15.8451%	10.5634%
0.7042%	2.4648%	6.3380%	11.2676%	0.7042%
0.7042%	1.7606%	3.1690%	2.1127%	0.0000%
1.4085%	4.2254%	4.9296%	2.1127%	0.0000%

Table 2: Oroville Dam Storage Volumes and Frequency of X2 positions

Capacity
Oroville Dam = 3,500,000

1997-2021

				X2 (Freq)				
Volume	**Storage**	**Frequency**		**40-49**	**50-59**	**60-69**	**70-79**	**80-89**
0-875,000	Below 25% Capacity	**0**	**0.00**	0	0	0	0	0
875,001-1,400,000	25-40% capacity	**45**	**0.16**	0	0	0	6	39
1,400,001-2,100,000	40-60% Capacity	**83**	**0.29**	0	0	4	35	44
2,100,001-2,625,000	60-75% Capacity	**56**	**0.20**	2	2	9	32	11
2,625,001-2,975,000	75-85% Capacity	**51**	**0.18**	3	5	15	23	5
2,975,001-3,150,000	85-90% Capacity	**20**	**0.07**	1	5	7	7	0
3,150,001-3,500,000	90%-Full Capacity	**26**	**0.09**	2	10	12	2	0

X2 (Cond. Prob)					
	40-49	**50-59**	**60-69**	**70-79**	**80-89**
0	0.00	0.00	0.00	0.00	0.00
45	0.00	0.00	0.00	0.13	0.87
83	0.00	0.00	0.05	0.42	0.53
56	0.04	0.04	0.16	0.57	0.20
51	0.06	0.10	0.29	0.45	0.10
20	0.05	0.25	0.35	0.35	0.00
26	0.08	0.38	0.46	0.08	0.00

X2 (joint Prob)

40-49	**50-59**	**60-69**	**70-79**	**80-89**
0.0000%	0.0000%	0.0000%	0.0000%	0.0000%
0.0000%	0.0000%	0.0000%	2.1127%	13.7324%
0.0000%	0.0000%	1.4085%	12.3239%	15.4930%
0.7042%	0.7042%	3.1690%	11.2676%	3.8732%
1.0563%	1.7606%	5.2817%	8.0986%	1.7606%
0.3521%	1.7606%	2.4648%	2.4648%	0.0000%
0.7042%	3.5211%	4.2254%	0.7042%	0.0000%

Table 3: Don Pedro Dam Storage Volumes and Frequency of X2 positions

Capacity
Don Pedro = 2,030,000

1997-2021

				X2(Freq)				
Volume	Storage	Frequency		**40-49**	**50-59**	**60-69**	**70-79**	**80-89**
0-507,500	Below 25% Capacity	**0**	**0**	0	0	0	0	0
507,051-812,000	25-40% capacity	**11**	**0.04**	0	0	0	0	11
812,001-1,218,000	40-60% Capacity	**33**	**0.12**	0	0	0	7	26
1,218,001-1,522,500	60-75% Capacity	**72**	**0.25**	0	0	9	23	40
1,522,501-1,725,500	75-85% Capacity	**117**	**0.41**	4	11	20	58	24
1,725,501-1,827,000	85-90% Capacity	**20**	**0.07**	2	1	5	12	0
1,827,001-2,030,000	90%-Full Capacity	**31**	**0.11**	2	12	13	4	0

X2 (Cond. Prob)					
	40-49	**50-59**	**60-69**	**70-79**	**80-89**
0	0.00	0.00	0.00	0.00	0.00
11	0.00	0.00	0.00	0.00	1.00
33	0.00	0.00	0.00	0.21	0.79
72	0.00	0.00	0.13	0.32	0.56
117	0.03	0.09	0.17	0.50	0.21
20	0.10	0.05	0.25	0.60	0.00
31	0.06	0.39	0.42	0.13	0.00

X2 (joint Prob)

40-49	**50-59**	**60-69**	**70-79**	**80-89**
0.0000%	0.0000%	0.0000%	0.0000%	0.0000%
0.0000%	0.0000%	0.0000%	0.0000%	3.8732%
0.0000%	0.0000%	0.0000%	2.4648%	9.1549%
0.0000%	0.0000%	3.1690%	8.0986%	14.0845%
1.4085%	3.8732%	7.0423%	20.4225%	8.4507%
0.7042%	0.3521%	1.7606%	4.2254%	0.0000%
0.7042%	4.2254%	4.5775%	1.4085%	0.0000%

The results show that when the storage volumes fall below 40% capacity within each of the three largest reservoirs the X2 position remains above 80km. When storage volumes are between 40-60% reservoir capacity more than half of the time the X2 position was above 80km.

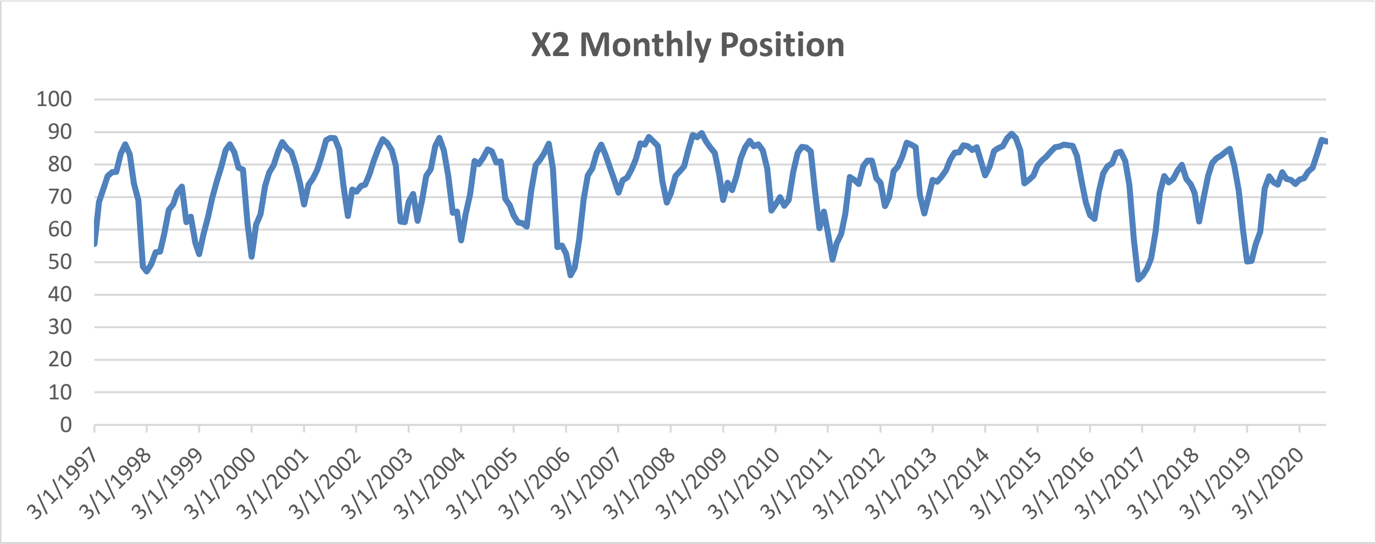
At 60-75% of the storage capacity we see a shift in the X2 is more often below 80km. The joint probabilities show the likelihood that at the lower storage volumes the X2 position will remain above 80. Equally important are the joint probability of 0%, where there is a highly likelihood of not reaching those X2 positions at the associated storage volumes. This is an indication of the limitations to manage X2 while managing water supply and ecosystems in dry conditions.

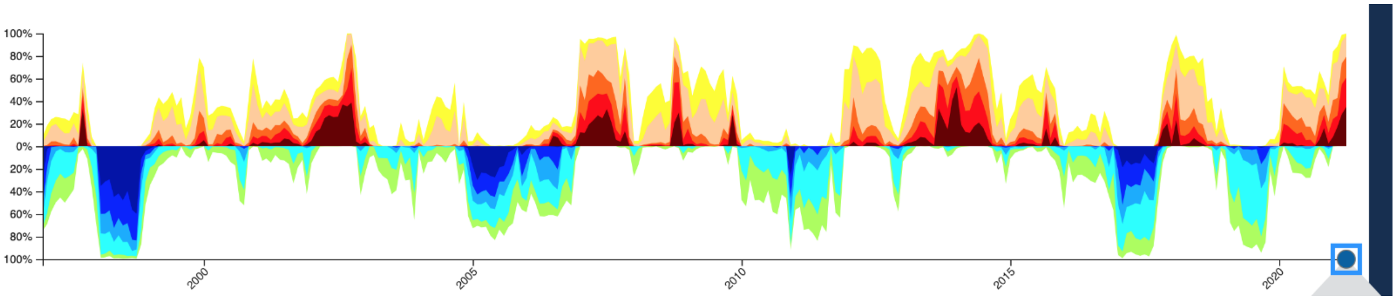
To better understand how drought years relates to X2 position, I reviewed historic drought periods in see if there is a correlation to the drought years with the periods where X2 remained consistently higher. The droughts in California since 1841 are summarized in *Table 4* [11].

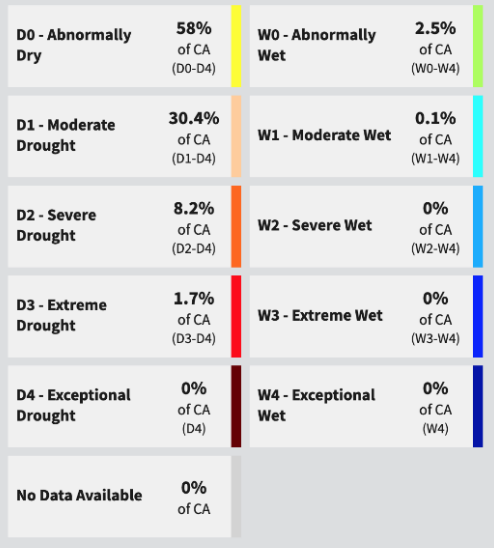
Table 4: Drought years in California

Drought Years in California	Durations (years)
1841	1
1864	1
1924	1
1928-1935	7
1947-1950	3
1959-1960	2
1976-1977	2
1986-1992	6
2006-2010	4
2011-2017	6
2018	1
2020-Present	2

The next step was to compare X2 position to the seasonal climate types for the San Francisco Bay Delta region. *Figure 2* presents a comparison of the X2 positions juxtaposed to the seasonal weather types. An important observation, the 2006-2010 drought and the 2011-2017 droughts show that the X2 positions remain above 60km and consecutively above 70km for more multiple years during the drought periods.







D0 - Abnormally Dry	**58%** of CA (D0-D4)	🟨	**W0 - Abnormally Wet**	**2.5%** of CA (W0-W4)	🟩
D1 - Moderate Drought	**30.4%** of CA (D1-D4)	🟧	**W1 - Moderate Wet**	**0.1%** of CA (W1-W4)	🟦
D2 - Severe Drought	**8.2%** of CA (D2-D4)	🟧	**W2 - Severe Wet**	**0%** of CA (W2-W4)	🟦
D3 - Extreme Drought	**1.7%** of CA (D3-D4)	🟥	**W3 - Extreme Wet**	**0%** of CA (W3-W4)	🟦
D4 - Exceptional Drought	**0%** of CA (D4)	🟫	**W4 - Exceptional Wet**	**0%** of CA (W4)	🟦
No Data Available	**0%** of CA				

*[11]

Figure 2: X2 positions compared to seasonal weather types

Figures 3 highlights the relationships between X2 and water levels to observe the influence of water levels on X2. *Figure 4* highlights the relationships between X2, water levels, and outflows to understand influence of outflow and water levels on X2. The results show a direct correlation between outflows and X2 positions. *Figure 4* demonstrates that outflows are a primary factor in control X2.

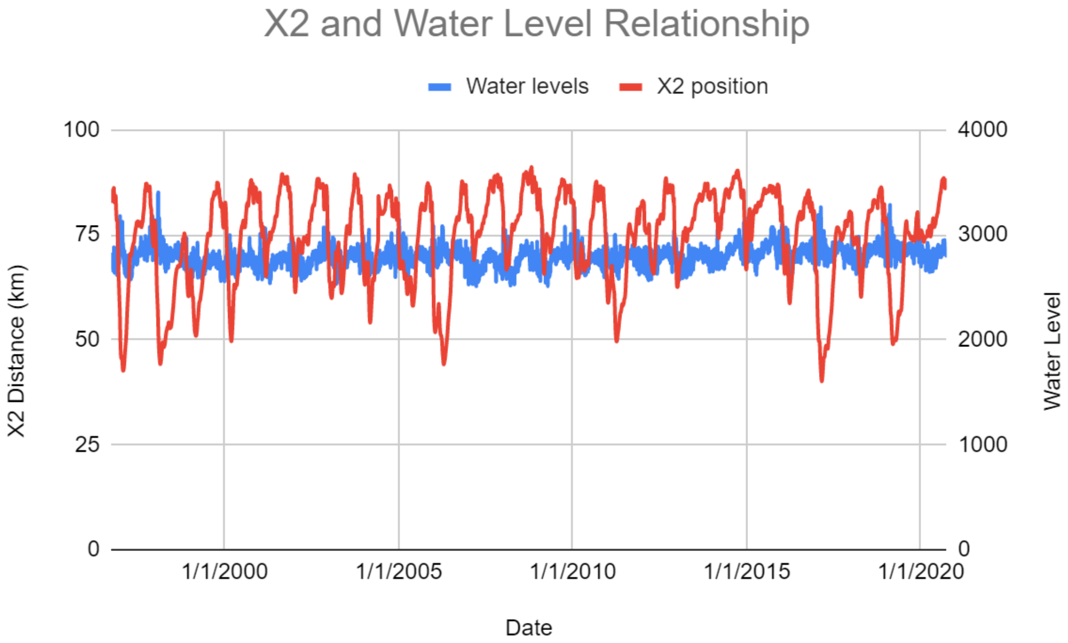


Figure 3: Relationship of X2 and water levels

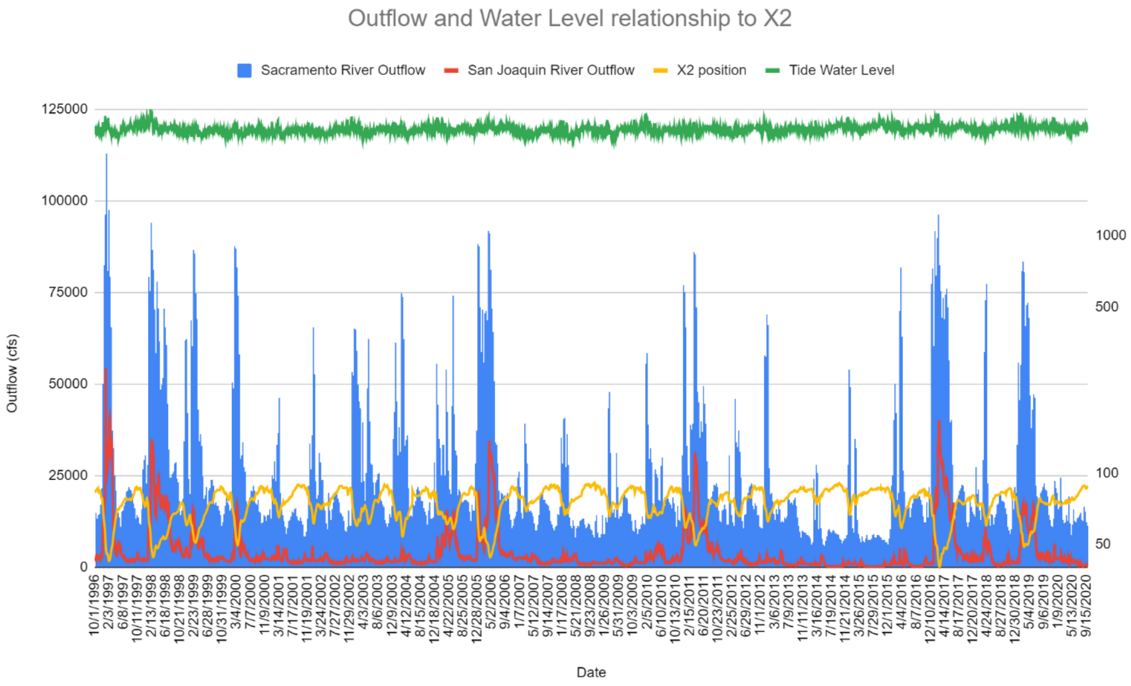


Figure 4: Interrelationships of Outflows, X2, and Water Levels

Conclusions

This analysis confirmed my hypothesis, in dry to critically dry years as experienced under prolonged drought conditions, the X2 position remained around 80km or above for sustained periods of the drought. The results show that over the last 30 years when reservoir volumes dropped below 60% capacity water resource managers are challenged to maintained X2 below 80km. As we are seeing in the start of the current drought in 2020-2021 as extreme heat increases the rate of evapotranspiration from the system and further reduces reservoir volumes, the ability to control X2 becoming increasing more difficult. This can have a cascade of effects on the system. The position of X2 to maintain low salinity in the San Francisco Bay Delta is used for water management in a system that supplies water to more than 20 million people and contains one of the most diverse ecosystems on the Pacific coast [8]. The increase in salinity in the Delta can impact this diverse ecosystem, for example suitable habitat for Delta Smelt and Longfin Smelt. Water supply and land use are impacted as salinity changes can cause saltwater intrusion on the surrounding groundwater and aquifers, ultimately affecting land use functions as well as economic impacts for large agricultural industry in this region dependent on water supply from this system. Water resource managers are forced into tough decisions around how much water to conserve for water supply through the uncertainty of the duration of a drought while also balancing the releases to support suitable habitat for the ecosystem dependent on the X2 position. Given the importance of salinity control for the San Francisco Bay-Delta it is critical for water resource managers to have a better understanding of what impacts could result under uncertainty to future climate scenarios in order to better plan and adapt as future climate conditions that challenge the system.

Recommendations and Limitations

For the first phase of this research the data was limited to the last 30 years. The next phase will begin to search historic flow records for the Sacramento and San Joaquin Rivers and water levels at the golden gate for a longer period of analysis to develop a better understanding of changes in the system over hundreds of years. The next step will simulate X2 based on historic timeseries data and paleo records. The paleo data and simulations will provide a basis for future climate scenarios. I will use projected future climate scenarios to model salinity changes under sea level rise coupled with hydrologic simulations of Sacramento and San Joaquin outflows to observe our ability to control X2 under future projected extreme events. Lastly, I will develop policy model to assist planners in operations planning and decision-making to balance water supply management decisions with ecosystems and land use functions.

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