ANALYSIS OF THE TIDAL RANGE IN THE SACRAMENTO SAN JOAQUIN DELTA FROM 1857 TO PRESENT

A Thesis
presented to
the Faculty of California Polytechnic State University,
San Luis Obispo

In Partial Fulfillment
of the Requirements for the Degree
Master of Science in Civil and Environmental Engineering

by
Elena Szlemp
June 2020
COMMITTEE MEMBERSHIP

TITLE: Analysis of the Tidal Range in the Sacramento San Joaquin Delta from 1857 to Present

AUTHOR: Elena Szlemp

DATE SUBMITTED: June 2020

COMMITTEE CHAIR: Stefan Talke, Ph.D., P.E.
Associate Professor of Civil & Environmental Engineering

COMMITTEE MEMBER: Rebekah Oulton, Ph.D., P.E.
Associate Professor of Civil & Environmental Engineering

COMMITTEE MEMBER: Robb Moss, Ph.D., P.E.
Professor of Civil & Environmental Engineering
ABSTRACT

Analysis of the Tidal Range in the Sacramento San Joaquin Delta from 1857 to Present

Elena Szlemp

The Sacramento San Joaquin Delta has been highly altered by human activity since the mid-1800s from mining, agriculture, dredging, and urbanization. Did the resulting modifications to channel width, depth, and length alter tidal range in the Sacramento San Joaquin Delta?

In this study, archival tidal records were evaluated at many stations throughout the San Francisco Bay and Delta, with a focus on records from San Francisco, Rio Vista, Sacramento, and Stockton daily, monthly, and annual tidal ranges. Monthly and seasonally averaged tidal ranges were analyzed to determine seasonal changes. In addition, tidal range was compared to daily Delta discharge to consider the effects of river flow.

Results show that the spatial pattern of tidal amplitude through the San Francisco Bay and Delta system have changed since the mid-nineteenth century and the changes are consistent with human and climate change impacts on the Delta landscape. There is a general 7% increase in mean annual tidal range in San Francisco from 1860 to 2018. In Stockton, mean annual tidal range increased from 0.6 meters to 0.9 meters between 1908 and the 1930s but decreased approximately 9% from the 1930s to 2011. Mean annual tidal range in Sacramento increased from zero to 0.5 meters between 1890 and the late 1930s and then decreased by 50% through the early 2000s to approximately 0.25 meters. Lower tidal ranges in the early 1900s are consistent with the effects of hydraulic mining. Increased tidal ranges in the mid-20th century are consistent with dredging throughout the system. Recent decreases in tidal ranges are consistent with wetland restoration, increased water storage, and further modifications to the geometry and management of the Delta. A peak river flow shift from late spring/early summer to early spring has contributed to increased tidal range between February and June by 0.1 and 0.6 meters in San Francisco and Stockton, respectively. In Sacramento, the least decrease in tidal range between 1939 and the present occurred during spring months, due to the decrease in river discharge during this period.

Tides have recorded the history of environmental change within the highly altered San Francisco Bay and Sacramento San Joaquin system. While not as notable as similarly altered systems, the changes described here were most significant in Sacramento where mean annual tidal range has ranged between zero and 0.5 meters since 1890 and, for any discharge below 1,000 cubic meters per second, mean daily tidal range is higher from 1938 to 1939 than from 1997 to 2018. Change in tidal range implies potential change in tidal velocities, salinity intrusion dynamics, and flood risk within the system, especially in Sacramento.

Keywords: Sacramento Delta, Tidal Range, Human Alteration
ACKNOWLEDGMENTS

I would like to thank my committee chair, Dr. Talke, for his assistance on this project. Having minimal background in the subject, his help has been imperative in my graduate education and the completion of this thesis. I would also like to thank my other committee members, Dr. Oulton and Dr. Moss, in their support with this project and my graduate education.

In addition, I would like to thank Todd Ehret from the National Oceanic and Atmospheric Association for providing important historical water level data. Finally, I want to thank my family and friends for their support during my college, undergraduate and graduate, career.
# TABLE OF CONTENTS

## LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>viii</td>
</tr>
</tbody>
</table>

## LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF FIGURES</td>
<td>ix</td>
</tr>
</tbody>
</table>

## CHAPTER

1. **INTRODUCTION**

   1.1 Background

   1.2 Research Question

2. **LITERATURE REVIEW**

   2.1 Overview

   2.1.1 Tidal Properties

   2.1.2 History

   2.1.3 Expected Tide Changes from Sea-Level Rise and Human Alterations

   2.2 Hydraulic Mining

   2.3 Flooding

   2.4 Diversions

   2.4.1 Impacts to Salinity and Tidal Flow

   2.5 Dams

   2.6 Dredging

   2.6.1 History of Dredging

   2.6.2 San Francisco Channel

   2.6.3 Delta Channels

   2.6.4 Current Dredging Activities

   2.6.5 Potential Tidal Changes from Dredging

   2.7 River Flow

   2.7.1 River Flow Changes in the Delta

   2.8 Sea-Level Rise

   2.8.1 Sea-Level Effects in the Delta

3. **RESEARCH METHODS**

   3.1 Water Level Data

   3.1.1 Collection of Archival Files

   3.1.2 Digitization of Archival Files

   3.1.3 Initial Station Information and Data Analysis

   3.2 Discharge Data

   3.2.1 Historical Discharge Estimations

   3.3 Tidal Theory
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.3.1 Tidal Range Analysis</td>
<td>42</td>
</tr>
<tr>
<td>3.3.2 Simple Tide Amplitude Model</td>
<td>43</td>
</tr>
<tr>
<td>4 RESULTS</td>
<td>48</td>
</tr>
<tr>
<td>4.1 Distance versus Tidal Range</td>
<td>48</td>
</tr>
<tr>
<td>4.2 Differences in Tidal Range Over Time</td>
<td>56</td>
</tr>
<tr>
<td>4.3 Discharge versus Tidal Range</td>
<td>59</td>
</tr>
<tr>
<td>4.4 Seasonal Patterns</td>
<td>64</td>
</tr>
<tr>
<td>5 DISCUSSION/CONCLUSION</td>
<td>69</td>
</tr>
<tr>
<td>5.1 Summary and Evaluation of Results</td>
<td>69</td>
</tr>
<tr>
<td>5.2 Recommendations for Improvement and Further Analysis</td>
<td>70</td>
</tr>
<tr>
<td>REFERENCES</td>
<td>71</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>79</td>
</tr>
<tr>
<td>A. Appendix A</td>
<td>79</td>
</tr>
</tbody>
</table>
# LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Sacramento and Stockton River Widths and Depths through History</td>
<td>18</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>San Francisco Coastal Bays Station Data Information</td>
<td>34</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Sacramento River Station Data Information</td>
<td>35</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>San Joaquin River Station Data Information</td>
<td>36</td>
</tr>
<tr>
<td>Table 4.1</td>
<td>Simple Model Parameters</td>
<td>53</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1 San Francisco Bay and Sacramento Delta Historical Timeline.</td>
<td>2</td>
</tr>
<tr>
<td>Figure 2.1 Illustration of land use changes from early 1800s to early 2000s (modified from Whipple et al., 2012).</td>
<td>5</td>
</tr>
<tr>
<td>Figure 2.2 Some of the modifications to the San Francisco Bay Coastal System (modified from Barnard et al., 2013).</td>
<td>5</td>
</tr>
<tr>
<td>Figure 2.3 Time series of sediment load from the Sacramento and San Joaquin Rivers compared to the Delta modifications and hydraulic mining (modified from Barnard et al., 2013 – modified from Ganju et al., 2008).</td>
<td>7</td>
</tr>
<tr>
<td>Figure 2.4 Levees in the Delta as of 2006 (modified from Lund et al., 2007).</td>
<td>10</td>
</tr>
<tr>
<td>Figure 2.5 Delta Infrastructure (modified from Lund et al., 2007).</td>
<td>12</td>
</tr>
<tr>
<td>Figure 2.6 Five main output locations within the Delta (modified from Fleenor &amp; Bombardelli, 2013).</td>
<td>13</td>
</tr>
<tr>
<td>Figure 2.7 Sacramento River Deep Water Ship Channel (modified from USACE, 2012).</td>
<td>17</td>
</tr>
<tr>
<td>Figure 2.8 Delta map showing: (A) historical tidal marsh area from the 1800s; (B) present shipping channels and water bodies; (C) present water bodies and flooded areas. Modified from Marineau &amp; Wright, 2015.</td>
<td>19</td>
</tr>
<tr>
<td>Figure 2.9 Delta map showing: (A) elevations within the Delta Tidal Prism; (B) average shear velocity to critical shear velocity at various sites; (C) sediment transport to and from the Delta from 1997 to 2010. Modified from Marineau &amp; Wright (2015).</td>
<td>20</td>
</tr>
<tr>
<td>Figure 2.10 Present mean annual cycle of freshwater inflow (left); predicted relative change in inflow by 2060 (right). Modified from Knowles &amp; Cayan (2004).</td>
<td>23</td>
</tr>
<tr>
<td>Figure 2.11 Sacramento versus San Joaquin maximum change (late June) in estuary contribution by 2060 (modified from Knowles &amp; Cayan, 2004).</td>
<td>25</td>
</tr>
<tr>
<td>Figure 2.12 State Water Project and Central Valley Project in California and the Delta (modified from Wang et al., 2011).</td>
<td>26</td>
</tr>
<tr>
<td>Figure 2.13 Evolution of Delta islands due to levee construction and island subsidence (modified from Mount &amp; Twiss, 2005).</td>
<td>28</td>
</tr>
<tr>
<td>Figure 3.1 Historical tide data recovery for California (modified from Talke &amp; Jay, 2017).</td>
<td>31</td>
</tr>
<tr>
<td>Figure 3.2 Archival daily high low data from Sacramento in August 1929.</td>
<td>32</td>
</tr>
<tr>
<td>Figure 3.3 Digitized data for the month of January for hourly Sacramento data from 1938 (Top). January 1938 Sacramento data with one value changed to a significantly different number (Bottom).</td>
<td>33</td>
</tr>
<tr>
<td>Figure 3.4 Datum shift for Antioch in October 2006 from NGVD29 to NAVD88.</td>
<td>38</td>
</tr>
</tbody>
</table>
Figure 3.5 Uncharacteristic tidal data of present Stockton data after 2011 (for further analyses, data after 2011 was removed)................................................................. 38
Figure 3.6 Delta discharge levels through history................................................................. 40
Figure 3.7 Average tidal datums for San Francisco between 1983 and 2001 relative to NAVD88 (NOAA)............................................................................................. 42
Figure 3.8 Distance versus width in kilometers for the Sacramento River system from approximately Port Chicago (65 km) to Sacramento (180 km)................................. 46
Figure 3.9 Lengths over which convergence e-folding scale calculation was considered. Red lines are the locations where the channel width was measured. Sacramento River Deep Water Ship Channel (SRDWSC) traced in blue, Steamboat Slough traced in green, and the Old River traced in purple........................................................................ 47
Figure 4.1 Distance from the coast versus average tidal range from 1997 to 2018 with Sacramento and San Joaquin rivers distinguished by color. The stations correspond to the following river kilometer readings: Golden Gate = 0 km, Mare Island = 45 km, Antioch = 85 km, Rio Vista = 100 km, Stockton = 145 km, and Sacramento = 180 km......................................................... 49
Figure 4.2 Map of average tidal range from 1997-2018 along the San Francisco Bay and Sacramento-San Joaquin Delta................................................................. 50
Figure 4.3 Distance from the coast versus tidal range for the San Joaquin River comparing 1870 to 1910 data and 1997 to 2018 data. The stations correspond to the following river kilometer readings: Golden Gate = 0 km, Mare Island = 45 km, Antioch = 85 km, and Stockton = 145 km.................................................................................. 52
Figure 4.4 Distance from the coast versus measured and modeled tidal range for the Sacramento River comparing 1870 to 1910 data and 1997 to 2018 data. The stations correspond to the following river kilometer readings: Golden Gate = 0 km, Mare Island = 45 km, Rio Vista = 100 km, and Sacramento = 180 km. ......................................................... 54
Figure 4.5 Map of average tidal range from 1870 to 1910 along the San Francisco Bay and Sacramento-San Joaquin Delta................................................................. 55
Figure 4.6 San Francisco, Rio Vista, Sacramento, and Stockton annual tidal range time-series with an 18.6-year sinusoidal fit that includes a linear trend. All records with 6 months of data or more are included as an annual average. The 20 year period in which the San Francisco gauge was in Sausalito (1877-1897) is excluded from the San Francisco fit. ........................................................................................................ 57
Figure 4.7 San Francisco, Rio Vista, Sacramento, and Stockton annual versus low flow tidal range time-series. All records with 6 months of data or more are included as an annual and low flow average except for Sacramento 1857 low flow which is a couple weeks in November................................................................. 58
Figure 4.8 Discharge versus tidal range for San Francisco comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25th percentile, and 75th percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue........................................................................................................ 60
Figure 4.9 Discharge versus tidal range for Mare Island comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25\textsuperscript{th} percentile, and 75\textsuperscript{th} percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue................................................................. 61

Figure 4.10 Discharge versus tidal range for Rio Vista comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25\textsuperscript{th} percentile, and 75\textsuperscript{th} percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue................................................................. 62

Figure 4.11 Discharge versus tidal range for Stockton comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25\textsuperscript{th} percentile, and 75\textsuperscript{th} percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue................................................................. 63

Figure 4.12 Discharge versus tidal range for Sacramento comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25\textsuperscript{th} percentile, and 75\textsuperscript{th} percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue................................................................. 64

Figure 4.13 Tidal range and discharge seasonal patterns for San Francisco comparing historical values to present: (a) monthly mean tidal range for 1898-1918, 1918-1938, and 1997-2018; (b) difference in monthly mean tidal range from 1997-2018 to 1898-1918; (c) NDOI for 1898-1918, 1918-1938, and 1997-2018; (d) difference in NDOI from 1997-2018 to 1898-1918............................. 65

Figure 4.14 Tidal range and discharge seasonal patterns for Sacramento comparing historical values to present: (a) monthly mean tidal range for 1938-1939 and 1997-2018; (b) difference in monthly mean tidal range from 1997-2018 to 1938-1939; (c) NDOI for 1938-1939 and 1997-2018; (d) difference in NDOI from 1997-2018 to 1938-1939. ................................................................. 66

Figure 4.15 Tidal range and discharge seasonal patterns for Stockton comparing historical values to present: (a) monthly mean tidal range for 1908, 1933-1954, 1979-1982, and 1997-2018; (b) difference in monthly mean tidal range from 1933-1954 to 1908; (c) NDOI for 1908, 1933-1954, 1979-1982, and 1997-2018; (d) difference in NDOI from 1933-1954 to 1908. ................................................................. 68
1 INTRODUCTION

1.1 Background

The San Francisco Bay (Bay) estuary and tidal river, which extends from the Golden Gate to the Sacramento-San Joaquin Delta (Delta), has been severely altered by humans since the mid-1800s. Though white settlement began in the early 1840s, the gold rush which began in 1849 brought large amounts of people to the Delta (Wells, 1882). Gold was extracted from the foothills of the Sierra-Nevada through hydraulic mining and the process introduced large amounts of sediment to the Delta system (Gilbert, 1917). Humans also altered the Delta region to enhance farming, improve commerce, and prevent flooding (Thompson, 1960). A total of 97 percent, or 437,830 acres, of wetlands were reclaimed as land for farming and residential settlement (Whipple et al., 2012). According to the California Department of Water Resources (DWR) Delta Conveyance and Flood Protection webpage (https://water.ca.gov/Programs/Flood-Management/Delta-Conveyance-And-Flood-Protection), landscape manipulation for flood control continues through this day.

Agriculture in the Delta and water demand in Southern California initiated water storage and the construction of dams and reservoirs. As shown in Figure 1.1, between 1928 and 1967 dams were implemented to control river flow in the Delta system (Singer, 2007). There is a combined storage of over 100 million m$^3$ in the seven largest dams of the Sacramento San Joaquin watershed. However, three out of seven have runoffs exceeding storage capacity making them at risk of failure during large floods (Singer, 2007).

Sedimentation effects from hydraulic mining were first seen around the 1870s and peaked around 1895 (Moftakhari et al., 2015). To deepen the shallowed channels from the hydraulic mining deposits and increase shipping navigation, dredging in the Delta began in the late 1910s. From the 1910s to the 1980s, the channels have been dredged to deepen them for larger cargo ships. Figure 1.1 identifies dredging events in Stockton, Sacramento, and San Francisco channels. Since 1850, there has been a combined total of 31 feet and 23 feet dredged in the Stockton and Sacramento shipping channels, respectively (Lund et al., 2007; US Army Engineer District, 1971). In addition to dredging and damming activities, Figure 1.1 shows a timeline of mining, diversion, and flood system human influences on the Delta.
Hydraulic mining sediment introduction and transport, flood control and diversion system implementation, dam and water storage formation, and dredging have all contributed to a change in river bathymetry (Barnard et al., 2013). These changes in bathymetry have the potential to drastically influence tidal transport in the river system. A study done on the Hudson River and New York Harbor, which had similar human alterations as the Delta, showed the tidal amplitude doubled near the head of tides as a result of channel depth more than doubling since the late 1800s (Ralston et al., 2019). If the San Francisco Bay estuary and tidal river system follows the same trends, an increased tidal range could put the infrastructure and agriculture in the area at risk from floods.

1.2 Research Question

Have modifications to channel width and depth in addition to river flow regulation changed tidal range in the Sacramento San Joaquin Delta? This study uses tidal and water level records from the mid-19th century to the present to characterize long term changes to tidal statistics and mean water level caused by hydraulic mining debris (19th and early 20th century).
and changes to width, depth, and other channel infrastructure in the 20th century. Water level data is compared to historical human interventions and historical bathymetry to determine if there is a correlation between changes in river bathymetry, river flow, and tide patterns. Available data includes short-term records from the late 19th and early 20th century, along with high resolution water levels from 1929-1954, the 1980s, and 2010-2011 in Stockton, and from the 1920s, 1930s, and 1984-present in Sacramento. Present-day data (late 20th century and early 21st century) was compiled from the National Oceanic and Atmospheric Administration (NOAA) and the California Department of Water Resources (DWR). Historical data (late 19th century and early 20th century) was digitized from a collection of archival data compiled by Talke & Jay (2017). Tidal datums such as mean low water, mean high water, mean water level, monthly averages, annual averages, annual extremes, and tidal ranges are analyzed in this study.
2 LITERATURE REVIEW

2.1 Overview

The San Francisco Bay estuary and the Sacramento-San Joaquin Delta have a total surface area of about 4,100 kilometers squared with a total watershed area of about 162,000 kilometers squared. The San Francisco Bay receives about 8 billion cubic meters per day of tidal flow through the Golden Gate strait (Barnard et al., 2013). The San Francisco Bay is the second largest estuary in the US and the largest estuary on the western coast of the US. The system has over seven million people inhabiting the surrounding area (Barnard et al., 2013).

2.1.1 Tidal Properties

The San Francisco Bay is split into the North Bay and South Bay. The northern channel is a long, progressive wave channel and the southern channel is a convergent and reflective lagoon-style estuary. The northern bays, San Pablo Bay and Suisun Bay, receive an average of 786 m$^3$/s (Marineau & Wright, 2015) from the Sacramento and San Joaquin Rivers. The South Bay has little freshwater inflow from small tributaries (Hollemann & Stacey, 2014). The North and South Bays have similar depths, where the northern bays have a channel maintained at 57-foot depth and the South Bay’s main channel has a depth of 40 to 65 feet. Large restoration projects are planned in both reaches of the bay to restore tidal action to wetlands and decrease rising sea-level effects. South San Francisco Bay will likely be more affected by sea-level rise do to its reflective, standing wave system (Hollemann & Stacey, 2014).

2.1.2 History

Mining, channel dredging, dam construction, freshwater diversions, watershed modification, ship traffic, non-native species intrusions, land reclamation, and wetland restoration are among the human induced activities conducted along the San Francisco Bay Coastal System (Figure 2.1 & 2.2). These activities result in a change of river bathymetry through sediment influx, relocation, or removal. The changes make the estuary of the San Francisco Bay and hydrologic system of the Delta one of the most human-altered systems in the world (Barnard et al., 2013).
Concurrent with hydraulic mining, the area was influenced by the large floods in January 1862, December 1867, and February 1891. These conditions increased the sediment influx into
the San Francisco Bay. Contrastingly, the implementation of dams in the mid 1900s reduced sediment inflow by holding back the sediment and reducing peak flows. Despite the decrease in sediment influx to the San Francisco Bay, significant amounts of hydraulic mining sediment have been found in the Bay floor. In 1990, sediment cores were found with as much as 43% of hydraulic mining sediment. Mercury contamination from the debris still poses a concern in the Bay today (Barnard et al., 2013).

Another source of sediment influx to the Bay is urbanization activities including construction and other activities. These activities can produce sediment influxes two magnitudes higher than stable urban areas (Barnard et al., 2013). Drastic waterfront construction and development in the Bay have decreased since the mid to late 20th century. This decrease and the reduction of hydraulic mining sediment have depleted the erodible sediment pool in the Bay (Schoellhamer, 2011).

Removal of sediment has also changed the bathymetry of the San Francisco Bay. At least 200 million meters cubed of sediment has been removed from the system over the past 100 years. This removal is a result of dredging, aggregate mining, and borrow pit mining. Dredging currently removes about 3 million meters cubed of sediment per year (Barnard et al., 2013).

Net influx of sediment to the Bay has decreased from about 10 megatons per year in the late 1800s to 3 megatons per year in the second half of the 1900s (Ganju et al. 2008). Moftakhari et al. (2015) found similar patterns, but a larger influx rate of around 15 megatons per year in the late 1800s. As Figure 2.3 shows, a decrease in sediment influx occurred during the time of Delta modifications following the high loading during the period of hydraulic mining. Dam construction starting in the late 1920s prevented the movement of the sediment through the system and the sediment from hydraulic mining had already mostly moved through the system by the late 1900s (Barnard et al., 2013).
Human alterations have greatly impacted the bathymetry of the Delta and it will likely never return to its historical state (Lund et al., 2007).

2.1.3 Expected Tide Changes from Sea-Level Rise and Human Alterations

A guide for what may happen to tides in the Delta can be found by analyzing similar regions around the world that have been heavily altered. Gaining an understanding of the altered tides is important for the future (Talke & Jay, 2020), as low-elevation coastal zones are highly populated and predicted to exceed 1 billion people by 2060 (Neumann et al., 2015).

Rising sea-level is increasing the chances of flooding worldwide because sea-level rise changes the depth and width of rivers and water depth has a strong effect on tides within rivers. Shallow rivers will be most affected by the change in depth from sea-level rise. By 2100, there is an expected sea-level rise of 0.3 to 1.3 meters (Sweet et al., 2017). However, often consistent with tidal property changes (Devlin et al., 2014), some areas have daily, monthly, and yearly variations in sea-level outside of general sea-level trends (Zhang & Church, 2012).

Human changes to the environment have also changed depth and underwater landscape of deltas and estuaries. Some estuaries have historically silted up with sediment loads as a result of agricultural, mining, or industrial practices. Recently, there has been a decrease in sediment

Figure 2.3 Time series of sediment load from the Sacramento and San Joaquin Rivers compared to the Delta modifications and hydraulic mining (modified from Barnard et al., 2013 – modified from Ganju et al., 2008).
supply as a result of the construction of many dams (Schoellhamer, 2011). Tides in estuaries, coastal bays, and deltas can be influenced by the following environmental changes (Talke & Jay, 2020):

- Changes to depth, width, and length from sea-level rise, dredging, and reclamation;
- Changes to mixing dynamics and energy dissipation from altered stratification, bed roughness, or nonlinear interaction with other forcing factors (wind circulation and wind waves);
- Changes to boundary forcing (i.e. coastal tides and river inflow).

Typically, tides have the largest changes further from the coast. Recorded tidal changes often exceed the 1900s sea-level rise of 0.14 to 0.19 m (Church & White, 2011) and the natural variability in tidal range of about +/- 3% over the 18.61-year nodal cycle. Typically, the cumulative effect of changes toward the sea and a reflective boundary are the reason for large changes in tidal rivers. Some studies of tidal records have shown tidal trends can change sign over time, on the order of decadal to century timescales. This is suggested in a study of Sacramento because tides disappeared from the hydraulic mining of the Gold Rush in the late 1800s (Gilbert, 1917) but have returned after dredging within the Delta.

Friction and reflection changes can cause a wide range of tidal responses in shallow systems through sea-level rise and bathymetry changes. Channel straightening, obstacle removal, dredging, and changes to sediment supply reduce friction in the channel. Bridges, piers, and many other engineered structures create the opposite effect by increasing dissipation (Talke & Jay, 2020).

A study of San Francisco Bay showed that sea-level rise increased tides with a consistent shoreline, but tides decreased when flooding was allowed (Holleman & Stacey, 2014). Sea-level rise, in general, increases flood hazard, raising infrastructure requirements and extreme flood risk. Considering this, other factors affect tides in addition to sea-level rise: wetland restoration, engineered structures, and others (Talke & Jay, 2020).
Shallow systems that are highly frictional often have the most tidal variations with the largest changes seen in dredged systems that have significant dredging activities, increasing depths. Sea-level rise may have great effects on the evolution of tides in the future. Based on unintentional results from historical human changes (i.e. dredging), future undesired tide predictions may be decreased or eliminated through careful human intervention. Talke & Jay (2020) state for a better understanding and future management of tidal systems, further analysis of tide dynamics and tidal evolution should be done.

2.2 Hydraulic Mining

The Sacramento San Joaquin Delta bathymetry alterations began with hydraulic mining. In the early 1850’s, California miners developed a process for hydraulic mining when they found gold in channels above the larger canyons of the Delta. The hydraulic mining process used pressurized water to reveal the gold, but also washed the sediment into those canyons below. By the time hydraulic mining was banned in 1884, it had produced over 1.1 billion meters cubed of hydraulic mining sediment (HMS). The HMS deposited in the bottoms of the Sacramento Valley and bays down to the San Francisco Bay. HMS deliveries to the bay were highest around 1880 (Ganju et al., 2008). By 1910, natural erosion sediment likely exceeded HMS deliveries (James, 2017).

The increase in HMS clogged river channels, affecting navigation, flood risk, tidal flux, and bay widths. Towards the end of the 1800s and through the beginning of the 1900s, substantial efforts were made to counteract these affects by improving navigation, decreasing flood risk, and allowing the tides to travel upriver again (James, 2017).

2.3 Flooding

The Sacramento Valley is a structural depression where excess water can gather. This depression, heavy rains, and fairly impermeable, steep slopes in the Coast Ranges, Klamath Mountains, Cascade Range, and Sierra Nevada make the Valley a floodplain. Due to their fertility, many floodplains are reclaimed for settlement and cultivation. Before settling in the Valley, many historical explorers noted mile wide creeks and rivers in the valley during the winter months in the 1830s and 1840s (Thompson, 1960). Here severe flooding occurred even before hydraulic mining activities began, but once it started the flood risk intensified in the Valley channels with hydraulic
mining debris buildup. Any increase in tidal amplitude and water level can increase the risk of flooding, especially in the flood prone area of the Sacramento Valley.

Despite the flood risk, European settlers have settled in the Central Valley since Sutter’s Fort was founded in the early 1840s (Wells, 1882). Now, the metropolitan area of Sacramento, located in the lowland floodplain, has a population of over 2 million. The present-day flow control system conveys high flows out of the Sacramento and Feather Rivers to the Sacramento and San Joaquin Delta and the San Francisco Bay through conveyance floodplains (Figure 2.4). The most hydrologically significant human alteration to the Delta prior to 1880 were levees implemented for flood control (MacVean et al., 2018). The levees prevented the discharge from reaching the floodplain, thus increasing river velocities. Other parts of the flood control system included flood control channels and floodplains implemented between 1930s and 1960s (Singer et al., 2008).

![Figure 2.4 Levees in the Delta as of 2006 (modified from Lund et al., 2007).](image-url)
Due in part to climate change, there is a higher potential of floods of increased magnitude and frequency that can affect this system (Singer et al., 2008). When the flood system was designed, it did not include sediment transport management. Since then, there have been sediment deposits in the flood bypass channels which has affected the functionality of the channels. Flood control authorities have spent time and funds to remove the built-up sediment from near the weirs of the channels and have installed some riprap to prevent further erosion. Deposits outside the vicinity of the weirs have not been studied or removed. If not regularly removed, sediment deposits in the flood control channels can increase flood risk in the Sacramento Valley (Singer et al., 2008).

Some of the sediment deposits contain mercury from the hydraulic mining activities. If a large flood occurs, the sediment could be released to the waters and introduce another influx of mercury into the San Francisco Bay. Certain locations are ecologically important, and new mercury releases can be detrimental to the ecology of the area (Singer et al., 2008).

Flooding can be detrimental to the infrastructure in the area (Figure 2.5) and could cost local government millions of dollars. A 2004 flood event due to levee failure of the Jones Tract cost over $44 million for repair, flood mitigation, emergency services, and island pumping. This estimate did not include costs for crop losses, job losses, or actions done to maintain water quality (Mount & Twiss, 2005). If tidal amplitude increases, these floods could be more likely to occur and very costly.
As a result of the 2004 levee failure, the budget for levee repairs was increased and two bond measures to increase funds for flood control passed in 2006. Beyond this funding, there was no more expansive plan for the Delta flooding issues (Lund et al., 2007).

Studies have shown that based on the timing of the last large flood, the next 100-year flood may occur by 2050 in the San Francisco Bay (Knowles, 2010), creating detrimental effects to the surrounding areas. While written in 1966, the following statement remains true: “The essential characteristic of the Sacramento Valley as a floodplain still remains” (Kelley, 1966).

2.4 Diversions

Diversions were implemented to distribute water to agriculture in the Delta system and throughout the Central Valley. By redistributing water flow, they decrease river flow to the San Francisco Bay and, as a result, may allow the tides to propagate further through the system. This
increases the salinity in the system. These effects are not necessarily observed in tidal measurements but do affect the how the system functions and are important to note.

In the early to mid 1900s, diversions were implemented as infrastructure to export water from the Delta to other nearby areas, the Central Valley, and southern California (Fleenor & Bombardelli, 2013). As of April 1997, there are 424 diversions above the I Street Bridge along the Sacramento River, 298 diversions in the San Joaquin River Basin, 2,209 diversions in the Delta, and 366 diversions in the Suisun Marsh. This is a total of 3,356 diversions, but some sites contained four or more diversions and were counted as one. These sites add 144 diversions if counted individually (Herren & Kawasaki, 2001). Five main output locations are shown in Figure 2.6.

Figure 2.6 Five main output locations within the Delta (modified from Fleenor & Bombardelli, 2013).
2.4.1 Impacts to Salinity and Tidal Flow

Historical records show that the San Joaquin River and nearby waterways would be fresher with less salinity content if unimpaired by diversions (Fleenor & Bombardelli, 2013). In addition, the Sacramento River would be fresher in the spring, but contain more salinity in the fall. Overall, salinity in the Delta has and will continue to increase with increased sea-level (Fleenor & Bombardelli, 2013).

Currently, export and diversion plans largely determine salinity impacts on the Delta. The addition of peripheral conveyance diverting water from the northern Delta channels to the southern Delta increases the salinity pumped through tidal flows propagating farther up the Sacramento River (Fleenor & Bombardelli, 2013). While the deposits of hydraulic mining sediment and reclamation of tidal floodplains decreased salinity in the Delta, upstream diversions result in increased salinity intrusion (Lund et al., 2007).

2.5 Dams

Dams regulate river flow and change seasonal river flow patterns. The magnitude of river flow changes affects the amplitude and propagation of tides in a river system. The change in seasonal river flow patterns caused by dams can, therefore, change seasonal tidal patterns. The effects of river flow on tides is further discussed in Section 2.7.

In the Sacramento-San Joaquin Delta, dams were implemented to control floods, combat the effect of diversions, and control salinity intrusion up the Delta. Upstream agricultural water diversions decreased water flows to the Delta in the summers of the early 1920s. This led to the installation of upstream dams in the 1930s to provide a regulated outflow to prevent saltwater intrusion from the ocean (Madani & Lund, 2012). Water storage for summer months and power generation were additional reasons for the installation of dams (Singer, 2007).

Dams affect ecology, channel morphology, and sediment conveyance. For most areas, dams increase frequency, magnitude, and duration of low flows, but decrease frequency, magnitude, and duration of floods. With increased distance downriver, there are less reductions in flood magnitude and mean monthly flow from the increased drainage area from the dam (Singer, 2007).
The Sierra Nevada, Coast Ranges, Modoc Plateau, and Trinity Mountains make up most of the 68,000 km² drained by the Sacramento River Basin. Seven large dams, with storage adding up to more than 100 million m³, control the area. The purpose of these dams includes combinations of the following: irrigation, flood control, recreation, water supply, and hydroelectricity. The dams were installed between 1940 and 1970 to decrease overall effects of large winter floods and store water from the spring for summer irrigation (Singer, 2007). The storage volume, about 35 kilometers cubed, of the major reservoirs created from the dams is about the capacity of the total annual freshwater releases (Knowles & Cayan, 2004).

For the most part, the large flood control dams only decrease peak flow right below the dam. Hence, the lower Sacramento River peak flows are not well controlled by the dams (Singer, 2007). Peak flows in the lower Sacramento River do not decrease because the dam flow regulation effects dissipate with distance downstream. Singer (2007) found that the least frequent floods are the same size, if not larger, than pre-dam floods. Similar to peak flow, annual flood volume decreases below the dams but further downstream, the dam river flow regulation is less apparent and flood control effects dissipate.

Dams in the lower Sacramento provide little flood control for the lower Sacramento River. Population along the lower Sacramento must rely on the weir and bypass system to prevent flooding, but that was built over 80 years ago and is at great risk of failing (Singer, 2007).

2.6 Dredging

The deepening of channels through dredging can have significant effects on tidal propagation through channels. Deepening a channel decreases the frictional effects of the riverbed felt in the water of the river (Talke & Jay, 2020). This section discusses the dredging history in the San Francisco Bay and Sacramento-San Joaquin Delta and the effects of dredging on tides.

2.6.1 History of Dredging

Estuaries and tidal rivers are often populated places due to their transportation opportunities and access to natural resources. City development has greatly modified their natural environment through dredging, hardening of shorelines, and filling of intertidal and shallow
subtidal waters. Often the ecosystem that inspired development in these areas is harmed by these physical changes (Ralston et al., 2019).

In the US, modifications of navigational channels started in the late nineteenth century and have continued to this day (Ralston et al., 2019). Many of these projects are deepening projects done to accommodate the larger ships made to pass through the Panama Canal. Not only does dredging change the depth of a channel, but it reduces the roughness through removing sand waves and reducing channel sinuosity. With low discharge, the reduction in effective drag from dredging allows further propagation of tides and storm surges (Ralston et al., 2019). With high discharge, the storm surge and tide are damped, and the river slope drives the water level in the upper tidal river. An unintended effect of dredging are potential hazards for navigation from the decrease in mean water level. Sea-level rise will also propagate up the channel more due to the decreased drag (Ralston et al., 2019).

2.6.2 San Francisco Channel

Channel deepening in the San Francisco main channel was, in part, done to prevent or decrease oil spills and costly delays in transportation of the regional petroleum products. Industry alternatives for deepening were “infeasible or unattractive.” Furthermore, the alternatives could have caused environmental problems (US Army Engineer District, 1971).

The natural San Francisco Bar had a natural depth of about 25 to 35 feet but has been deepened throughout the past century. In the late 1900s, the San Francisco deepening project included adding 7 feet of depth to the main shipping channel in the San Francisco Bar and required an excavation of over 8 million cubic yards. The project increased the depth from -50 feet mean lower low water (MLLW) to –57 feet MLLW and started in April of 1971 (US Army Engineer District, 1971).

2.6.3 Delta Channels

In the mid-1800s, the primary shipping channels to Stockton and Sacramento were known as the “Old Channel” and “Steamboat Slough,” respectively. Due to hydraulic mining debris, the primary channel of the Sacramento River switched to the “Old Channel” of the Sacramento River by the late 1870s (House of Representatives, 1891). Major dredging operations began in the early 1900s by the US Army Corps of Engineers. The “Old Channel”
between Suisun Bay and Sacramento was sustained as a 7 feet deep channel until 1927 and was then deepened to 10 feet. Later, a bypass to Sacramento was converted to a deep-water port through Congressional authorization. In 1963, an artificial 30-foot-deep channel between Collinsville (mile 0 in Figure 2.7) and Sacramento was completed (Table 2.1, Figure 2.7). The Old River diverts from this deep-water channel at mile 15 (Figure 2.7). However, the terminus of the deep-water channel in Sacramento is separated from the Sacramento River by a canal lock, now in-operational (https://cdn.ymaws.com/floodplain.org/resource/resmgr/2019_conference/presentations/wednesday/stonelock_fma2019_09.04.19_f.pdf). Therefore, this channel does not directly affect Sacramento tides, though it may increase the tidal prism in the delta somewhat.

![Figure 2.7 Sacramento River Deep Water Ship Channel (modified from USACE, 2012).](image_url)
The channel to Stockton followed a similar chain of events. The Stockton channel was naturally 6 feet deep (California Engineering Department, 1917). At some point in the late 1800s or early 1900s, the primary channel of the San Joaquin River was moved from the Old River branch and became what is now the Stockton Deep Water Ship Channel (House of Representatives, 1944; Figure 2.8). From 1913 to the late 1920s, it was maintained as a 9 feet deep channel. The channel was deepened to 26 feet over a 300-foot width and straightened over a 14 mile stretch during a 5-year project that ended in 1933 (House of Representatives, 1931). The channel was further dredged to 30 feet in 1950 and 37 feet in 1987 (Table 2.1). The changes in channel geometry on both the Sacramento and San Joaquin Rivers also altered the primary length and pathway that a tide wave must travel between Suisun Bay and the cities of Stockton and Sacramento. These length changes must also be considered to help interpret any changes in tidal amplitudes. It should also be noted that these considerations help frame the complexity of tidal propagation in the Delta, since there are multiple pathways a tide may take to the same point.

**Table 2.1 Sacramento and Stockton River Widths and Depths through History**

<table>
<thead>
<tr>
<th>Year</th>
<th>Sacramento Depth (ft)</th>
<th>Stockton Depth (ft)</th>
<th>Sacramento Width (ft)</th>
<th>Stockton Width (ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Past-1913</td>
<td>7</td>
<td>6</td>
<td>150-200²</td>
<td>100³</td>
</tr>
<tr>
<td>1913-1927</td>
<td>7</td>
<td>9</td>
<td>150-200²</td>
<td>100³</td>
</tr>
<tr>
<td>1927-1933</td>
<td>10</td>
<td>9</td>
<td>150-200²</td>
<td>100³</td>
</tr>
<tr>
<td>1933-1950</td>
<td>10</td>
<td>26</td>
<td>150-200²</td>
<td>300⁴</td>
</tr>
<tr>
<td>1950-1963</td>
<td>10</td>
<td>30</td>
<td>150-200²</td>
<td>225-400⁵</td>
</tr>
<tr>
<td>1963-1987</td>
<td>30</td>
<td>30</td>
<td>200-300²</td>
<td>225-400⁵</td>
</tr>
<tr>
<td>1987-2020</td>
<td>30</td>
<td>37</td>
<td>200-300²</td>
<td>600⁶</td>
</tr>
</tbody>
</table>

¹Lund et al. (2007); USACE (2012).
²USACE (1981).
³House of Representatives (1916).
⁴House of Representatives (1931).
⁵USACE. (1958).
According to a study on the effects of human alterations on the hydrodynamics and sediment transport in the Delta, the permanent flooding of islands or restoration of tidal marsh in the Delta lead to an increase in friction and shear velocity below the flooded islands (Marineau & Wright, 2015). Conversely, the widening and deepening of channels lead to a decrease in friction and shear velocity (Figure 2.9).
Figure 2.9 Delta map showing: (A) elevations within the Delta Tidal Prism; (B) average shear velocity to critical shear velocity at various sites; (C) sediment transport to and from the Delta from 1997 to 2010. Modified from Marineau & Wright (2015).

About 97% of tidal marshes were leveed, drained, and used for agriculture by the end of the 1800s (Whipple et al., 2012). Additionally, Stockton and Sacramento deep water shipping channels were constructed by humans for transportation of goods and water collection which created islands out of the drained marsh areas. Some of these islands have flooded many times, but all have flooded at least once (Marineau & Wright, 2015).

2.6.4 Current Dredging Activities

To maintain their depth, the main transportation channels, Sacramento and Stockton, are dredged regularly by the US Army Corps of Engineers (USACE) (Marineau & Wright, 2015). While the shipping channel depths are maintained by the USACE, the Dredged Material Management Office (DMMO) also helps manage the dredging and where the material is deposited (DMMO, 2019).
The Sacramento River Deep Water Ship Channel (SRDWSC) has a dredging project in plan which will deepen the channel from 30 feet Mean Lower Low Water (MLLW) to 35 feet MLLW. This increased depth has the potential to increase tidal amplification and propagation to the Sacramento area, thus increasing the risk of flooding.

The SRDWSC dredging process is predicted to produce 9.8 million cubic yards of dredged material and the project includes alternative placement sites for the material. About half of the dredged material, around 5 million cubic yards, is proposed for wetland restoration and levee repair. A conservative estimate of 10 years for ultimate completion of the project is assumed in the plan (USACE, 2012).

The SRDWSC is a 45.8 mile long channel that starts at the mouth of the Sacramento River then diverges from the Cache Slough through a manmade channel to end at the Port of West Sacramento (Figure 2.7). The manmade section is approximately 28.8 miles and includes Reach 3, Reach 4, and Reach 5. The SRDWSC was originally deepened to 30 feet MLLW from 1956 to 1963 and then was authorized to deepen to 35 feet MLLW in 1969. The dredging project is only 43.3 miles long because the beginning 2.5 miles of the SRDWSC is naturally deeper than 35 feet (USACE, 2012). It is important to note that this channel diverges from the Sacramento River as a bypass from mile 15 until it reconnects at Sacramento (Figure 2.7). The actual Sacramento River has a depth of only about 15 feet (https://charts.noaa.gov/OnLineViewer/18661.shtml; https://www.charts.noaa.gov/OnLineViewer/18662.shtml).

In 1989, deepening of the SRDWSC started, but due to utility and financing issues, the Port of Sacramento paused construction in 1990. Ultimately, the project resumed in March of 2008 after the funds were given to the San Francisco District. However, according to the US Army Corps website page on the project, deepening work was put on hold again in 2014. The resumption will commence once there is enough economic demand and projected commodities for the project (USACE, 2012).

2.6.5 Potential Tidal Changes from Dredging

Channel deepening is known to decrease frictional effects in channel flow (Talke & Jay, 2020). Less friction allows flow within the channel, whether upstream or downstream, easier
travel. In tidal equations, frictional decreasing is inversely proportional to water depth (Friedrichs & Aubrey, 1994). An increased depth causes a decreased hydraulic drag which amplifies tides and storm surge. Increased tides and storm surge can increase flood hazard in an area (Familkhalili & Talke, 2016). If the water has high sediment concentration, fluid mud can further decrease frictional effects on flow, amplifying tides and leading to higher turbidity conditions (Winterwerp & Wang, 2013).

Ralston et al. (2019) analyzed the effects of dredging in the Hudson River. Their study looked at tidal changes in the New York Harbor and Hudson River from human alterations, including dredging, that were similar to those done in the San Francisco Bay Coastal System. Modifications including doubling channel depths, reclaiming wetlands, widening navigational channels, and regulating river flow have been completed since the late nineteenth century. To analyze the effects of these modifications, time-series and seasonal patterns of water levels and river discharge were plotted. Similar plots were made in this study and are discussed in the results section of this report.

The results of the Hudson River study showed changes in tidal amplitude were largest, doubling, at the river limit where tidal effects become minimal. Close to the coast there were minimal changes. Increased tidal amplitude upstream was seen as a result of decreased friction from channel dredging. Like tidal range, storm surge also increased upstream, however, mean water level decreased enough with dredging that, with the decreased peak river flow events from flow regulation, decreased the 10-year recurrence level by 3 meters (Ralston et al., 2019). In addition to tidal amplification, this study showed mean water level can decrease as a result of dredging. During low flow river conditions, ships might be restricted to only travel around high tide if the mean water level decrease is too significant (Jay et al., 2011).

2.7 River Flow
High river flow stops the tide closer to the coast and significantly decreases tidal propagation through a channel (Moftakhari et al., 2013). As river flow increases, tidal wavelength and wave speed decrease and tidal amplitude fades quicker upstream (Godin, 1999; Lanzoni &
With a high river discharge, tidal patterns diminish, and seawater does not travel as far up the channel.

2.7.1 River Flow Changes in the Delta

Climate change and human interventions have changed river flow patterns in the Delta. Human interventions include dam installation, and flood control and diversion for irrigation and human consumption. Before dam constructions in the 19th century, peak flows mostly occurred in spring from snowmelt. Flood control and diversions occurred in the 20th century, which reduced overall flows and assisted in the movement of peak flows to winter or early spring. Climate changes have decreased precipitation, but also increased snowmelt from increased temperature. Increased temperature leads to increased runoff in winter and an earlier peak flow in spring (Moftakhari et al., 2013).

Model results show a shift from snowmelt to rainfall runoff for water in mid-elevations of the Sacramento River Basin. This shift changes the patterns and amounts of inflow and salinity in the Bay estuary (Knowles & Cayan, 2004). The runoff peak shift to winter in California - due to higher sea levels, less snow, and more rain as a result of climate warming - has made flooding more likely (Lund et al., 2007). Using current trends to predict future patterns, the spring to winter inflow shift is predicted to be about 3 kilometers cubed by 2060 (Figure 2.10).

Figure 2.10 Present mean annual cycle of freshwater inflow (left); predicted relative change in inflow by 2060 (right). Modified from Knowles & Cayan (2004).
Future river flow projections could help in predicting future tidal changes because, as mentioned earlier, river flow affects tidal propagation. In a 2004 study by Knowles & Cayan, results show a projected net increase of salinity as a result of the changes of inflow in the 1,300 to 2,200-meter elevation range of the Sacramento River Basin. This elevation range is the location where snowpacks are currently disappearing and providing less freshwater to the basin.

A similar seasonal shift in river flow has been observed in the Columbia River between Washington and Oregon. Talke et al. (2020) found an increase in tidal range from May to July where peak flows have decreased. However, this decrease in river discharge during late spring, early summer only causes roughly 10% of the tidal range change, on an annual basis.

Considering annual averages, Moftakhari et al. (2013) found overall flows in the Delta have decreased about 40% since 1850. Yet, Knowles & Cayan (2004) predicted total flow to stay fairly steady until 2060 because the spring to winter losses and gains are about equal. They also predict an increase in salinity in the spring and summer periods because the lower inflows allow the seawater to intrude further up the Bay system. The shift in inflow pattern also has the potential to affect the river temperature which could harm the ecosystem downstream (Knowles & Cayan, 2004).

While there is still a predicted increase in salinity, dry years are expected to experience less of a change due to small seasonal changes and consistent low flow conditions. The Sacramento River Basin is the primary supply of predicted change in flow because of the lower elevation of its source water (Figure 2.11). The decrease in flow from the San Joaquin River will likely be justified as an unmet amount of diversion volume and will not change the release amount from the dams to the Delta and Bay system (Knowles & Cayan, 2004).
Considering climate change, predicted precipitation levels in California vary greatly over the next 100 years. Depending on the model and emission predictions, the results show both wetter and drier precipitation levels (Wang et al., 2011).
Based on the Wang et al. (2011) study of the projections of sea-level rise and seasonal runoff effects, the climate change impacts to the California water supply are dominated by annual river flow changes by mid 2000s, while sea-level rise dominates by the late 2000s. Less river flow will decrease the allowable water diverted because dams have a required flow release to prevent excess salinity intrusion. Increased sea-level will also require more dam flow release to combat the additional salinity intrusion. Seasonal flow patterns are not projected to have a significant impact in the State Water Project (SWP) and Central Valley Project (CVP) water supplies (Figure 2.12). The SWP and CVP provide about 12 billion cubic meters per year of water through reservoirs and aqueducts for urban and agriculture use (Wang et al., 2011).

2.8 Sea-Level Rise

Sea-level rise and rate of acceleration are important factors to consider when evaluating flood risk. Any rise in water level, sea-level, or tide amplitude will add strain to the flood control system that is old and already at risk of failure. Understanding future sea-level rise, tidal
amplitude as well as their combination, is important for the San Francisco Bay and Delta population.

Some studies show sea-level rise has been focused on the western Pacific Ocean in the past 10 years. Strong, northwesterly winds have decreased the global sea-level rise in the San Francisco, in addition to the rest of the west coast of the US since 1980 (Bromirski et al., 2011). In the next couple decades, this focus and rise might change to the eastern Pacific Ocean and California coast (Roos & De Vries, 2011).

Specifically, in San Francisco, sea-level has increased an average of 0.2 centimeters per year in the past century and this is expected to increase (IPCC, 2007). Further inland, at Port Chicago in Suisun Bay, it is slightly higher at 0.225 centimeters per year (https://tidesandcurrents.noaa.gov/sltrends/sltrends.html). By 2100, sea-level is expected to increase by 0.4 to 1.7 meters in California (National Resource Council, 2012), and in San Francisco, the 50-percentile projected increase is about 0.6 meters (Griggs et al., 2017).

2.8.1 Sea-Level Effects in the Delta

Not considering future changes, sea-level rise and land subsidence have already had significant effects on the Sacramento-San Joaquin Delta. These changes can be measured by anthropogenic accommodation space, or space in the Delta that’s below sea-level and is not filled with sediment or water. The consequences of sea-level rise and subsidence can be effectively measured by anthropogenic accommodation space. The sea-level rise and subsidence also lead to an increase in the chances of levee failure. There is a high chance the Delta will see catastrophic change and flooding in the next 30 years (Mount & Twiss, 2005).

The main cause of Delta subsidence is microbial oxidation and compaction of organic-rich soils as a result of farming activities. About 2.5 billion cubic meters of anthropogenic accommodation space has been created due to subsidence from the years 1900 to 2000. Subsidence rates have since decreased and are expected to continue doing so through 2050. These lower rates are due to better land use practices and depletion organic material (Mount & Twiss, 2005).
Subsidence and sea-level rise are leading to an increase in water pressure forces that cause levee failures in the Delta (Figure 2.13). Without support for levee upgrades, there will likely be an increase in flooding and repair costs. Based on past large floods, there is a two thirds chance that a 100-year flood or earthquake will occur by 2050 with potentially devastating consequences (Mount & Twiss, 2005).

**Figure 2.13** Evolution of Delta islands due to levee construction and island subsidence (modified from Mount & Twiss, 2005).
Subsidence and sea-level rise are continuing in the Delta, increasing levee instability and therefore, increasing risk of floods and landscape change through 2050. Due to politics within California government entities and a lack of produced scientific information, there have not been sufficient actions taken to address levee instability and flood risk (Mount & Twiss, 2005).

With sea-level rise, the dikes that protect the islands sitting below sea-level will have greater risk of failure (Fleenor & Bombardelli, 2013). Currently, 120,000 hectares of the Delta are under sea-level and anticipated sea-level rise is adapting the 1 in 100-year storm event to a more likely 1 in 10-year storm event. In the future, choices will have to be made on which islands to save because maintaining them will become too costly and unsustainable (Roos & De Vries, 2011).

While depth increases in river channels lead to decreased friction in the channel and changed tidal amplification, inundation as a result of sea-level rise will increase friction in the channel and flooded area. If original channel shorelines are maintained, increased sea-level could increase tidal amplification through decreased friction. Overall, increased sea-level is expected to decrease net tidal amplification due to inundation. Flooding or intensive flood control systems may be necessary to adapt to the combination of sea-level rise and possibly increasing tidal ranges (Holleman & Stacey, 2014).
Section 3 discusses research methods including water level and discharge data collection, initial visual inspection, and tidal range analysis. These methods were used to produce results shown in Section 4. This section discusses water level data in 3.1, then discharge data in 3.2, and tidal analysis in 3.3.

3.1 Water Level Data

Water level data for the San Francisco Bay and the Delta were primarily compiled from the California Department of Water Resources (DWR) website, the National Oceanic and Atmospheric Association (NOAA) website, and archival files. Some historical averages from the late 1800s and early 1900s were found in a US Coast and Geodetic Survey report about the San Francisco Bay and Delta systems (Disney, 1925). In this study, I compiled data for a total of 40 stations.

3.1.1 Collection of Archival Files

A study completed in 2017 collected archival water-level measurements from around the world, of which the United States was the primary country where data was recovered. Archival research shows large amounts, over 1,000 station-years, of data remain undigitized. The undigitized, historical tide data can show how tidal water levels have changed and how historical anthropogenic activities have changed tidal patterns (Talke & Jay, 2017). Figure 3.1 shows some of the tidal records found for the West Coast.
Archival data from Stockton, Sacramento, and San Francisco were used in this study. An example page of high low archival data from Sacramento in August 1929 is shown in Figure 3.2.
3.1.2 Digitization of Archival Files

For this project, archival data was read and digitized in an excel template by students. The template used “Conditional Formatting” as quality assurance to minimize human errors. If one value was significantly different than nearby values, the colors would have an irregular transitional gradient indicating the student needed to fix the entry. An example excel file with and without input error is shown in Figure 3.3. The digitized excel files were then read into MATLAB to be analyzed.

Figure 3.2 Archival daily high low data from Sacramento in August 1929.
3.1.3 Initial Station Information and Data Analysis

Table 3.1, 3.2, and 3.3 present datum, time period, data type, and source of data for all stations considered in this study. Table 3.1 lists San Francisco Bay data, Table 3.2 describes Sacramento River data information, and Table 3.3 has San Joaquin River data information. Stations are listed by distance from coast. Datums are identified with acronyms which include station datum (STND), National Geodetic Vertical Datum of 1929 (NGVD29), and North American Vertical Datum of 1988 (NAVD88). The source column also uses acronyms that include National Oceanic and Atmospheric Administration (NOAA), California Department of Water Resources (DWR), US National Archives: Coast and Geodetic Survey Records (CGSR), and the NOAA Environmental Document Access and Display System: Version 2 (EV2). If the ID is a number, it is the NOAA station number; if the ID is three capital letters, it is the DWR station ID.

Figure 3.3 Digitized data for the month of January for hourly Sacramento data from 1938 (Top). January 1938 Sacramento data with one value changed to a significantly different number (Bottom).
### Table 3.1 San Francisco Coastal Bays Station Data Information

<table>
<thead>
<tr>
<th>Station</th>
<th>ID</th>
<th>Datum</th>
<th>Time Period Available</th>
<th>Data Type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Point Reyes</td>
<td>9415020</td>
<td>STND -1.214 m¹</td>
<td>1975-2018</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td>San Francisco</td>
<td>9414290</td>
<td>STND -1.804 m¹</td>
<td>1898-2018</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td>Alameda</td>
<td>9414750</td>
<td>STND -1.086 m¹</td>
<td>1976-2018</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td>Richmond</td>
<td>9414863</td>
<td>STND -11.57' ²</td>
<td>1997-2011</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td>Mare Island</td>
<td>9415218</td>
<td>STND -0.782 m¹</td>
<td>1997-2011</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1985-1987</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1936-1937</td>
<td>Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1905-1907</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1901</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1878-1879</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1857-1858</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td>Crockett</td>
<td>9415143</td>
<td>STND -2.094 m¹</td>
<td>1979/1990-1991</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Martinez</td>
<td>MRZ</td>
<td>NGVD29 until Oct. 1, 2006. NAVD88 since 8/26/2005 10:00 AM with conversion factor to NGVD29 of -2.68 applied.</td>
<td>2006-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1909</td>
<td>Daily Range</td>
<td>CGSR</td>
</tr>
<tr>
<td>Port Chicago</td>
<td>9415144</td>
<td>STND -0.880 m¹</td>
<td>1979-2018</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td>Mallard Island</td>
<td>MAL</td>
<td>NGVD29 until Oct. 1, 2006. NAVD88 since 8/26/2005 12:00 PM with conversion factor to NGVD29 of -2.68 applied.</td>
<td>1995-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Pittsburgh</td>
<td>PTS</td>
<td>Not found</td>
<td>1952</td>
<td>Monthly Tidal Range</td>
<td>CGSR</td>
</tr>
</tbody>
</table>

¹Relative to NAVD88  
²Relative to station MLLW  
³Relative to NGVD29
<table>
<thead>
<tr>
<th>Station</th>
<th>ID</th>
<th>Datum</th>
<th>Time Period Available</th>
<th>Data Type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sacramento River</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Collinsville</td>
<td>CSE</td>
<td>Not found</td>
<td>2009-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1979/1990-1991</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1939-1940</td>
<td>Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1936-1937</td>
<td>Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1929-1932</td>
<td>Monthly/HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1908-1909</td>
<td>HiLo/HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1867,1878,1890</td>
<td>HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td>Decker Island</td>
<td>SDI</td>
<td>Not found</td>
<td>12/2013-1/2014</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Three Mile Slough (Sac)</td>
<td>9415236</td>
<td>Not found</td>
<td>1991-1992</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1938-1939</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1929-1932</td>
<td>HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td>Rio Vista</td>
<td>RVB</td>
<td>STND -0.6' 3; NGVD29 until Oct. 1, 2006. NAVD88 since 8/9/2005 9:15 AM with conversion factor to NGVD29 of -0.82 applied.</td>
<td>1984-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1949-1967</td>
<td>Monthly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1938-1940</td>
<td>HiLo/HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1908</td>
<td>HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td>Downstream of Isleton</td>
<td>SOI</td>
<td>Not found</td>
<td>2015-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Isleton</td>
<td>9415352</td>
<td>Not found</td>
<td>1979-1980</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td>Walnut Grove</td>
<td>WGS</td>
<td>Not found</td>
<td>1984-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1979-1980</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1938-1940</td>
<td>HiLo/HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1929-1932</td>
<td>HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td>Snodgrass</td>
<td>SGX</td>
<td>Not found</td>
<td>9/2019-11/2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Clarksburg</td>
<td>9415846</td>
<td>Not found</td>
<td>1979-1980</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1938-1940</td>
<td>HiLo/HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td>Freeport</td>
<td>FPT</td>
<td>Not found</td>
<td>1984-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Sacramento</td>
<td>IST</td>
<td>NGVD29 until Oct. 3, 2016. NAVD88 since then with conversion factor to NGVD29 of -2.37 applied.</td>
<td>1984-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1980-1984</td>
<td>Hourly</td>
<td>EV2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1979-1980</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1975-1979</td>
<td>Hourly</td>
<td>EV2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1965-1969</td>
<td>Hourly</td>
<td>EV2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1938-1939</td>
<td>HiLo/HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1929-1932</td>
<td>HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td>Station</td>
<td>ID</td>
<td>Datum</td>
<td>Time Period Available</td>
<td>Data Type</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------------</td>
<td>------</td>
<td>-------------</td>
<td>-----------------------</td>
<td>-----------------</td>
<td>--------</td>
</tr>
<tr>
<td>Verona</td>
<td>VON</td>
<td>STND -3.0' 3</td>
<td>1911</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td>Knights Landing</td>
<td>KNL</td>
<td>NAD83</td>
<td>11/1857</td>
<td>HiLo</td>
<td>CGSR</td>
</tr>
<tr>
<td>Byron Jackson Pumps</td>
<td>BJP</td>
<td>Not found</td>
<td>1991-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Below Wilkins Slough</td>
<td>WLK</td>
<td>Not found</td>
<td>1997-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Meridian Pumps</td>
<td>MPS</td>
<td>Not found</td>
<td>1997-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Colusa</td>
<td>COL</td>
<td>STND -2.95' 3</td>
<td>1992-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
</tbody>
</table>

1 Relative to NAVD88
2 Relative to station MLLW
3 Relative to NGVD29

Table 3.3 San Joaquin River Station Data Information

<table>
<thead>
<tr>
<th>Station</th>
<th>ID</th>
<th>Datum</th>
<th>Time Period Available</th>
<th>Data Type</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>San Joaquin River</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Antioch</td>
<td>ANH</td>
<td>NGVD29 until Oct. 1, 2006. NAVD88 since 8/19/2005 11:15 AM with conversion factor to NGVD29 of -0.33 applied.</td>
<td>1984-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1979/1990-1991</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1936-1937</td>
<td>Monthly/Harmonic</td>
<td>CGSR</td>
</tr>
<tr>
<td>Jersey Point (SJ)</td>
<td>SJJ</td>
<td>Not found</td>
<td>2013-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Three Mile Slough (SJ)</td>
<td>SR3</td>
<td>STND -11.36' 2</td>
<td>2016-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1992</td>
<td>Hourly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1938-1940</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1929-1934</td>
<td>HiLo/Hourly</td>
<td>CGSR</td>
</tr>
<tr>
<td>Prisoners Point</td>
<td>PRI</td>
<td>STND -10.22' 2</td>
<td>2006-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Venice Island</td>
<td>VNE</td>
<td>Not found</td>
<td>1985-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Stockton</td>
<td>SKT</td>
<td>Not found</td>
<td>2010-2011</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1977-1982</td>
<td>Monthly</td>
<td>NOAA</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1933-1954</td>
<td>Hourly</td>
<td>EV2</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>1928</td>
<td>HiLo</td>
<td>EV2</td>
</tr>
<tr>
<td>Station</td>
<td>ID</td>
<td>Datum</td>
<td>Time Period Available</td>
<td>Data Type</td>
<td>Source</td>
</tr>
<tr>
<td>-----------------------</td>
<td>----</td>
<td>------------------------</td>
<td>-----------------------</td>
<td>-----------</td>
<td>--------</td>
</tr>
<tr>
<td>Garwood Bridge</td>
<td>SJG</td>
<td>Not found</td>
<td>2003-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Brandt Bridge</td>
<td>BDT</td>
<td>NGVD29 until Oct. 1, 2006. NAVD88 since 8/17/2005 9:00 AM with conversion factor to NGVD29 of -0.81 applied.</td>
<td>2006-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Dos Reis</td>
<td>SJD</td>
<td>Not found</td>
<td>2017-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Old R Near Lathrop</td>
<td>SJL</td>
<td>NGVD29 until Oct. 1, 2006. NAVD88 since 8/11/2005 1:00 PM with conversion factor to NGVD29 of -0.60 applied.</td>
<td>2007</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Mossdale Bridge</td>
<td>MSD</td>
<td>STND -0.0'</td>
<td>1999-2006</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Vernalis</td>
<td>VNS</td>
<td>STND -0.0'</td>
<td>1993-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
<tr>
<td>Maze River Bridge</td>
<td>MRB</td>
<td>Not found</td>
<td>2007-2019</td>
<td>Hourly</td>
<td>DWR</td>
</tr>
</tbody>
</table>

1 Relative to NAVD88  
2 Relative to station MLLW  
3 Relative to NGVD29

Time periods and source of data available are outlined in above tables. If found, datum and datum changes were noted for each station. In addition, an initial visual analysis was done on timeseries of water levels. If datum shifts (Figure 3.4) or uncharacteristic data (Figure 3.5) were noted, the records were corrected or removed.
Figure 3.4 Datum shift for Antioch in October 2006 from NGVD29 to NAVD88.

Figure 3.5 Uncharacteristic tidal data of present Stockton data after 2011 (for further analyses, data after 2011 was removed).
3.2 Discharge Data

In this study, dayflow data was used for Delta discharge values from 1930 to 2017. Dayflow data is published by the California Department of Water Resources (DWR) and calculated to estimate the daily average outflow of the Sacramento-San Joaquin Delta (https://water.ca.gov/Programs/Environmental-Services/Compliance-Monitoring-And-Assessment/Dayflow-Data). The estimate is referred to as the Net Delta Outflow Index (NDOI). The DWR states the NDOI “is an estimate of the net difference between ebbing and flooding tidal flows at Chipps Island (~ +/- 150,000 cfs), aliased to a daily average.” Flow data from various responsible agencies of 10 inflow locations and 6 export locations all over the Delta is requested to make these calculations at the start of the water year (October 1). See Appendix A for responsible agencies and a map of the input stations.

The estimate does not account for tidal flows, the fortnight lunar fill-drain cycle of the estuary, or barometric pressure changes. The fortnightly lunar fill-drain cycle and the spring-neap cycle can affect river flow, thus affecting the accuracy of the NDOI estimate. Also affecting the accuracy, the DWR made some changes in the calculation method for the NDOI throughout the years it was calculated (1940, 1956, and 1997).

3.2.1 Historical Discharge Estimations

Based on tidal theory, as discharge increases, tidal amplitudes decrease because of bed friction. In this study, historical discharge is used to determine if the relationship between river flow and tides at a location have changed, and if seasonal cycle of tidal range has altered. River discharge estimation produced by Moftakhari et al. (2013) was used in my analysis when comparing tidal levels to discharge.

Measuring river discharge to the ocean through the Delta is challenging because of the many sources (e.g. tributaries, precipitation) and sinks (e.g. diversions, flooding) of the water in the area, and the presence of tidally reversing flow. The NDOI is not calculated before 1929 because of the lack of this data. Moftakhari et al. (2013) estimate discharge from tidal records when discharge data is not available. Using the relationship between San Francisco, CA tide data and Sacramento River Delta outflow index (NDOI) from 1930 to 1990, a river discharge estimate
for 1858 to 1929 for the Sacramento San Joaquin Delta was calculated. The equation below was used to estimate the river discharge:

\[ Q_R = \alpha + \beta T_{R}^{\gamma} \quad \text{where} \quad \frac{2}{3} \leq \gamma \leq 2 \]  

(1)

Coefficients \( \alpha \) and \( \beta \) are determined from data and \( T_{R} \) is a tidal property ratio where \( T_{R} = T_{R_{X}}/T_{R_{ref}} \). \( T_{R_{X}} \) is a tidal property at point \( x \) and \( T_{R_{ref}} \) is a reference tidal property that doesn’t have the influence of river flow (Moftakhari et al., 2013). Equation 1 shows that tidal range and river discharge are related. In this study, I tested whether a similar relationship was found with Delta station data.

The discharge data, estimated and calculated, is shown in Figure 3.6.

![Discharge Levels](image)

**Figure 3.6** Delta discharge levels through history.

The estimation method used tidal constituents, astronomical forcing, and a model of the frictional relationship between river discharge and flow to determine average monthly river flows in a tidal discharge estimation method (TDE). The TDE was compared to measured discharge data around the Delta to validate the estimation relationship found (Moftakhari et al., 2013).
Another tidal estimation method has been established, the Multiple-gauge Tidal Discharge Estimate (MTDE) method, which produces more accurate high and low flow estimations (Moftakhari et al., 2016). However, MTDE flow data was not available for this study. If gauge data is available, MTDE could be used for future analyses of the Sacramento Delta to estimate more accurate discharge values before 1930.

### 3.3 Tidal Theory

Tidal theory is important in understanding tidal behavior and what might change tides. Friction and convergence have significant effects on tidal behavior. In a prismatic channel with a rectangular cross-section, the shallow water wave equation reduces to a damped second-order wave equation (Ippen, 1966):

\[
\frac{\partial^2 \eta}{\partial t^2} + r \frac{\partial \eta}{\partial t} = c_0^2 \frac{\partial^2 \eta}{\partial x^2} \tag{2}
\]

Where \( t \) is time, \( x \) is distance, \( c_0 \) is frictionless gravity wave speed, and \( r \) is a constant friction factor. Tides behave differently depending on convergence of a channel. Tidal transport \( Q \) and elevation \( \eta \) are affected by width \( b \) and depth \( h \):

\[
Q \approx b^{+1/2}h^{+1/4} \tag{3}
\]

\[
\eta \approx b^{-1/2}h^{-1/4} \tag{4}
\]

Further research has shown that for weak and strong convergence tidal flats change the effects of transport and elevation (Jay, 1991):

\[
Q \approx b_T^{+1/4}b^{+1/4}h^{+1/4} \tag{5}
\]

\[
\eta \approx b_T^{-1/4}b^{-1/4}h^{-1/4} \tag{6}
\]

Total width \( b_T \) includes tidal flats while width \( b \) is momentum conveying width. Wave propagation is slowed by a factor of \((b/b_T)^{1/2}\) on tidal flats. Increased friction increases tidal dampening and, if present, river flow increases frictional dampening (Jay, 1991). In a first order momentum equation, the linearized friction factor \( r \) is (Freidrichs & Aubrey, 1994):

\[
r = \frac{8}{3\pi} \frac{c_dU}{h} \tag{7}
\]
Where $C_d$ is a drag coefficient, $U$ is the tidal velocity scale, and $h$ is the depth. Hence, the friction factor $r$ is inversely proportional to depth. The larger the depth, the smaller the friction factor. Therefore, frictional effects decrease with dredging (Friedrichs & Aubrey, 1994), often leading to an increase in tidal amplitudes (Winterwerp et al., 2013; Talke & Jay, 2020).

3.3.1 Tidal Range Analysis

In this study, tidal range calculations were performed on the tidal water levels collected. Tidal range is calculated as the difference between the approximately two high waters and two low waters each day. Usually there are four, sometimes three, high and low water levels that occur each day. These water level extrema are defined as a higher high water (HHW), a lower low water (LLW), a high water (HW), and a low water (LW). Figure 3.7 shows mean values of tidal datums including HHW, LLW, HW, and LW for San Francisco between 1983 and 2001 relative to NAVD88.

![Figure 3.7 Average tidal datums for San Francisco between 1983 and 2001 relative to NAVD88 (NOAA).](image-url)
Daily, monthly, annual, and low flow average tidal ranges were analyzed. Low flow tidal ranges were analyzed because, as discussed in the Literature Review section, river flow can diminish tides and low flow water level records will minimize river flow impacts to tidal patterns. For this study, low flow averages were defined as the annual average between July and October. This period is considered low flow because the annual average NDOI (from 1850-2017) is about 900 cubic feet per second, while between July and October the average NDOI is only about 300 cubic feet per second.

3.3.2 Simple Tide Amplitude Model

To further analyze tidal changes through time, an analytical model described in Jay (1991) and simplified for highly frictional, weakly convergent conditions by Talke & Jay (2020) was applied to the Sacramento channel in the San Francisco Bay and Delta system. The model does not accurately reflect tidal patterns in the Stockton channel because it is not weakly convergent, and it is also possible that the Stockton channel is affected by reflection.

In this model I assume that wave length is long compared to depth (Jay, 1991) and the tidal amplitude is small compared to depth (Talke & Jay, 2020). In addition, based on the e-folding scale discussed later, the Sacramento channel is weakly convergent, thus frictional damping dominates convergence for M2 tide because tidal amplitudes decrease with distance (Jay, 1991; Lanzoni & Seminara, 1998). Reflection can be ignored because tidal range diminishes to zero past Sacramento (see Results). Further, I assume a constant depth because the majority of the Sacramento channel is held a constant depth through dredging. This model reflects low flow conditions because it assumes river flow is small compared to tidal currents.

With the assumptions above, the mass balance and momentum equations are:

\[
\frac{\partial Q}{\partial x} + b \frac{\partial \eta}{\partial t} = 0 \tag{8}
\]

\[
\frac{\partial Q}{\partial x} + \frac{\partial}{\partial t}\left(\frac{Q^2}{A}\right) + gA \frac{\partial \eta}{\partial x} + bT = 0 \tag{9}
\]

Where \(Q\) is tidal flow, \(A\) is the cross-sectional area, \(g\) is gravity, \(\eta\) is tidal amplitude, \(b\) is the width, and \(T\) is the frictional resistance. Width is assumed to converge from the mouth in the relationship \(b(x) = B \exp(-x/L_e)\) where \(B\) is the width at the mouth and \(L_e\) is the e-folding scale. Frictional
resistance is approximately \((C_d u h)\) and is commonly linearized to be inversely proportional to depth \(h\), and proportional to the drag coefficient \(C_d\) and the velocity \(u\).

Using the solution procedure outlined in Jay (1991), Talke & Jay (2020) present the following equation:

\[
\eta(x, t) = \exp\left(\frac{x}{2L_e}\right) \ast \text{Re}\left[(A_0 \exp(iqx) + B_0 \exp(-iqx)) \exp(i\omega t)\right]
\]  (10)

Where \(q\) is:

\[
q = \frac{\omega}{\sqrt{gH}} \left(1 - \frac{gh}{4L_e^2} \frac{r}{\omega^2} \right)^{1/2}
\]  (11)

In addition, \(A_0\) equals 0 and there is no incident wave if there is no reflection and tidal amplitude goes to zero as \(x\) increases to infinity. The revised equation with \(A_0 = 0\) can be written as:

\[
\eta(x, t) = \exp\left(\frac{x}{2L_e}\right) \ast \text{Re}[\eta_0(\exp(-iqx)) \exp(i\omega t)]
\]  (12)

Where \(\eta_0\) is the tidal amplitude at the coast, and through Euler’s identity \(\exp(-iqx) = \cos(qx) + isin(qx)\) and \(\exp(-i\omega t) = \cos(\omega t) + isin(\omega t)\). The following equations show Equation 12 can be reworked with a wave number \(k\) and a phasor \(p\) (Jay, 1991):

\[
q = k + ip
\]  (13)

Where

\[
k = \frac{\omega}{\sqrt{gh}} \left(1 - \frac{gh}{4\omega^2 L_e^2} \right)^{1/2} + \frac{r^2}{\omega^2} \frac{1}{\omega} \cos(\varphi)
\]  (14)

\[
p = \frac{\omega}{\sqrt{gh}} \left(1 - \frac{gh}{4\omega^2 L_e^2} \right)^{1/2} + \frac{r^2}{\omega^2} \frac{1}{\omega} \sin(\varphi)
\]  (15)

\[
\varphi = \frac{1}{2} tan^{-1} \left(-\frac{r}{\omega}\right)
\]  (16)

Where \(\omega\) is wave frequency, \(r\) is the friction factor (Eq. 7), \(h\) is depth, and \(g\) is gravity. In this study, \(\omega\) is based on the M2 tidal period, \(C_d\) and \(U\) are manipulated to best fit the data, and \(h\) is 3 feet added to the controlled dredging depth of 7 feet (MLLW) before 1927 and 15 feet (MLLW)
presently. The 3 feet is added to the reported depth to approximately convert to mean water levels.

The e-folding scale is calculated based off of a best-fit exponential trendline of the data where $L_e$ is the negative inverse of the coefficient of $x$ in the exponential and $C$ is a constant. Studies of other channel convergence show an exponential fit is often appropriate (e.g., Talke & Jay, 2020). The relationship is shown in the equation below.

$$y = Ce^{-\frac{1}{L_e}x}$$  \hspace{1cm} (17)

Based off an analysis of distance versus width of the Sacramento River, the e-folding scale is ~40 kilometers (Figure 3.8). Distance versus width was measured with Google Earth from around Port Chicago (65 km) to Sacramento (180 km). Measurements start at 65 kilometers because it marks the start of the converging channel and the start of tidal amplitude decay (see Results). With an $R^2$ value of 0.59 (Figure 3.8), the fit is only adequate, but there is a variable width through the channel and a convergence of about 40 kilometers is representative of the controlling width. If the exponential fit is applied between 65 kilometers to 120 kilometers, the convergence e-folding scale is about 15 kilometers; beyond this point, the channel is approximately constant width. However, considering spatial changes in convergence and their effect on tides is outside of the scope of this study. To better model tidal range, future studies could consider these changes and their effects on tides.
In this study, I considered the multiple channels - the Sacramento River Deep Water Ship Channel (SRDWSC), the Sacramento River “Old River,” and Steamboat Slough - leading from near Collinsville to Sacramento, for the convergence e-folding scale calculation. As shown in Figure 3.9, all channels flow alongside each other. The SRDWSC and Steamboat Slough are approximately 15 miles (USACE, 2012) and 7 miles (House of Representatives, 1891) shorter, respectively, than the Old River branch of the Sacramento River. Steamboat Slough effectively brings Sacramento closer to the ocean, but the SRDWSC does not reconnect to the Sacramento River at Sacramento. The question lies, should the SRDWSC, the Old River, Steamboat Slough, or the combined width of all be used for the convergence e-folding scale? In this study, I used the Old River to measure convergence. This is because most of the data stations available both historically and today follow the Old River (Figure 3.9). The Old River replaced Steamboat Slough in 1880 as the primarily channel for ships (House of Representatives, 1891). However, the SRDWSC became the main transportation channel when it was completed in 1963, but again, this channel dead ends before it can reconnect to the Sacramento River in Sacramento (USACE,
A future analysis could consider the damping of the tides in the SRDWSC, and its effect on tides in the delta, using the several DWR gauges within the channel. Figure 3.9 shows the lengths of river I considered for the calculation of the e-folding scale.

Figure 3.9 Lengths over which convergence e-folding scale calculation was considered. Red lines are the locations where the channel width was measured. Sacramento River Deep Water Ship Channel (SRDWSC) traced in blue, Steamboat Slough traced in green, and the Old River traced in purple.

Further details on the development of the simple model can be found in Talke & Jay (2020) and the associated supplementary material. Results of this model are plotted with distance versus tidal range in the results section below.
4 RESULTS

In this section I evaluate tidal range as a function of time, distance from the coast, river discharge, and season. Stations with a few months of available data or more in the early 1800s and late 1900s that were spread through the river system were prioritized in this analysis. Primary stations analyzed in the study include San Francisco, Rio Vista, Stockton, and Sacramento. Current and historical tidal ranges were analyzed against distance from the San Francisco coast for most stations. In addition, I analyzed the effects of discharge on tidal range for Collinsville, Mare Island, and other primary stations. Current and historical tidal range and discharge seasonal patterns were also compared for the primary stations. Results are displayed and analyzed below.

4.1 Distance versus Tidal Range

As tides propagate up the San Francisco Bay and Delta system, the tidal energy dissipates with friction from Richmond to Sacramento and through the San Joaquin River, but where the channel is convergent from the Three Mile Slough to Stockton, the tides amplify (Figure 4.2). Figure 4.1 and 4.2 show that from 1997 to 2018 in the San Francisco and Sacramento system, the tidal range decreased in the upstream direction after a maximum of about 1.5 meters around Richmond. Both Sacramento and San Joaquin Rivers follow the trend down to zero (Figure 4.1). Over the course of about 90 kilometers, tidal range in the Sacramento River goes from approximately 0.9 meters to 0.3 meters from Collinsville to Sacramento (Figure 4.2). On the San Joaquin River, tidal range decreases from a little over 0.8 meters to 0 meters over the approximately 110 kilometers from Antioch to Vernalis (Figure 4.2). However, decay in tidal range in the San Joaquin follows a variable pattern. Before the tidal range decreases to 0 meters, there is an increase of about 0.4 meters from Three Mile Slough to Stockton (Figure 4.1). After Stockton, the tidal range decreases back from 0.9 meters to zero over the next 50 kilometers.
Figure 4.1 Distance from the coast versus average tidal range from 1997 to 2018 with Sacramento and San Joaquin rivers distinguished by color. The stations correspond to the following river kilometer readings: Golden Gate = 0 km, Mare Island = 45 km, Antioch = 85 km, Rio Vista = 100 km, Stockton = 145 km, and Sacramento = 180 km.

In the early 20th century, tidal range decreased from a maximum of about 1.4 meters at Mare Island to 0.6 and 0.1 meters at Stockton and Sacramento, respectively. From 1870 to 1910, the tidal range decreased from 1.4 meters to 0.6 meters on the San Joaquin River (Figure 4.3). Present data from 1997 to 2018 also decreases about 0.8 meters over 100 kilometers, but the maximum tidal range occurs closer to the coast. The damping of tidal range in the Sacramento River exhibited a faster rate of decrease from 1870 to 1910 than from 1997 to 2018 (Figure 4.2 & 4.5). Over 90 kilometers, from 1870 to 1910 tidal range decreased 1.2 meters between Collinsville and Sacramento, while from 1997 to 2018 the rate of tidal range decrease was halved at 0.6 meters over the same distance (Figure 4.4).
Figure 4.2: Map of average tidal range from 1997-2018 along the San Francisco Bay and Sacramento-San Joaquin Delta.
Tidal range between Mare Island and Suisun Bay was 0.2 to 0.4 m higher historically (1870-1910) than in the present (1997-2018). Tidal ranges from 1870 to 1910 in Stockton and Sacramento were 0.3 and 0.1 m lower than from 1997 to 2018, respectively (Figure 4.3 & 4.4). Contemporary observers attributed the lower historic tidal range in Sacramento to sedimentation of the delta channels caused by hydraulic mining effects (Gilbert, 1917). The sediment reduced the depth of the channel which, as discussed previously in the tidal theory section, would increase frictional effects. The Sacramento range about doubled between the early 1900s and the present, while the Stockton tidal range increased by about 50% (Figure 4.3 & 4.4). The change in tidal range in Sacramento is likely influenced by the movement of the hydraulic mining sediment pulse out of the system (Gilbert, 1917), deepening of the Old Channel reach to a present day depth of about 15 feet from 7 feet historically, and construction of the Sacramento River Deep Water Ship Channel (SRDWSC) and other system alterations.
Figure 4.3 Distance from the coast versus tidal range for the San Joaquin River comparing 1870 to 1910 data and 1997 to 2018 data. The stations correspond to the following river kilometer readings: Golden Gate = 0 km, Mare Island = 45 km, Antioch = 85 km, and Stockton = 145 km.

The simple model described in Section 3.3.2 is shown in Figure 4.4 and compared with the measured data. Wave frequency, $\omega$, is based on the lunar tidal constituent $M_2$. The amplitude of the tide is assumed to be half the tidal range. Drag coefficient $C_d$ and velocity scale $U$ were varied to best fit the measured data but do lie within typical ranges. The modern velocity scale is consistent with typical measurements in the Sacramento River, such as depicted in Bennett & Burau (2015). Depth, $h$, is 3 feet added to the MLLW reported depth to represent mean depth conditions. For present data, the Sacramento River depth was used instead of the Sacramento River Deep Ship Channel (SRDWSC) for the reasons described in Section 3.3.2. The modern depth is based on NOAA charts 18661 and 18662 (https://www.charts.noaa.gov). The reported
depths centered around 15 feet, but 18 feet was used in this model to approximately represent mean water levels. Convergence e-folding scale, $L_e$, was calculated as described in Section 3.3.2, and is assumed to be the same during both periods. The model is only applied between river kilometer 80 (near Collinsville) and Sacramento, since this is the Section in which tidal damping occurs. Parameters that fit the observed tides well are given in Table 4.1.

<table>
<thead>
<tr>
<th>Period</th>
<th>$\omega$ (s$^{-1}$)</th>
<th>$C_d$</th>
<th>$U$</th>
<th>$h$ (ft)</th>
<th>$L_e$ (km)</th>
<th>$\eta_o$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997-2018</td>
<td>$1.4 \times 10^4$</td>
<td>0.0025</td>
<td>0.7</td>
<td>18</td>
<td>40</td>
<td>0.55</td>
</tr>
<tr>
<td>1870-1910</td>
<td>$1.4 \times 10^4$</td>
<td>0.0025</td>
<td>0.3</td>
<td>10</td>
<td>40</td>
<td>0.7</td>
</tr>
</tbody>
</table>

Both historical and present data are modeled fairly accurately, but the modeled data follows more of an exponential trend while the recorded data is more linear (Figure 4.4). The slight difference is likely due to the complex system of channels leading to Sacramento (see Section 3.3.2) and an overestimation of decay in the model from assuming constant velocity over a long length of river. The assumption of a constant depth is also an approximation. In addition, the historical model diverges farther than the present model from the measured value at Sacramento. The model assumption that tidal amplitude is small compared to depth is likely inaccurate for historical bathymetry, which was only an average of 10 feet. For such reasons, the simple model was unable to accurately reflect tidal ranges in shallow conditions. To produce a better model of results, the effect of other channels such as Steamboat Slough and the SRDWSC should be evaluated. Still, the simple model shows that depth increases in the Old Channel of the Sacramento River contributed to the increase in tidal range in Sacramento. This is partially mitigated by the overall smaller amplitude of tides at the boundary of the model at Mare Island.
Figure 4.4 Distance from the coast versus measured and modeled tidal range for the Sacramento River comparing 1870 to 1910 data and 1997 to 2018 data. The stations correspond to the following river kilometer readings: Golden Gate = 0 km, Mare Island = 45 km, Rio Vista = 100 km, and Sacramento = 180 km.
Figure 4.5: Map of average tidal range from 1870 to 1910 along the San Francisco Bay and Sacramento-San Joaquin Delta.
4.2 Differences in Tidal Range Over Time

To further analyze tidal range in the San Francisco Bay and Sacramento San Joaquin Delta over time, I produced time series for San Francisco, Rio Vista, Sacramento, and Stockton. It is important to note that annual average tidal range is affected by yearly and long-term changes in river flow and for that reason short tidal range records may not accurately reflect average tidal range. Without a long time series, it is difficult to accurately interpret long-term trends, but they will provide an indication of how average conditions might have changed. To calculate trends, I fit a linear trend in addition to a sinusoid to describe the 18.6-year tidal cycle (Woodworth, 2010).

San Francisco tidal ranges increased by 7.5% from 1860 to 2019. This is similar to the published increase in tidal amplitude constituent M₂ of about 7% for San Francisco in the 20th century (Jay, 2009; Rodriguez-Padilla & Ortiz, 2017). In addition, San Francisco has a statistically significant linear trend of 0.62 +/- 0.04 millimeters per year since 1860 with a p-value on the order of 10⁻²⁹ (Figure 4.6). Since 1857, tidal range varied the most in Sacramento, with amplitudes between 0 and 0.5 meters. Around 1890, the tidal range was zero due to the buildup of hydraulic mining sediment (Gilbert, 1917). By 1938 to 1939 tidal range increased to approximately 0.5 meters. Thereafter, tidal range decreased by 50% to an average of 0.25 meters in the 1984 to 2019 period (Figure 4.6). Tidal range in Sacramento therefore exhibits a decreasing linear trend of 2.42 +/- 0.79 millimeters per year from the late 1930s to present, where 0.79 mm is the standard error in the fit. (Figure 4.6).

Other locations – Rio Vista and Stockton – follow a similar pattern and also exhibit a mid-20th century maximum in tidal range. In the early 1900s, their tidal ranges were 0.9 and 0.6 meters, respectively, but by the mid to late 1900s they increased to about 1 meter (Figure 4.6). Thereafter, a slight decrease is observed in both locations. Stockton tidal range decreases about 9% from 1933 to 2011 and Rio Vista tidal range decreases about 24% from 1950 to 2019 (Figure 4.6). The linearly decreasing trend in Stockton is 1.06 +/- 0.45 millimeters per year from the mid-1900s to the early 2000s (Figure 4.6). However, the decreasing linear trend is 4.00 +/- 0.24 millimeters per year in Rio Vista from the mid-1900s to the early 2000s (Figure 4.6). Though reasons for the recent decreases in Sacramento, Rio Vista, and Stockton are unclear, I note that
wetland restoration and increased water storage and diversion through the California State Water Project occurred around the same time (Marineau & Wright, 2015; DWR, 2008). Other studies have noted that restoration of wetlands in the Delta could affect tides (Wagner, 2012).

Since the early 1900s, there was an overall increase in tidal range in from 0 to 0.25 meters in Sacramento and 0.6 to about 0.8 meters in Stockton. This is consistent with increased depth from dredging and flood control channel restriction, though more analyses are needed to ascertain the reason. By contrast, the tidal range in Rio Vista from the early 1900s to the 2000s stayed about the same at around 0.8 meters.

![Figure 4.6](image)

**Figure 4.6** San Francisco, Rio Vista, Sacramento, and Stockton annual tidal range time-series with an 18.6-year sinusoidal fit that includes a linear trend. All records with 6 months of data or more are included as an annual average. The 20 year period in which the San Francisco gauge was in Sausalito (1877-1897) is excluded from the San Francisco fit.

To visualize the frictional effects of river flow on tidal range through time, I compared annual to low flow averages. Low flow (July to October) averages are similar to annual averages, but some low flow values in Stockton and Rio Vista are slightly higher. In 1908 in Stockton and
1940 in Rio Vista, the low flow annual averages are about 0.1 meters and almost 0.5 meters higher than total annual average, respectively (Figure 4.7). Average annual NDOI in 1908 was approximately two thirds of the average annual NDOI from 1850 to 2017, but average 1908 low flow NDOI was about one third of overall average low flow NDOI. Average low flow NDOI in 1940 was also about one third the overall average low flow NDOI, but the annual average was much higher at 1.5 times the overall annual average NDOI. Tidal measurements in Stockton and Rio Vista partially coincided with the higher differences in flow periods. The tide magnitudes were damped based on well-known frictional effects of river flow on tides (Godin, 1999; Lanzoni & Seminara, 1998; Moftakhari et al., 2016).

Outside of differences between low flow and annual averages, Figure 4.7 includes a low flow point without an annual average for 1857 in Sacramento. This point is the average of only two weeks of data during the low flow period, but it shows that there was tidal range above zero prior to the late 1800s when the tide was diminished by hydraulic mining sediment.

**Figure 4.7** San Francisco, Rio Vista, Sacramento, and Stockton annual versus low flow tidal range time-series. All records with 6 months of data or more are included as an annual and low flow average except for Sacramento 1857 low flow which is a couple weeks in November.
4.3 Discharge versus Tidal Range

As discharge increases, tidal range diminishes. These effects can be seen more clearly further from the coast. The San Francisco, Mare Island, Rio Vista, Stockton, and Sacramento discharge versus tidal range plots below show these results by comparing daily discharge to average daily tidal range. The x-axis is the reported DWR daily Net Delta Outflow Index (NDOI) values as daily discharge. The y-axis is the mean daily tidal range. I am using a daily approach to capture the day to day variability in river flow and its effects on tides. However, this approach may not be able to assess the tide/river flow relationship observed on a monthly timescale in San Francisco (Moftakhari et al., 2013). The daily approach produces naturally occurring weekly and monthly tidal patterns. This creates a wide range of points when a scatter plot of discharge versus tidal range is produced (see e.g., Figure 4.8). For that reason, I took the average response by binning the data and plotting the median and quarter percentiles. All daily data points are plotted out in the background, while the bin averaged median, 25th percentile, and 75th percentile lines of the data are plotted to show the average trend. Median lines are solid, percentile lines are dashed, and present versus historic data are blue and red, respectively. It is important to note that some data periods only include a couple years and may not accurately represent natural historical variability.

San Francisco and Mare Island exhibit no relationship between tidal range and discharge, using my methodology (Figure 4.8 & 4.9). However, daily tidal range is shown to be a function of daily river flow in Rio Vista, Stockton, and Sacramento (Figure 4.10, 4.11, & 4.12). While Moftakhari et al. (2013) documents a well-known $M_2$ response in San Francisco, Figure 4.7 shows little to no relationship between discharge and tidal range. The lack of observed relationship is probably due to the natural variability in tides at Golden Gate, which masks any tidal range changes with discharge. Tidal range versus discharge in Mare Island in the late 1936 is about 0.1 meters higher than from 1997 to 2017 (Figure 4.9). Tidal range versus discharge in Rio Vista is also 0.2 meters to 0.05 meters higher from 1938 to 1940 than from 1997 to 2017 (Figure 4.10). Compared to the late 1930s, present tidal range is less sensitive to discharge.
These trends noted are uncertain because historic data shown is only 1 year and 3 years for Mare Island and Rio Vista, respectively.

**Figure 4.8** Discharge versus tidal range for San Francisco comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25th percentile, and 75th percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue.
Figure 4.9 Discharge versus tidal range for Mare Island comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25th percentile, and 75th percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue.
Figure 4.10 Discharge versus tidal range for Rio Vista comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25th percentile, and 75th percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue.

Not much change is observed in the discharge versus tidal range relationship in Stockton between the mid-20th century and the present (Figure 4.11). By contrast, Sacramento tidal range between 1997 and 2017 is about 0.15 meters lower than between 1938 and 1939 at low flow. In addition, tidal range from 1997 to 2017 is lower than 1938 to 1939 for any given flow below 1,000 cubic meters per second (Figure 4.12). However, historical Sacramento data considered only consists of two years of data and, therefore, may not fully reflect historic conditions.
Figure 4.11 Discharge versus tidal range for Stockton comparing historical values to present. All daily data points are plotted in the background, while bin averaged median, 25\textsuperscript{th} percentile, and 75\textsuperscript{th} percentile lines of the data are plotted to show the average trend. Historic data trendlines are red and present data trendlines are blue.
4.4 Seasonal Patterns

To analyze seasonal patterns, I calculated average monthly tidal ranges and NDOIs each year I had water level data, and then calculated monthly averages in that time period. Next, I calculated the difference of tidal range and discharge for selected time periods. I compared seasonal tidal range changes to seasonal discharge changes for San Francisco, Sacramento, and Stockton.

Figures 4.13d and 4.14d show a discharge decrease in late spring/early summer of about 1,000 cubic meters per second and an increase in the beginning of the year of about 100 cubic meters per second. These values support the Hutton et al. (2017) observation of a statistically
significant decreasing trend in February, April, and May. However, Hutton et al. (2017) also found an increasing trend in July and August that is not observed in Figures 4.13d and 4.14d.

In San Francisco there is an increase in average tidal range throughout spring and summer over the past 100 years (Figure 4.13b). There is a peak average tidal range increase of 0.1 meters in June and a minimum range increase of 0.04 meters in October and December (Figure 4.13b). While the peaks of discharge and tidal range do not completely line up, discharge is still approximately 500 cubic meters per second less in June at the peak tidal range difference. This shows that river flow may be a contributing factor to tidal range changes in San Francisco.

![Figure 4.13 Tidal range and discharge seasonal patterns for San Francisco comparing historical values to present: (a) monthly mean tidal range for 1898-1918, 1918-1938, and 1997-2018; (b) difference in monthly mean tidal range from 1997-2018 to 1898-1918; (c) NDOI for 1898-1918, 1918-1938, and 1997-2018; (d) difference in NDOI from 1997-2018 to 1898-1918.](image)

In contrast, Sacramento has an average decrease in tidal range for the majority of the year apart from February through April (Figure 4.14b). The only months with no tidal range
decrease align with months that exhibited the largest decrease in discharge. The discharge differences between San Francisco and Sacramento time periods considered are similar with the exception of February and March. Discharge in February and March of the late 1930s were about 500 cubic meters per second higher than the early 1900s (Figure 4.13d & 4.14d). In the month of peak tidal range difference, the difference in discharge almost reaches 1,500 cubic meters per second in February between the Sacramento time difference of early 2000s to late 1930s, while the difference in discharge for the San Francisco time difference of early 2000s to early 1900s only reaches about 500 cubic meters per second in June (Figure 4.13b, 4.13d, 4.14b, & 4.14d). Sacramento shows a stronger relationship between seasonal tidal range and discharge differences than San Francisco. However, Sacramento historical data may not be representative of actual conditions because it only includes two years of data from 1938 to 1939.

Figure 4.14 Tidal range and discharge seasonal patterns for Sacramento comparing historical values to present: (a) monthly mean tidal range for 1938-1939 and 1997-2018; (b) difference in monthly mean tidal range from 1997-2018 to 1938-1939; (c) NDOI for 1938-1939 and 1997-2018; (d) difference in NDOI from 1997-2018 to 1938-1939.
In Stockton, an increased monthly mean tidal range is also observed in April through July when comparing present to early 1900s patterns. The peak is about 0.6 meters in April and the minimum difference is about 0.2 meters in September and October (Figure 4.15b). In this plot, due to a longer record and similar tidal range trends, I looked at the difference between 1933 to 1954 and 1908 over 2010 to 2011 and 1908. In contrast to San Francisco and Sacramento, discharge difference in this comparison increases from past to present. However, the NDOI consists primarily of Sacramento River flows. This makes the San Joaquin River flow more applicable than the NDOI for comparison with Stockton tidal range. The San Joaquin River hydrology is known to have changed through dam implementation from 1930s through the 1960s. According to a DWR River Discharge Report, most of the natural flow is now stored or used before Stockton (California Department of Water Resources, 1999). Prior to the 1930s, snowmelt used to increase river flow in late spring which is consistent with the lower tidal range in April through June of 1908. Stockton data past the 1930s show little to no response to river discharge (Figure 4.15a). However, with only one year of historical data, it is important to note that Stockton data may not accurately represent natural historical trends.
San Francisco, Sacramento, and Stockton all have either no decrease or increase in average tidal range ranging up to 0.6 meters in late spring, early summer from past to present data. This increase aligns with an overall decrease in river flow of 500 to 1,500 cubic meters per second at the same time seasonally (Figure 4.13 & 4.14).
5 DISCUSSION/CONCLUSION

5.1 Summary and Evaluation of Results

Human influences on the Delta landscape have affected the channel width, the channel depth, the channel length between locations, and therefore the spatial pattern of tidal amplitude through the San Francisco Bay and Delta system. Hydraulic mining sediment shallowed the Delta channels, causing a reduction in tidal amplitude, particularly in Sacramento (Figure 4.6). The natural progression of the sediment wave, plus dredging, cleared out most of the hydraulic mining sediment and decreased the frictional effects of the channel by the 1930s. The Sacramento River "Old Channel" has been deepened around 8 feet from its original depth of 7 feet and the Stockton channel has been deepened 28 feet from its original depth of 6 feet. The distance that the tide travels to Sacramento has increased since the mid-1800s but has decreased for Stockton. In Suisun Bay between 1870 to 1910 and 1997 to 2018, tidal range increased between 0.2 and 0.4 meters. In Stockton, tidal range increased from 0.6 meters to 0.9 meters between 1908 and the 1930s but decreased approximately 9% from the 1930s to 2011. Tidal range in Sacramento increased from zero to about 0.5 meters between 1890 and the late 1930s but decreased to an average of 0.25 meters in the early 2000s.

River flow changes from climate change and dam construction have also changed tidal patterns throughout time. Historically, flows peaked in late spring, early summer from snow melt, but with climate change and decreased snowpacks, the peak has shifted to early spring from high runoff. This shift has contributed to increased tidal range in late spring, early summer by 0.1 and 0.6 meters in San Francisco and Stockton, respectively. In Sacramento, the least decrease in tidal range since 1938 to 39 occurred during the same spring freshet season.

Tides have recorded the history of environmental change within the highly altered San Francisco Bay and Sacramento San Joaquin Delta system. These changes are most significant in Sacramento where mean annual tidal range has ranged between zero and 0.5 meters since 1890 and, for any discharge below 1,000 cubic meters per second, mean daily tidal range was higher from 1938 to 1939 than it was from 1997 to 2018. While these are notable changes, they are not as large as those seen in other systems with similar human alterations (Ralston et al., 2019; Talke & Jay, 2020). Change in tidal range suggests possible changes in tidal velocities, salinity
intrusion dynamics, and flood risk, but further analyses are needed to determine the full implications of change in tidal range.

5.2 Recommendations for Improvement and Further Analysis

While key stations were discussed in this study, there is more available historical data for other stations that can be digitized and analyzed to increase understanding of the human influence on tidal patterns in the Delta. More data stations considered can solidify conclusions made in this study or reveal other results and conclusions.

Further analyses of data discussed in this study could be done through harmonic analyses, extreme analyses, and numerical models. Harmonic analyses are likely to show changes in harmonic constituents through the late 1800s to present as a result of the human alterations of the Delta. Extreme analyses, like a storm surge risk analysis, would give an idea of the flood risk to the Bay area and Delta population. Numerical models that are more extensive than the simple model used in this study and can accurately reflect the effects of the complex channel system leading to Sacramento could provide future predictions on the tidal behavior. Future predictions could be used for development and infrastructure planning in the area.

Humans often see the earth as something we can take and modify for our benefit, but modifications tend to have unseen effects that can harm us in other ways. Other tidal analyses have shown similar results to human alterations and can be reviewed to further this exploration.
REFERENCES


https://www.google.com/books/edition/Congressional_Serial_Set/1xJUAAAAIAAJ?hl=en&gbpv=1&q=stockton+deep+channel+width&pg=PA336&printsec=frontcover


### Appendix A

#### Table A.1 Dayflow Program: Responsible Agencies and Input Data

<table>
<thead>
<tr>
<th>Responsible Agency</th>
<th>Input data</th>
</tr>
</thead>
<tbody>
<tr>
<td>USGS</td>
<td>Sacramento River at Freeport, Yolo Bypass at Woodland, Cosumnes River at Michigan Bar, San Joaquin River at Vernalis, Delta Cross Channel, Georgiana Slough</td>
</tr>
<tr>
<td>USACOE</td>
<td>Calaveras River</td>
</tr>
<tr>
<td>EBMUD</td>
<td>Mokelumne River at Woodbridge</td>
</tr>
<tr>
<td>DWR O&amp;M</td>
<td>Precipitation at Stockton Fire Department, Clifton Court Forebay gate flow, Barker Slough export, Byron Bethany ID depletion, X2 (only when outflow is negative)</td>
</tr>
<tr>
<td>DWR Bay-Delta</td>
<td>Estimated Delta island consumptive use</td>
</tr>
<tr>
<td>DWR DPLA</td>
<td>Sacramento Weir spill, Lisbon Weir flow</td>
</tr>
<tr>
<td>USBR</td>
<td>Delta Cross-Channel gate status, Tracy export, Contra Costa export</td>
</tr>
<tr>
<td>SCWD</td>
<td>Lake Barryessa releases, Lake Solano inflow, Putah Creek</td>
</tr>
</tbody>
</table>
Figure A.1 Dayflow Input Stations