SAN FRANCISCO ESTUARY INSTITUTE
4911 Central Avenue, Richmond, CA 94804 • p 510-746-7334 • f 510-746-7300 www.sfei.org

Natural Flow Hydrodynamic Modeling Technology Support Phase 1 Technical Memorandum

March 2014

Prepared For
Metropolitan Water District of Southern California
1121 L Street, Suite 900
Sacramento, CA 95814

Prepared By
San Francisco Estuary Institute
4911 Central Avenue
Richmond, CA 94804

Contents

1 Summary

This technical memorandum summarizes the work to date carried out by the San Francisco Estuary Institute (SFEI) to generate a bathymetric-topographic digital elevation model (DEM) of the historical Sacramento-San Joaquin Delta (representative of early 1800s conditions). It satisfies the deliverable of Subtask 3 of the Bay-Delta Natural Flow Hydrodynamics and Salinity Transport modeling project (Phase I; Task Order No. 9, Agreement No. 119900 between Resource Management Associates, Inc. and the Metropolitan Water District of Southern California) to provide written technology and data support for input into the technical memorandum described in Subtask 4 of the above task order.

This project was carried out in close collaboration with partners at the UC-Davis Center for Watershed Sciences (UC-Davis) and Resource Management Associates, Inc. (RMA), but the work conducted by each of these partners will only be referenced in this memorandum and not described in detail. Instead, the focus of this document will be on the steps and methods developed and implemented by SFEI itself. The historical DEM described in this document (and shown in **Figure 1**) is an interim/draft product completed for Phase I of the Bay-Delta Natural Flow Hydrodynamics and Salinity Transport modeling project. It is expected that the product and methods described here will be refined during a second phase of the project.

The sections below will describe the historical data sources used to generate the DEM and the methods developed to process the historical data into a form that could be adapted to conventional surface generation techniques. Data layers compiled or developed for this project include historical channel, marsh, and natural levee planform vectors, natural levee crest lines, and marsh drainage divides, which were all provided to RMA to establish the historical Delta's planform geometry for model grid construction (Section 2). Each of these layers was in some way derived from or informed by the Sacramento-San Joaquin Delta Historical Ecology ('Delta HE') study produced by the San Francisco Estuary Institute-Aquatic Science Center (SFEI-ASC; Whipple et al. 2012; available for download at http://www.sfei.org/DeltaHEStudy). To establish the vertical dimensions of the historical Delta, we digitized bathymetric soundings and topographic data from 19th and early-20th century surveys (Section 3 and Section 4). Historical elevation data were converted to a modern datum (Section 5) and further processed in partnership with UC-Davis scientists to generate a draft triangulated irregular network (TIN) and DEM of the Delta circa 1800 (Section 6). Finally, historical data obtained from local, state, and regional archives on historical tidal range, tidal inundation depth, and head of tide were georeferenced for use as model calibration data (Section 7).

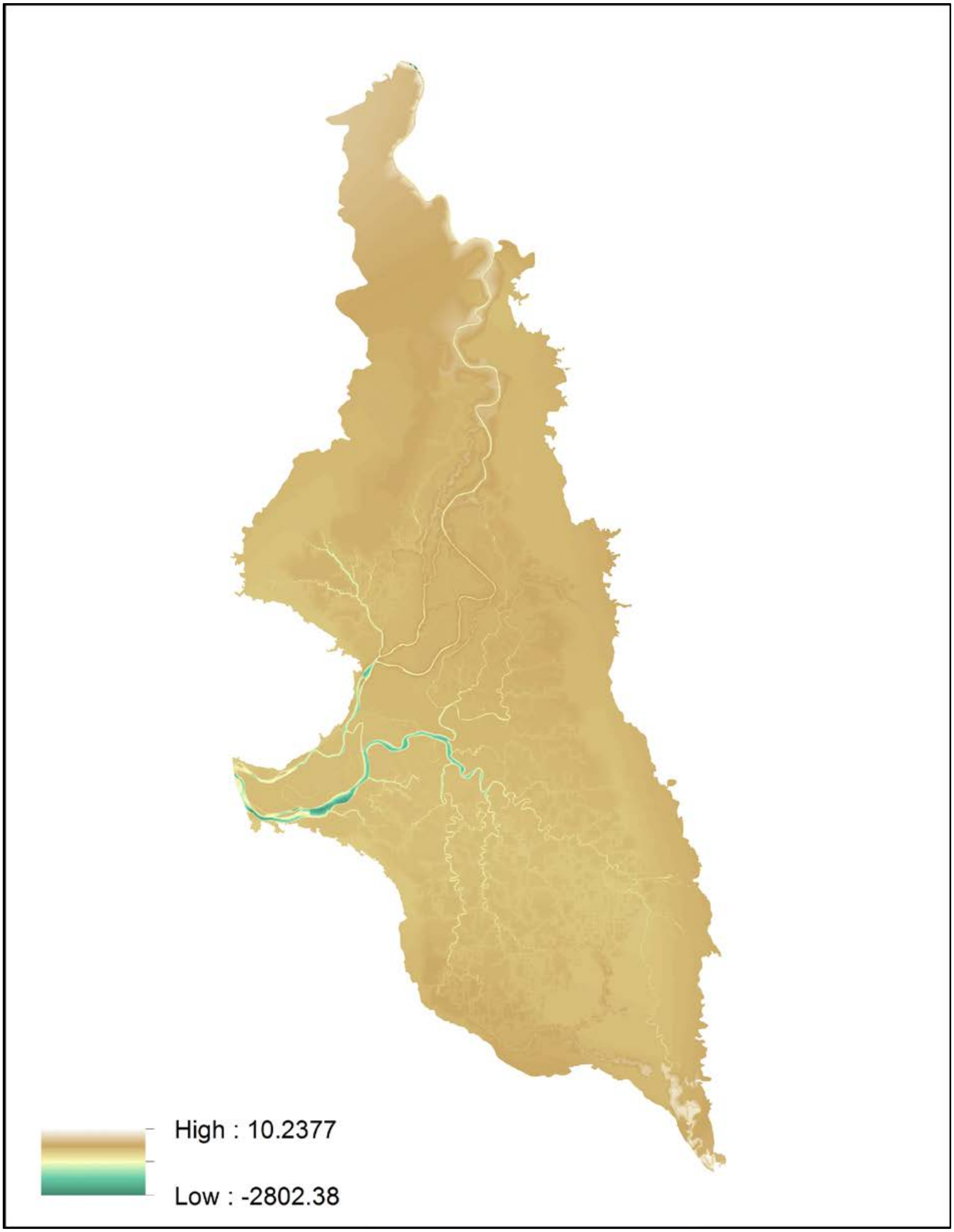

Figure 1. Phase I interim historical Delta digital elevation model (DEM).

2 Planform data for developing the historical Delta UnTRIM 3D model grid

SFEI developed a suite of GIS data layers that were provided to RMA for the purposes of constructing the historical Delta UnTRIM model grid. Together, these layers established the planform geometry of the historical Delta, to which the vertical dimensions of the historical Delta could be later added with the DEM. Brief descriptions of each layer follow. For all of the work described in this technical memorandum, the project study extent was defined by the SFEI-ASC Sacramento-San Joaquin Delta Historical Ecology ("Delta HE") Study GIS layers (Whipple et al. 2012).

2.1 Channel planform

This layer is a polygonal shapefile of all channels digitized as part of the Delta HE Study (Whipple et al. 2012) and thus represents the Delta's historical "shoreline" (**Figure 2**-**Figure 4**). Readers should refer to that report for detailed methods on how the Delta's historical channels were researched and mapped. Channels less than 15 m wide were originally mapped in the Delta HE study as one-dimensional polylines. To give these channels a width, we buffered the original channel line layer ("historical_creeks_Delta" from the Delta HE project's deliverable GIS data) by 3.5 m on each side to give the channels a width of 7 m (approximately half of the HE study's minimum mapping unit of 15 m). The buffered line layer was then dissolved with the channels that were originally mapped as polygons. Specifically, we selected polygons from the original habitat type layer ("historical_habitats_Delta" from the project's deliverable GIS data) that were classified either as *'fluvial low order channel,' 'fluvial mainstem channel,' 'tidal low order channel,' or 'tidal mainstem channel'*. Polygons associated with the Sacramento River above its confluence with the Feather River were removed. Additional, but minor, edits to the original Whipple et al. (2012) polygons were also made to correct channel topology.

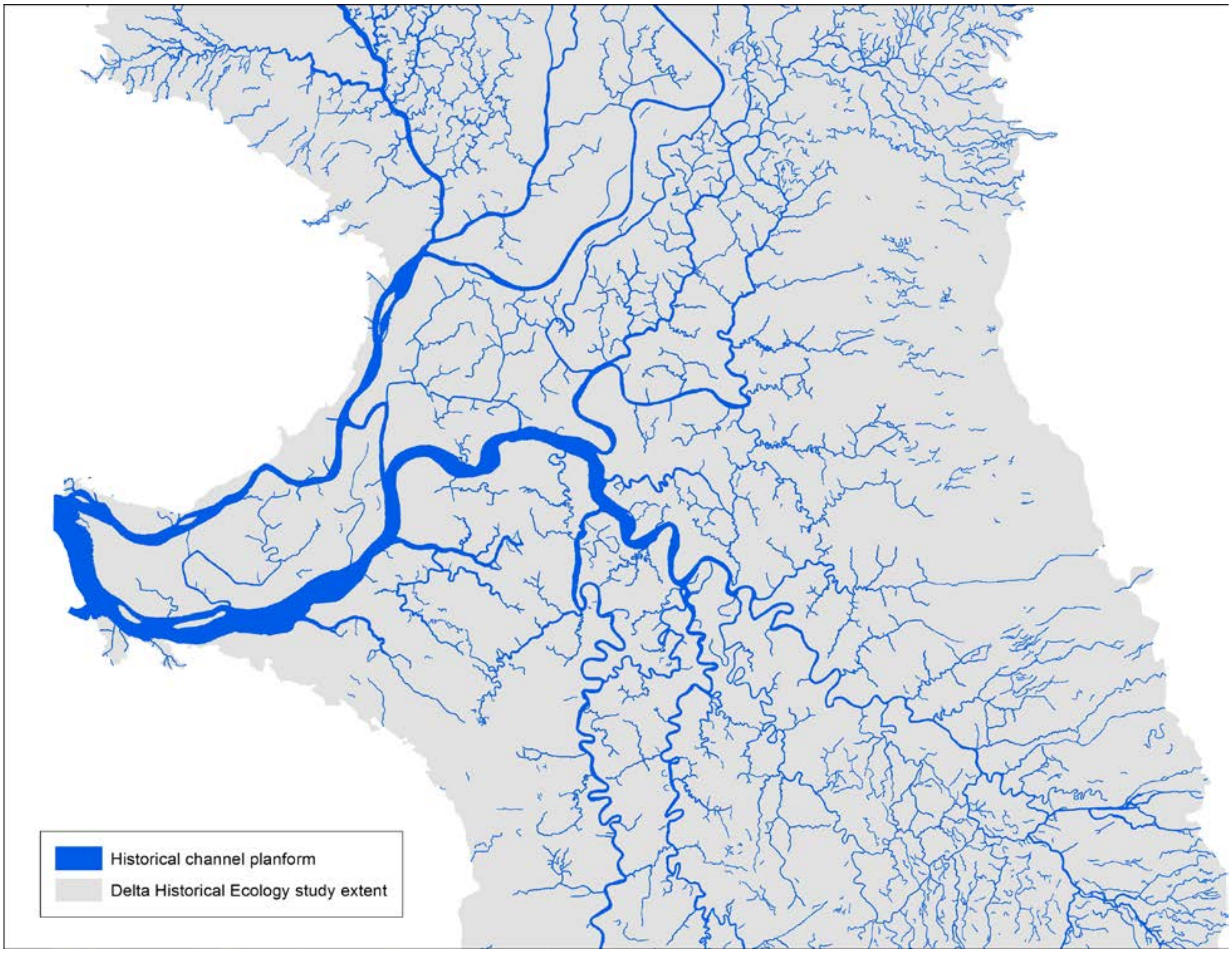

Figure 2. Subset of Central Delta historical channel planform data provided to RMA for model grid construction.

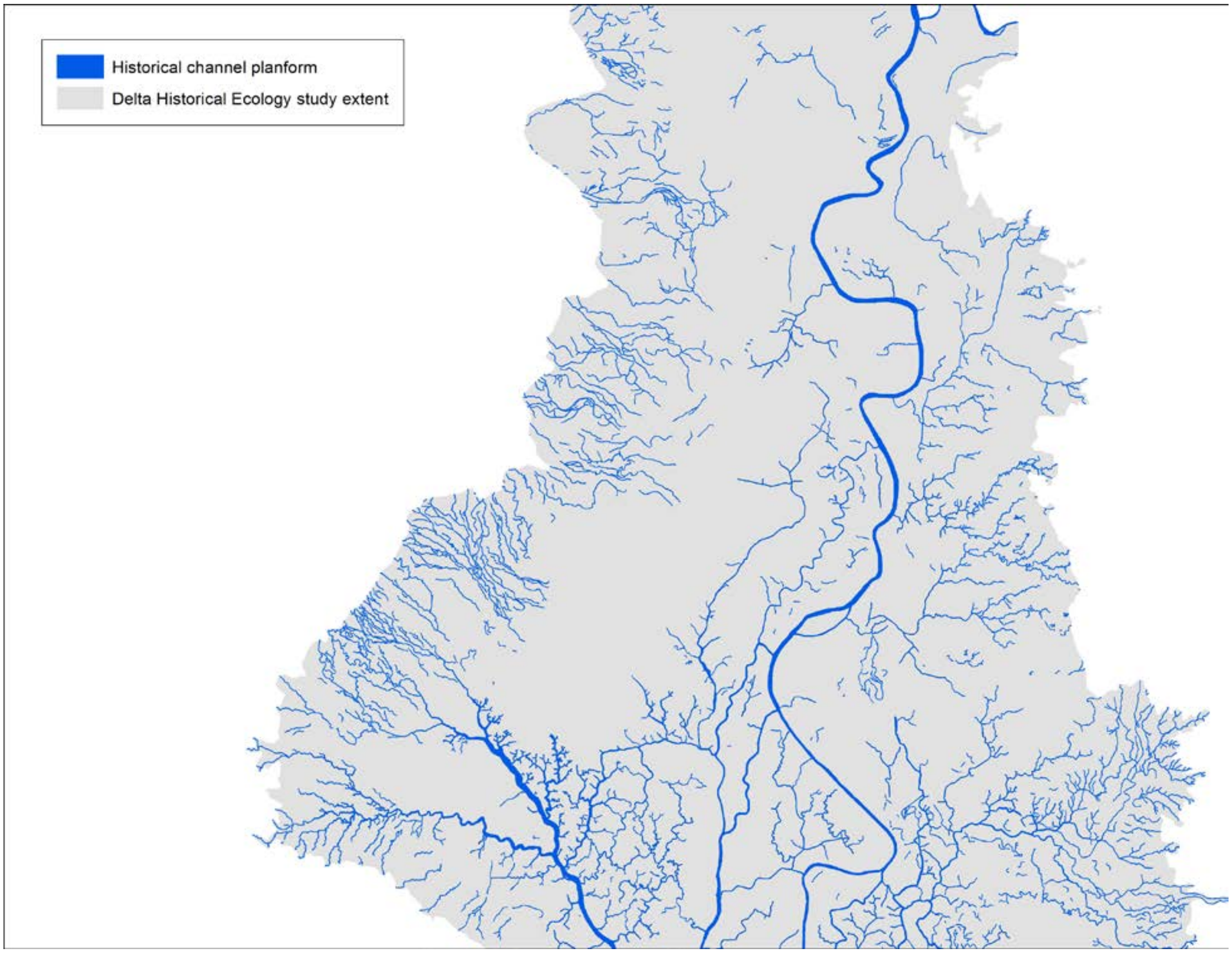

Figure 3. Subset of North Delta historical channel planform data provided to RMA for model grid construction.

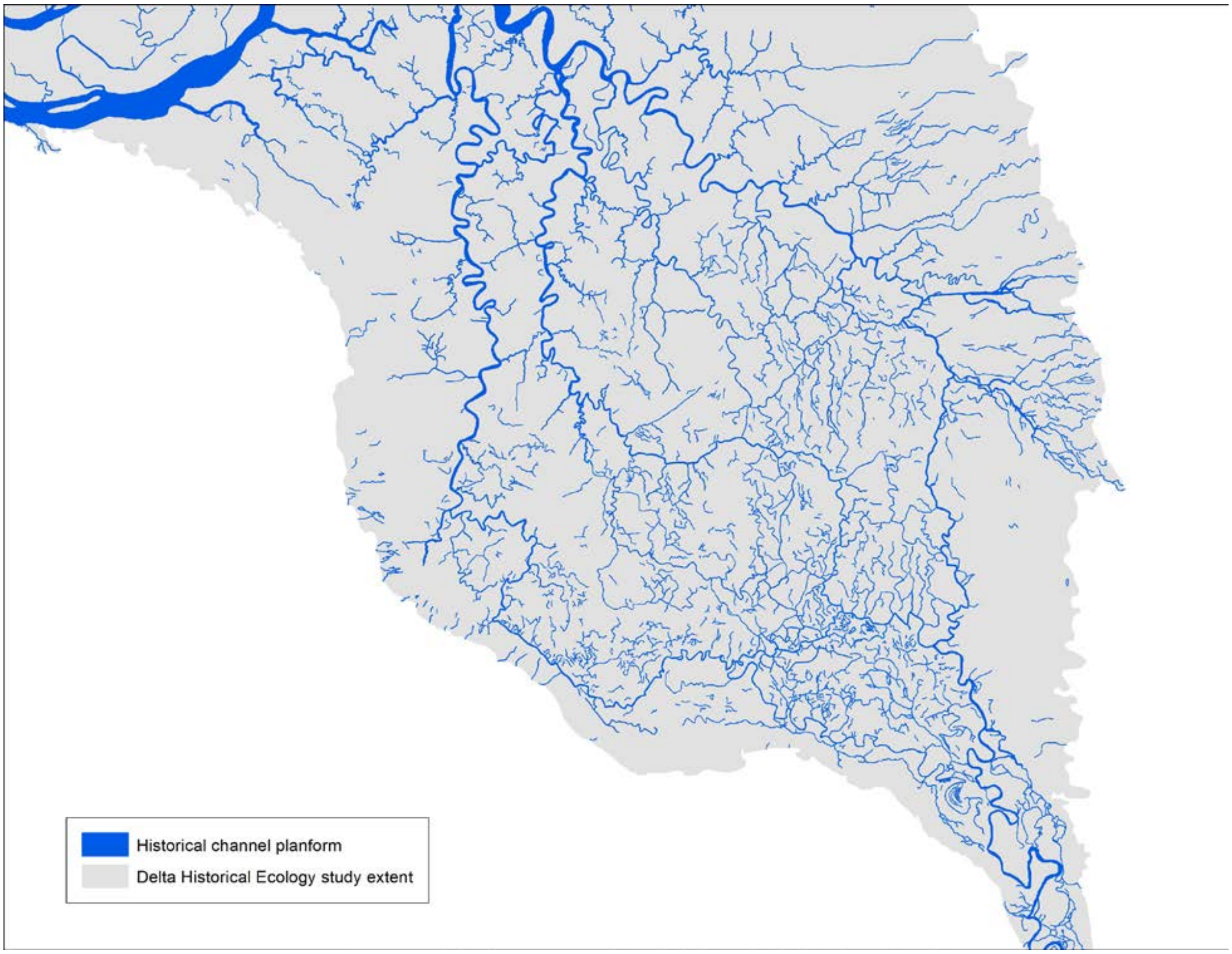

Figure 4. Subset of South Delta historical channel planform data provided to RMA for model grid construction.

2.2 Priority channels

Since the process of generating a model grid is labor-intensive, we developed a layer that identified the priority channels to be represented directly with grid geometry. Non-priority channels will still be represented in the natural Delta model, but using sub-grid geometry derived from the DEM. Three groups of channels were called out in the priority channel layer:

- **Any tidal channel represented as a polygon in the Delta HE study**. Since they were originally digitized as polygons these channels represent large (>15 m wide), well-documented channels
- **Any other "mainstem" tidal channel.** Mainstem channels, as defined by Whipple et al. (2012), were high order channels with large contributing watersheds (including the rivers and major streams of the Delta) or subtidal sloughs that delineated Delta islands.

- **Other priority channels.** This layer captured additional channels we felt were particularly important parts of the historical channel network (e.g., the main trunks of extensive dead-end slough networks and tidal channels originally mapped with a high certainty level).

2.3 Tidal marsh planform

This layer was a polygonal shapefile with all of the tidal marsh mapped in the Delta HE study. It was generated by selecting polygons from the Delta HE historical habitats layer (Whipple et al. 2012; "historical_habitats_Delta") that were classified as '*tidal freshwater emergent wetlands.'* The extent these polygons represents the expected maximum extent of historical tidal inundation.

2.4 Nontidal marsh planform

This layer was a polygonal shapefile with all of the nontidal marsh mapped in the Delta HE study. It was generated by selecting polygons from the Delta HE historical habitats layer (Whipple et al. 2012; "historical_habitats_Delta") that were classified as '*nontidal freshwater emergent wetlands.'* The extent of these polygons represents area we expect was not historically inundated by tides.

2.5 Tidal ponds and lakes planform

This layer was a polygonal shapefile with all of the tidal ponds and lakes mapped in the Delta HE study. It was generated by selecting polygons from the Delta HE historical habitats layer (Whipple et al. 2012; "historical_habitats_Delta") that were classified as either '*tidal perennial pond/lake'* or '*tidal intermittent pond/lake'*. Most of the features had clear connections with tidal channels, while some did not (but were still located within tidal marsh).

2.6 Tidalsheds

This polyline layer was created based on discussion during the SFEI-UCD-RMA meeting on November 15th, 2013. The lines represent our best attempt at representing flow divides (or "tidalsheds") between tidal channel networks and will be treated as breaklines in the hydrodynamic modeling. Lines were drawn by hand equidistant between adjacent historical channel networks based on our best professional judgment (**Figure 5**). Given the uncertainty concerning which historical areas were served by which channels, there are very few "closed" tidalsheds (lines were not drawn up to the edge of mapped tidal marsh, but stopped near the upstream extent of the tidal channels themselves). As we understand, these features will be fully incorporated into the model using an iterative process and will not be permanently fixed boundaries. In total, 122 tidalshed breaklines were drawn for inclusion in the model.

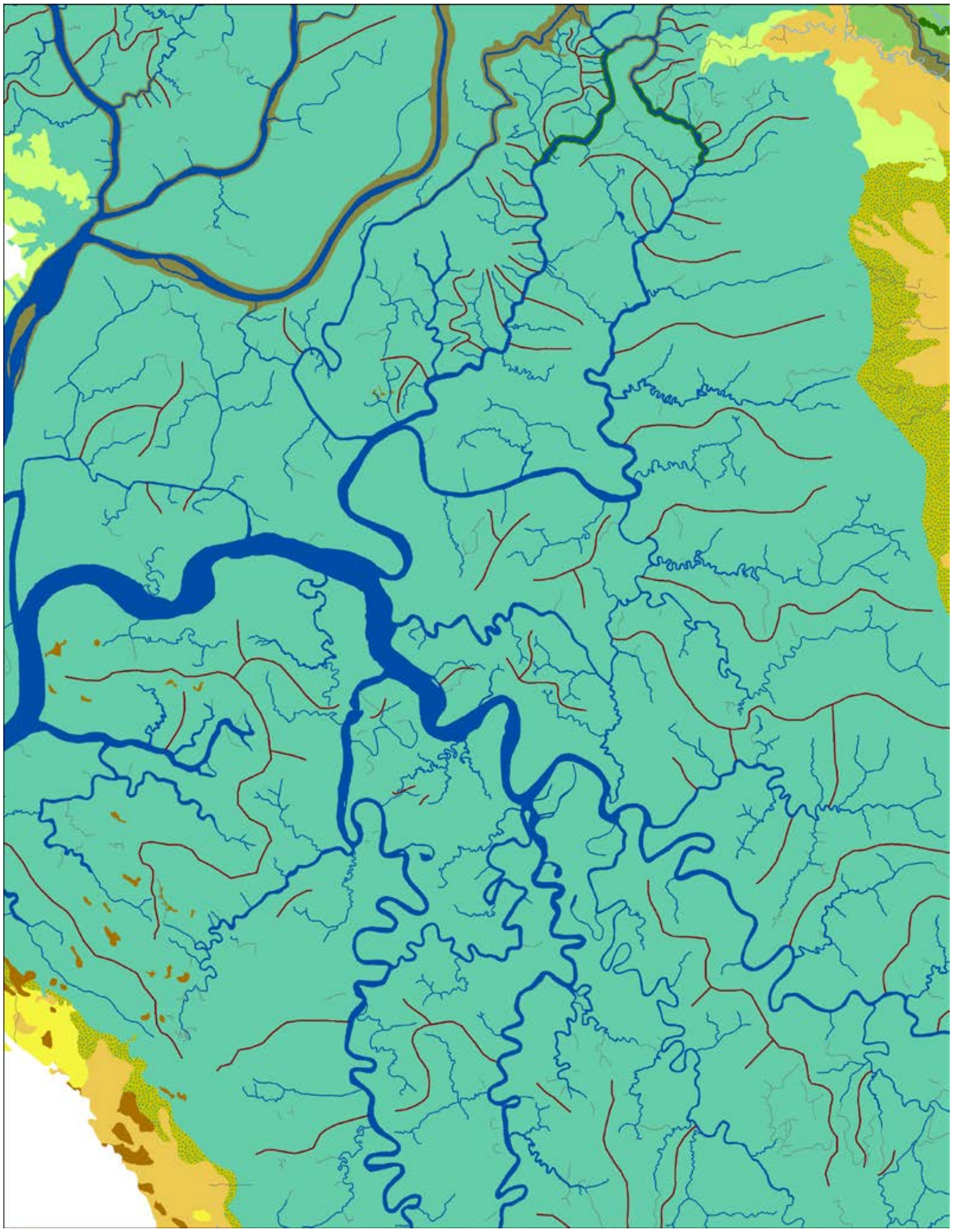

Figure 5. Subset of flow divides or "tidalsheds" (red lines) drawn equidistant between tidal channel networks (blue lines/polygons). Tidalsheds lines will be incorporated into hydrodynamic model as breaklines that prevent short circuiting between distinct networks.

2.7 Natural levee planform

A polygon file indicating the extent of historical natural levee features in the historical Delta. This layer was generated by selecting polygons from the Delta HE project's historical habitats layer ("historical_habitats_Delta" from the project's deliverable GIS data) that were classified as either *'valley foothill riparian'* or *'willow riparian scrub/shrub.'* These habitat types were both (almost exclusively) associated with natural levees (which were elevated above the level of the tides and composed of inorganic sediment). We therefore have identified the extent of natural levees based on their associated vegetation communities (and not, directly, from historical topography).

2.8 Natural levee crest lines

This polyline file indicates the approximate location of natural levee crests. Crest lines were generated by buffering polygonal channels that adjoin riparian habitat type polygons by 25 m. Channel polygons were taken from the layer described above (see "Channel planform" section), which was derived from the Delta HE project's GIS data (Whipple et al. 2012; http://www.sfei.org/DeltaHEStudy). Only channels that were fully connected to the mainstem network were buffered to generate natural levee crest lines (we chose not to buffer channels that extended only part way into the back side of a natural levee and did not connect through to the mainstem channel). See the "Natural levee planform" section above for a description of the riparian habitat type polygons used in this step.

The 25 m buffer distance was determined by haphazardly measuring distances between creek edge and the crest of natural levees as drawn on Debris Commission maps and historical USGS Quads. Crest location was determined from topographic lines or from the location of artificial levees and roads (which were assumed to be built at the apex of the natural levee). Across the Delta and with few exceptions, the distance between creek edge and natural levee crest was between 20 and 30 meters. While it eliminates the slight local and regional complexities in the location of the natural levee crest, the buffer method has the advantage of being efficient and reproducible. It also provides a work-around to the problem of imperfect alignment between the locations of historical channels as digitized for the Delta HE Study and the locations of channels in the georeferenced Debris Commission maps and USGS Quads. It is expected that this step in the DEM generation process will be revisited during Phase II of the project.

Where riparian habitat type polygons were < 25 m wide, buffers indicating the location of natural levee crests were not generated. In these cases, one of two alternate methods was used to generate a crest line. When only small segments of an otherwise greater than 25 m wide riparian forest were less than the 25 m buffer width, the resulting gaps in the crest polyline were filled by converting the natural levee planform layer (described above) to an outline, clipping the line representing the outer edge of the natural levee layer, and merging it with the 25 m buffer polyline. Crest polyline segments generated with this method are identified in a field titled "Gap" with a value of 1. When entire lengths of riparian forest were less than 25 m wide, a smaller buffer width was utilized. These particular lengths of riparian forest were not generally directly mapped from historical sources and were instead originally generated in the Delta HE study by buffering the channel by 15 m (see Whipple et al. 2012). Considering this, we buffered these channels by a width of 5 m to generate natural levee crest polylines (assuming the natural levee crest was closer to the inner edge of the riparian polygon than the outer edge). Crest polyline segments generated with this method are identified in a field titled "Five_m_buffer" with a value of 1. Crest polylines generated with 25 m buffers and 5 m buffers were misaligned where they met. The unaligned ends of these polylines were clipped and then connected with manual sketching in ArcGIS. These "connector" segments are identified in a field titled "Five_m_connector" with a value of 1.

Finally, a small number of naturally levee crests were digitized manually in places where they were not generated by any of the above methods. These segments are identified in a field titled "Other_manual" with a value of 1. The outcome is a single polyline representing the natural levee crests throughout the historical Delta.

3 Historical bathymetry

In order to assign a vertical dimension to the two-dimensional channel planform data (section 2.1), we compiled the best available bathymetric data for the historical Delta. Bathymetric data were obtained from mid-19th century sources, including US Coast Survey hydrographic sheets and early surveys of the Sacramento and San Joaquin rivers. Each of the sources utilized is summarized below in **Table 1**.

Table 1. Sources for historical Delta bathymetry utilized in this study.

Citation	Source/s	Digitized soundings
Cordell 1867 (Figure **6**)	"Hydrography of part of Sacramento and San Joaquin Rivers California"	4,809
Ringgold 1850a (Figure **11**)	Ringgold C. 1850a. Chart of Suisun & Vallejo Bays with the confluence of the Rivers Sacramento and San Joaquin. Courtesy of David Rumsey Map Collection, Cartography Associates.	97
Ringgold 1850b (Figure **12**)	Ringgold C. 1850b. Chart of the Sacramento River from Suisun City to the American River. Courtesy of David Rumsey Map Collection, Cartography Associates.	426
Gibbes 1850	Gibbes CD. W.B. Cooke & Co. 1850. Map of San Joaquin River. San Francisco, CA. Courtesy of Peter J. Shields Library Map Collection, UC Davis.	199
Debris Commission 1908-1923 (Figure **13**)	Wadsworth HH. U.S. Engineer Office. 1908a. Map of the Sacramento River: from the mouth of Feather River to Suisun Bay at Collinsville. San Francisco, CA. 1:4,800 Courtesy of the California State Lands Commission, Sacramento Wadsworth HH. U.S. Engineer Office. 1908b. Map of San Joaquin River, California: from Stockton to Suisun Bay at Collinsville. San Francisco, CA. 1:4,800 Courtesy of California State Lands Commission, Sacramento.	762

Historical bathymetric sources varied in their time-period, spatial accuracy, coverage, and sounding density. Because of this, historical soundings were digitized, utilized, and ultimately incorporated into the historical DEM using multiple methods. Due to data availability, the methods used to generate bathymetry for the historical DEM differed for the Delta mouth (downstream of Sherman Island) and above the Delta mouth (upstream of Sherman Island).

3.1 Bathymetry of the Delta mouth

The 1867 U.S. Coast Survey hydrographic sheet of the Delta mouth (Cordell 1867; **Figure 6**) is an early and spatially accurate source. While it was developed after the start of hydraulic mining in the Sierra foothills (a practice that significantly raised channel bed elevations in the Delta--particularly along the Sacramento River--between 1852 and the turn of the 19^{th}

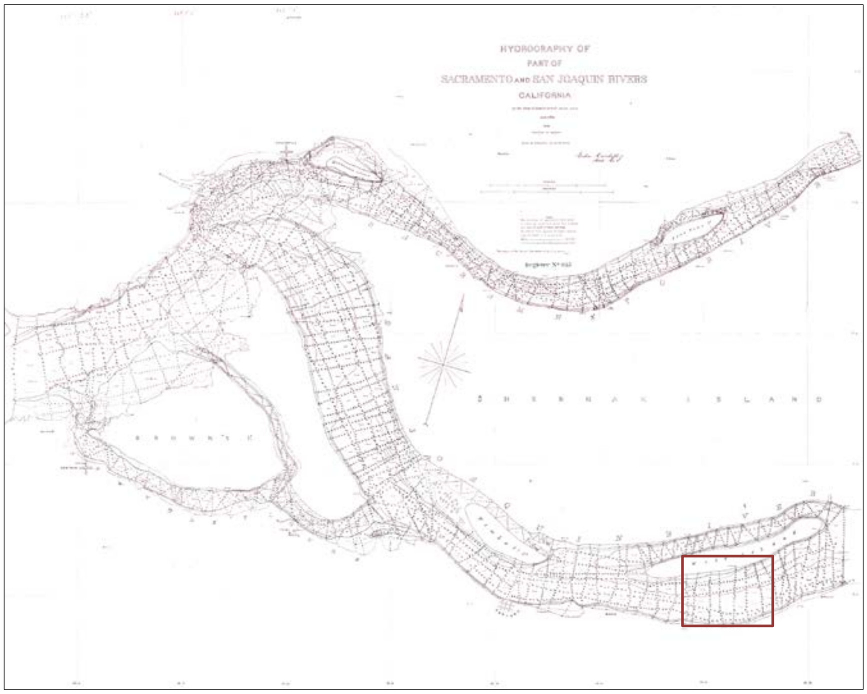

Figure 6. Cordell 1867 (United States Coast Survey). “Hydrography of part of Sacramento and San Joaquin Rivers California [H00935].” Hydrographic sheet (“H-Sheet”) with historical bathymetry at the Delta mouth. Detailed H-Sheets were created during the mid-19th century for the Bay, but did not extend upstream of Sherman Island. See **Figure 7** for detail of area bounded by red rectangle.

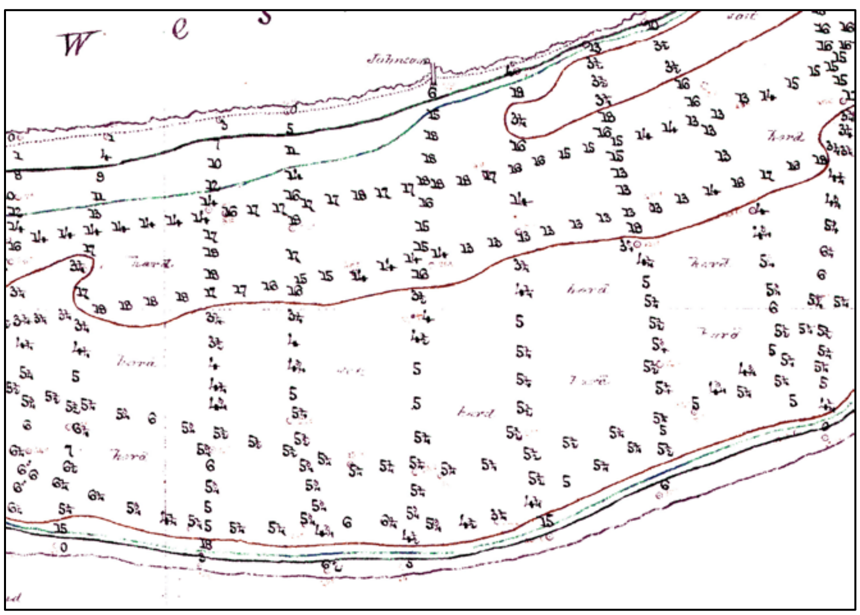

Figure 7. Detail of Cordell 1867 (United States Coast Survey). “Hydrography of part of Sacramento and San Joaquin Rivers California [H00935].” See **Figure 6** for full map and location of detailed area shown here. Soundings are expressed in feet up to 18 feet and beyond this depth in fathoms.

century; Whipple et al. 2012), we assumed for the purposes of this study that the map is representative of historical conditions. Although channel bed levels in Sacramento were approximately 3 ft. higher in 1867 than in 1850 (Jones 1967; **Figure 8**), we expect these differences were less pronounced at the Delta mouth, which has a higher tidal prism than Sacramento and is downstream of the Sacramento's confluence with the San Joaquin River (which was less affected by hydraulic mining debris).

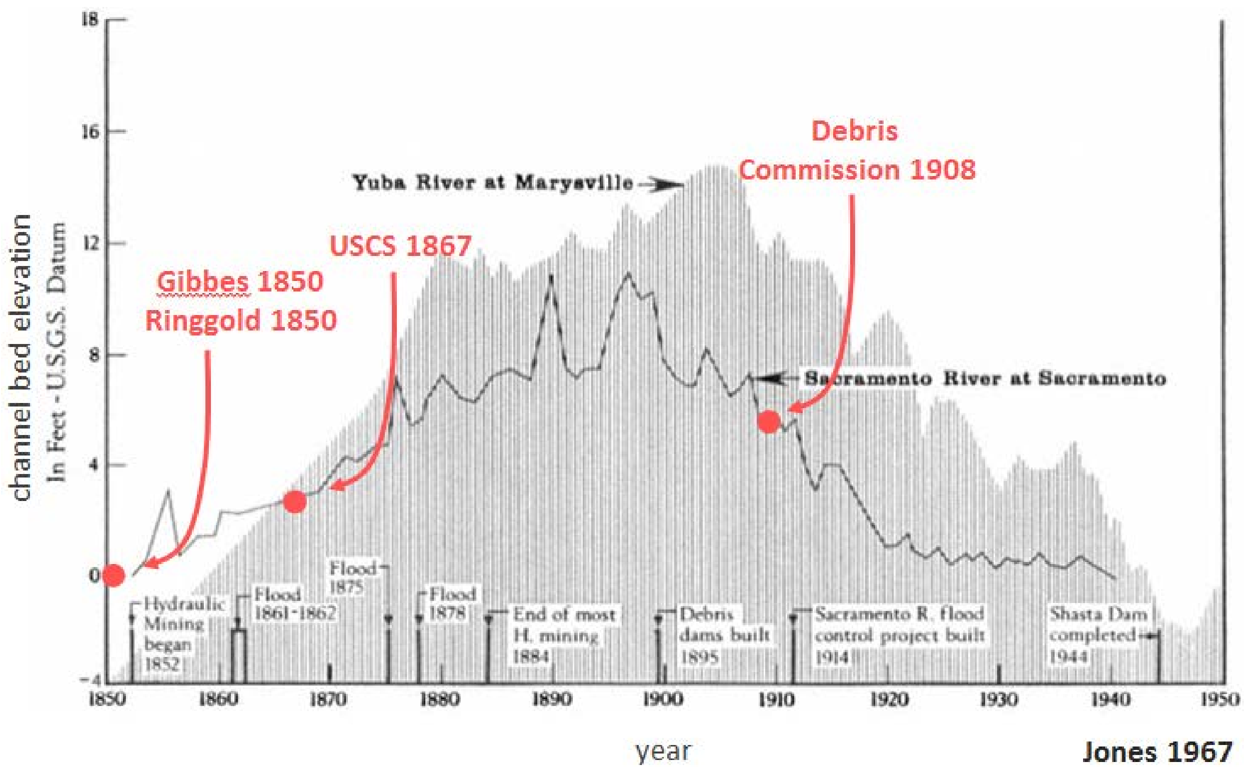

Figure 8. Channel bed elevation in the Sacramento River at Sacramento and Yuba River at Maryville from Jones (1967). Changes are associated with the influx of hydraulic mining debris from the Sierra foothills. Our sources for bathymetric data have been mapped onto the original chart based on their year (in red). Debris Commission data were used very selectively due to the changes in Delta bathymetry from earlier conditions.

The spatial accuracy and sounding density of the USCS map allowed us to confidently digitize soundings directly from a georeferenced version of the map (carried out by UC-Davis partners). 4,809 soundings were digitized from the map within the study extent (**Table 1**). After converting the digitized soundings to NAVD88 (see section 4), the points were used directly as TIN inputs by UC-Davis staff to generate the DEM bathymetry at the Delta mouth.

3.2 Bathymetry upstream of the Delta mouth

The U.S. Coast Survey produced detailed 19th century bathymetric maps for the San Francisco Bay Estuary only as far upstream as Sherman Island (**Figure 9**).

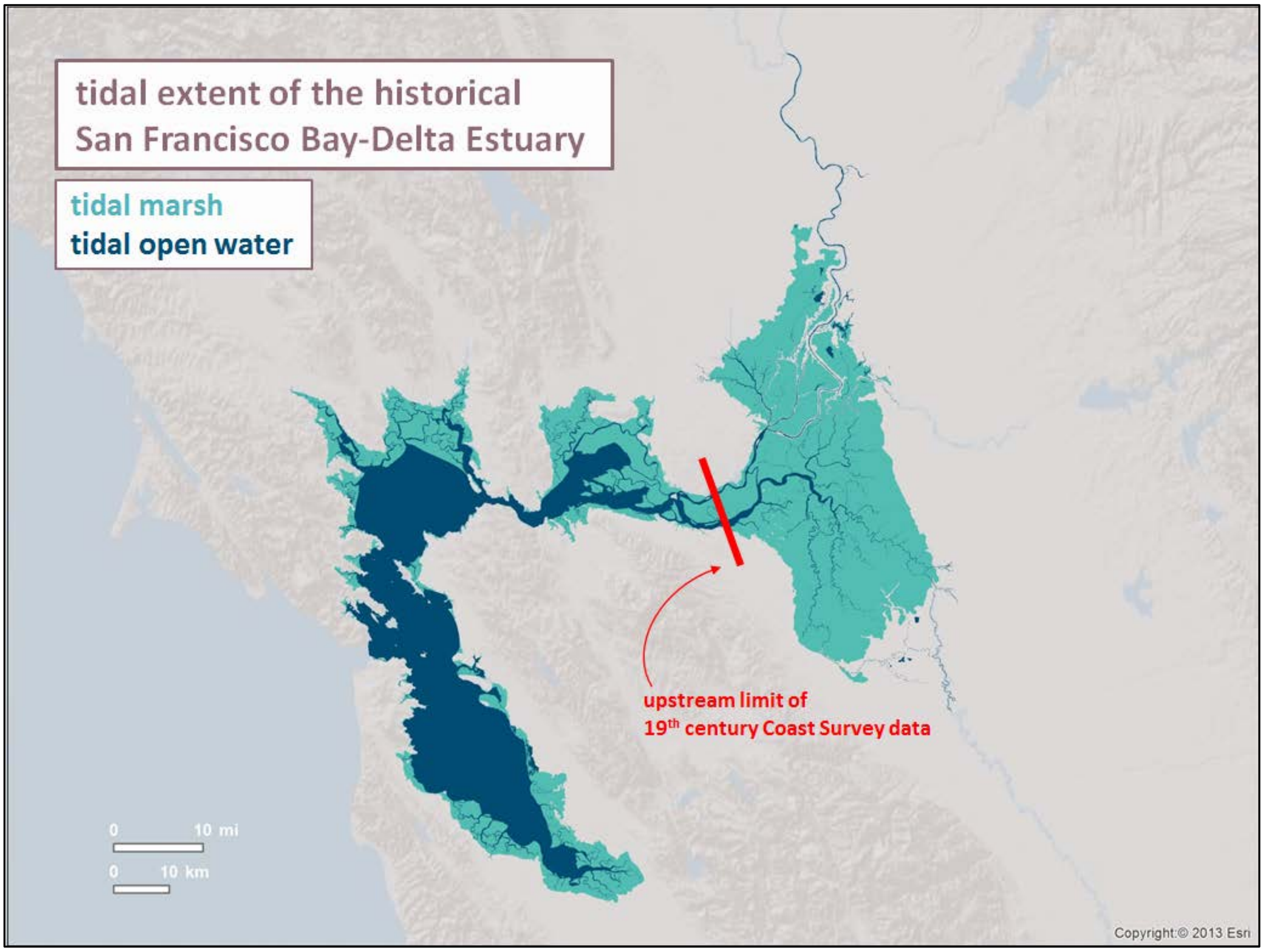

Figure 9. Map of the historical San Francisco Bay-Delta Estuary marked with the upstream limit of 19th century Coast Survey Data. The majority of our study extent falls upstream of this line. We therefore relied on additional data sources.

Bathymetry upstream of this location was derived from three historical maps made by Cadwalder Ringgold (1850a & 1850b) and Charles Gibbes (1850). Each of these maps was produced before the extensive mid-to-late-19th century hydraulic mining in the Sierra Nevada foothills (**Figure 8**). Working with these early historical sources posed a number of unique challenges and novel methods were developed to process the historical data into a form that could be adapted to conventional surface generation techniques. First and foremost, the mid-19th century sources only offered bathymetry for a portion of the study extent (**Figure 10**).

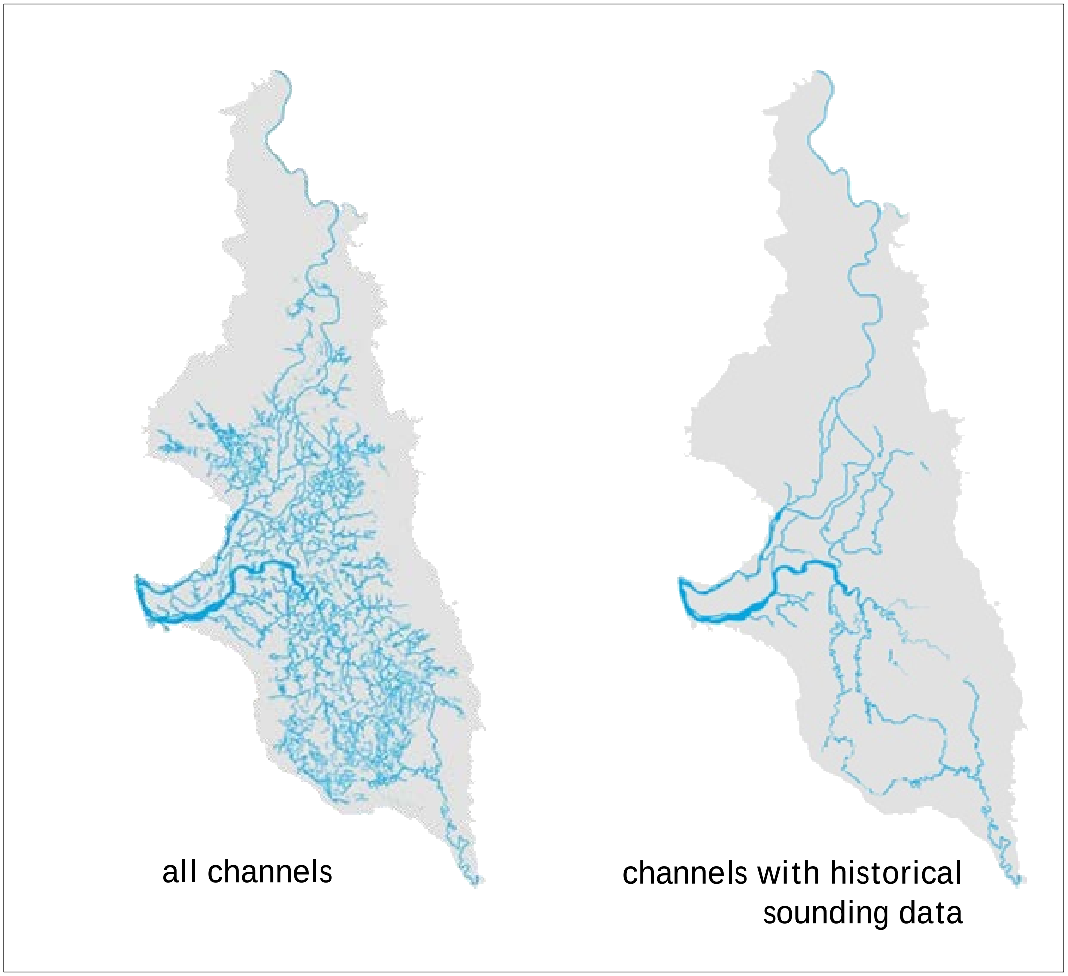

Figure 10. All historical tidal channels (left) versus historical tidal channels for which there was available historical sounding data (right). Historical sources did not generally indicate the depth of smaller (non-navigable) channels. In light of these data gaps, we extrapolated channel depths from channel widths with a regression built from the historical soundings (see section 3.2).

Because of this, we sought to determine historical channel depths from historical channel widths (which were available for the whole study extent from the 2D planform data; see section 2.1) by generating a regression relating channel width to thalweg depth. The relationship between these two variables was determined with the available historical bathymetry. We then assumed a parabolic shape for the Delta's channels and generated channel cross sections at regular intervals based on the extrapolated thalweg depth. This final step was carried out by UC-Davis staff with an ENVI script that outputted points indicating channel depth at regular intervals along each channel cross section. These points were converted to NAVD88 (see section 4) and then used by UC-Davis staff as mass points when creating the TIN surface of bathymetry above the Delta mouth. The work carried out by SFEI in the above steps is detailed below. Work conducted by UC-Davis staff is referenced as needed to provide the necessary context to understand the overall methodology.

- **Georeferencing historical bathymetry data**

  The maps by Ringgold (1850a & 1850b; **Figure 11** & **Figure 12**) and Gibbes (1850) have no known projection or features from which to establish reliable control points and lack the spatial accuracy of the U.S. Coast Survey maps.

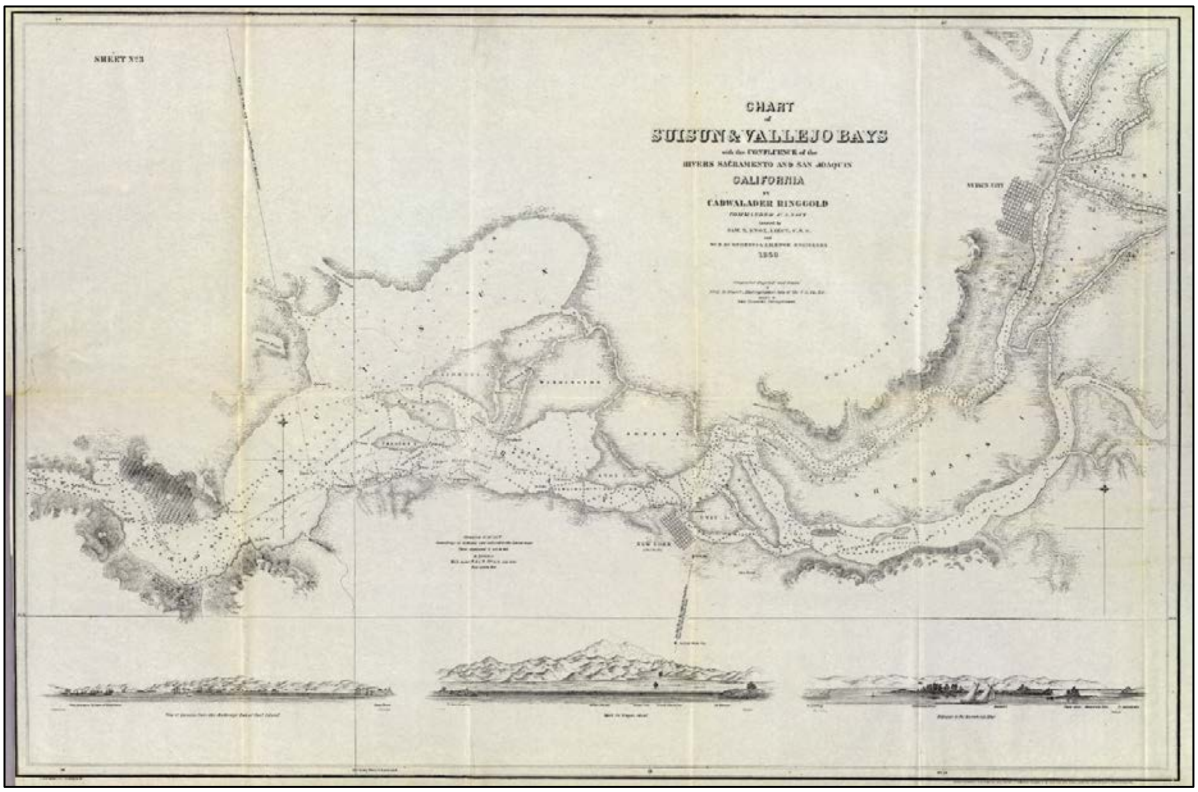

Figure 11. Ringgold 1850a. "Chart of Suisun & Vallejo Bays with the confluence of the Rivers Sacramento and San Joaquin." Courtesy of California State Library, Sacramento. An early source for thalweg depths up the Sacramento River. *Courtesy of David Rumsey Map Collection, Cartography Associates.*

When georeferenced, they do not exhibit close alignment with the channel planform established by the Delta HE study (Whipple et al. 2012) that was provided to RMA for developing the historical Delta model grid (Section 2). We were thus unable to directly digitize historical soundings from georeferenced maps. The soundings recorded by

Ringgold (1850a & 1850b) and Gibbes (1850) were instead georeferenced by matching channel meanders and confluences on the historical maps with meanders and confluences in the Delta HE channel centerline layer (soundings were generally taken at the apex of meanders) and placing the soundings relative to these features. Any soundings that were difficult to place were discarded.

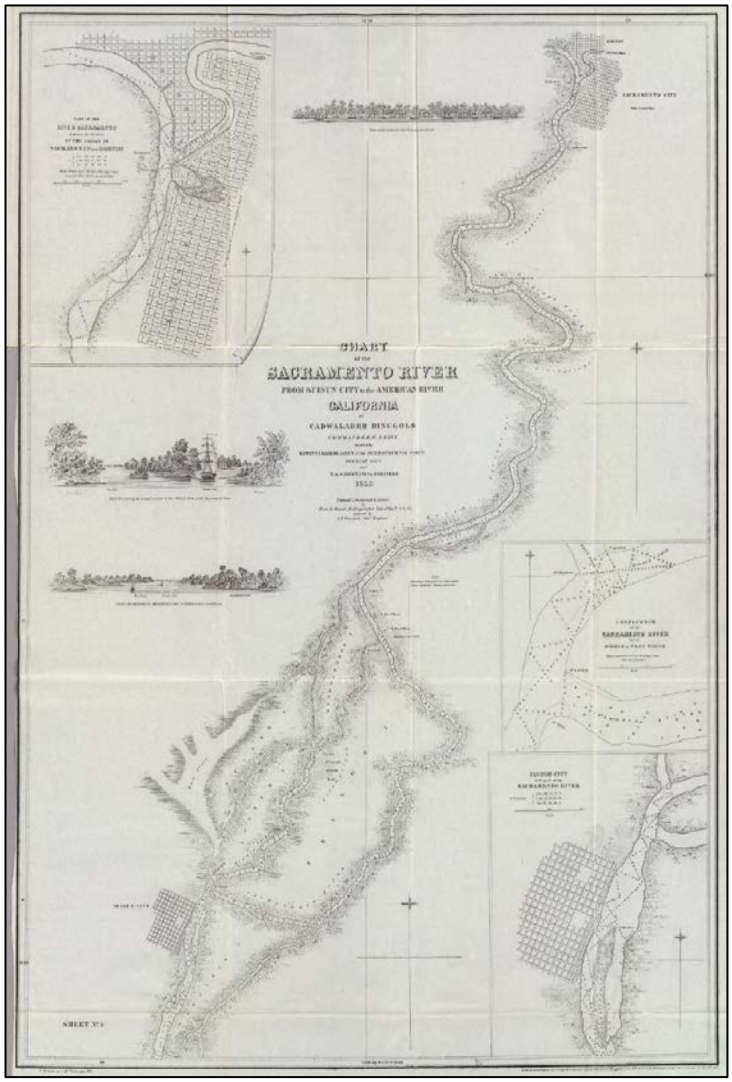

Figure 12. Ringgold 1850b. "Chart of the Sacramento River from Suisun City to the American River." An early source for thalweg depths up the Sacramento River. *Courtesy of David Rumsey Map Collection, Cartography Associates.*

Critical locations were substituted with soundings from maps created by the California Debris Commission between 1908 and 1913 (**Table 1**; **Figure 13**). The Debris Commission was established in 1893 to address problems associated with hydraulic mining debris. As part of this effort, the Debris Commission produced a series of maps that provide highly detailed depictions of channel bathymetry for the primary channels of the Delta. Since the Debris Commission maps were made after substantial alteration of Delta waterways from hydraulic mining debris (**Figure 8**), channel cuts, and dredging, we limited our use of Debris Commission bathymetric data to channel reaches with minimal physical alteration.

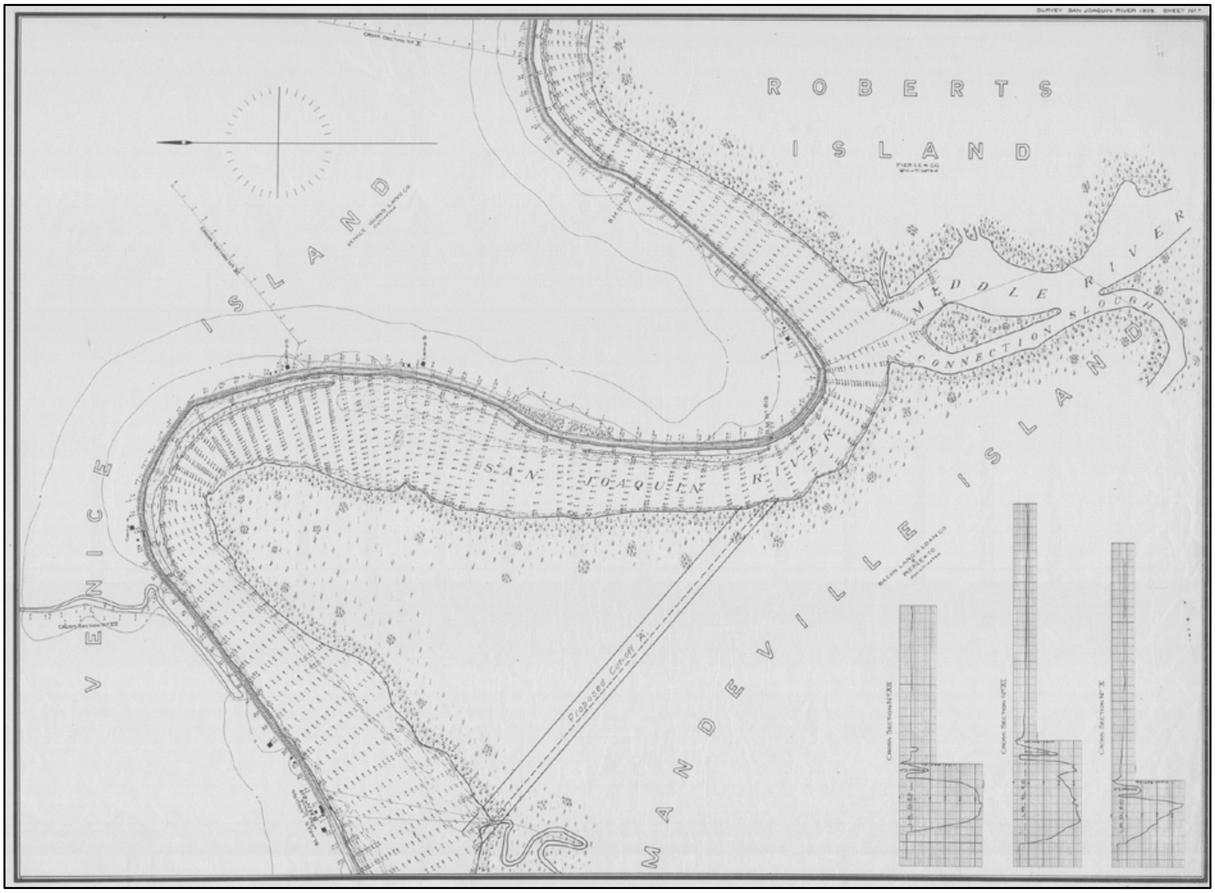

Figure 13. A representative Debris Commission Map (Debris Commission 1908-1928) from the vicinity of Mandeville Island. Between 1908 and 1928 the California Debris Commission produced hundreds of individual maps along the Sacramento, Feather, Mokelumne, and San Joaquin Rivers. Approximately 90 maps from the Debris Commission depicted early 20th-century bathymetry within our study extent.

For these sources (Ringgold 1850a, Ringgold 1850b, Gibbes 1850, and Debris Commission 1908-1923), only thalweg depths were recorded. All georeferenced historical soundings were snapped to the Delta HE channel centerline layer (this centerline was later modified by UC-Davis staff to better represent an actual thalweg line).

- **Converting georeferenced soundings to a common tidal datum**

Soundings represent the depth of the channel bed below the water surface. For use in the width-depth regression, all georeferenced soundings were converted to meters and referenced to the same tidal datum ("low water" or mean lower-low water [MLLW] during low river stages). Notes on Ringgold 1850a & 1850b explicitly state that the soundings were "reduced to the lowest water." We assumed that the soundings measured by Gibbes 1850 also represent low water conditions (as is the standard for navigational charts), but this was not stated explicitly on the map. Different Debris Commission charts used different reference grades for soundings. When the reference grade was not explicitly stated to be MLLW during "a continuous low water period," profiles accompanying the charts relating the reference grade to various tidal datums allowed us to convert Debris Commission soundings to MLLW.

- **Using georeferenced soundings to establish relationship between channel width and depth**

Georeferenced historical soundings were only available for a portion of the channels within the study extent (**Figure 10**). In light of these data gaps, we extrapolated channel thalweg depths from channel widths with a regression built from the georeferenced historical soundings. The regression was only generated with georeferenced historical soundings from within the extent defined by Whipple et al. (2012) as historically subject to tides (the focus of Phase I modeling efforts).

Channel widths were assigned at 100 m intervals to the SFEI HE channel centerline layer using a custom Python tool developed by SFEI for a related project (unpublished manuscript). The georeferenced soundings were then spatially joined to the centerline to create a dataset of historical channel widths with associated MLLW thalweg depths. Historical widths and depths were plotted against one another and fitted with a power function (**Figure 14**). A power function was selected because of known power relationships between width and depth in fluvial systems and because it avoided generating negative depths at smaller channel widths.

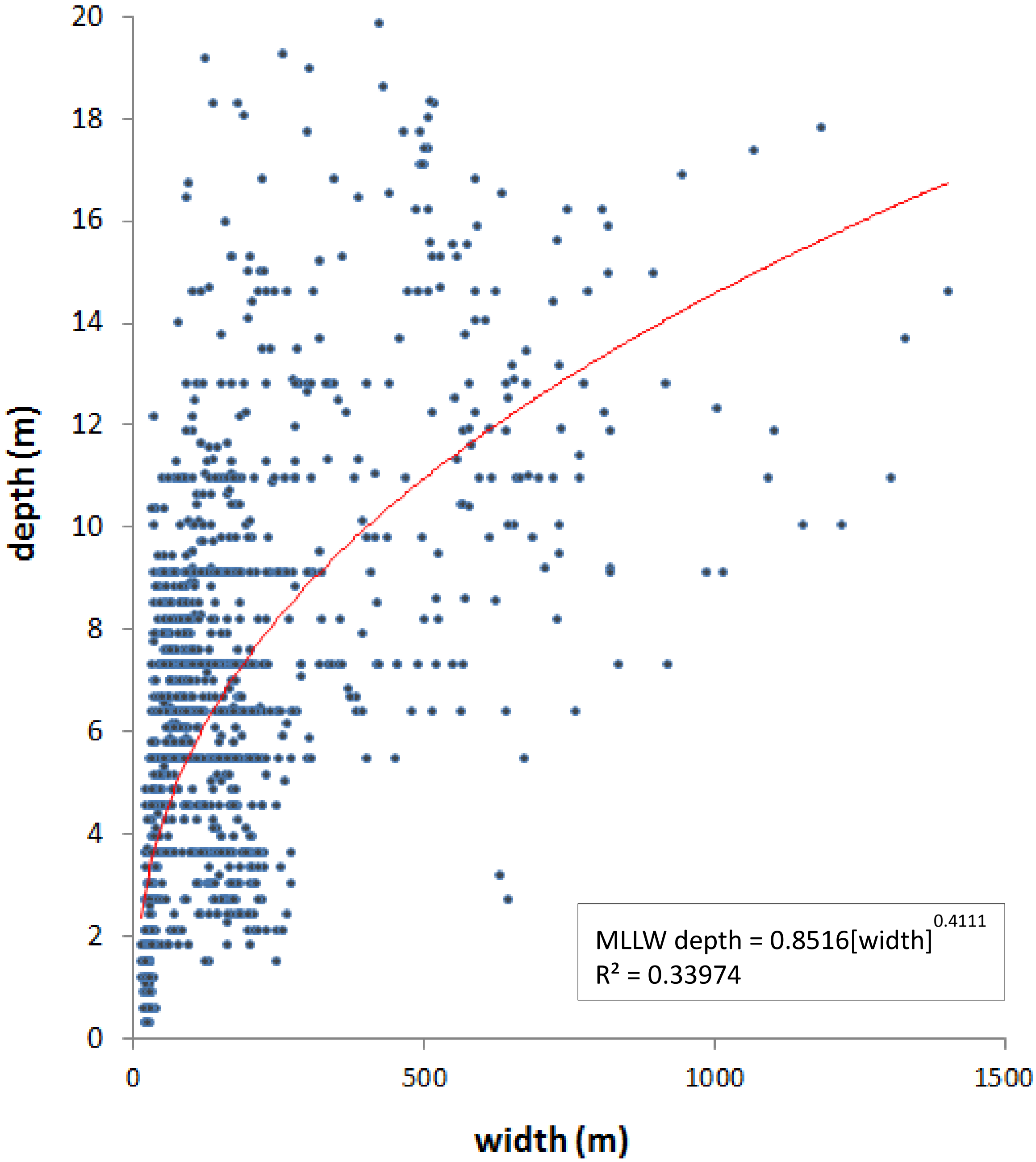

Figure 14. Scatter plot of historical channel depth vs. historical channel width. Each data point represents one historical sounding (adjusted to MLLW and representative of the thalweg depth) plotted against the width of the historical channel at the sounding's location (as derived from the historical channel planform layer; N = 1,484). Data points have been fitted with a power function (red line) with the boxed equation.

While not perfect, this method was selected after extensive conversations with experts on tidal marsh morphology, and appears to provide reasonable estimates of channel depth given the available information. The function took the following form and was used to extrapolate depths for all channels:

Let y = channel depth at MLLW
Let x = channel width

$$y = 0.8516x^{0.4111}$$
$$R^2 = 0.33974$$

- **Extrapolating historical thalweg depths across the whole study extent**

The above equation was used to extrapolate the widths of all mapped historical channels upstream of the Delta mouth. Since width was calculated at 100 m intervals, so too was channel thalweg depth.

Small historical channels (with widths < 15 m) were originally digitized as polylines and thus did not have a precisely known width for use in the regression. We assigned these channels a width of 7 m (approximately half the minimum mapping unit for digitizing channels polygons) when extrapolating depths using the width-depth regression.

- **Applying a parabolic channel shape (UC-Davis)**

Since the regression only allowed us to extrapolate historical channel thalweg depths, another step was required to give channels a shape *around* the thalweg. Based on conversations with experts on tidal marsh morphology, we settled on a parabolic shape for channels above the Delta mouth. While this shape inevitably simplifies channel morphology, we felt it best represented channel cross-sectional area given the available data. Determining how sensitive the hydrodynamic model is to this assumption and researching other possible channel shapes is a priority for Phase II modeling efforts.

UC-Davis partners established channel shape by generating parabolic channel cross-sections from the historical channel thalweg and shoreline. Cross-sections were generated along channel transects generated by SFEI at 100 m intervals and outputted as a series of points (**Figure 15**). These points were converted to NAVD88 (see Section 4) and then used by UC-Davis staff as mass points for creating the TIN of historical surface elevation above the Delta mouth.

For the sake of efficiency, parabolic cross sections were only generated for channels originally mapped in the Delta HE study as polygons (channels > 15 m wide). Smaller channels (originally mapped as only polylines) were given a simple triangular shape during TIN creation by directly connecting the buffered channel shorelines (set 7 m apart) and thalweg. We expect that, since the volume of these smaller channels constitutes only a fraction of the Delta's total volume, that this channel morphology will not dramatically impact hydrodynamic modeling. This remains to be tested, however, and should be further explored during Phase II modeling.

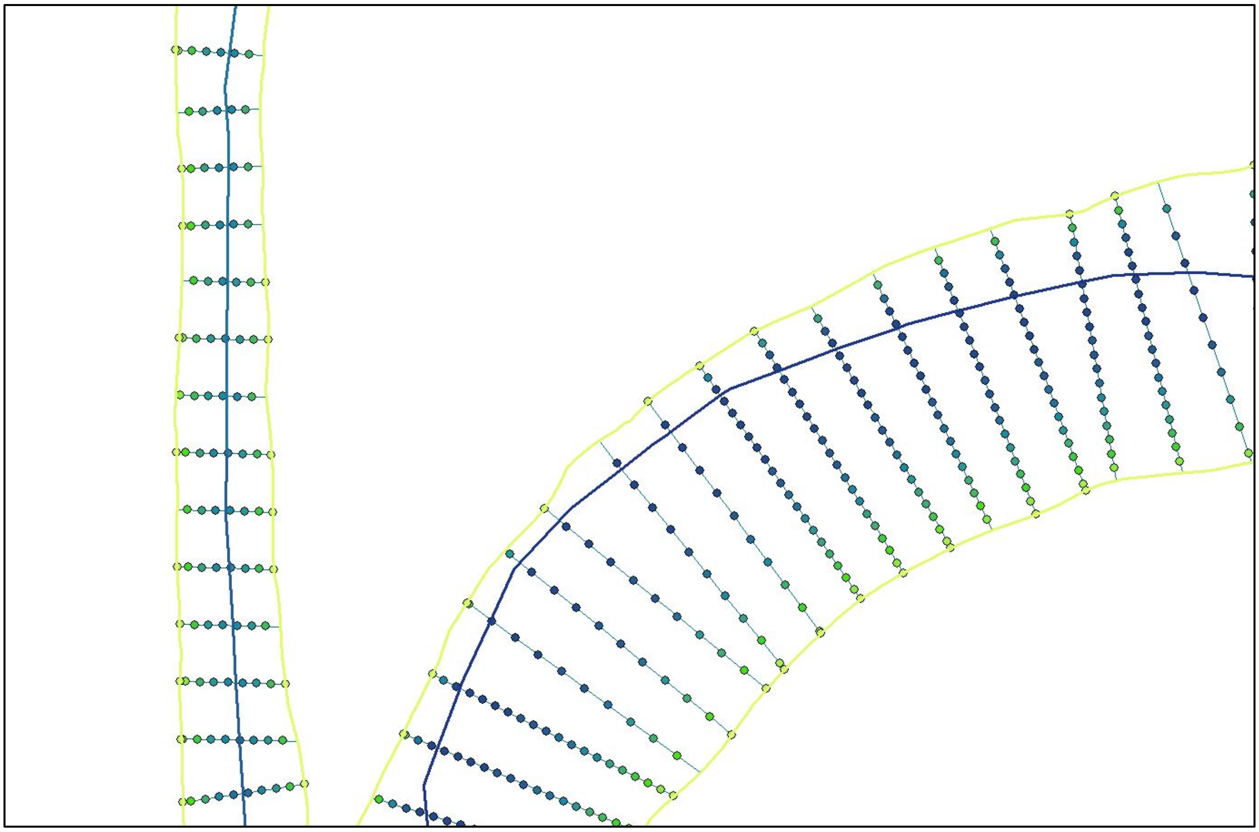

Figure 15. Points generated from an ENVI script along channel cross-sections at 100 m intervals. Points were generated along the transects and their depth based on channel thalweg depth (the blue line) and channel shoreline depth (set to 0 or MLLW). These points were later converted to NAVD88 (see Section 4) and then used by UC-Davis staff as mass points for creating the TIN of historical surface elevation above the Delta mouth.

4 Historical topography

4.1 Natural levee elevation

Historical natural levee crest elevations were obtained from early-20th century Debris Commission maps (Debris Commission 1908-1913; **Table 1**; **Figure 13**). Elevations written on the maps were digitized as point files, converted to a modern datum (NAVD88; see Section 0), and provided to UC-Davis partners who attributed the elevations to natural levee crestlines for use in TIN creation. The Debris Commission maps noted natural levee elevations in one of two ways: 1) as part of elevation cross sections or 2) as “spot elevations”. From the Debris Commission cross-sections (**Figure 16**), we used best professional judgment to identify the maximum elevation of the natural levee (“crest elevation”).

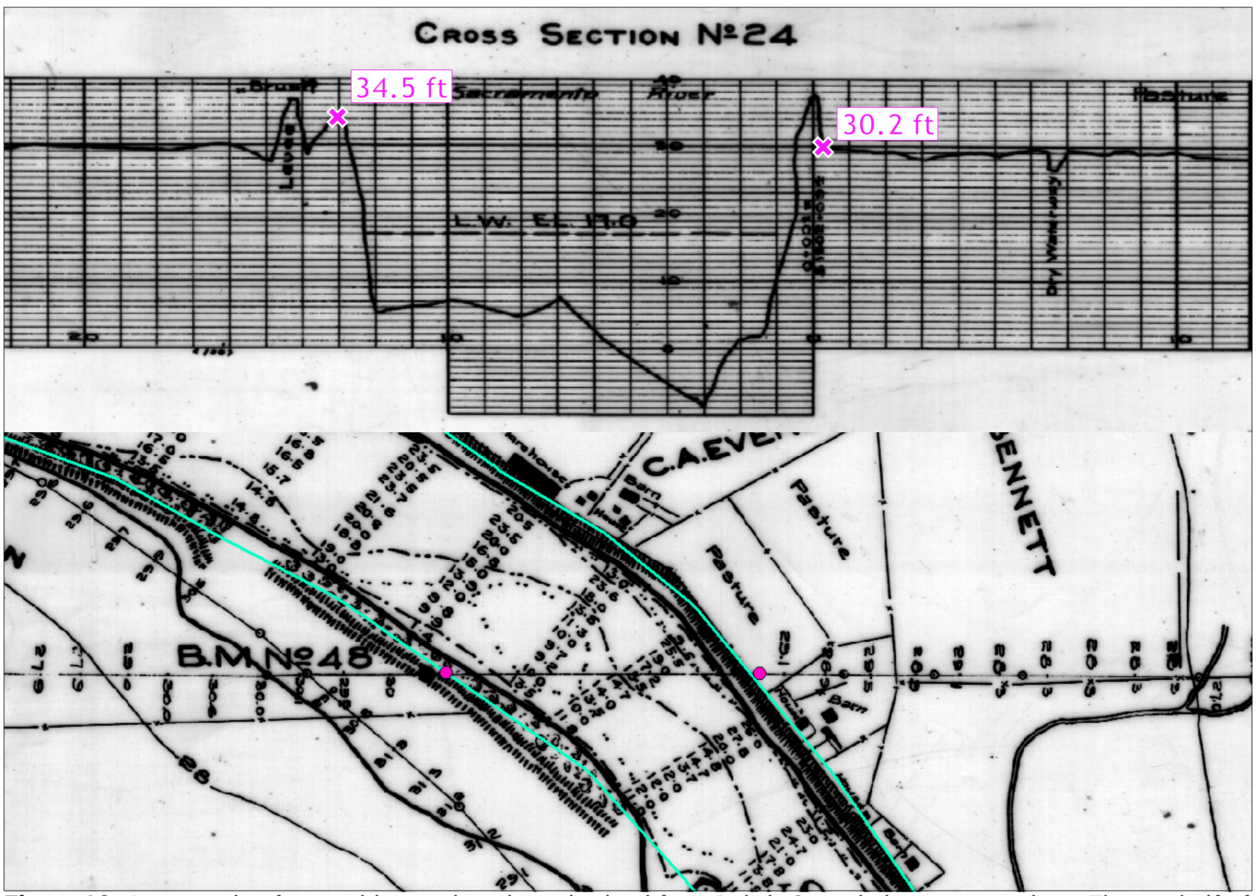

Figure 16. An example of natural levee elevations obtained from Debris Commission cross-sections. The top half of the figure shows the cross-sectional profile of the line drawn on the map in the bottom half of the figure. Crest elevations were identified from the elevation profile (pink crosses) and then attributed to points digitized from the georeferenced maps (pink dots). The teal polylines show the natural levee crest lines (see Section 2.8). Crest elevations were ultimately attributed to crestlines by UC-Davis staff for TIN/DEM generation (Section 6).

This was not always obvious, as artificial levees had already been constructed on top of natural levees at the time the Debris Commission maps were produced. Crest elevation was generally identified on the cross-section profiles as directly behind the artificial levees at the break in slope. In other cases, where artificial levees were absent set back from the channel, natural levee elevations were easily identified. We digitized elevations from cross-sections on both channel banks. When extensive topographic modification made it especially difficult to determine the elevation of natural levee crests, cross-sections were not used.

In addition to latitudinal elevations associated with cross-sections, the Debris Commission maps also indicate longitudinal elevation at regular intervals along creek banks ("spot elevations"; **Figure 17**). Because spot-elevations are not associated with latitudinal cross-sections, they are not guaranteed to represent maximum crest elevations. Most spot-elevations were taken behind artificial levees and thus probably underestimate historical natural levee height. Creeks with only one artificially leveed bank allow us to compare spot elevations taken behind artificial levees to those taken directly adjacent to the creek edge. Spot-elevations taken behind natural levees are generally 3-4 ft. lower than those on the opposing un-leveed bank (Figure 2). We did not, however, attempt to correct for this difference. When both cross-sections and spot elevations were available, preference was given to elevations derived from cross-sections.

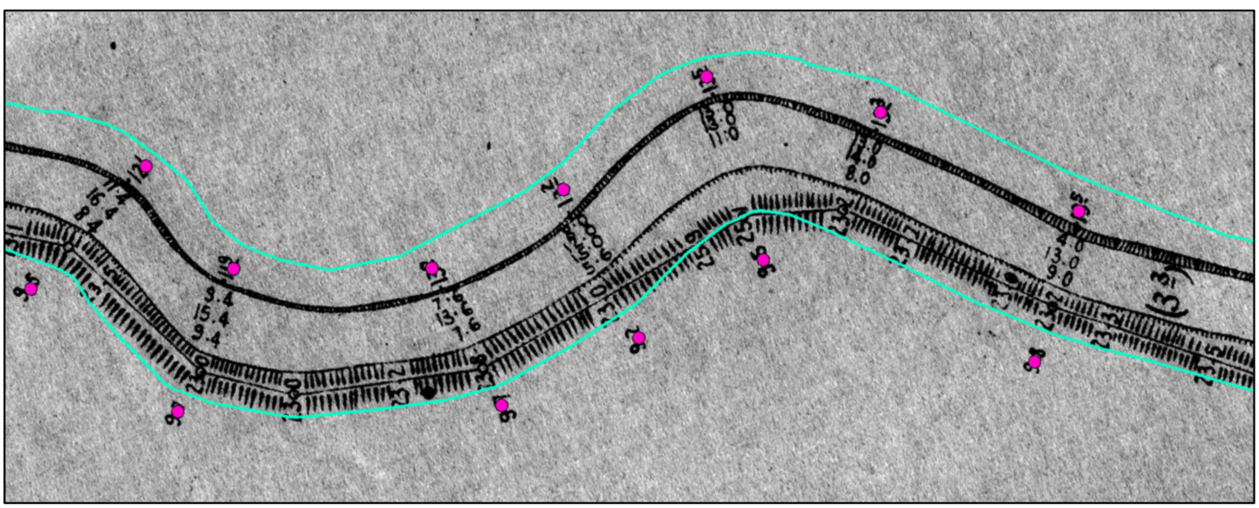

Figure 17. Examples of natural levee elevations digitized from Debris Commission spot-elevations (pink dots). Spot-elevations are not associated with cross-sectional elevation profiles and are thus not guaranteed to represent maximum crest elevations. Most spot-elevations were taken behind artificial levees (as seen on the lower bank in the image above) and thus probably underestimate natural levee height.

In total, 705 points indicating the crest elevation of natural levees were obtained from the Debris Commission maps. With few exceptions, this selection of points provided reasonable coverage of nearly all of the historical Delta's natural levees. That said, the Debris Commission maps rarely noted the elevation of natural levees at intervals of less than 100 m. While this captures patterns across large spatial extents, any fine-scale variation in natural levee heights is currently underrepresented in the DEM. Elevations form the Debris Commission maps were corroborated with information from the historical record and will be compared against (or possibly derived from) LiDAR data in Phase II DEM work.

4.2 Marsh plain elevation

In the Phase I historical DEM, the elevation of the historical marsh plain was approximated by UC-Davis partners by using a value relative to our preliminary raster of historical mean sea-level (MSL) elevation (see Section 5.2). Major modifications to this methodology are expected for Phase II of the project.

5 Converting historical data to NAVD88

The hydrodynamic model developed by RMA required absolute elevations referenced to a modern fixed datum (NAVD88). Our historical sources for bathymetry and topography, however, were created well before the development of a standardized vertical datum (the Sea Level Datum of 1929, for instance). Since our early sources of bathymetry (**Table 1**) were referenced to a low water surface (Section 3.2), we were required to attempt the complicated task of converting a historical tidal datum to a modern fixed datum (NAVD88). The method developed in Phase I for converting our historical soundings to NAVD88 bed elevations entailed two primary steps:

Step #1) Convert historical mean lower-low water (MLLW) depth to historical local mean sea level (MSL) depth by adding tidal amplitude (or one-half the tidal range) to MLLW depth.

Step #2) Obtain historical bed elevation (in NAVD88) by subtracting MSL depth from MSL elevation (in NAVD88)

It is important to note that step #1 assumes that mean tide level (MTL; the arithmetic mean of mean high water and mean low water) is approximately equal to mean sea level (MSL; the arithmetic mean of hourly heights observed over a given time period, usually a month, year, or tidal epoch). While this is not explicitly true, the values in the Delta are often very close. Step #1, then, can be summarized with the following simple equation:

$$(\text{MLLW depth}) + .5(\text{tidal range}) = (\text{MTL depth}) \approx (\text{MSL depth})$$

Step #2:

$$(\text{MSL elevation, NAVD88}) - (\text{MSL depth}) = (\text{bed elevation, NAVD88})$$

To implement these equations, we were thus required to determine two variables: a) historical Delta tidal range and b) historical Delta mean sea level elevation, both of which vary spatially. We developed two raster surfaces quantifying each of these variables across the full study extent. Once completed, we were able to use the raters to convert the historical bathymetry (represented as points and described in Section 3) to a modern fixed datum for DEM creation and hydrodynamic modeling. The development of these rasters is described below.

5.1 Historical tidal range surface

The historical tidal range raster developed for Phase I is shown in **Figure 18**.

The historical tidal range surface was developed by interpolating between georeferenced tidal range values pulled from historical sources (shown in **Figure 18**) using the 'Create TIN' tool in ArcGIS 10.1. Quotes from the textual record georeferenced to develop the tidal range surface include, "The tide at low water rises about **eight inches** where the west line of Von Schmidt's survey crosses Dry creek" (Gray 1859), "The tide of the ocean sets back to the height of **two feet** at Sacramento" (McCollum 1850), and "There is tide all the way up to the mouth of Dry Creek at which point it affects it about **an inch**" (van Scoyk 1859). Additional points were created at the boundary between tidal and nontidal creek reaches as mapped in the Delta HE study (Whipple et al. 2012). Where records were too far apart for the TIN to successfully/realistically interpolate between, best professional judgment was used to add values between known points. In total, 75 georeferenced points of historical tidal range were used to generate the surface. In addition to the georeferenced tidal range values (which

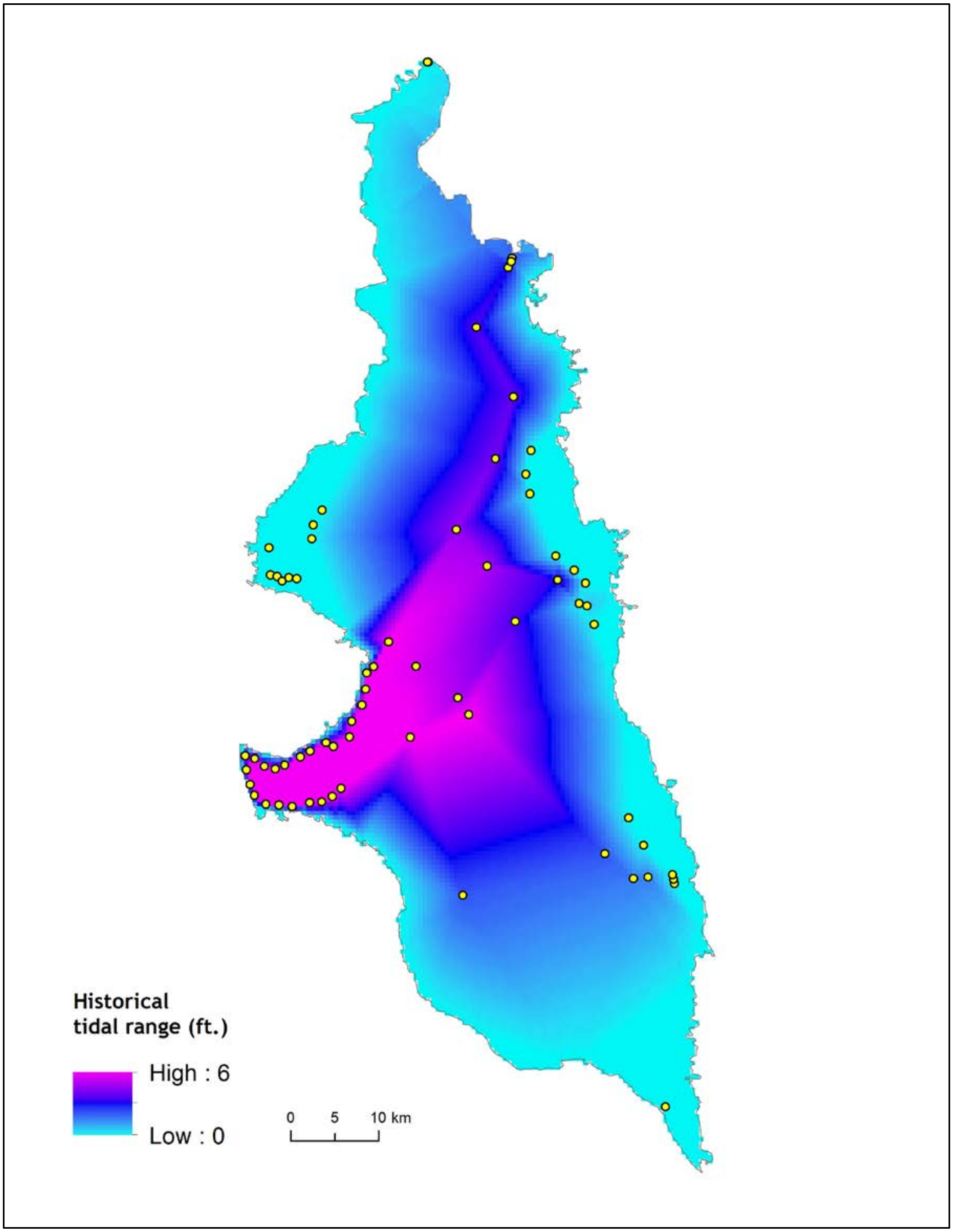

Figure 18. Historical Delta tidal range surface interpolated from georeferenced historical accounts (yellow dots). Except for where the Sacramento River acted as the study boundary, the study outline was treated as a breakline with a tidal range of 0 ft. (nontidal).

were treated as masspoints), TIN inputs also included the historical study area boundary, which was treated as a soft breakline with a tidal range value of 0 ft.

It is expected that the methods for developing this surface will be revisited and refined during Phase II of the study.

5.2 Historical local mean sea level elevation surface

The historical local mean sea level elevation raster developed for Phase I is shown in **Figure 19**). The surface and methods used to develop it were crude and are currently being overhauled for Phase II DEM development. For the purposes of developing the Phase I historical DEM, we assumed that MSL across the Delta is equal to that of today, minus historical sea level rise. This simplification ignores the possible effects of land subsidence, water exports, flooded islands, and the construction of levees, among other changes.

We collected local MSL elevation data from 9 USGS and NOAA published benchmarks around the Delta and 59 low water elevations published by the Debris Commission (1908-1913) outside of tidal range to generate the interim local MSL elevation surface (Debris Commission elevations were converted to NAVD88 using the methods described in Section 5.3).

MSL values obtained from these sources were adjusted to account for sea level rise (SLR) since 1850 before generating the MSL surface. We used the research of Atwater et al. (1977), who reported that the rate of relative sea-level rise in southern San Francisco Bay "has average 0.1-0.2 cm/yr from 6,000 years ago to the present." Assuming 2 mm SLR/yr since 1850, we subtracted 326 mm (1.07 ft) from contemporary elevations, 126 mm (0.41 ft) from 1913 Debris Commission elevations, and 116 mm (0.38 ft) from 1908 Debris Commission elevations.

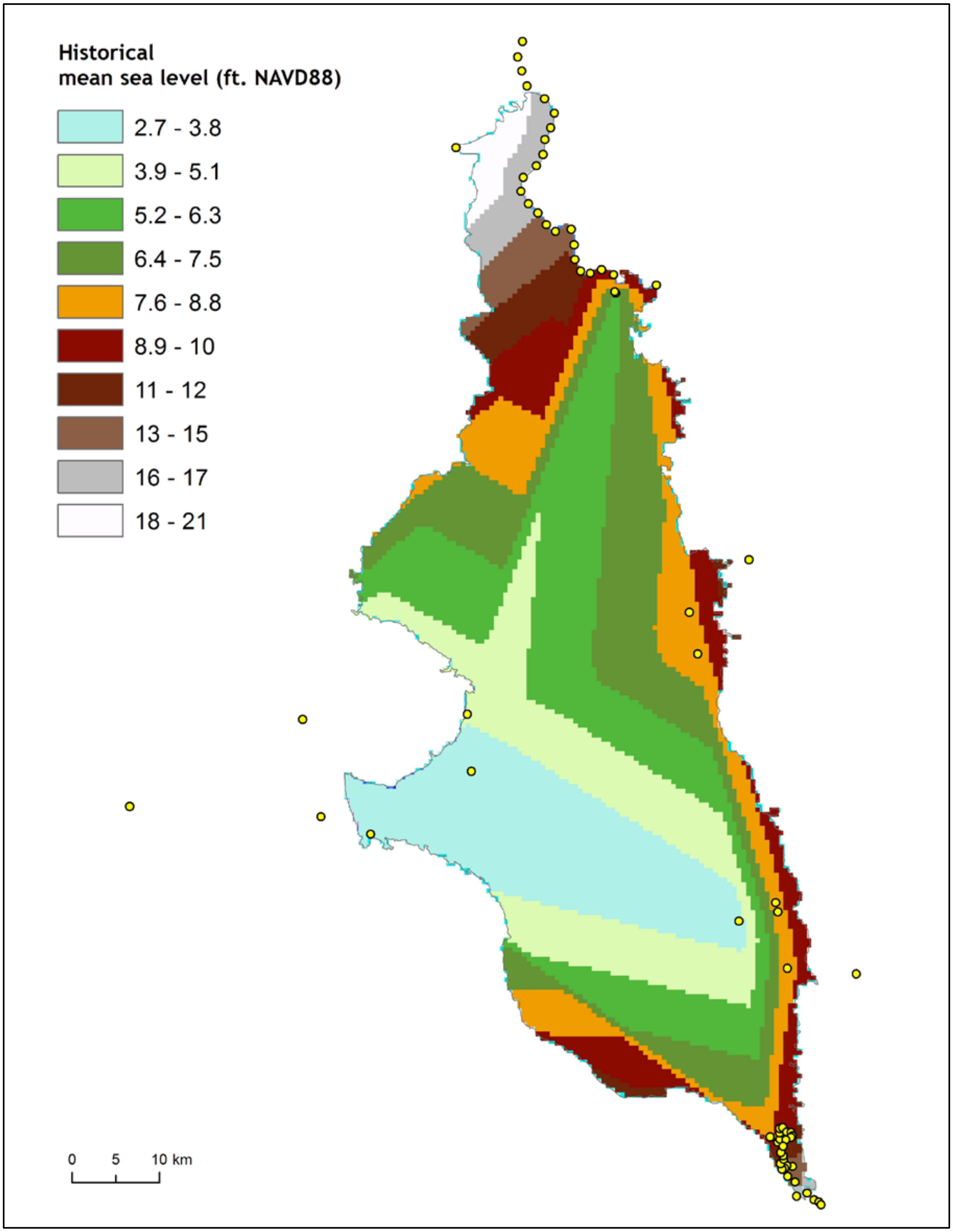

Figure 19. Historical local mean sea level elevation (ft. NAVD88) surface interpolated from 20th and 21st century values adjusted for sea level rise (yellow dots) and classified into 10 groups for display.

5.3 Debris Commission elevations

The Debris Commission (1908-1913) maps note that "elevations are in feet above datum of Engineering Department, U.S. Army, 3.6 feet below mean sea level as determined by U.S. Coast and Geodetic Survey." We assume that the early Engineering Department datum, referenced to "mean sea level" is similar to that of the early USGS topographic maps of the Delta (1909-1918), which references "sea level." While this makes it difficult to be confident of exact elevations within several feet, the USGS datum has been roughly equated to the National Geodetic Vertical Datum (NGVD29), which was originally called the "Sea Level Datum of 1929" and was established by measuring mean sea level at 26 tide gauges in the U.S. and Canada (Whipple et al. 2012). If the datum utilized by the Debris Commission is 3.6 ft above USCGS's "mean sea level" and we accept the assumption that "sea level" can be roughly equated to the NGVD29 datum, then we can subtract 3.6 ft. from the Debris Commission elevations to convert to NGVD29.To then convert from NGVD29 to NAVD88, we add 3 ft. minus a slight adjustment value that varies across the Delta (Mosbacher 2006). All told, the actual difference between NGVD29 and NAVD88 can vary in the Delta between 2.0 and 3.0 feet. By using an intermediate value of 2.5 ft., and combining the above steps, converting between the Debris Commission historical datum and NAVD88 can accomplished by subtracting 1.1 ft. from the printed Debris Commission elevations. Natural levee crest (Section 4.1) and water surface elevation values (Section 5.2) taken from the Debris Commission maps were adjusted to NAVD88 in this manner.

6 TIN inputs used to generate Phase I historical DEM (UC-Davis)

UC-Davis project partners performed the final steps of creating a TIN and DEM of the historical Delta. The inputs used to generate the TIN are outlined below:

1. **Channel shorelines**- outline of 2D channel planform data (Section 2.1), the elevations of which were set to local MSL elevation as defined by the MSL raster (Section 5.2).
2. **Delta mouth bathymetry points**- taken from the 1867 U.S. Coast Survey H-Sheet (Section 3.1) and adjusted to NAVD88 using the conversion rasters described in Section 5.1 and Section 5.2
3. **Bathymetry points upstream of the Delta mouth-** generated from thalweg depths extrapolated based on historical bathymetry/channel width and an ENVI script that

generated parabolic channel cross-sections around the thalweg (Section 3.2) and adjusted to NAVD88 using the conversion rasters described in Section 5.1 and Section 5.2.

4. **Natural levee crest lines-** generated by buffering relevant channels (Section 2.8) and attributing these lines with elevations taken from Debris Commission maps (Section 4.1) converted to NAVD88 (Section 5.3)
5. **Tidal marsh and other areas**- approximated for Phase I by adding a small constant value to the MSL raster (Section 4.2 & Section 5.2). The methodology relating this component will be substantially modified during Phase II efforts.

The resulting TIN was converted by UC-Davis partners into both 2 and 10 m DEMs using ArcGIS (**Figure 1**). The Phase I interim DEMs were then provided to RMA staff for initial tests of the hydrodynamic modeling. Using the 10 m DEM, RMA staff was able to produce successful model runs, albeit with unrealistic results. Project partners have worked together to identify a list of historical DEM artifact types negatively impacting the hydrodynamic model (these are detailed in a separate technical memorandum produced by RMA). Work has already begun to fix some of these artifacts and will be further addressed during Phase II of the project.

7 Hydrodynamic model calibration data

Hydrodynamic models are often calibrated using observed data. While the modern Delta hydrodynamic model can be calibrated with contemporary stage, flow, and electrical conductivity time series, these detailed data are not available for the historical study period (early 1800s). In light of this, we instead compiled and georeferenced location-specific information from historical sources on relevant hydrodynamic properties such as tidal range (**Appendix I- Table 2**), the depth of tidal inundation on the marsh surface (**Appendix I- Table 3**), and water depth in channels at specific tidal intervals (**Appendix I- Table 4**). We also compiled and georeferenced data on less quantitative properties such as temporal dynamics, the head-of-tide or tidal limit, and marsh drainage patterns (**Appendix I- Table 5**).

Most of the historical data included in the calibration dataset were originally collected, synthesized, and georeferenced for the SFEI-ASC Sacramento-San Joaquin Delta Historical Ecology Study. The study collected and reviewed thousands of historical documents from over 50 state, local, regional, and electronic archives (Whipple et al. 2012). In total, 52 points with relevant hydrodynamic information were extracted from the textual documents for inclusion in the model calibration dataset (**Figure 20**).

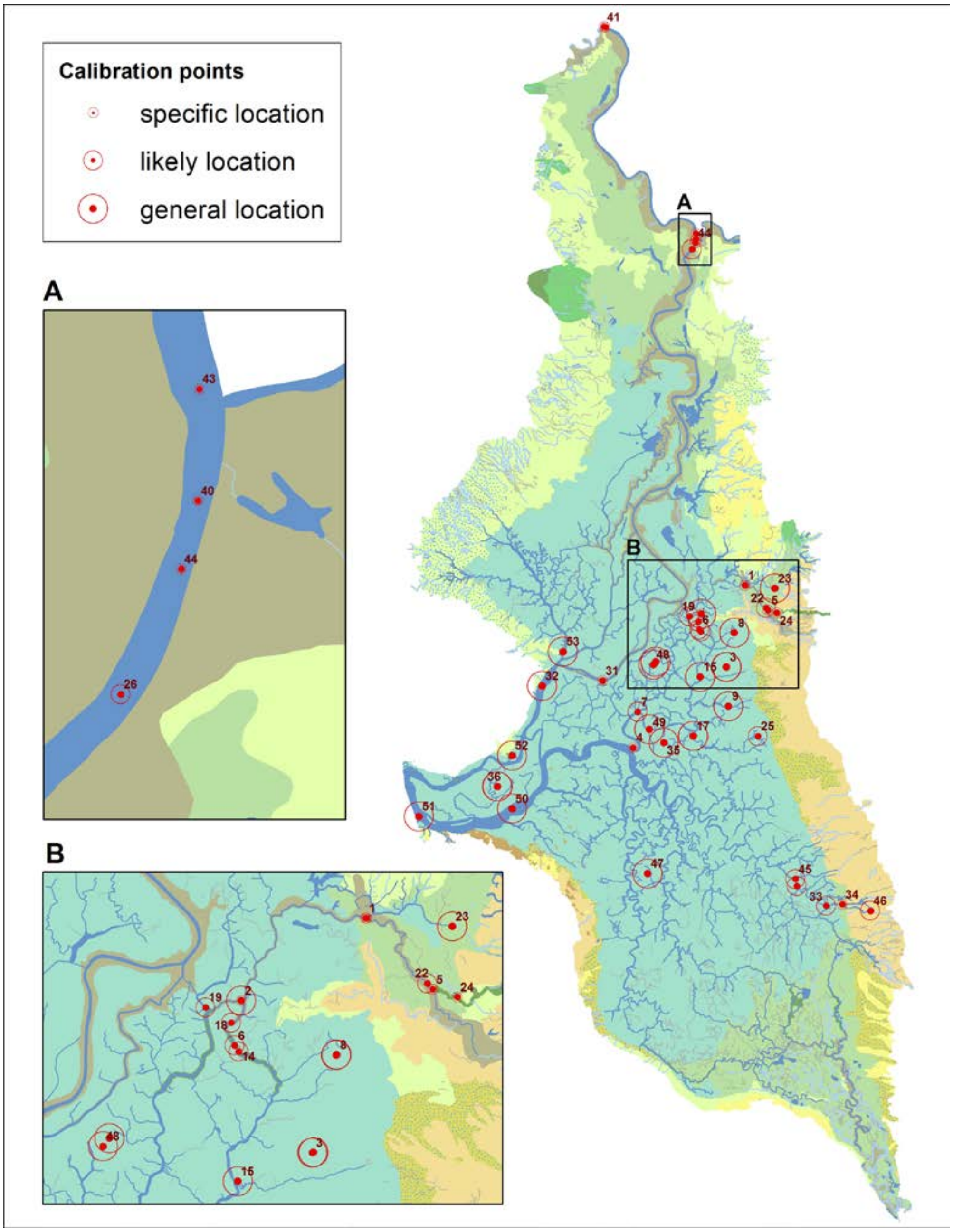

Figure 20. Historical textual data compiled and georeferenced for calibrating historical Delta hydrodynamic model. The circle around each point reflects its locational certainty. See **Appendix I** for the data associated with each point.

Qualitative data on salinity at the mouth of the Delta were also compiled for the Delta HE study (Whipple et al. 2012) and are included here in **Appendix I- Table 6.**

8 Works cited

Atwater BF, Hedel CW, and Helley EJ. 1977. Late Quaternary Late Quaternary Depositional History, Holocene Sea-level Changes, and Vertical Crust Movement, Southern San Francisco Bay, California. U.S. Geological Survey Professional Paper 1014, 15 p.

California Debris Commission (Debris Commission). 1908-1913. Maps of the Sacramento, Feather, American, Mokelumne, and San Joaquin Rivers. San Francisco, CA. Courtesy of the California State Lands Commission, Sacramento.

Gibbes CD. W.B. Cooke & Co. 1850. Map of San Joaquin River. San Francisco, CA. Courtesy of Peter J. Shields Library Map Collection, UC Davis.

Gray GN. 1859. U.S. v. Anastasio Chaboya, Land Case No. 406 ND [Sanjon de los Mequelemnes], U.S. District Court, Northern District. 405. Courtesy of The Bancroft Library, UC Berkeley.

Jones, G. 1967. Alteration of the regimen of Sacramento River and tributary streams attributable to engineering activities during the past 116 years. Manuscript, for the American Society of Civil Engineers, Sacramento Section, California State Archives.

McCollum WS. [1850]1960. California as I saw it; pencillings by the way of its gold and gold diggers, and incidents of travel by land and water. Los Gatos, CA: Talisman Press. Courtesy of Library of Congress.

Mosbacher M. 2006. NAVD88: New vertical datum in the Delta. DSM2 Users Group presentation.

Ringgold C. 1850a. Chart of Suisun & Vallejo Bays with the confluence of the Rivers Sacramento and San Joaquin. Courtesy of David Rumsey Map Collection, Cartography Associates.

Ringgold C. 1850b. Chart of the Sacramento River from Suisun City to the American River. Courtesy of David Rumsey Map Collection, Cartography Associates.

Whipple AA, Grossinger RM, Rankin D, Stanford B, Askevold RA . 2012. Sacramento-San Joaquin Delta Historical Ecology Investigation: Exploring Pattern and Process. Prepared for the California Department of Fish and Game and Ecosystem Restoration Program. A Report of SFEI-ASC's Historical Ecology Program, SFEI-ASC Publication #672, San Francisco Estuary Institute-Aquatic Science Center, Richmond, CA.

van Scoyk J. 1859. U.S. v. Anastasio Chaboya, Land Case No. 406 ND [Sanjon de los Mequelemnes], U.S. District Court, Northern District. 251. Courtesy of The Bancroft Library, UC Berkeley.

Appendix I

Tables with hydrodynamic calibration data compiled from historical record (see Section 7).

Table 2. Historical textual data on tidal range compiled and georeferenced for calibrating historical Delta hydrodynamic model. See **Figure 20** for the location of each table entry.

Tidal range	Dat	Source	Location	Quote
3.5 ft (spring tide)	1859	406 ND 1859, Samuel R. Thornton, 208	Benson's Ferry	[q23] How high do the spring tides rise in the M river at Bensons ferry? [a23] I would suppose about 3½ feet.
1 inch	1859	406 ND 1859, J. Van Scoyk, 260	mouth of dry creek	[a30-] There is tide all the way up to the mouth of dry creek at which point it affects it about an inch.
3.5 ft (regular tide)	1859	406 ND 1859, J. Van Scoyk, 261	5 mi below Bensons, N or S fork?	[q31] How high do the tides rise in the M five miles below Bensons?[a31] about three feet and a half which will bring it about a mile or a mile and a half below the head of the Island as near as I can judge.
4 - 5.5 ft	1859	406 ND 1859, J. Van Scoyk, 261	mouth of them	[q312]dhow high do the tides rise at their highest point at the mouth of them [a32] From what I noticed I should not suppose more than four or five and a half feet. I could not tell exactly how much it is raised there. I should think it to be about that.
3 ft.	1859	406 ND 1859, William C. Miller, 312	Benson's ferry	at this time of the year [dry season] the tide sets up the Moquelumne as high as three feet at
4 ft. (6 inches neap tide)	1859	406 ND 1859, C. L. Thayer, 398	Benson's Ferry	[q43] How high does the tide rise at Bensons ferry? [a43] I should judge about four feet, except at neap tide when I should judge it rose about six inches higher. [q44] What is the average depth of the water at Bensons ferry? [a44] When the tide is out the bed of the river is nearly all bare by the house, except about a foot and half [sic] deep in the channelâ€"where the boat is it is about two feet deep. The tide comes in about four
8 inches	1859	406 ND 1859, George N. Gray, 409	where west line of survey crosses	Ans 15. The tide at low water rises about eight inches where the west line of Von Schmidt's survey crosses Dry creek.
3 ft.	1845, July 20	Clyman and Camp 1960[1845]	landing opposite Sutter's Fort	the sacramento river here is upward of 200 yards wide deep and navigable the tide water ebbing and flowing about three feet
2 ft.	1880	Hall, W. H. 1880: 3 "Memorandum concerning the improvement of the	mouth of the American River	the tidal influence is not perceptible above the mouth of the American River, where formerly there was two feet of tidal action
4.5 ft.	1811, Oct 23	â€œFather Ramon Abella's Expeditionâ€ in Cook 1960. Colonial Expeditions to the interior of California Central Valley, 1800-1820: 263	downstream of Rough and Ready Is	The previous night we slept in the tule swamp and the water reached our blankets at the turn of the tide. The whole area is this way for several leagues. The water rose about one and one- half varas.
3 ft. (but post mining debris)	1879	Hall Field Books #45-65, Box 1, 45:8-32	at Isleton	Mr. Pool says that 3 ft is the difference between high and low tide at Isleton at present time
1 - 2 ft.	1849	Morgan 1960 in Dawdy 1989	as you approach Stockton	The tide of the ocean... sets up here, from one to two feet
1 - 2 ft.	1849	McCollum 1849, California as I saw it	Stockton	Our first evidence that we were nearing the new city in the wilderness, was the discovery through and above the trees, of the masts of some thirty brigs and schooners. The harbor is a deep bay, or arm [slough] of the river, four miles long, and generally, about three hundred yards wide. The grounds, of the new city are generally, from four to five feet above tide water. The tide of the ocean and Bay of San Francisco, sets up here, from one to
tide rose and fell	ca. 1840s	Mills 1904	Knight's Landing	the tide rose and fell every day at Knights Landing
2 ft.	1849	McCollum 1849	Sacramento City	The tide of the ocean sets back to the height of two feet at Sacramento.
6 - 14 inches	1849, Sept 22	Derby and Farquhar 1932	Sacramento City	The tide rises and falls at Sacramento City, causing a varation in the depth between high and low tides of from six to fourteen inches
22 inches	1862	Sacramento Daily Union, Is the Sacramento Valley	Sacramento City	At lower water the tide is felt about a hundred miles further up the river. At Sacramento it is some twenty-two inches, and at Fremont just perceptible.
just perceptible	1862	Sacramento Daily Union, Is the Sacramento Valley	Fremont	At lower water the tide is felt about a hundred miles further up the river. At Sacramento it is some twenty-two inches, and at Fremont just perceptible.
2 ft.	1880	Young 1880, Report of the state engineer to the Legislature of the State of California, vol 2	American River	The influence of the tides used to felt at low water stages of the stream as far up as the mouth of Feather River, but since the rising of bed, occasioned by the flow of sands in the past few years, the tidal influence is not perceptible above the mouth of the American River, where formerly there was two feet of tidal action
2 ft. (prior to 1862)	1862	Brewer 1966, and Bancroft 1890 in Taylor ca. 1862	at Sacramento	[After the 1862 floods] The bed of the Sacramento River at Sacramento was raised more than 7 feet; the 2-foot tides were no more
2 ft.	1885	US Army 1885 Annual Report of the Chief of Engineers, p. 2356	The Narrows: 4 miles downstream from the junction of Stockton Slough and San Joaquin	Above the Devil's Elbow, and a short distance below Stockton Slough, we find each year a deposit of clean white sand, which is brought down the San Jaoquin River during high water. The shoal is generally about 2,000 feet in length, and at low water and low tide there was less than 5 feet water before dredging was commenced. The rise and fall of the tide is about 2 feet during the low water season.
10 - 12 inch tidal bore under certain conditions	1855-70s	Taylor 1969:58 [Grunksy 1855-1877]	Mormon Slough? just W of California St bridge, at 'Rosebush'	Just west of where the California Street bridge now crosses the slough was the Rosebush¦The Rosebush marked the extreme upper level of tidal effect. A few hundred yards further west we often watched and even ran from a small-scale tidal bore, perhaps ten to twelve inches high, which would form under certain conditions of wind and rising tide
6.12 ft.	1861	Hall 1861, S&O Reports Correspondence. Beaumont, Duncan. District No. 22	Bouldin Island, District No. 22	The average difference between high and low tide is 6.12 feet and the average overflow at high tide is 0.492 feet or nearly 6 inches on the banks of the streams, the land gradually falling as you go back from the banks. / In making the circumference of the island the line crosses 3 Beaver cuts and 3 sloughs [aw: Bouldin, Doolyâ€™s, Lanumâ€™s]. The Beaver cuts being from 4 to 7 feet deep and the sloughs from 10 to 20 feet...The sloughs keep their width and depth for some distance inland and the surface being low at their heads, the cost of leveeing both banks and crossing on low land would be much in excess of the cost of the bulkhead as proposed. The banks of these sloughs is of such a light spongy nature (resembling peat) that after the upper sod is once off, teams could not haul over it and the embankment would have to be made with barriors and
3.5 - 6.5 ft.	1869	Daily Herald, July 10, 1869 in M. D. Carr & Co. 1869, Fresh water tide lands of California, 21-2	Sherman Island	Although the high tide rises about half a foot above the surface level of the soil, yet the water, on the inside of the ditch, is from three to four, and can be made six feet below it. In fact, the water can be kept so low as to make it necessary to let it in at times for irrigation. [General description] The surface of the land is perfectly level, being about six inches below high and from three to six feet above low tide
4 - 6 ft.	ca. 1850	Whipple et al. 2012, 129		At the Delta mouth, tidal range was between four and six feet (1.2-1.8 m; Abella and Cook
6 ft.	1895	Whipple et al. 2012, 247		Tidal range [of Cache Slough] was reported to be from nearly six feet at low water to about one foot at extreme flood stages (Rose et al. 1895)

Table 3. Historical textual data depth of tidal inundation above the marsh surface compiled and georeferenced for calibrating historical Delta hydrodynamic model. See **Figure 20** for the location of each table entry.

	Tidal inundation depth	Date	Source	Location	Quote
1	> 0 during spring tides (banks), 0 at MHHW (banks)	1859	406 ND 1859, J. Van Scoyk, 259	mouth of M	I have never been there when the water has been high enough to be over its banks except at spring tides. There is not much difference at spring tides and low tide.
5	> 0 during spring tides, 0 at MHHW	1859	406 ND 1859, J. Van Scoyk, 262	along sloughs E of S fork of M	[q35] what is the character of the country through which these sloughs run-is it dry land or tule lands subject to overflow at high tide. [a35] It is tule land-the spring tides come up to the top of the ground or nearly so, all over the part of the country I have been in. The tide comes up in the sloughs and at their heads flows over into the tule _I allude to those sloughs below the head of the island, the others above a boat cannot go through an account of the
6	> 0 MHHW (banks; in some places)	1859	406 ND 1859, J. Van Scoyk, 264	banks of sloughs	[q39] are not the banks of these sloughs covered with water at high tide? [a39] No sir-not entirely in some places the tide comes to the top of the ground in spring tides, in other places the tide does not come to the top of the ground. [q40] do you mean to say that the banks of more of these sloughs are overflowed at high tide? I answered that before. They are overflowed in some places and in some places not.
7	1-2 ft. MHHW [more than most other accounts]	1859	406 ND 1859, Edwin A. Sherman, 336	from haystacks	[a14] We had no conveniences in the boat for sleeping [why he camped] the tide waters of the San Joaquin Covering for about a foot or two feet all over the country when it was high tide, so we had to use the haystack for camping. [a15] I should judge about 15 or 18 feet [high the haystacks]
13	> 0 MHHW (banks Otter Sl. inundated at high tide)	1859	406 ND 1859, Edwin A. Sherman, 343	Otter and tributary sloughs	[q28] How were the banks of Otter slough and of the sloughs empting into it: were they subject to inundation or otherwise at high tide? [a28] They were.
	6 - 8 inches at times	1859	406 ND 1859, C. L. Thayer, 388	S of ridge, W of grant line	[q9] To what height does the tide rise there? [a9] About 6 or 8 inches above the ground, indicated by the water mark left upon the tule.
24	at least 1 ft. at times	1859, Nov	406 ND 1859, George N. Gray, 418-9	up slough about 7 mi in boat	Q44. how deep was the water through which you waded after leaving the boat? A44 after going about 20 rods from the boat I waded in places nearly to the tops of my bootsâ€"went as far as I could without getting over my boottops.
26	6 inches MHHW	1869	Daily Herald, July 10, 1869 in M. D. Carr & Co. 1869, Fresh water tide lands of California, 21-2	Sherman Island	Although the high tide rises about half a foot above the surface level of the soil, yet the water, on the inside of the ditch, is from three to four, and can be made six feet below it. In fact, the water can be kept so low as to make it necessary to let it in at times for irrigation. [General description] The surface of the land is perfectly level, being about six inches below high and from three to six feet above low tide
28	2 ft. MHHW (prior to 1862)	1879	Tucker Field Notes, Hall S.E.D. Field Books, Box 8, Item 94	Wood Island	it is nearly one mile and a half long and averages, say, 600 feet wide, though in one or two places it is more than 800 feet wide. / According to the survey made in 1859, there are 98 acres of land in the island; but since that time there has been an immense amount of sediment deposited on the banks and I think that now there is considerable more than 98 acres. / I came here to live in 1857, at that time an ordinary high tide came two feet over the land, between that time and 1862 it did not change much. During the flood of 1862, the whole island was filled up and raised about three feet
30	6 inches MHHW (banks)	1861	Hall 1861, S&O Reports Correspondence. Beaumont, Duncan. District No. 22	Bouldin Island, District No. 22	The average difference between high and low tide is 6.12 feet and the average overflow at high tide is 0.492 feet or nearly 6 inches on the banks of the streams, the land gradually falling as you go back from the banks. / In making the circumference of the island the line crosses 3 Beaver cuts and 3 sloughs [aw: Bouldin, Doolyâ€™s, Lanumâ€™s]. The Beaver cuts being from 4 to 7 feet deep and the sloughs from 10 to 20 feet...The sloughs keep their width and depth for some distance inland and the surface being low at their heads, the cost of leveeing both banks and crossing on low land would be much in excess of the cost of the bulkhead as proposed. The banks of these sloughs is of such a light spongy nature (resembling peat) that after the upper sod is once off, teams could not haul over it and the embankment would have to be made with barriors and
31	> 0 at MHHW (banks of island flooded at high tide)	1895	Rose, Manson and Grunsky 1895	Sherman Island	Its banks were just flooded at high tide; they were comparatively firm, but the interior of the island was of peaty formation
33	0 at MHHW	1862	Sacramento Daily Union, Swamp and Overflowed Lands, 1 January 1862	Tyler Is	[Tyler Island] is low and nearly level, elevated above high tide an average of only about two feet, the first five miles from the north gradually falling from an elevation of seven or eight feet down to the general level. The surface is highest at the islandâ€™s edge, and gradually sinks towards the interior. The soil is loamy
34	0 at MHHW	ca. 1915	History of Bacon Island p.2, Haggin Museum	Bacon Island	[Bacon Island] The land in its native state was above the level of the ordinary high tides. Cultivation of it, however, rapidly compacted and settled the light peaty material so that by the time the land was in shape for cropping it was all below the
37	0 at MHHW	1861	CA Swampland Commissioners 1861, First Annual Report, 13th Session, 15	Tyler Island	the Island is low, and nearly level, elevated above high tide an average of only two feetâ€"the first five miles from the north gradually falling from an elevation of seven or eight feet down to the general level. The surface is highest at the water, and gradually sinks towards the interior; the streams retain their depth close up to the banks, which rise almost perpendicular out of the water
38	1.5 ft. during spring tide		Whipple et al. 2012, 130		an account from a farmer at Horseshoe Bend on the Sacramento River stated that his two and one half foot (0.76 m) high levee was â€œabout one foot above the spring-tide mark,â€ meaning that the pre-leveed marsh was likely overflowed by a foot and a half (0.46 m)
39	6 - 14 inches	1849, Sept 22	Derby and Farquhar 1932	Sacramento City	The tide rises and falls at Sacramento City, causing a varation in the depth between high and low tides of from six to fourteen inches
40	22 inches	1862	Sacramento Daily Union, Is the Sacramento Valley	Sacramento City	At lower water the tide is felt about a hundred miles further up the river. At Sacramento it is some twenty-two inches, and at Fremont just perceptible.
41	just perceptible	1862	Sacramento Daily Union, Is the Sacramento Valley	Fremont	At lower water the tide is felt about a hundred miles further up the river. At Sacramento it is some twenty-two inches, and at Fremont just perceptible.
43	2 ft.	1880	Young 1880, Report of the state engineer to the Legislature of the State of California, vol 2	American River	The influence of the tides used to felt at low water stages of the stream as far up as the mouth of Feather River, but since the rising of bed, occasioned by the flow of sands in the past few years, the tidal influence is not perceptible above the mouth of the American River, where formerly there was two feet of tidal action
44	2 ft. (prior to 1862)	1862	Brewer 1966, and Bancroft 1890 in Taylor ca. 1862	at Sacramento	[After the 1862 floods] The bed of the Sacramento River at Sacramento was raised more than 7 feet; the 2-foot tides were no more
45	2 ft.	1885	US Army 1885 Annual Report of the Chief of Engineers, p. 2356	The Narrows: 4 miles downstream from the junction of Stockton Slough and San Joaquin	Above the Devil's Elbow, and a short distance below Stockton Slough, we find each year a deposit of clean white sand, which is brought down the San Jaoquin River during high water. The shoal is generally about 2,000 feet in length, and at low water and low tide there was less than 5 feet water before dredging was commenced. The rise and fall of the tide is about 2 feet during the low water season.
46	10 - 12 inch tidal bore under certain conditions	1855-70s	Taylor 1969:58 [Grunksy 1855-1877]	Mormon Slough? just W of California St bridge, at 'Rosebush'	Just west of where the California Street bridge now crosses the slough was the Rosebush¦The Rosebush marked the extreme upper level of tidal effect. A few hundred yards further west we often watched and even ran from a small-scale tidal bore, perhaps ten to twelve inches high, which would form under certain conditions of wind and rising tide
49	6.12 ft.	1861	Hall 1861, S&O Reports Correspondence. Beaumont, Duncan. District No. 22	Bouldin Island, District No. 22	The average difference between high and low tide is 6.12 feet and the average overflow at high tide is 0.492 feet or nearly 6 inches on the banks of the streams, the land gradually falling as you go back from the banks. / In making the circumference of the island the line crosses 3 Beaver cuts and 3 sloughs [aw: Bouldin, Doolyâ€™s, Lanumâ€™s]. The Beaver cuts being from 4 to 7 feet deep and the sloughs from 10 to 20 feet...The sloughs keep their width and depth for some distance inland and the surface being low at their heads, the cost of leveeing both banks and crossing on low land would be much in excess of the cost of the bulkhead as proposed. The banks of these sloughs is of such a light spongy nature (resembling peat) that after the upper sod is once off, teams

50	3.5 - 6.5 ft.	1869	Daily Herald, July 10, 1869 in M. D. Carr & Co. 1869, Fresh water tide lands of California, 21-2	Sherman Island	Although the high tide rises about half a foot above the surface level of the soil, yet the water, on the inside of the ditch, is from three to four, and can be made six feet below it. In fact, the water can be kept so low as to make it necessary to let it in at times for irrigation. [General description] The surface of the land is perfectly level, being about six inches below high and from three to six feet above low tide
51	4 - 6 ft.	ca. 1850	Whipple et al. 2012, 129		At the Delta mouth, tidal range was between four and six feet (1.2-1.8 m; Abella and Cook
53	6 ft.	1895	Whipple et al. 2012, 247		Tidal range [of Cache Slough] was reported to be from nearly six feet at low water to about one foot at extreme flood stages (Rose et al. 1895)

Table 4. Historical textual data on water depth in channels referenced to a particular tidal datum compiled and georeferenced for calibrating historical Delta hydrodynamic model. See **Figure 20** for the location of each table entry.

	Water depth (channel)	Date	Source	Location	Quote
10	8 inches water as tide runs out (water 4 ft wide)	1858	406 ND 1859, William Watson, 275	mouth of Dry Creek	[q6] What was the depth and width of Dry Creek where the western line of the Survey crosses it, at the time you made the exploration. [a6] Tide running out-four feet wide eight
14	3 ft. water at low tide	1859	406 ND 1859, Milton Lambet, 319-20	about one mile and a half on east side of island below its head	I think the waters of the Moquelumne river flow on the west side of the island: The reasons are because at low tide the waters divide at a certain point on the east side of the island, and at that point the waters flow either way, and the slough is narrower and shallower at that point than any other: and the main channel of the Moquelumne river lies to the north west of that point. That point where the waters divide is situated about one mile and a half on the east side of the island below its head...[q11] How long after the tide turns do the waters flow from the point you have designated a the dividing point northwesterly towards the Moquelumne [a11] About one hour and a quarter. [q12] How deep is the said slough at the said dividing point at
21	1.5 ft. water at low tide	1859	406 ND 1859, C. L. Thayer, 398	Benson's Ferry	[q43] How high does the tide rise at Bensons ferry? [a43] I should judge about four feet, except at neap tide when I should judge it rose about six inches higher. [q44] What is the average depth of the water at Bensons ferry? [a44] When the tide is out the bed of the river is nearly all bare by the house, except about a foot and half [sic] deep in the channelâ€"where the boat is it is about two feet deep. The tide comes in about four
45	< 5 ft. water at low tide (on a shoal)	1885	US Army 1885 Annual Report of the Chief of Engineers, p. 2356	The Narrows: 4 miles downstream from the junction of Stockton Slough and San Joaquin	Above the Devil's Elbow, and a short distance below Stockton Slough, we find each year a deposit of clean white sand, which is brought down the San Jaoquin River during high water. The shoal is generally about 2,000 feet in length, and at low water and low tide there was less than 5 feet water before dredging was commenced. The rise and fall of the tide is about 2 feet during the low water season.

Table 5. Other forms of historical textual data georeferenced for calibrating historical Delta hydrodynamic model. These include data on the extent of tides, temporal dynamics, flow direction, and tidalsheds. See **Figure 20** for the location of each table entry.

	Data type	Date	Source	Location	Quote
2	Temporal dynamics	1859	406 ND 1859, Julius Styne, 236	N and S fork of Mokelumne	[q14] do the tides flow up through the north and south forks of the M. [a14] They do when the water is low the tide is about an hour longer in getting up the south fork than up the other, to the head of the island. I know of no other reason for the difference than that the south fork is longer[the tide has further to go the boatmen allow about 10 miles an hour for the flow of the tide. [q15] has the M river been gradually filling since you first knew it. Or has it remained about the same
3	Tidalshed	1859	406 ND 1859, J. Van Scoyk, 253	tules of M river	[a8] At low water the tide flows out of the M river up the sloughs and fills the tules. At high water the water runs over the banks of the river above and flows off into the tules.[q9] At what point or points at high water does the M river overflow its bank into the tules?[a9] I have seen it run over its banks first below the ferry at Bensons and from that point up some four miles at different places.
11	Temporal dynamics	1859, Nov 8	406 ND 1859, William Watson, 279	point B from Exhibit B, at forks	[a11] commencing at point C. on exhibit B on the north slough the tides commence to flow from C to B one hour and ten minutes earlier than from A to B and while it is flow tide from C to B it was found to be ebb tide from B to A. I observed this on the 8th of Nov. 1859. IN other words, when the tide is coming up what is called the north fork it reaches the point B one hour and ten minutes sooner than the tide reaches the same point coming up the other fork
12	Tidalshed	1859	406 ND 1859, William Watson, 280	south of Hawkins point and west of the survey	After making a thorough exploration of all the waters to the east of the south fork of the M, I am satisfied that the tules lying to the south of Hawkins point and west of the survey are affected entirely by the waters and tides of the San Joaquin.
16	Flow direction; Temporal dynamics	1859	406 ND 1859, Edwin A. Sherman, 342	along Otter [potato] slough	[q24] state whether or not you observed the action of the tides in passing through what you designated as otter slough; and can you state whether or not the tides in said slough proceeded from the San Joaquin or from what is designated on exhibit no. 1 as the south fork of the M...this water is fresh which rises and falls, and is caused by the flux and reflux of the tide, which hold these waters, as it were in abeyance. IN passing through, Otter slough I noticed the action of the tides to be very swift, running about five miles an hour, there were the back waters of the San Joaquin, the water was then flowing towards the San Joaquin â€“the tide going all the time. [q25] How were the tides as you returned through otter slough. [a5] When we got about a mile and a half on our return, we had the tide or current coming in from the San
18	Flow direction	1859	406 ND 1859, Edwin A. Sherman, 344-5	about a half mile from head of island	[q31] In a former answer you said that n what is termed the south fork of the M a short distance below the head of the island, the water ran both ways; explain what you meant by this statement and how you ascertained the fact. [a31] About the flood of the tide, when the tide turned, my attention was directed to pieces of tule and sticks some going one way and some the other with the tide-that is some going towards the north fork of the M as
19	Flow direction	1859	406 ND 1859, Edwin A. Sherman, 371	Snodgrass slough	[q87] At low and at high tide which way does the current run through Snodgrass slough? [a87] I believe when the tide is going out that it runs into the M river or slough. I Never passed it at high water or at dead low water. At the time I passed it, it was running into the M. I passed it going up the M at that point it was about half as
22	Tidal limit	1859	406 ND 1859, C. L. Thayer, 399	2.5 mi from Benson's ferry	[q45] How far do the tides extend above Bensons ferry in the Moquelumne river? [a45] I should judge about 2 1/2 miles.

23	Tidal limit	1859	406 ND 1859, George N. Gray, 407	Indian Rancheria to mouth of Cosumnes	Ques. 9. Describe the character of the Cosumnes river from the Indian Rancheria to its mouth. State whether or not it has a distinct channel, or whether it spreads out in the wet season on both sides, and how far it is affected by the tides. Ans 9. It has a distinct channel at low water, it spreads out on both sides in the wet season, in low water it is affected by the tides about two miles from its mouth, perhaps more: at high water much further
29	Tidal limit	1880	Hall, W. H. 1880: 3 "Memorandum concerning the improvement of the	mouth of Feather River	The influence of the tides used to be felt at low water stages of the stream as far up as the mouth of Feather River

Table 6. Early textual descriptions of salinity conditions at the mouth of the Delta. Most evidence describes freshwater conditions at the Delta mouth, but there is some evidence for occasional brackish conditions. From Whipple et al. (2012).

Quote	Date	Flow (MAF, Meko et al. 2001)	Location	Reference
"finding the water fresh and still"	1772, March 30	19.5	from Willow pass, "camp this night was probably westward of Antioch" (from footnote)	Crespi and Bolton 1927
"where some rivers empty and take the saltiness of the water which there becomes sweet, the same as in a lake"	1775	18.7	mouth of the Delta	de Cañizares et al. 1909
"Yslas Razas entre aqua dulce" [flat or low islands in sweet water]	1775 [1781]	18.7	Islands at the Delta mouth and Suisun Bay	de Cañizares 1781
"the water is unfit for drinking because it is so salty"	1776, April 2	9.1	above Selby, below Carquinez (from footnote)	Anza and Bolton 1927
Puerto Dulce [sweet harbor] "I tasted the water and found it salty, although not so salty as that of the sea outside"	1776, April 2	9.1	Suisun Bay	Anza and Bolton 1927
"it was now very fresh, but we noted that it was changeable"	1776, April 3	9.1	near Antioch	Anza and Brown 1998
"before arriving at the Strait [Carquinez] the water is already salty"	1811, Oct 29	22.8	Crossing Suisun Bay	Abella and Cook 1960
"we found the water perfectly sweet"	1837, Oct 26	14.1	where the Sacramento "becomes a narrow stream" entering its mouth	Belcher et al. 1979
"camped, without water, that of the river being still brackish"	1841, Aug	5.56	likely near Antioch: 11 miles from Suisun Bay, 2 miles north, then 3 miles up the "southeast arm of the Sacramento," which they then find actually leads them to the San Joaquin	Wilkes 1845
"the water being fresh here all the year"	1847	19.8	Rio Vista	Californian 1847
"which if the tides was to wet it the salt would destroy the value of the coal"	1865	18.5	vicinity of New York [Pittsburg] and Antioch	Clayton 1865
The vegetation is from[by?] fresh water	1865	18.5	vicinity of New York [Pittsburg] and Antioch	Clayton 1865
"Northerly point near the New York where the water is generally so brackish as to be useless for animals"	1865	18.5	New York [Pittsburg]	Stratton 1865

"It is such as is peculiar to both salt and fresh water marshes—Some tule and some salt grass … Sometimes fresh sometimes salt [water]. In summer season high tide would be salt—I have tried the water being in a boat"	1865	18.5	vicinity of New York [Pittsburg] and Antioch	Taylor 1865
"The line of brackish water is at the lower end of Sherman Island...water in the rivers and sloughs above this point rises and falls with the tide and is always fresh"	1869	14.9	foot of Sherman Island	Alexander 1869
"The water along the San Joaquin frontage is fresh for ten months out of the twelve, and, in most years, is fresh the entire year; even in very dry seasons it is fresh at low water"	1879	15.4	vincinity of Antioch	Smith & Elliot [1879]1979
"Natural growth is three cornered tule and sweet grasses. No salt grass or alkli [sic] weed"	1912	11.4	Chipps Island	Unknown 1912