California Regional Water Quality Control Board
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Linda S. Adams
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MEMORANDUM

Date: June 28, 2011

To: File: Laguna de Santa Rosa; TMDL Development and Planning

From: Steve Butkus

Subject: Constructing Stream Flow Rating Power Equations for the Pre-settlement Lakes in the Laguna de Santa Rosa Watershed

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The development of the Laguna de Santa Rosa (Laguna) Total Maximum Daily Load (TMDL) for impairment of beneficial uses due to low dissolved oxygen and high nutrients requires a "linkage analysis" (CSWRCB 2005). A linkage analysis describes the method used to establish the relationship between pollutant loading and instream water quality response. Regional Water Board staff developed a water quality model for the current geometry of Lake Jonive in the Laguna de Santa Rosa Watershed. Lake Jonive (Cummings 2004), the open water area south of Occidental Road near Sebastopol, was selected to represent lentic areas of the Laguna watershed.

The Lake Jonive water quality model was prepared using the River and Stream Water Quality Model (QUAL2K) (Chapra et al. 2006). The QUAL2K construct is a one-dimensional model that simulates steady state hydraulics by assuming a channel that is well-mixed vertically and laterally within each model segment. The model simulates diel water-quality conditions under steady-state conditions. The QUAL2K model was written as open source code for model improvements. One such model upgrade, the QUALKw model version (Pelletier et al. 2006; Pelletier and Chapra 2008), was used for the Lake Jonive model. Results of the QUAL2Kw model development and evaluation of the Lake Jonive model are reported in Butkus (2011).

The Lake Jonive water quality model was developed to represent lentic areas of the Laguna watershed. The model will be used to simulate various conditions to advise the TMDL allocation process and implementation decisions. Model simulations allow a comparison of current pollutant loading to an estimated historical loading based on land cover that existed prior to European settlement. Pre-settlement in the Laguna watershed is defined as the period of time prior to the General Land Office surveys conducted during the mid 19th century. The estimate of pre-settlement conditions will be used to estimate what water quality conditions may have been prior to major landscape disturbance. The model was developed to simulate land cover and hydrology that existed in the Laguna watershed prior to significant European settlement to help assess natural background sources and processes. The analysis of natural conditions provides context for setting TMDL allocations for desirable and feasible future conditions.

The mainstem Laguna prior to European settlement contained large areas of open water even in the summer. Three lakes have been identified from early records: Ballard Lake, Lake Sebring, and Cunningham Lake (Cummings 2004). Lake Sebring was renamed locally as Lake Jonive around 1900 after the northern portion of the water body had filled with sediment. None of the earliest maps of the Laguna region dating from 1867 to 1877 specifically identify these lakes (Figures 1 – 8). These early maps provide only a generalized representation of open water boundaries and do not indicate the time of year depicted.

Ballard Lake

Ballard Lake was formed near the original location of the mouth of Mark West Creek. A sediment plug deposited from Mark West Creek in the mainstem Laguna partially blocked the mainstem and formed a wider open water area of the lower Laguna upstream of the confluence with Mark West Creek, between what is today Guerneville Road and River Road. Ballard Lake was reported to be 25 feet deep in places. In the 1940s dynamite was used to remove the sediment plug forming Ballard Lake. Sediment from Mark West Creek was used to fill the lake area for conversion to agricultural purposes (Cummings 2004).

Sebring Lake / Lake Jonive

Sebring Lake was a permanent open water area that stretched from south of Santa Rosa Creek to Sebastopol. The Lake was formed by a sediment plug deposited by Santa Rosa Creek. Increased erosion from watershed development filled the northern portion of the lake with sediment in the late 1800s. By 1900, the remaining southern portion of the open water area had been renamed locally as Lake Jonive. Early reports described Lake Jonive as 30 feet deep, large enough to support navigation uses. In 1889, the *Sebastopol Times* suggested that gunboats with "torpedo destroyers" be deployed in the Laguna to guard the town from a potential invasion by the Spanish coming up the Russian River (Cummings 2004).

Cunningham Lake

Blucher Creek was a source of the sediment plug that resulted in formation of a large open water area near the Cunningham business area (near the current location of Todd Road). Cunningham Lake does not specifically appear on any early maps, but the lake is referred to in early newspaper reports as being used by local residents for swimming and fishing (Cummings 2004).

Annual Climatic Boundaries

The open water boundaries of the lakes in the Laguna varied considerably depending on annual climate. The wide range of open water boundaries on early maps was influenced by the antecedent precipitation immediately prior to when the map was drawn. The early maps do not indicate the time of year the maps were drawn. The open water boundaries from year-to-year likely varied considerably prior to European settlement and hydraulic modifications placed in the watershed. The boundaries between open water and marshlands were very dynamic depending on the season and annual climate. For example, in early photos Lake Jonive essentially disappeared about 1910 and reappeared again in the late 1920s (Cummings 2004).

The pre-settlement boundaries of the open water areas during both wet and dry climate years were derived from early maps, soil and landform characteristics. The pre-settlement open water boundary for wet years was derived from boundaries of open water depicted on two early maps (Bowers 1867; Thompson 1877). Adjacent areas with hydric soil type within the basin floor landforms were added to the early map open water boundaries to define the upper pool elevation of open water areas (USDA 2007) (Figure 9). Hydric soils are defined by U.S. Department of Agriculture as “sufficiently wet in the upper part to develop anaerobic conditions during the growing season" (USDA, 2010). Hydric soils are formed under conditions of saturation, flooding or ponding that exists long enough to develop anaerobic conditions. Soils become hydric after exposure to anaerobic conditions for prolonged periods that are repeated annually. These areas were assumed submerged through the summer during wet climatic years.

The historical open water boundary during dry years was derived from the boundary of open water depicted on the 1860 Laguna map (Figure 10). The 1860 map presented the smallest open water area of all the available early maps. The open water boundaries from an image of the 1860 map were digitized and rectified into spatial data (LSRF, 2009). The areas between the boundaries of the open water for wet and dry years were likely shallow marshy wetlands during the dry years.

Pre-settlement Lake Bathymetry Construction

The geometry of the Lake Jonive water quality model were modified to represent the pre-settlement lakes identified. Geometric representations for the model were constructed for the three pre-settlement lakes (i.e., Ballard Lake, Sebring Lake and Cunningham Lake) during both wet and dry climatic years. Geometric representation for Ballard Lake during dry years was not constructed since only a stream channel likely existed in that location during dry climatic years.

Channel cross-sections were selected from Deas (2007) to represent the upper, middle and lower reaches of the pre-settlement lakes (Figures 11- 15). Only a single cross section was available for Cunningham Lake during dry years (Figure 15). Cross section locations were identified using the length of the thalweg from the National Hydrography Dataset (Simley and Carswell 2009), since Deas (2007) did not identify the precise river mile locations associate with the cross-section data (Figures 16 -18).

The cross-sections (Deas 2007) were collected only for the stream channel bathymetry. The upland floodplain measurements were collected at single locations away from the edge of the stream channel. The floodplain areas upland from the stream channel appear as simple angled straight lines in the cross- sections collected (Figures 11 – 15). These upland areas do not have the refinement required to estimate the bathymetry of the pre-settlement lakes. To better represent these floodplain areas, the elevation profile was measured perpendicular to the selected channel cross-section using 10-meter resolution elevation spatial data (NED 2006). The floodplain elevation profiles were combined with the stream channel cross sections to provide a complete elevation at these locations (Figures 19 – 29).

Current elevations are shown with the pre-settlement lake boundaries in Figures 16 -18. The comparison shows that some areas along the pre-settlement lake shoreline have relatively higher elevations than nearby lake areas. These higher elevations along the shoreline edges represent real geologic features that were not likely to be impounded under the pre-settlement lake areas. The anomalies are a result of the low spatial precision in the maps used to define the lake areas (i.e., boundaries of open water depicted on two early maps; Bowers 1867 and Thompson 1877). Width of the pre-settlement lakes was modified at each cross section to select the same pool elevation and minimize the spatial precision errors introduced from the early maps (Table 4).

Estimates for the amount of sediment deposited in the pre-settlement lakes were derived from PWA (2004) and lake surface areas. PWA (2004) conducted a sediment budget for the Laguna watershed. Sediment yield rates were estimated using several separate analytical approaches which all converged to relatively the same estimate. Sediment yield rates were also derived for different catchments in the Laguna watershed. Sediment yield rates from upstream of Llano Road were assumed to be the catchment for Cunningham Lake, which includes Gossage, Washoe, Wilfred, Hinebaugh, Crane, Five and Copeland Creek catchments. Sebring Lake was assumed to be the catchment for sediment yield estimates of Colgan, Blucher, and Santa Rosa Creek catchments. Ballard Lake was assumed to be the catchment for sediment yield estimates of the Mark West Creek catchment (Table 3).

Estimates of sediment deposition rates to each of the pre-settlement lakes were derived from PWA (2004). The sediment budget derived for the Laguna showed that 50 percent of the yield is coarse sediment that settles out in the headwaters and flood control channels and is not delivered to lentic waters. The trapping efficiency of the lentic areas was shown to be 50 percent based on Brune's curve. The Brune (1953) curve is a widely used method for estimating the sediment retention in reservoirs. Therefore, 25 percent of the sediment yield from the watershed is deposited in the lentic areas.

Estimates were made of the sediment volume and depths deposited in each pre-settlement lake since 1830 (Tables 3 & 4). The estimated depth deposited in Lake Sebring (1.6 feet) was relatively the same as was measured by PWA (2004) from a sediment core (1.5 feet). The current and pre-settlement water surface and bottom elevation profiles are presented for each cross section in Figures 30 – 40. Hypsometric curves were developed for each pre-settlement cross section (Figures 41-51). The hypsometric curves represent cross section geometry by comparing elevation with the corresponding wetted area of the cross section.

Flow rating curves were developed from the hyposmetric curves for each pre-settlement cross section using the Manning's formula (Linsley et al. 1982). Channel slope was measured from the 10-meter resolution elevation spatial data (NED 2006). Thalweg length was measured from the National Hydrography Dataset (Simley and Carswell 2009). A roughness coefficient of 0.080 was applied to represent sluggish reaches, with a weedy margin (Chow 1959). The pool elevation at zero flow was assumed to be the dry year pool elevation (Table 2). Flow rating curves for each pre-settlement cross section are presented in Figures 52 -62.

The QUAL2Kw model framework used to develop the Lake Jonive water quality model represents geometry as stream flow rating equations of velocity and depth in metric units. The flow rating curves for each pre-settlement cross section were converted to metric units and fitted to a power equations (i.e, depth = αQ^{β}) using nonlinear regression for representation in the QUAL2Kw model framework (Tables 5 & 6). All of the cross sections showed significant results with a high explained variance. The values in these tables are planned to be used in constructing the model geometry for developing water quality models for each of the pre-settlement lakes using the QUAL2Kw model framework.

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TABLES

Table 1. Longitudinal Reach Ranges and Cross Sections Selected for Laguna Pre-settlement Lake Water Quality Model Construction

Lake	Deas (2007) Cross-Section Selected (RM)	Range Represented for Model Reach (Rkm)	Model Reach length (km)	Number of 10-meter Model Segments in Model Reach
Ballard Lake - Wet Year Boundary	3.94	6.30 - 7.89	1.59	159
	5.95	7.90 - 10.19	2.29	229
	6.70	10.20 - 11.20	1	100
Cunningham Lake – Wet Year Boundary	14.66	23.60 - 24.19	0.59	59
	15.42	24.20 - 25.79	1.59	159
	16.59	25.80 - 28.00	2.2	220
Cunningham Lake – Dry Year Boundary	16.59	10.20 - 11.21	1.01	101
Sebring Lake – Wet Year Boundary	9.05	13.00 - 15.19	2.19	219
	9.79	15.20 - 16.59	1.39	139
	13.26	16.60 - 23.20	6.6	660
Sebring Lake - Dry Year Boundary	9.79	15.80 - 16.59	0.79	79
	10.83	16.60 - 17.79	1.19	119
	11.25	17.80 - 18.10	0.3	30

Table 2. Width and Pool Elevations of Laguna Pre-settlement Lakes at Selected Cross Sections

Lake	Pool Elevation		Cross Section River Mile	Channel Width	
	feet	meters		feet	meters
Ballard Lake - Wet Year Boundary	66.0	20.1	3.94	1521	4989
			5.95	1706	5596
			6.70	2380	7809
Cunningham Lake – Wet Year Boundary	76.7	23.4	14.66	672	2205
			15.42	176	576
			16.59	1913	6275
Cunningham Lake – Dry Year Boundary	74.7	22.7	16.59	340	1116
Sebring Lake – Wet Year Boundary	68.5	20.9	9.05	3067	10064
			9.79	1787	5861
			13.26	148	485
Sebring Lake - Dry Year Boundary	57.3	17.5	9.79	584	1914
			10.83	93	307
			11.25	90	295

Table 3. Sediment Deposition Volumes in Laguna Pre-settlement Lakes

Metric	Cunningham Lake	Ballard Lake	Sebring Lake
Sediment Yield (ac-ft/yr) (PWA, 2004; page 56)	37	28	64
Sediment Deposition (ac-ft/yr) (25% of Yield per PWA, 2004; page 56)	9.25	7	16
Pre-settlement <1830 (years)	180	180	180
Sediment Volume Deposited (ac-ft)	1665	1260	2880

Table 4. Depth of Sediment Deposition in Laguna Pre-settlement Lakes

Lake	Sediment Volume Deposited (m^3)	Lake Surface Area (m^2)	Sediment Depth Deposited (m)	Sediment Depth Deposited (ft)
Ballard Lake - Wet Year Boundary	1,554,187	2,513,966	0.62	2.0
Cunningham Lake – Wet Year Boundary	2,053,747	2,208,792	0.93	3.1
Cunningham Lake – Dry Year Boundary	51,501	55,389	0.93	3.1
Sebring Lake – Wet Year Boundary	3,552,428	7,270,595	0.49	1.6
Sebring Lake - Dry Year Boundary	90,446	185,111	0.49	1.6

Table 5. Depth Rating Curve Equation Terms for Laguna Pre-settlement Lakes at Selected Cross Sections

Pre-settlement River Mile	Coefficient (a)	Exponent (b)	Explained Variance (%)	Probability
3.94	1.2	0.349	99.1%	< 0.01
5.95	13.7	0.464	99.4%	< 0.01
6.7	9.2	0.317	97.9%	< 0.01
9.05	35.1	0.006	79.5%	0.027
9.79	1.0	0.452	99.2%	< 0.01
10.83	1.1	0.417	99.9%	< 0.01
11.25	2.8	0.383	97.1%	< 0.01
13.26	2.9	0.547	99.9%	< 0.01
14.66	0.9	0.503	99.7%	< 0.01
15.42	1.8	0.580	100.0%	< 0.01
16.59	0.7	0.498	99.8%	< 0.01

Table 6. Velocity Rating Curve Equation Terms for Laguna Pre-settlement Lakes at Selected Cross Sections

Pre-settlement River Mile	Coefficient (a)	Exponent (a)	Explained Variance (%)	Probability
3.94	0.084	0.284	99.9%	< 0.01
5.95	0.095	0.299	99.9%	< 0.01
6.7	0.080	0.289	99.7%	< 0.01
9.05	0.002	0.983	100.0%	< 0.01
9.79	0.003	0.973	100.0%	< 0.01
10.83	0.015	0.838	99.5%	< 0.01
11.25	0.031	0.902	99.6%	< 0.01
13.26	0.043	0.845	99.6%	< 0.01
14.66	0.003	0.972	100.0%	< 0.01
15.42	0.006	0.970	100.0%	< 0.01
16.59	0.006	0.922	99.9%	< 0.01

FIGURES

FIGURES

Figure 1. 1840 Map of the Laguna (B-492 El Molino).
Courtesy of The Bancroft Library, University of California, Berkeley, CA 94720-6000; http://bancroft.berkeley.edu/

Figure 2. 1844 Map of the Laguna (B-128 Llano de Santa Rosa)
Courtesy of The Bancroft Library, University of California, Berkeley, CA 94720-6000; http://bancroft.berkeley.edu/

Figure 3. 1845 Map of the Laguna (B-664 San Miguel)
Courtesy of The Bancroft Library, University of California, Berkeley, CA 94720-6000; http://bancroft.berkeley.edu/

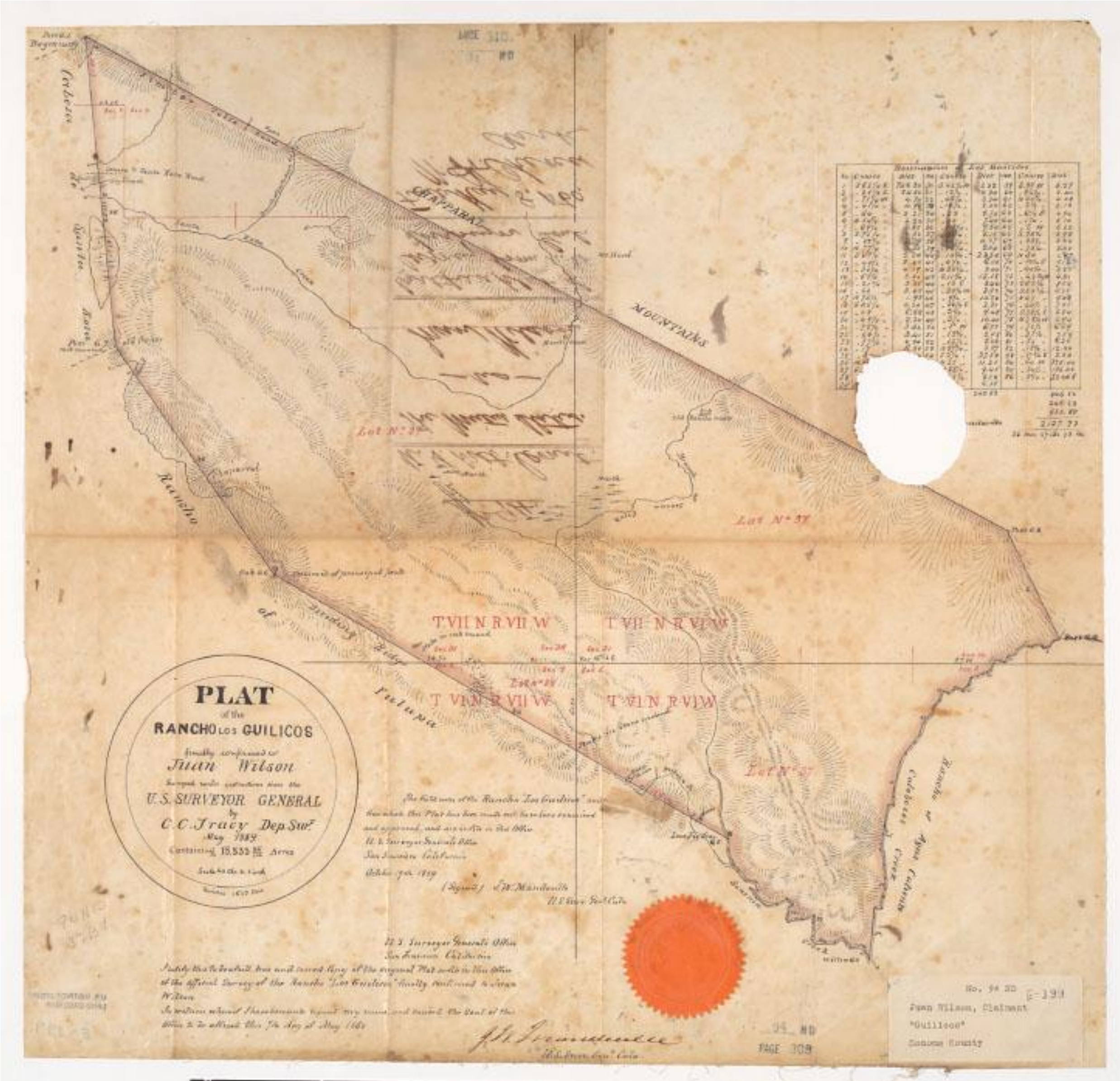

Figure 4. 1859 Map of the Laguna (E-199 Rancho Los Guillicos)
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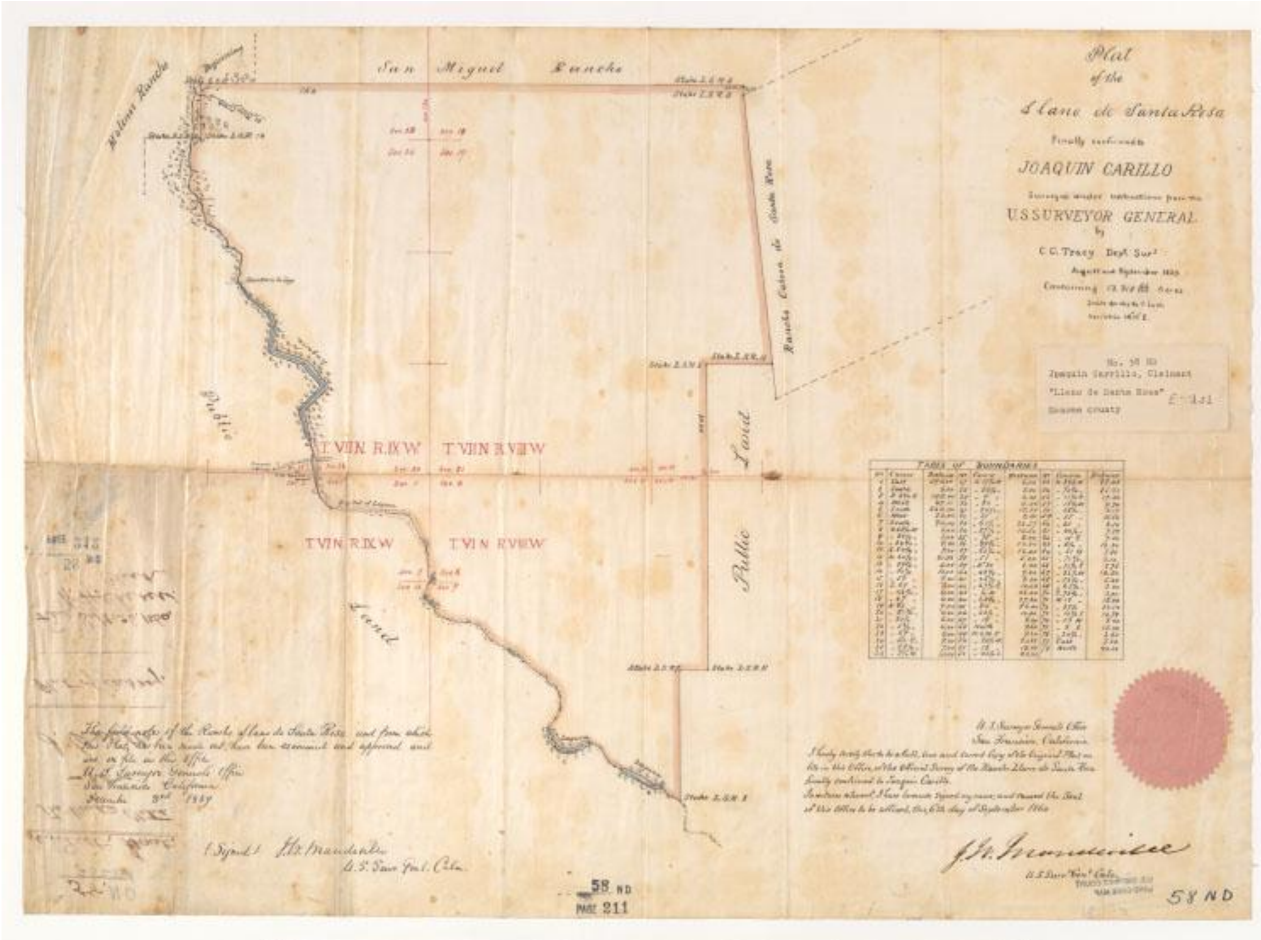

Figure 5. 1860 Map of the Laguna (E-131 Llano de Santa Rosa)
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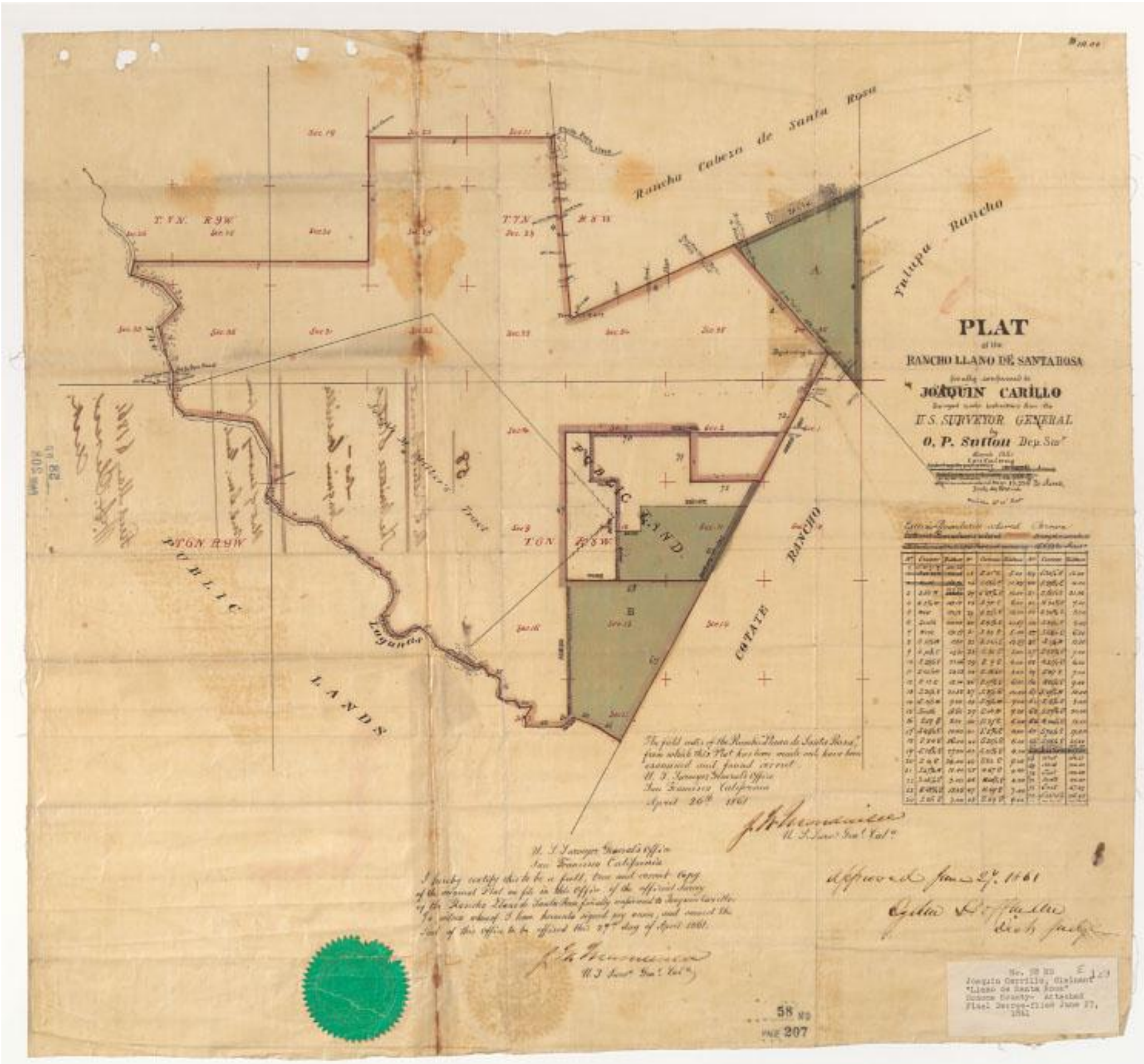

Figure 6. 1861 Map of the Laguna (Llano de Santa Rosa)
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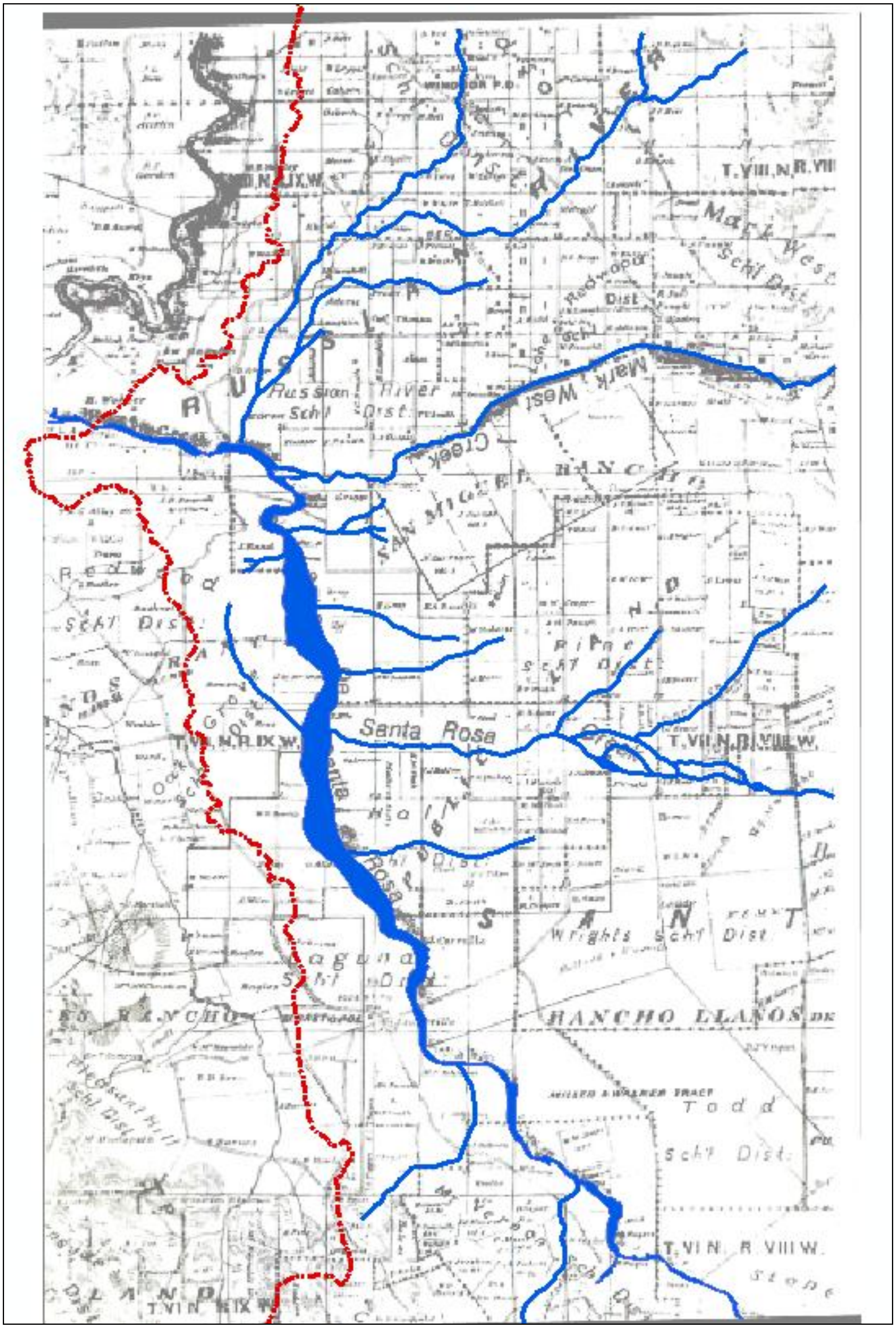

Figure 7. 1867 Map of the Laguna (Bowers, 1867)

Figure 8. 1877 Historical Atlas of Sonoma County overlaid with Laguna watershed boundary (Thompson, 1877).

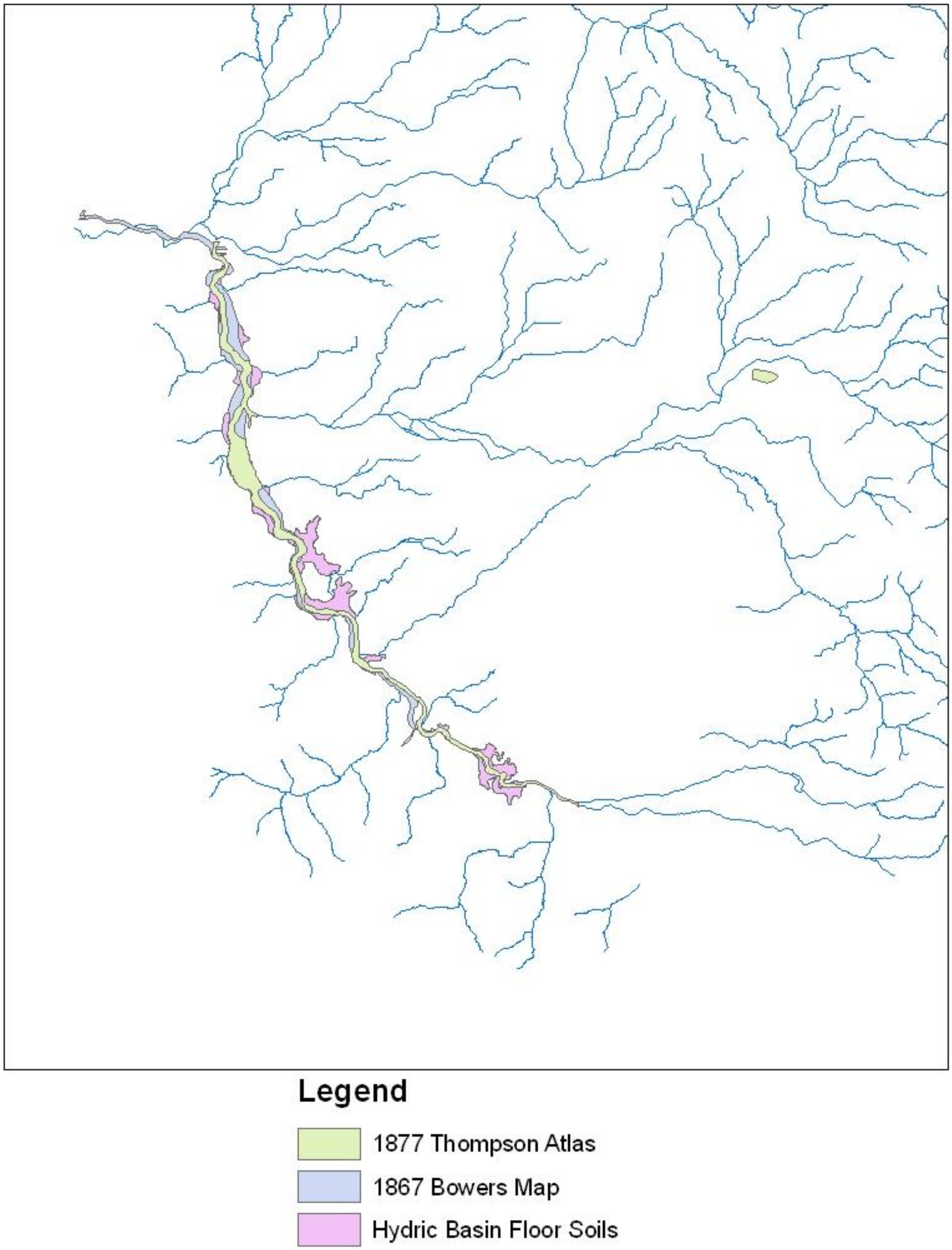

Figure 9. Boundaries of Laguna Open Water Areas from Historical Maps with adjacent Basin Floor Hydric Soils.

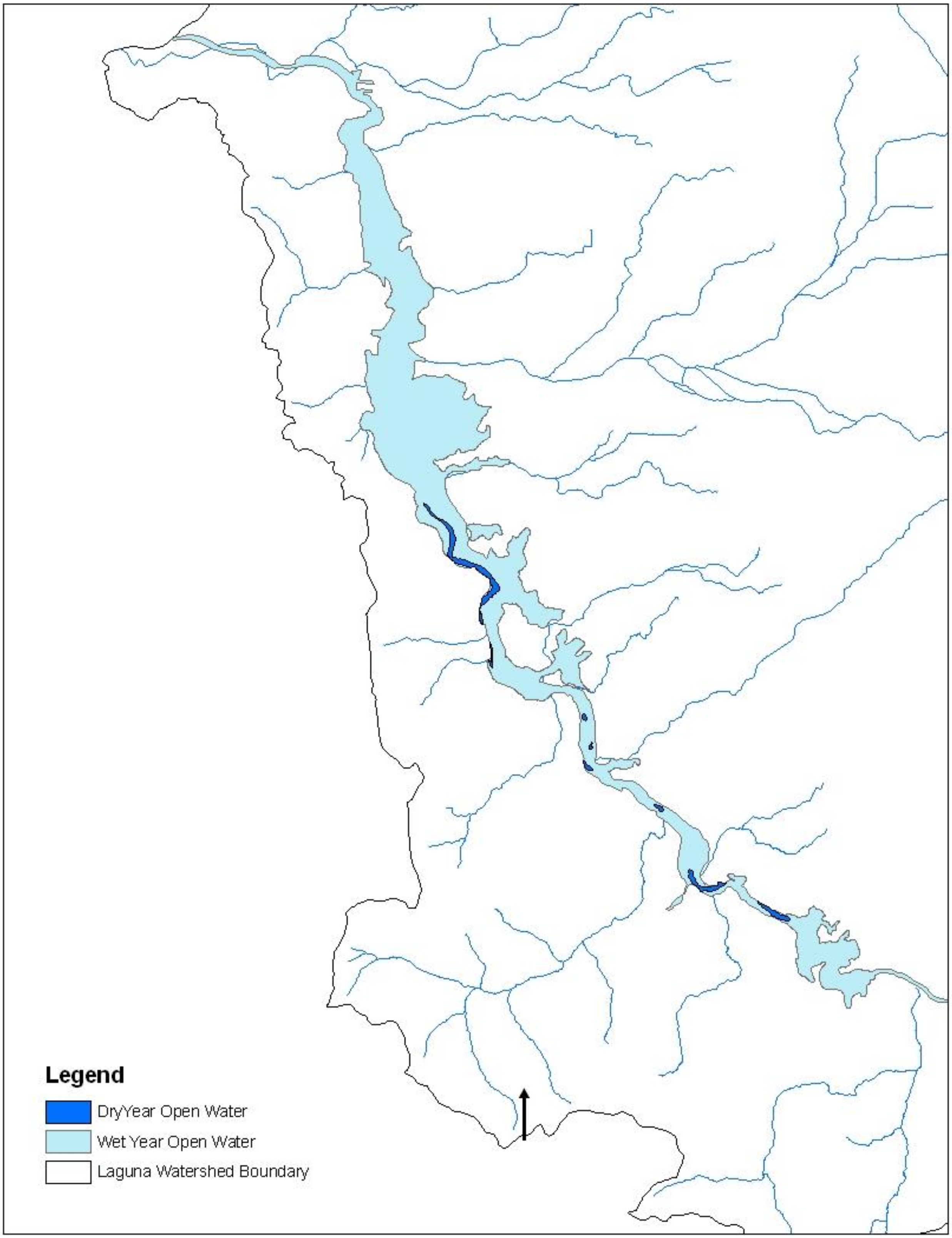

Figure 10. Boundaries of Historical Laguna Open Water Areas in Wet and Dry Climate Years.

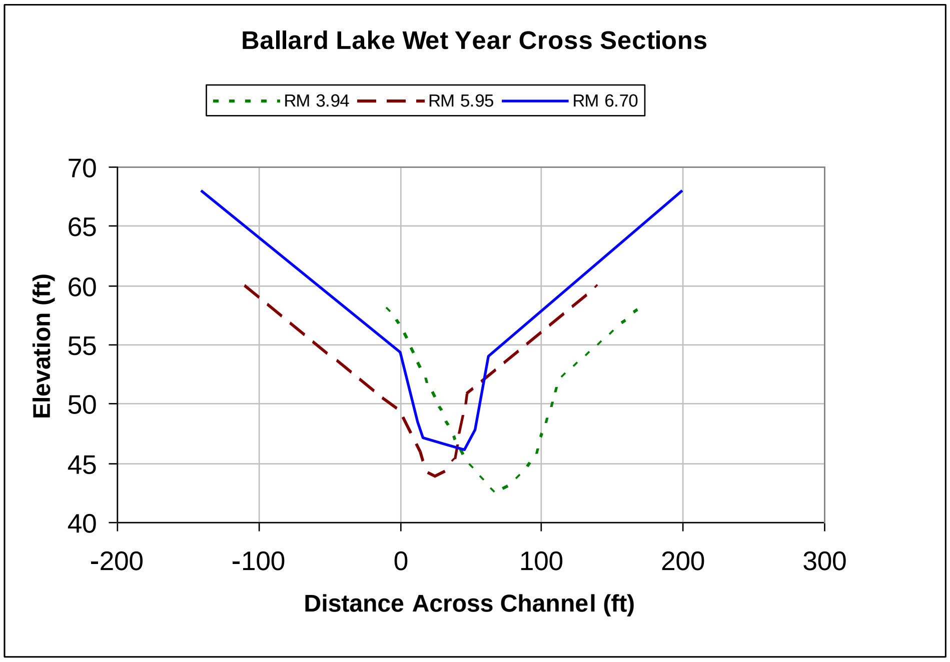

Figure 11. Ballard Lake Wet Year Cross Sections

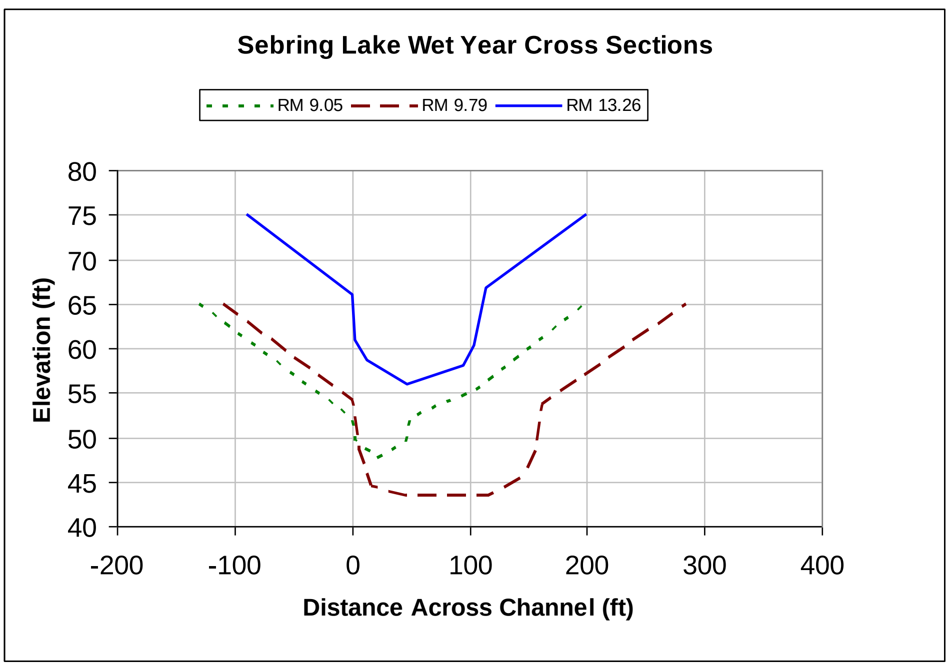

Figure 12. Sebring Lake Wet Year Cross Sections

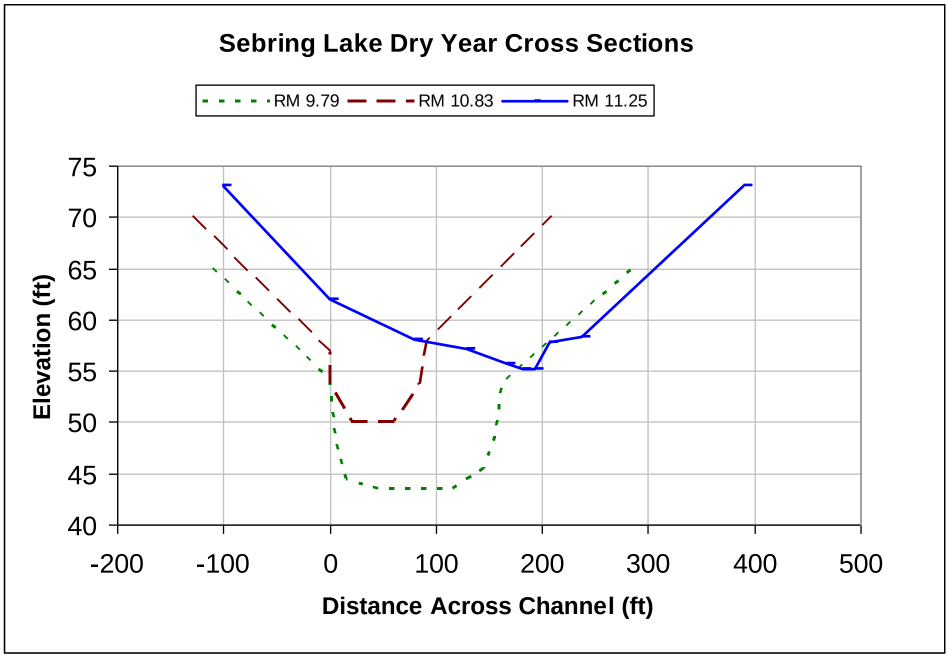

Figure 13. Sebring Lake Dry Year Cross Sections

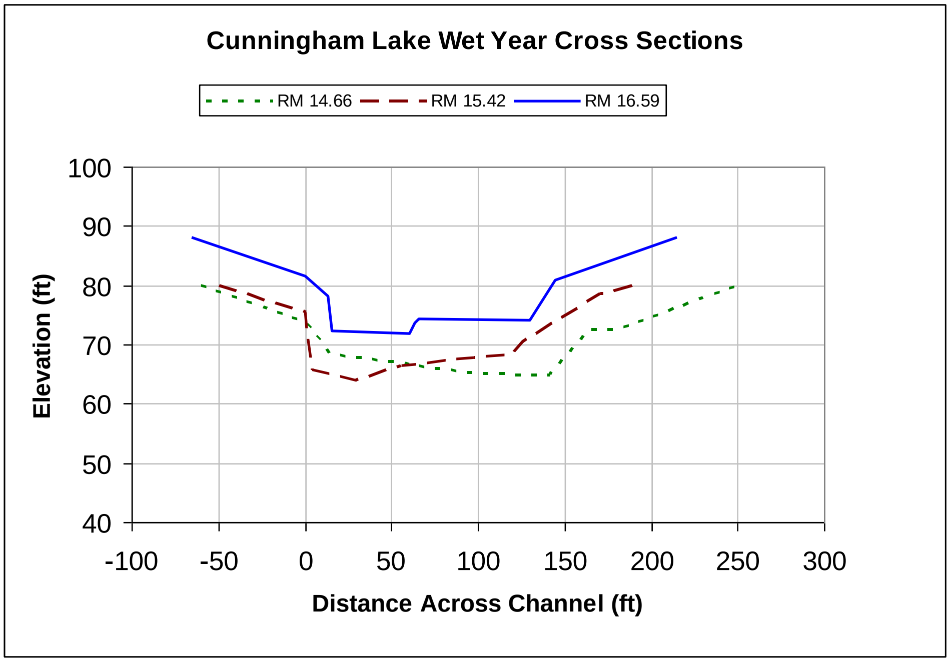

Figure 14. Cunningham Lake Wet Year Cross Sections

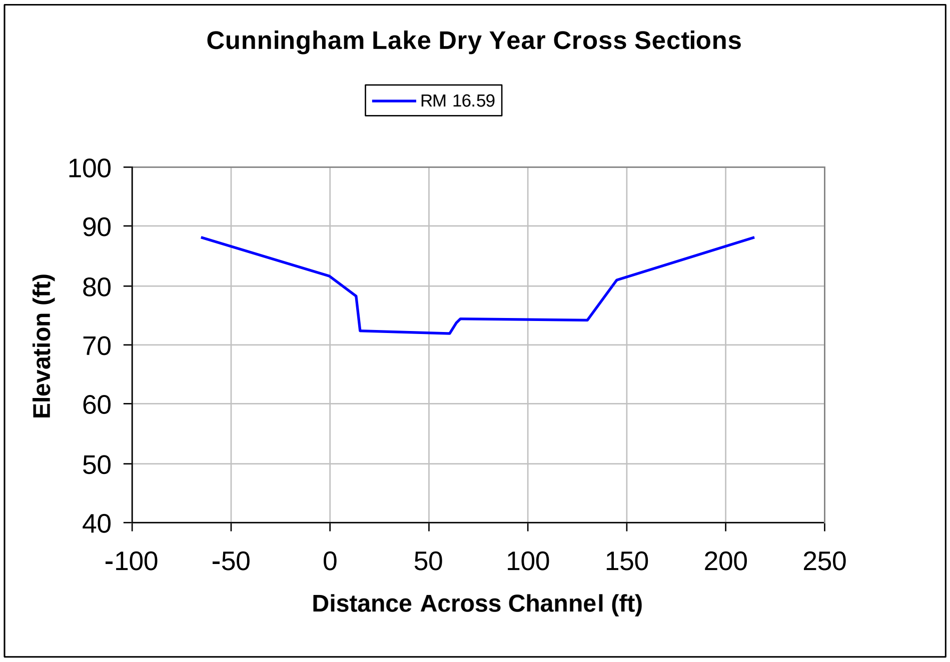

Figure 15. Cunningham Lake Dry Year Cross Sections

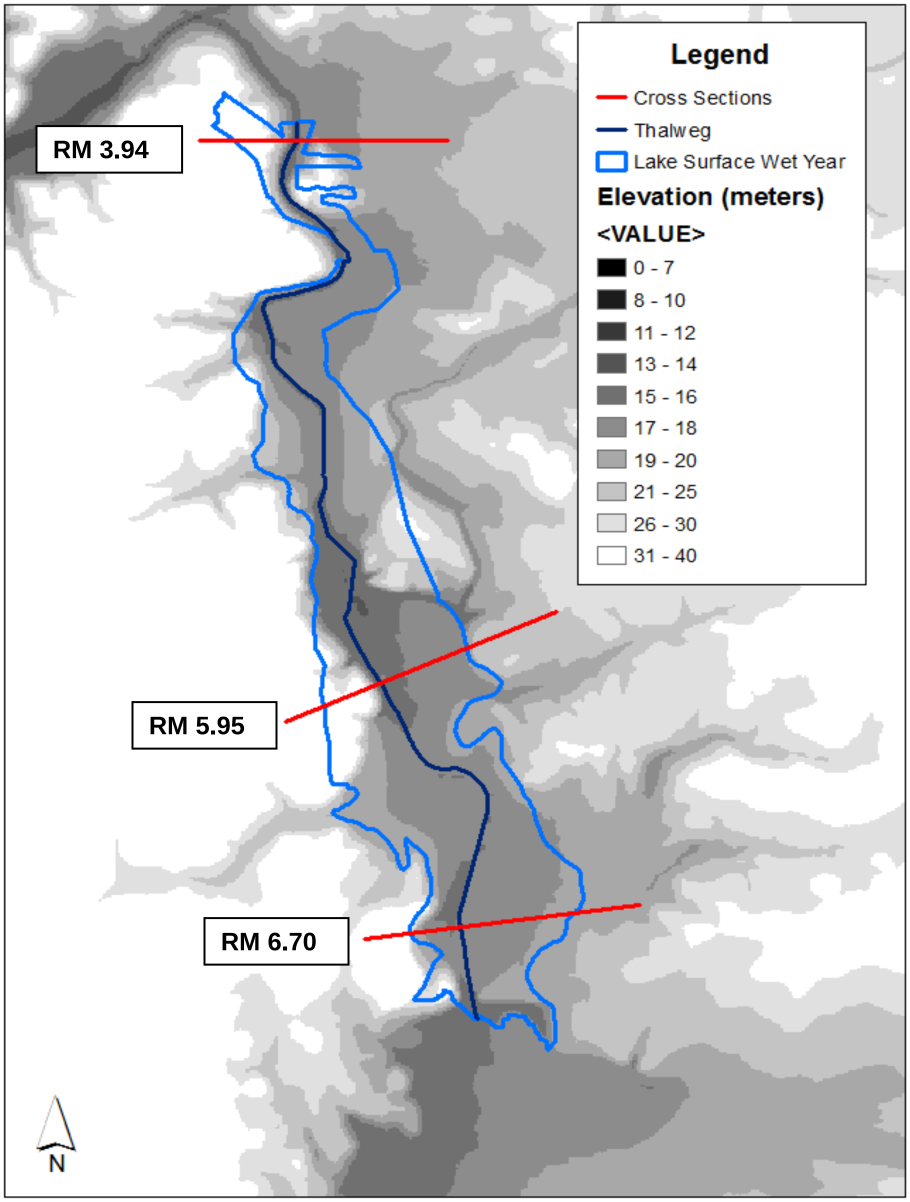

Figure 16. Cross Section Locations for Ballard Lake

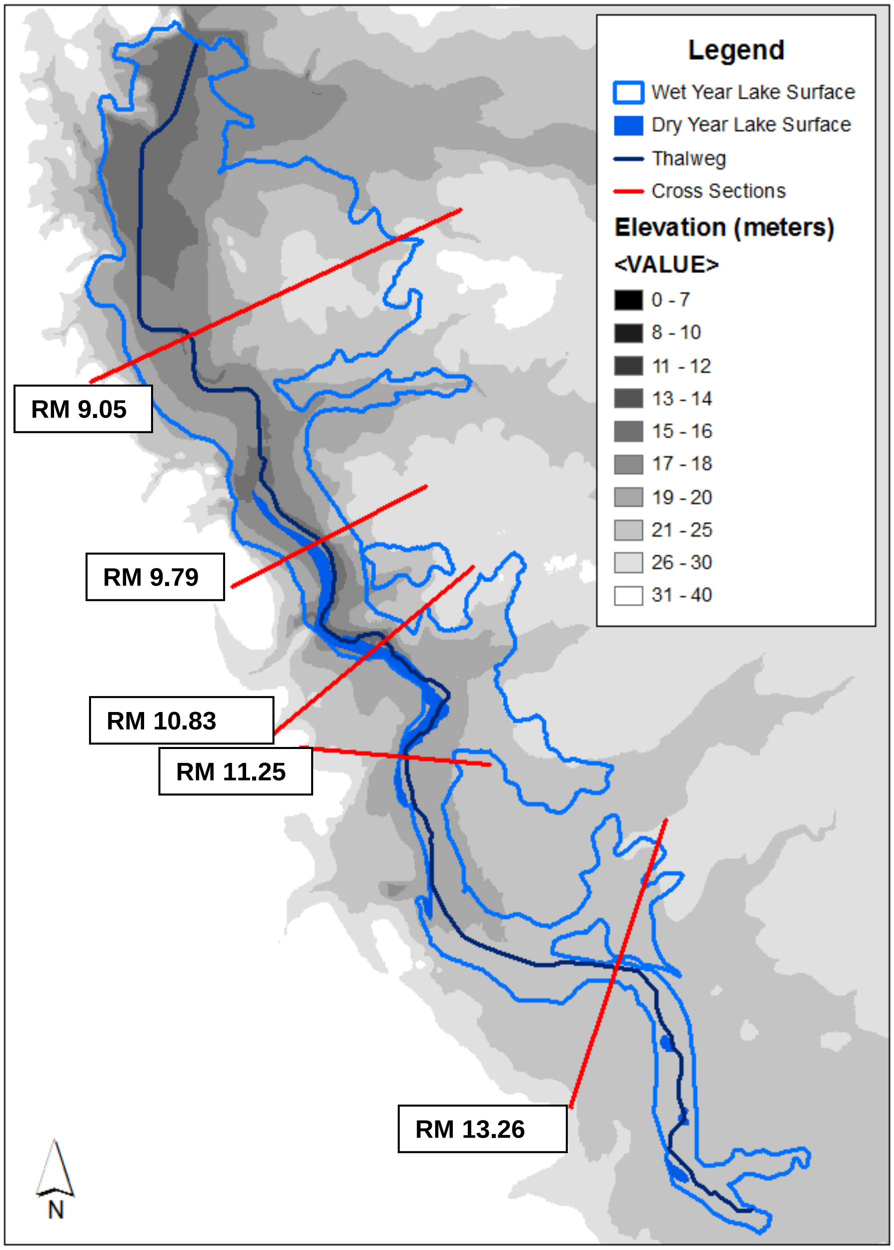

Figure 17. Cross Section Locations for Sebring Lake

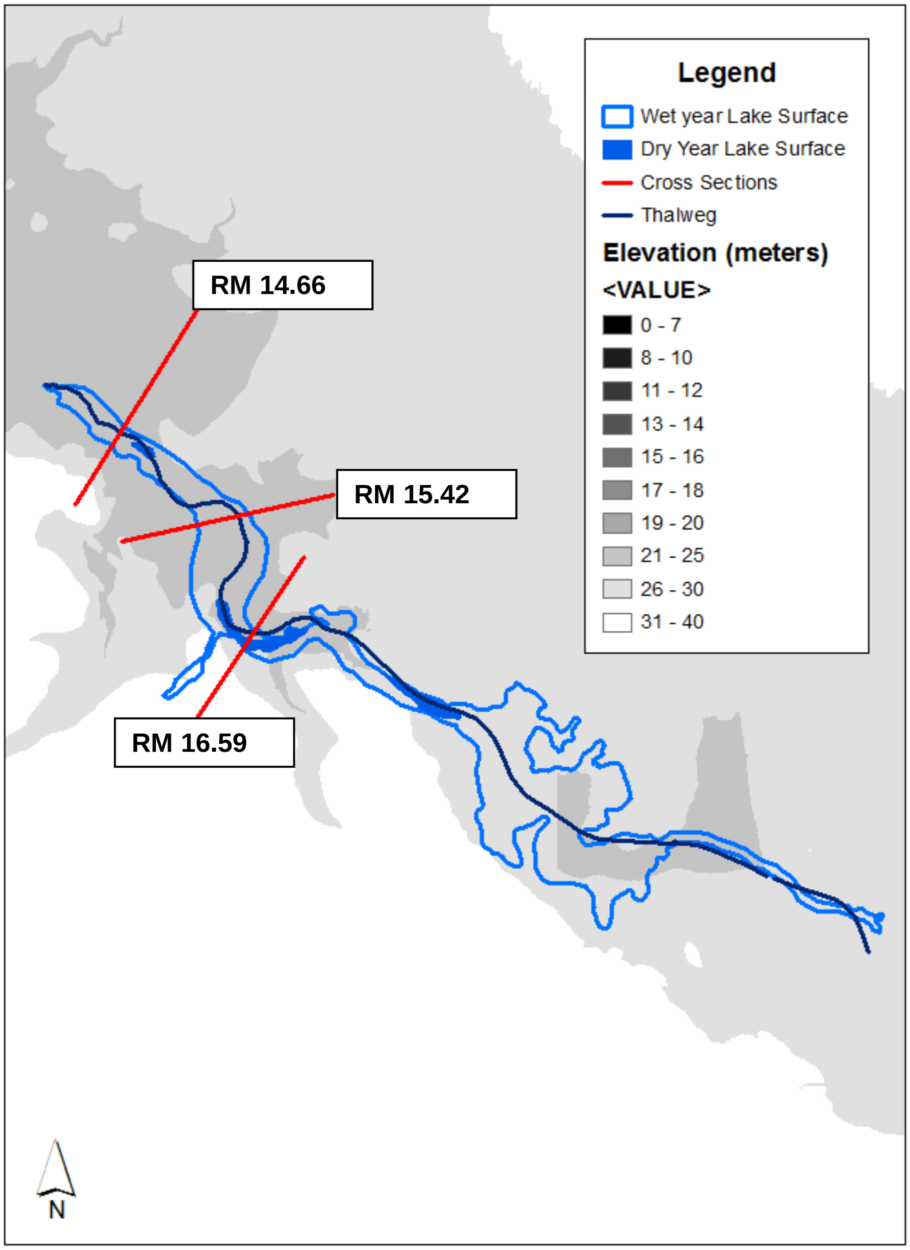

Figure 18. Cross Section Locations for Cunningham Lake

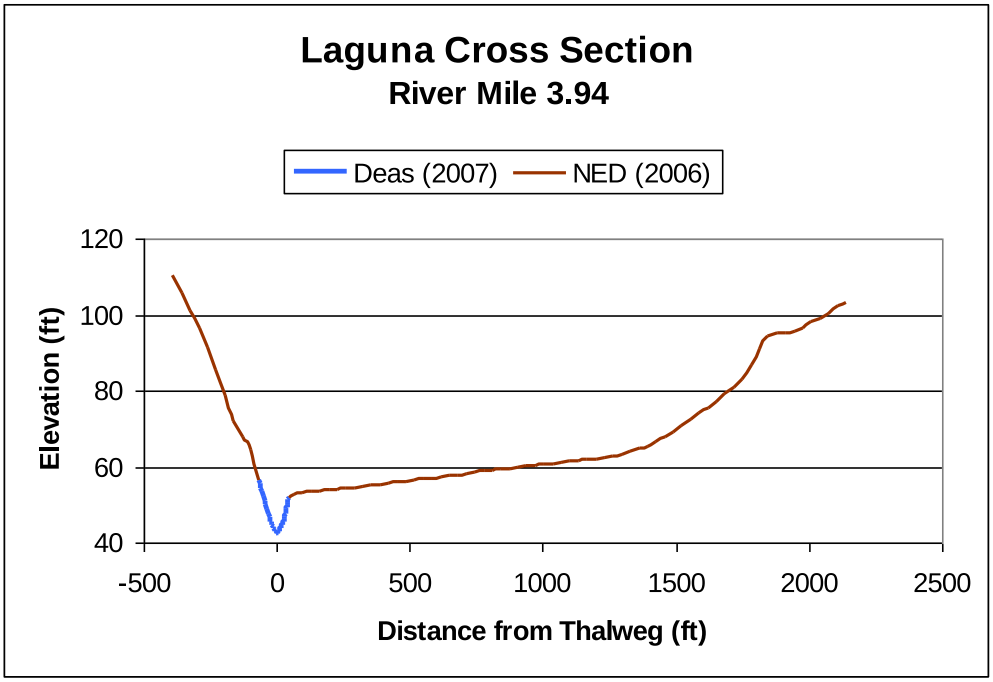

Figure 19. Elevation Profile at Laguna River Mile 3.94

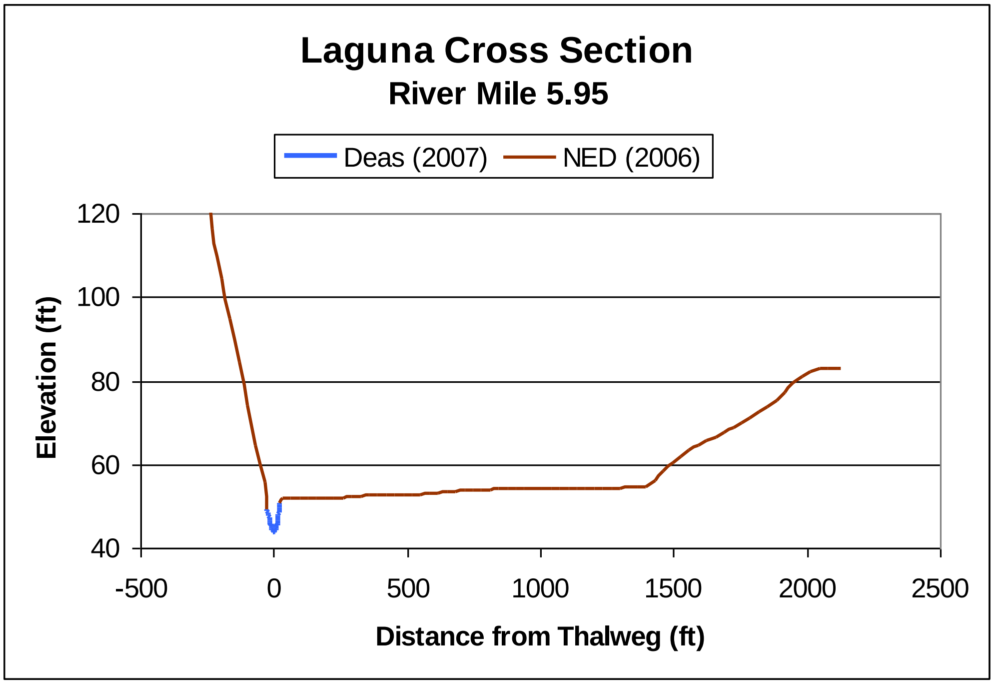

Figure 20. Elevation Profile at Laguna River Mile 5.95

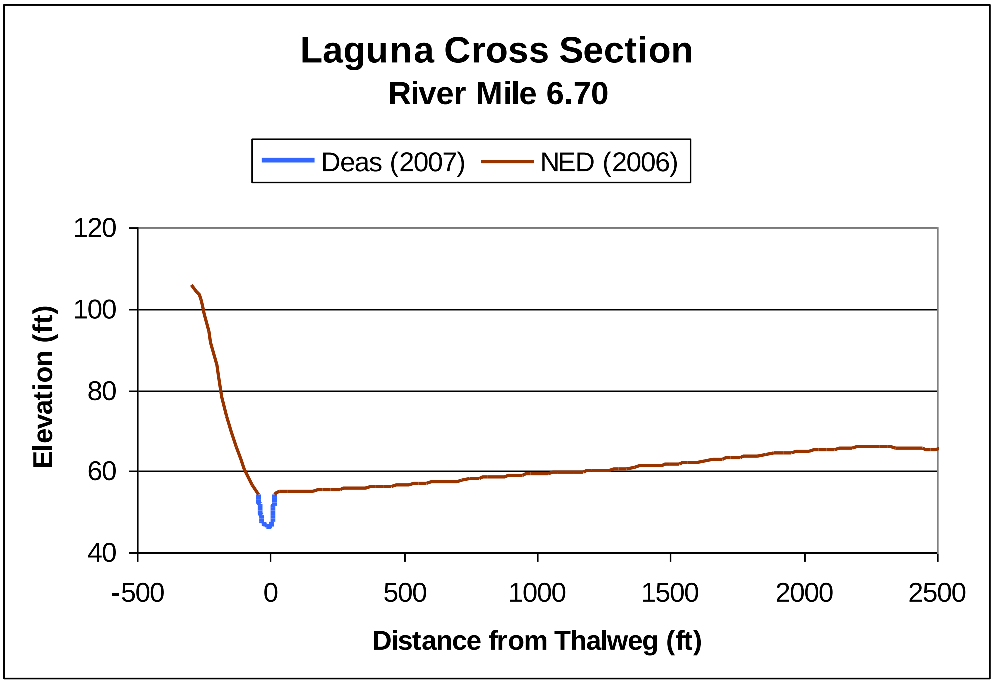

Figure 21. Elevation Profile at Laguna River Mile 6.70

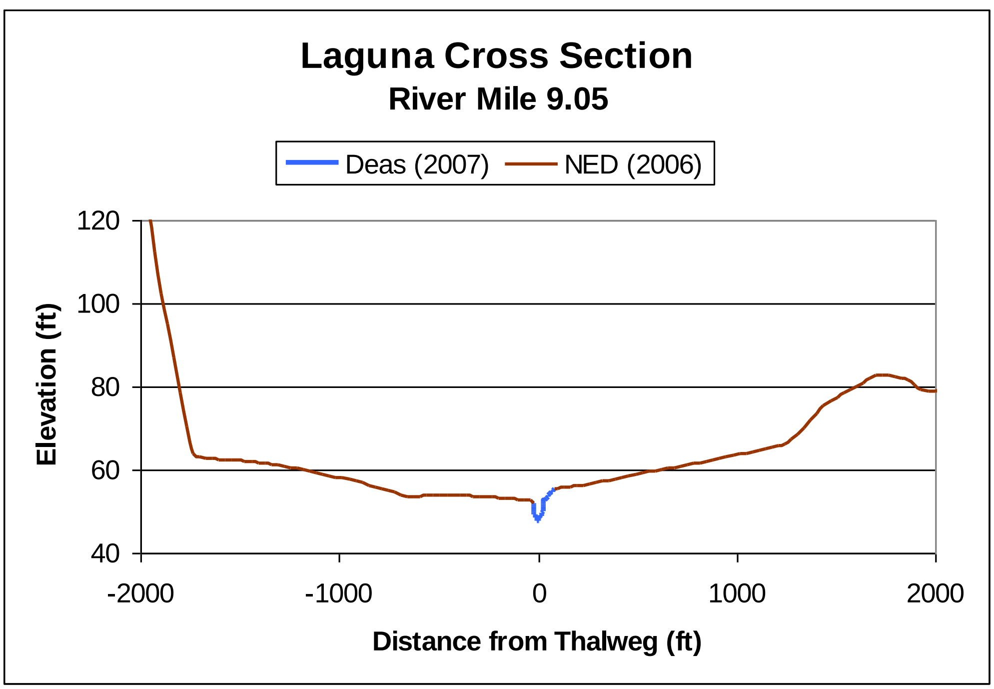

Figure 22. Elevation Profile at Laguna River Mile 9.05

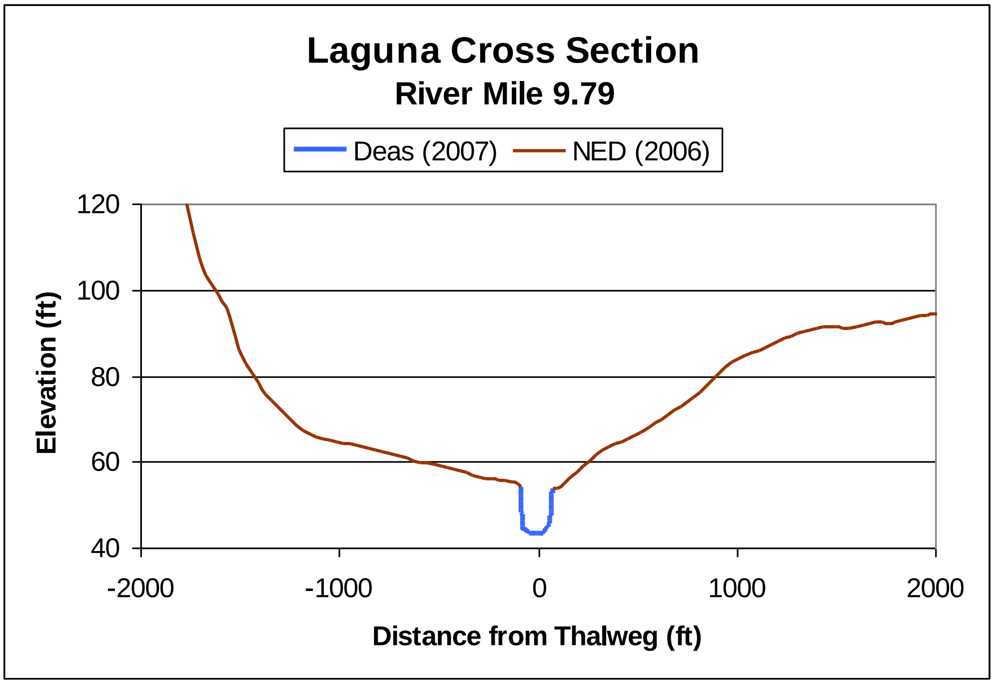

Figure 23. Elevation Profile at Laguna River Mile 9.79

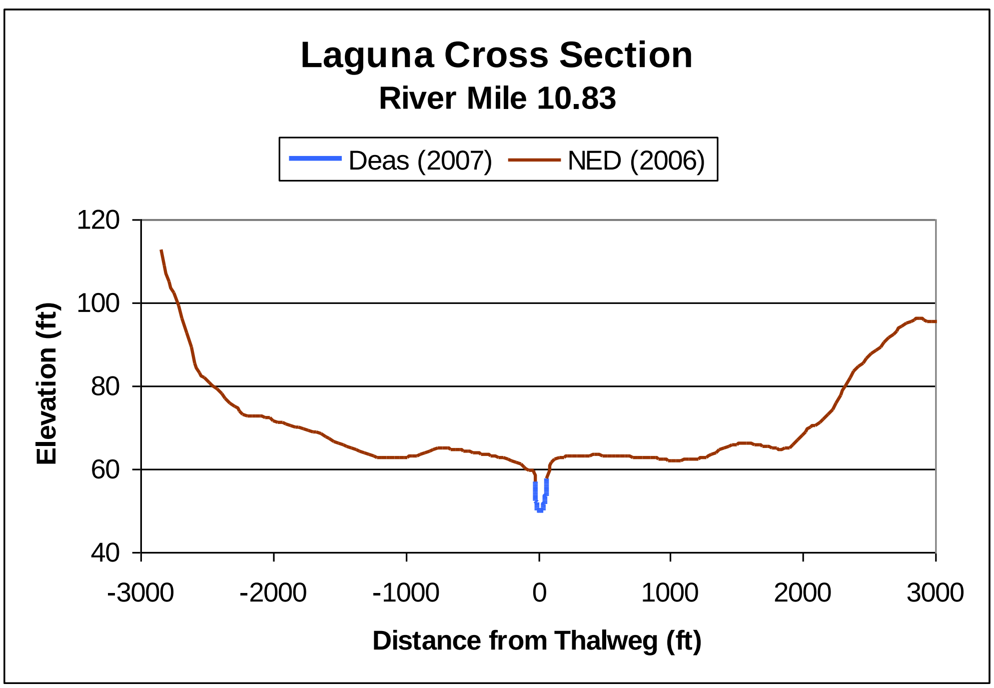

Figure 24. Elevation Profile at Laguna River Mile 10.83

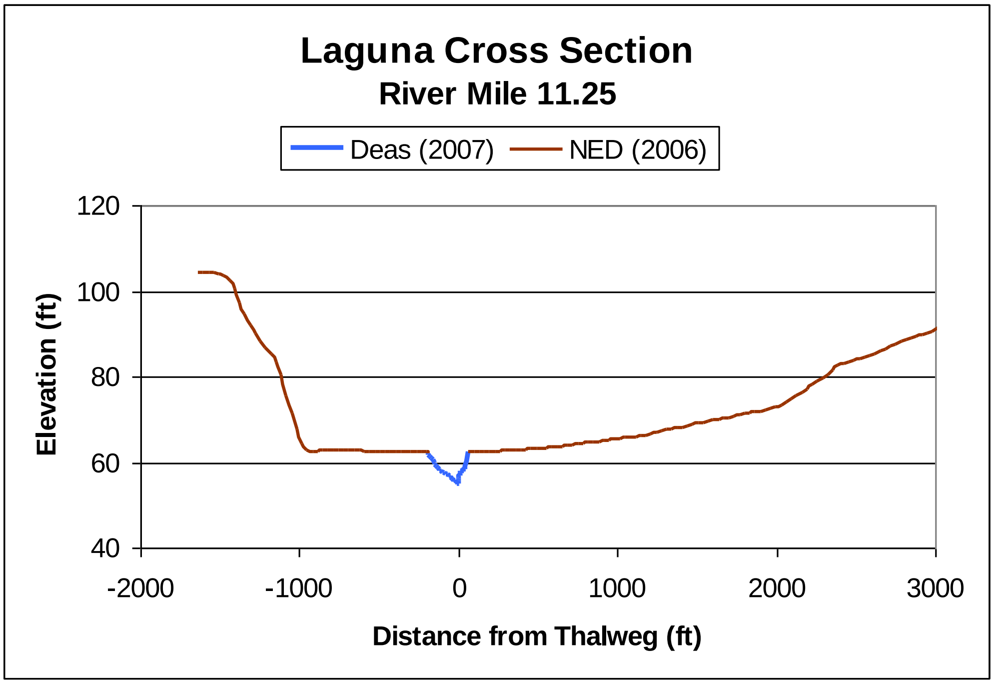

Figure 25. Elevation Profile at Laguna River Mile 11.25

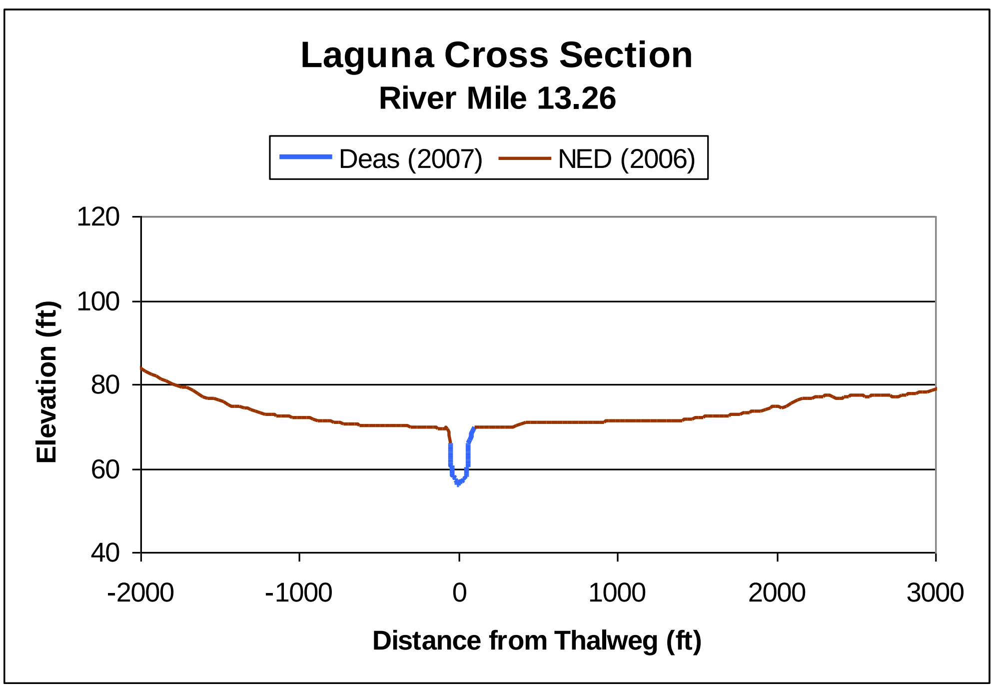

Figure 26. Elevation Profile at Laguna River Mile 13.26

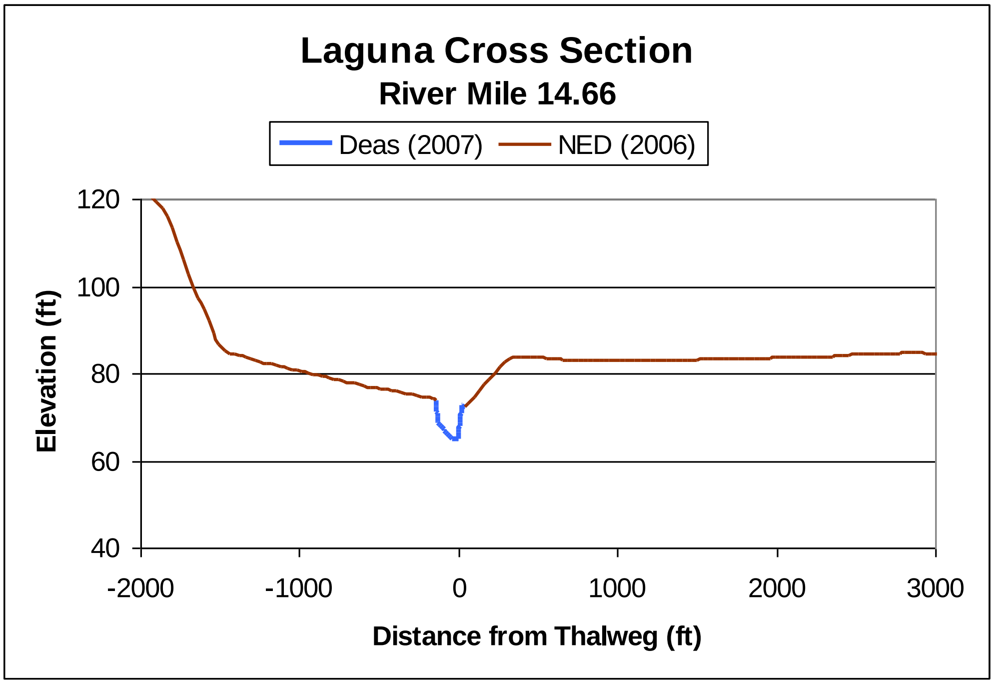

Figure 27. Elevation Profile at Laguna River Mile 14.66

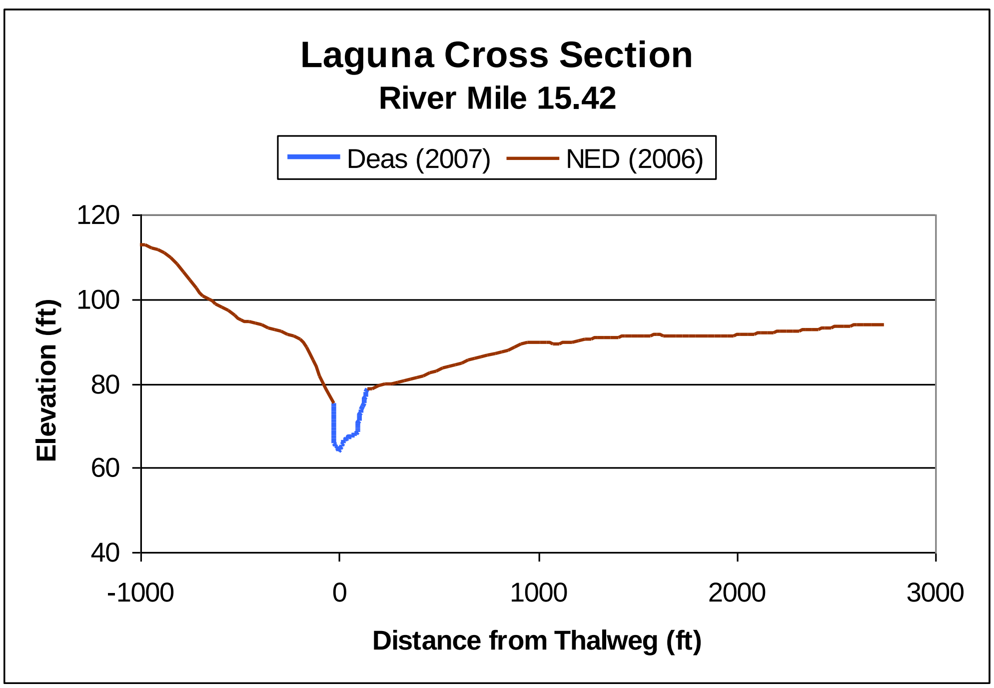

Figure 28. Elevation Profile at Laguna River Mile 15.42

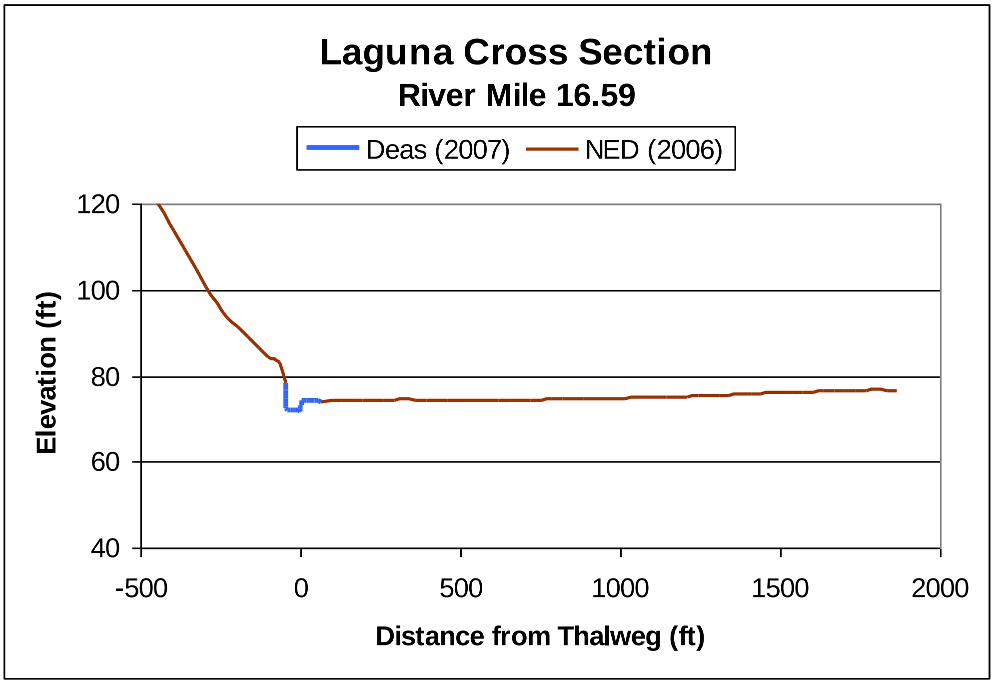

Figure 29. Elevation Profile at Laguna River Mile 16.59

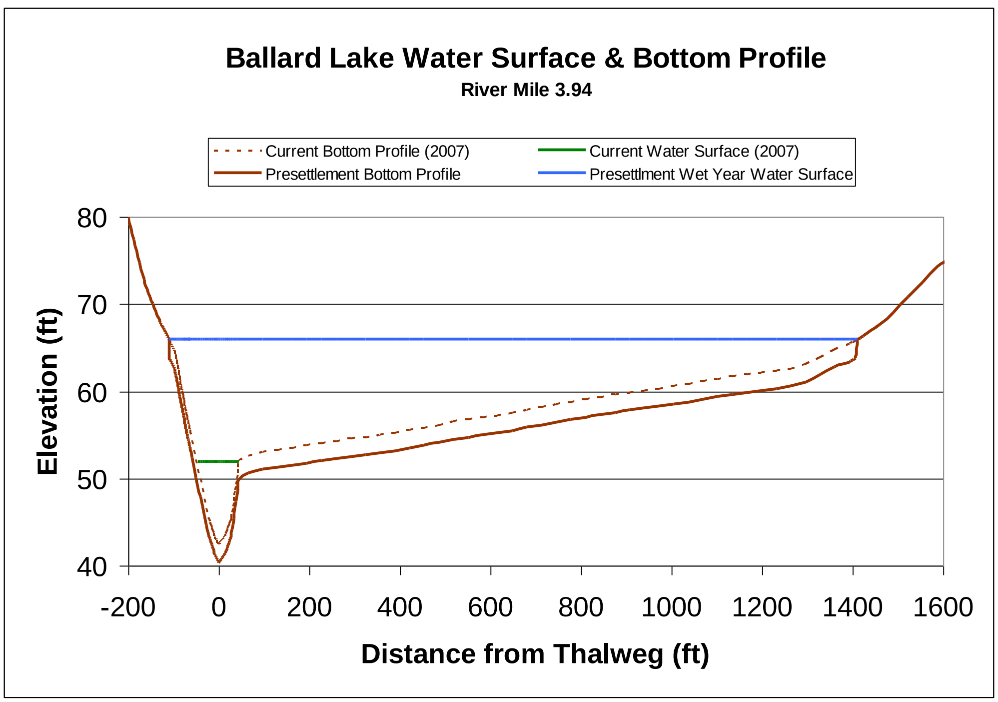

Figure 30. Water Surface and Bottom Profiles at Laguna River Mile 3.94

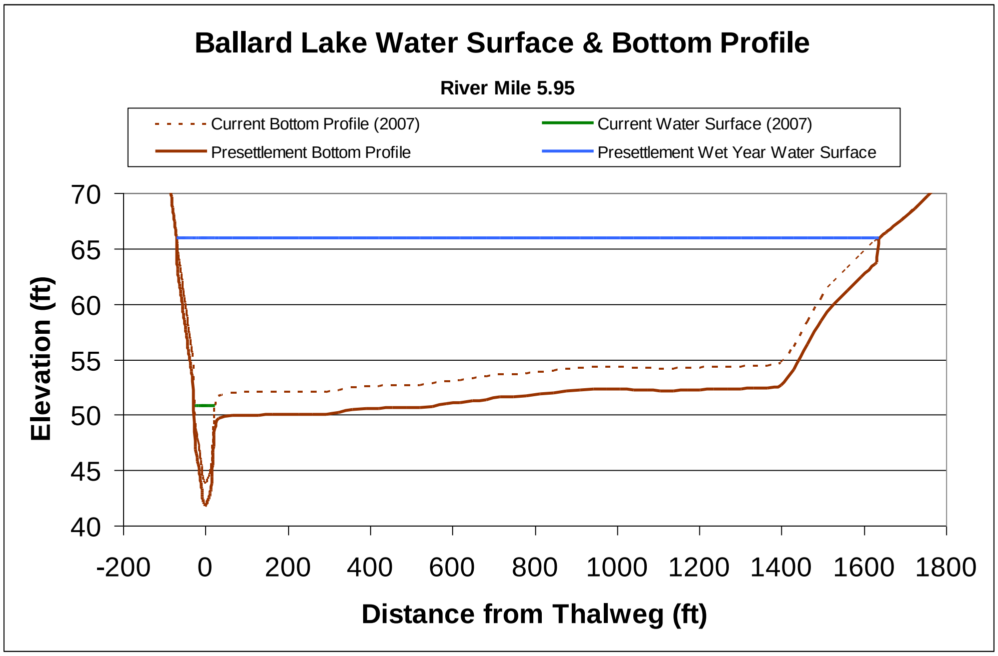

Figure 31. Water Surface and Bottom Profiles at Laguna River Mile 5.95

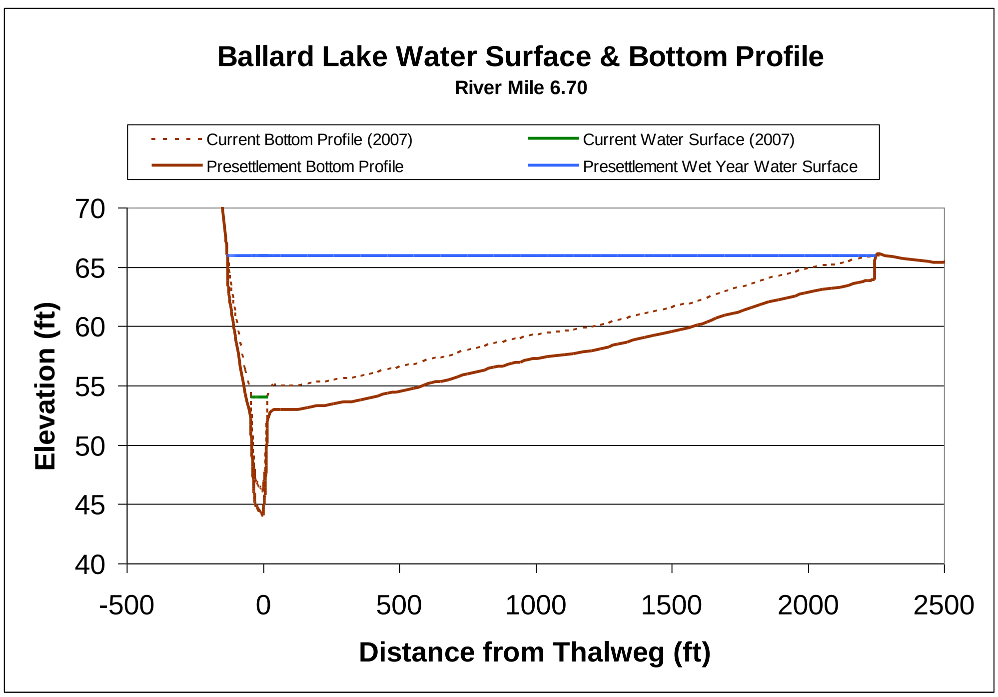

Figure 32. Water Surface and Bottom Profiles at Laguna River Mile 6.70

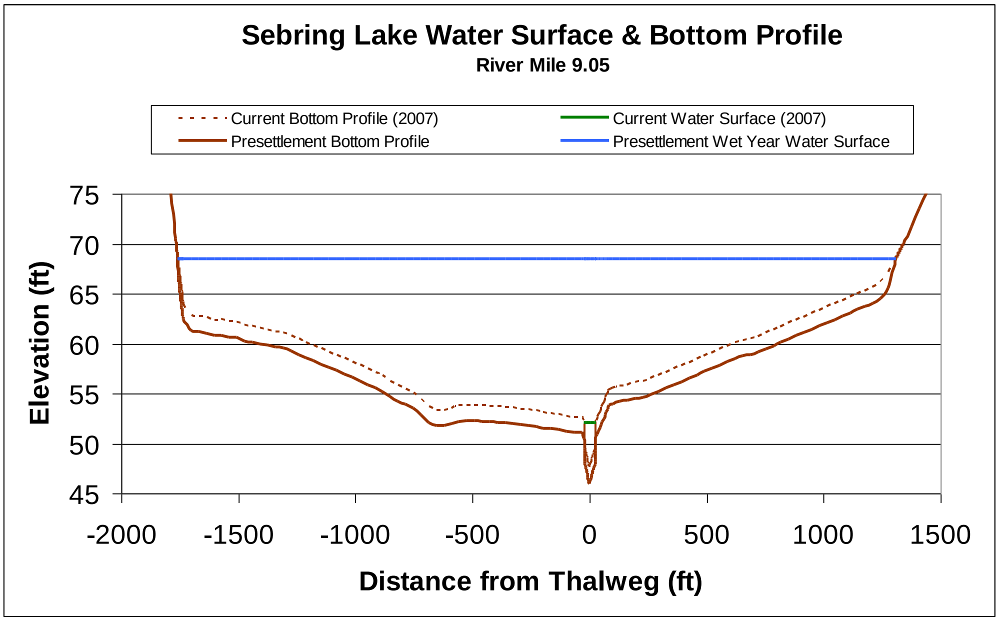

Figure 33. Water Surface and Bottom Profiles at Laguna River Mile 9.05

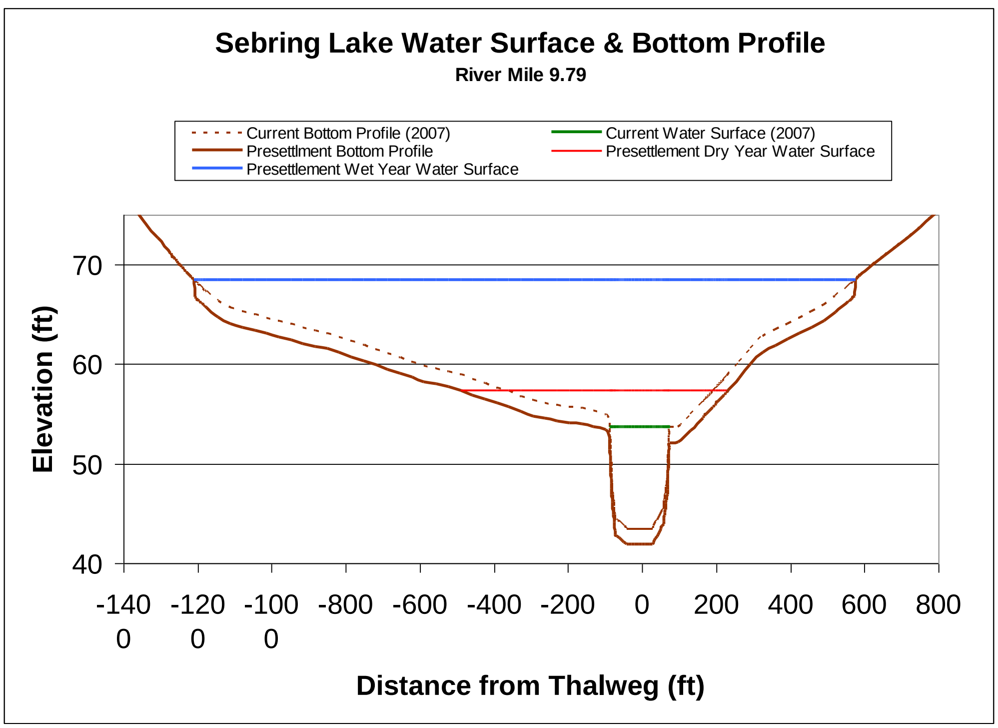

Figure 34. Water Surface and Bottom Profiles at Laguna River Mile 9.79

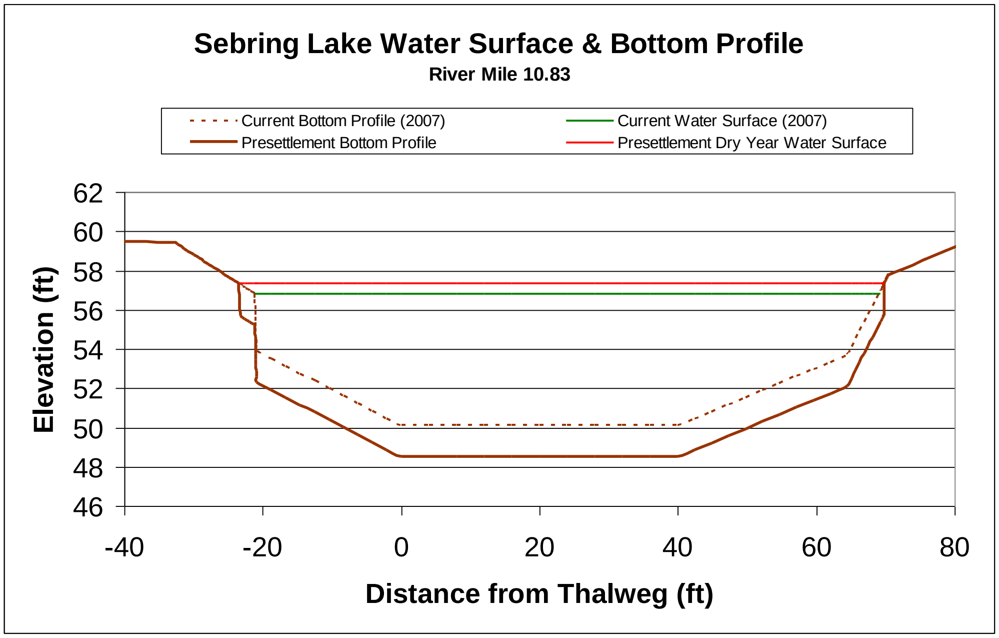

Figure 35. Water Surface and Bottom Profiles at Laguna River Mile 10.83

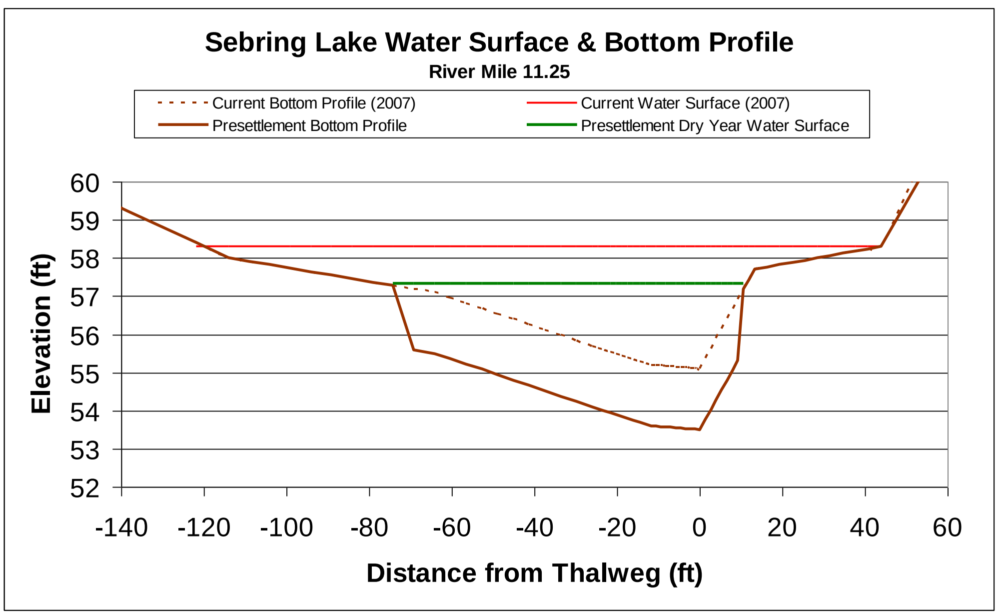

Figure 36. Water Surface and Bottom Profiles at Laguna River Mile 11.25

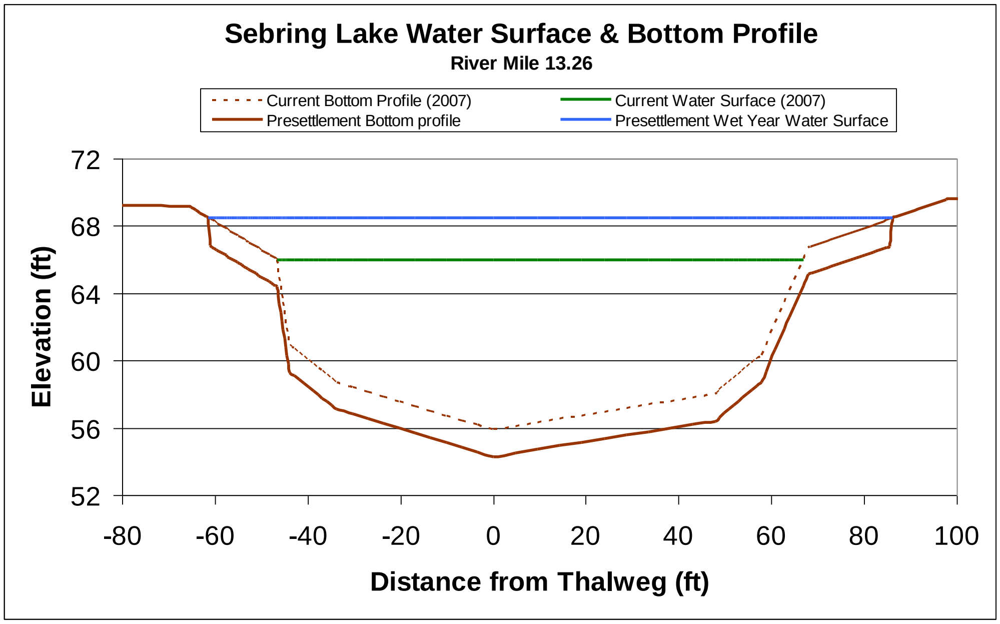

Figure 37. Water Surface and Bottom Profiles at Laguna River Mile 13.26

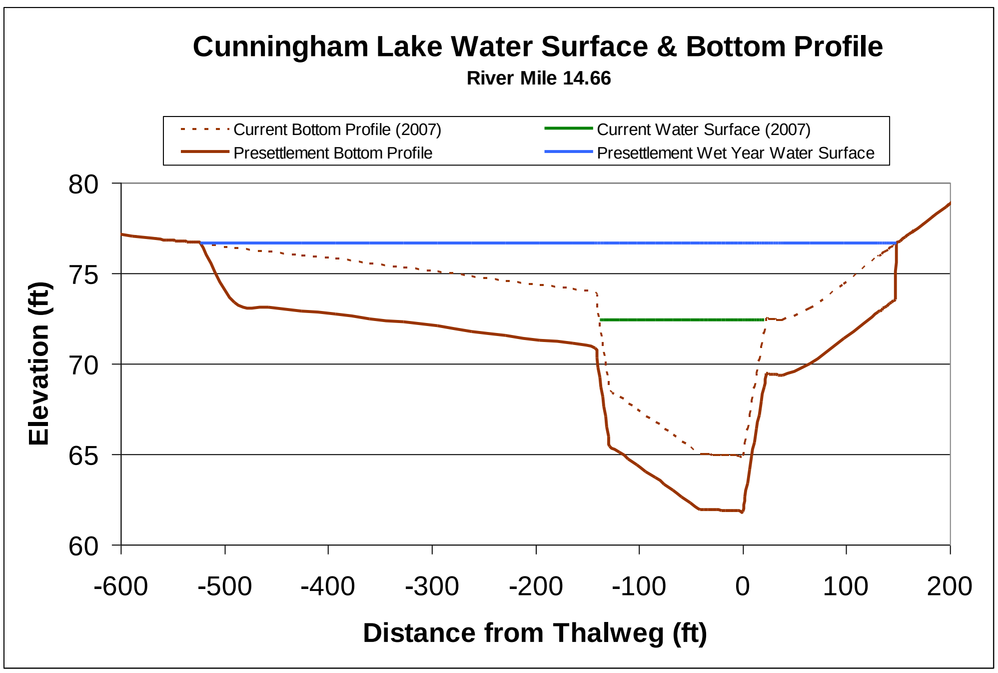

Figure 38. Water Surface and Bottom Profiles at Laguna River Mile 14.66

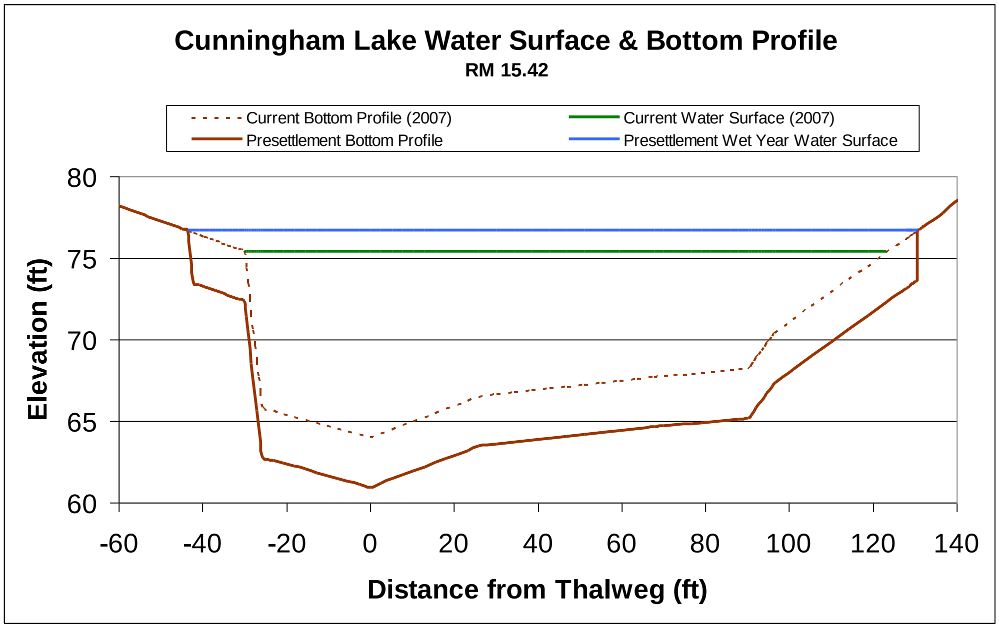

Figure 39. Water Surface and Bottom Profiles at Laguna River Mile 15.42

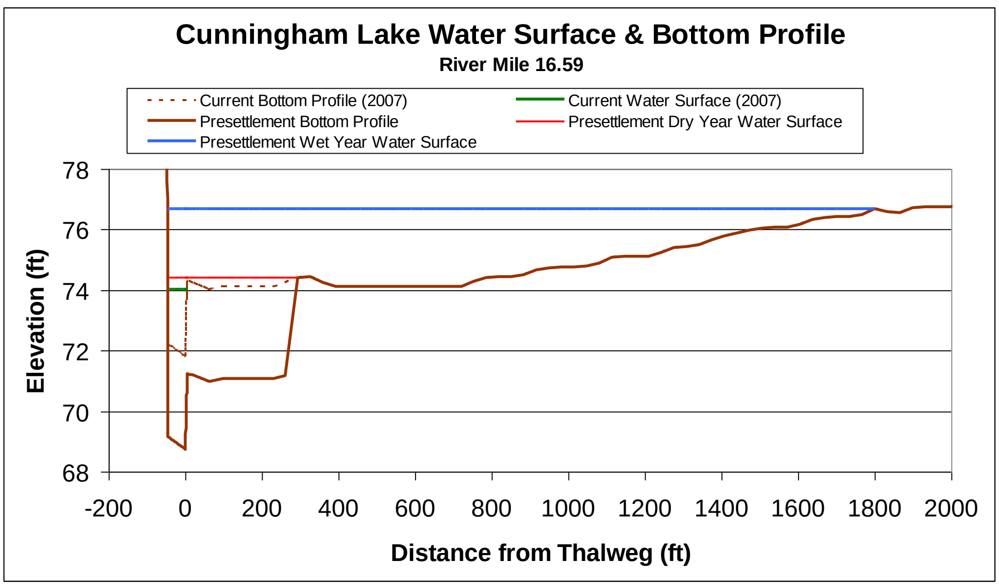

Figure 40. Water Surface and Bottom Profiles at Laguna River Mile 16.59

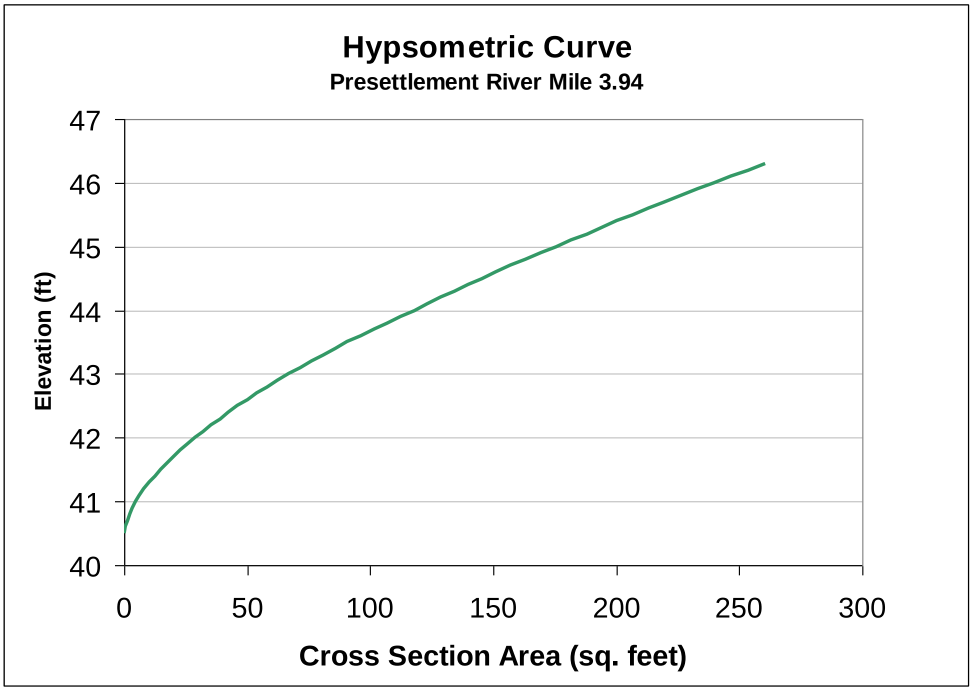

Figure 41. Hypsometric Curve at Pre-settlement River Mile 3.94

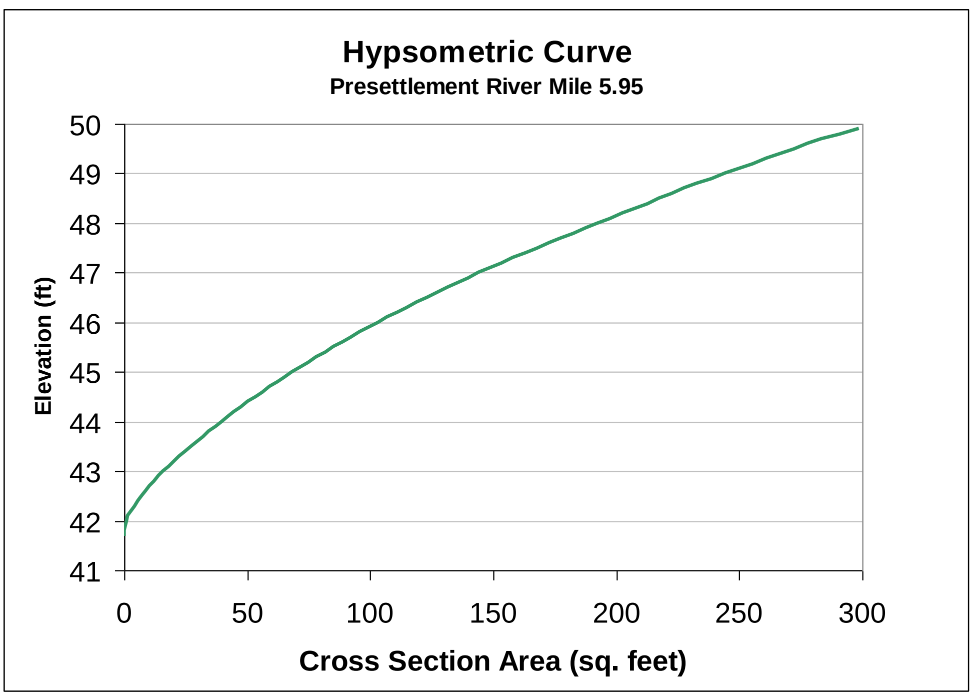

Figure 42. Hypsometric Curve at Pre-settlement River Mile 5.95

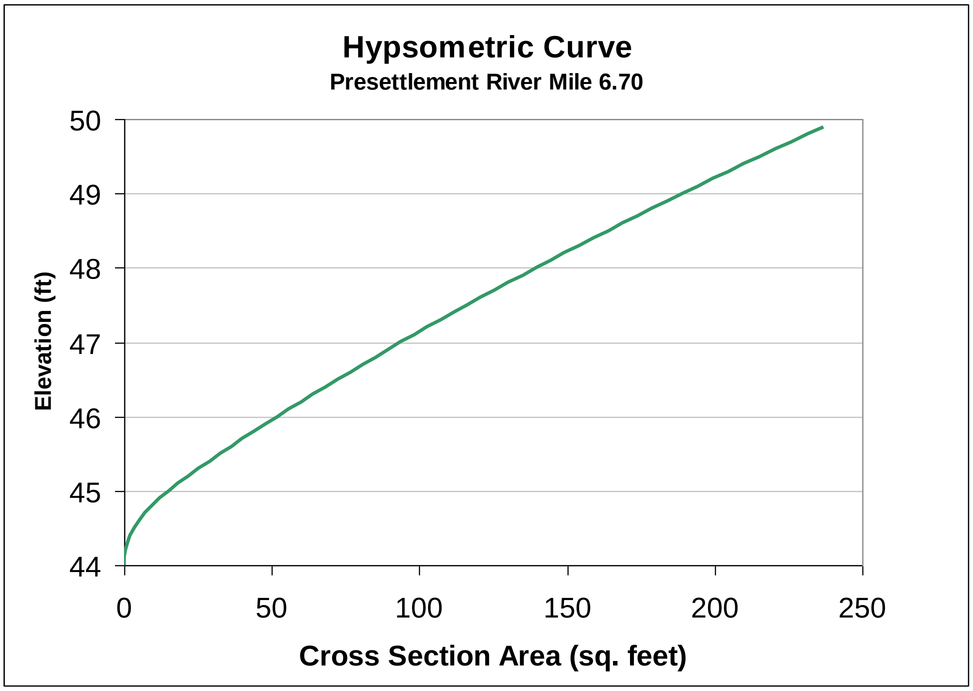

Figure 43. Hypsometric Curve at Pre-settlement River Mile 6.70

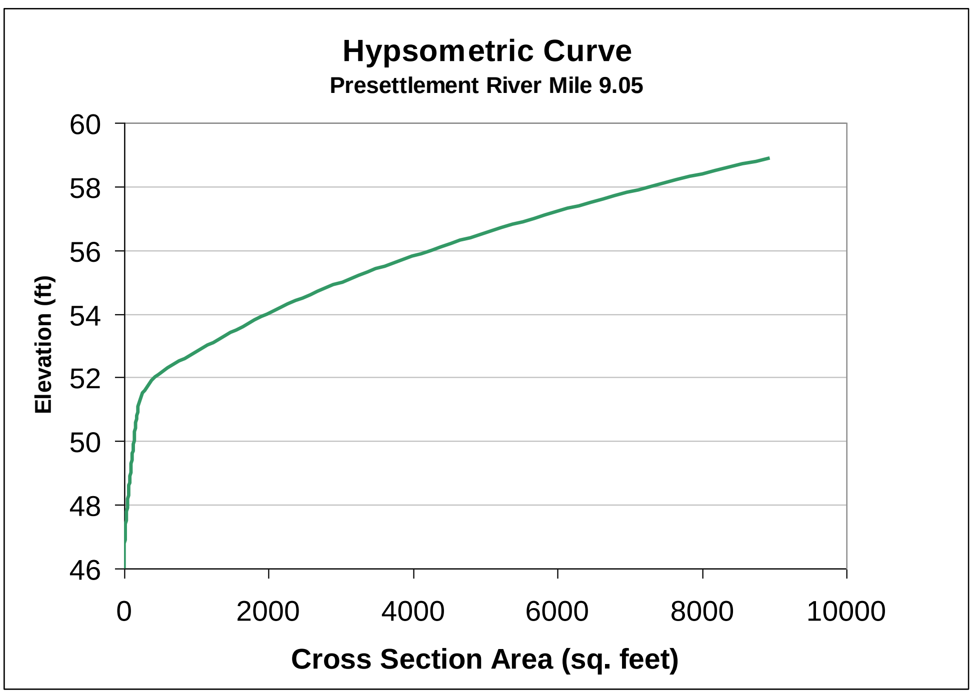

Figure 44. Hypsometric Curve at Pre-settlement River Mile 9.05

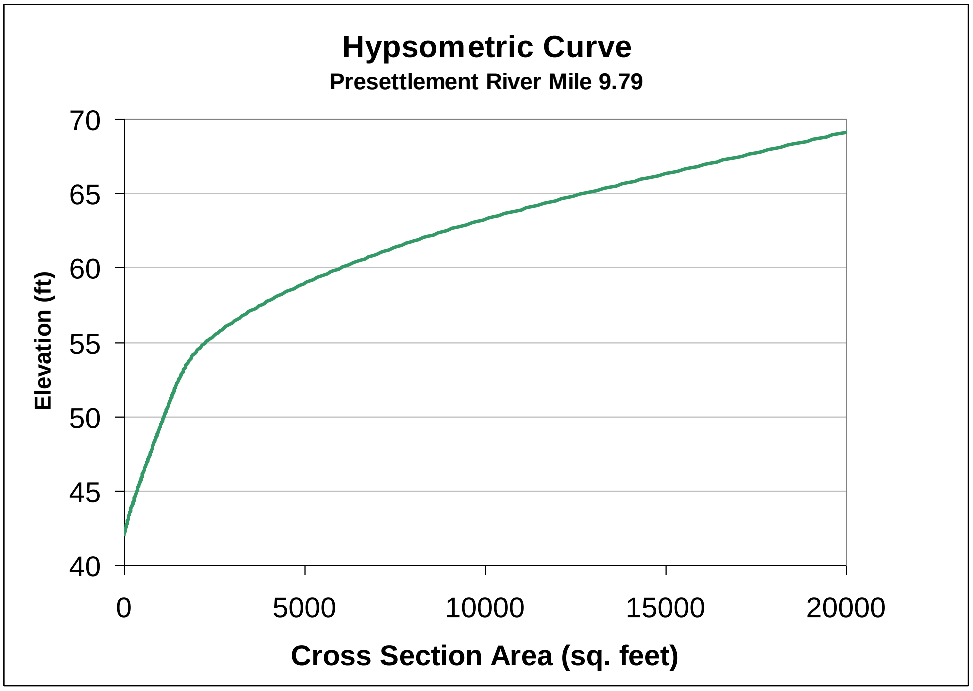

Figure 45. Hypsometric Curve at Pre-settlement River Mile 9.79

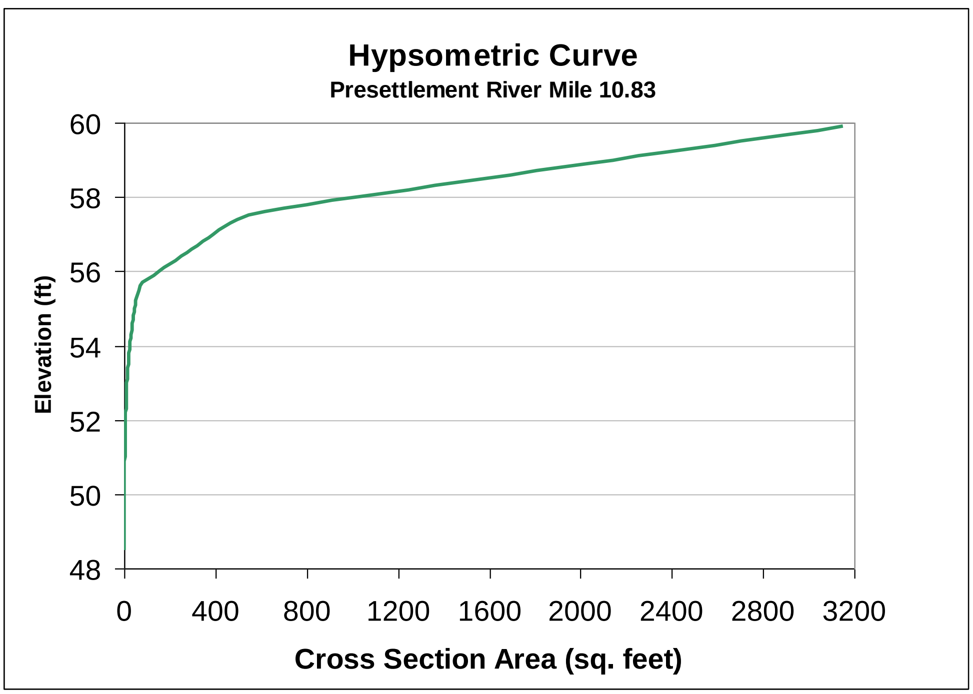

Figure 46. Hypsometric Curve at Pre-settlement River Mile 10.83

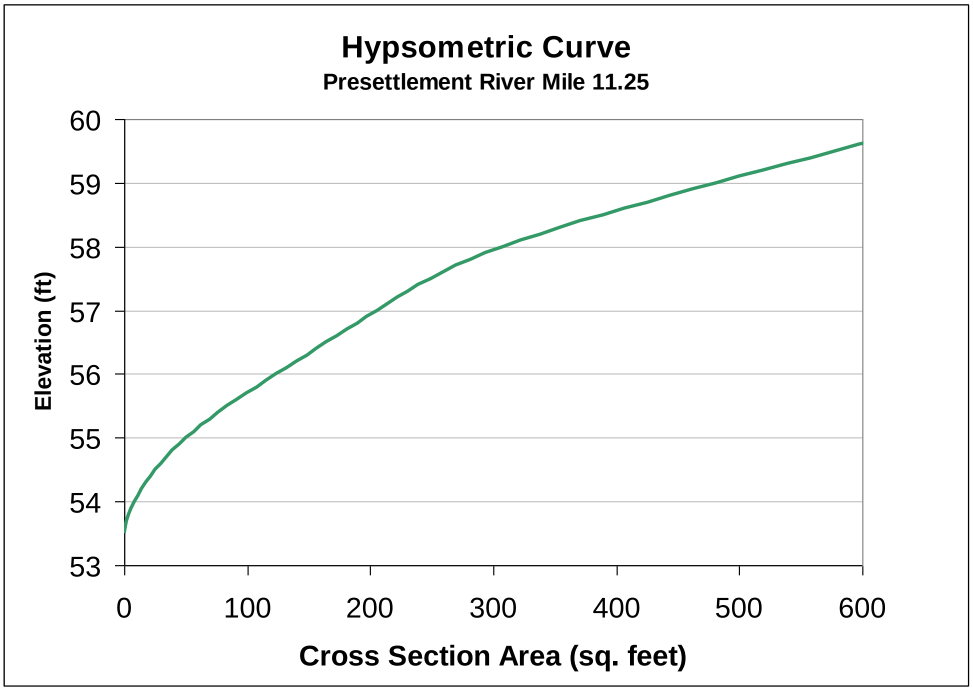

Figure 47. Hypsometric Curve at Pre-settlement River Mile 11.25

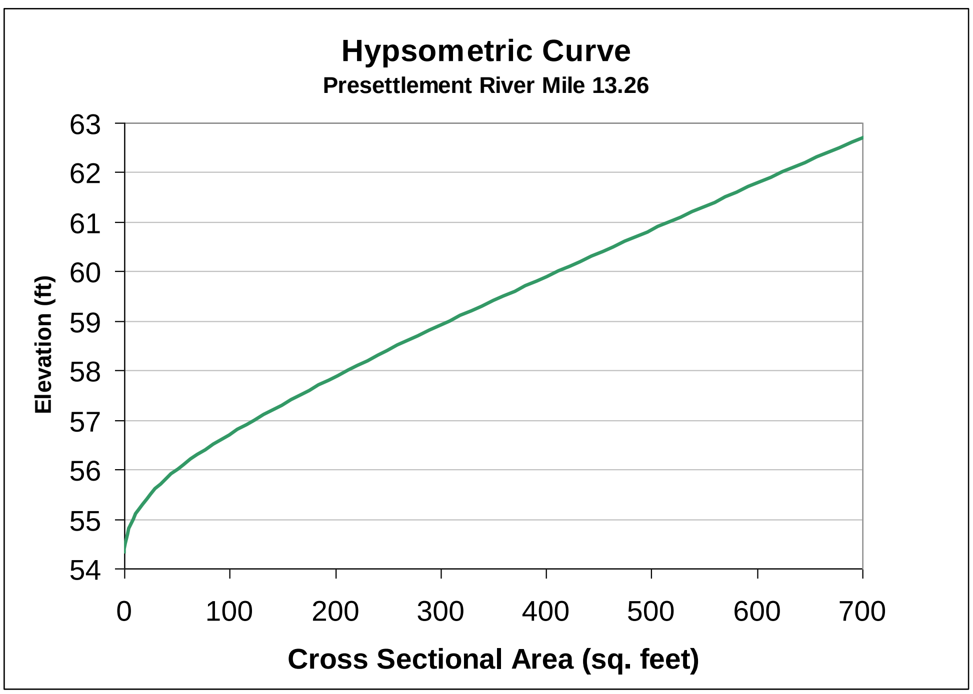

Figure 48. Hypsometric Curve at Pre-settlement River Mile 13.26

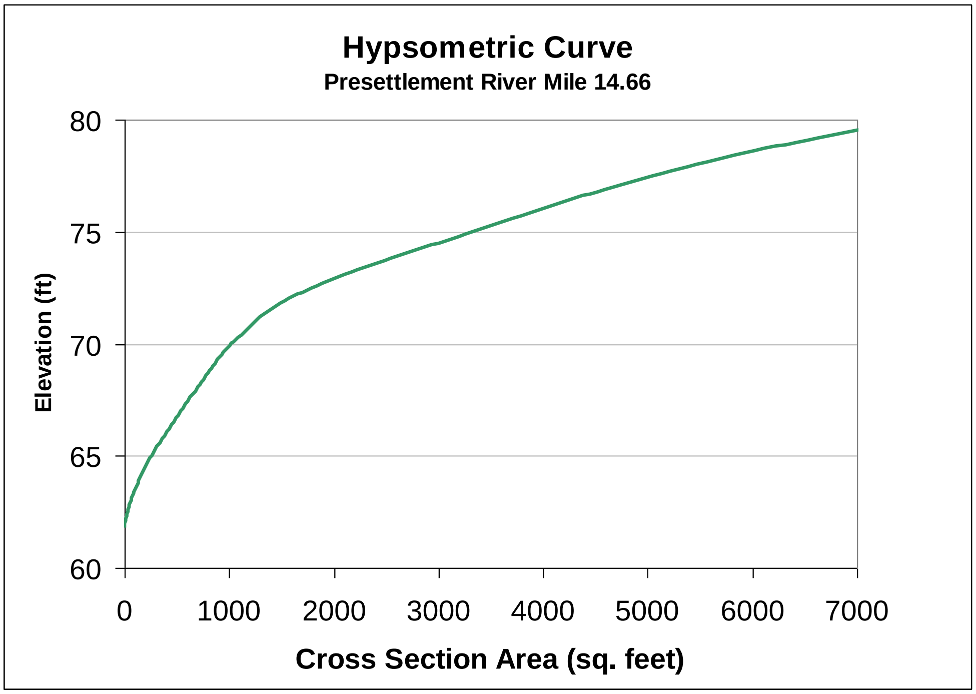

Figure 49. Hypsometric Curve at Pre-settlement River Mile 14.66

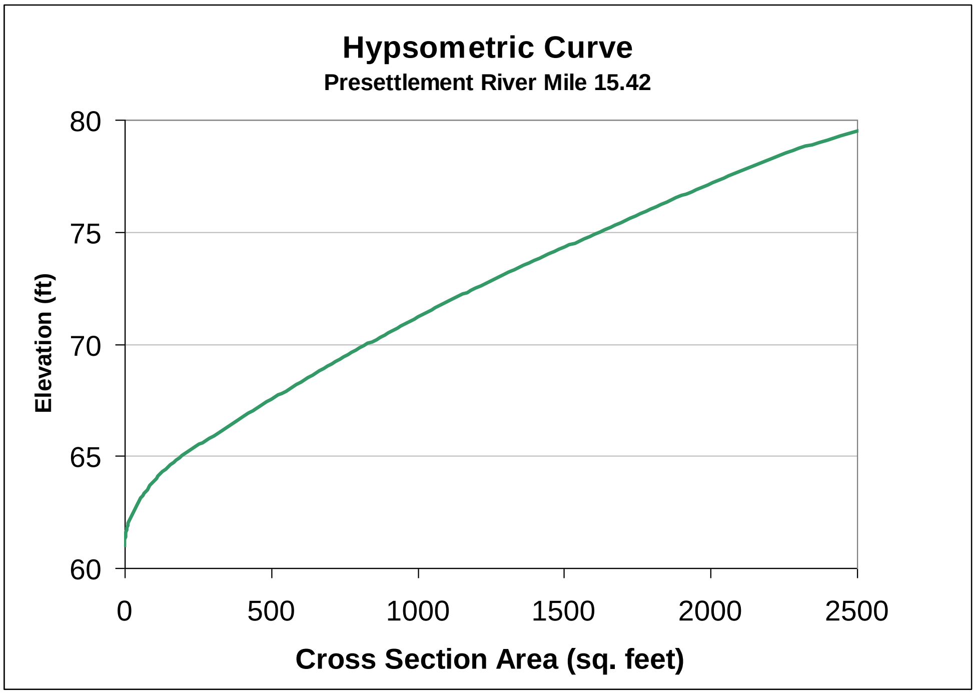

Figure 50. Hypsometric Curve at Pre-settlement River Mile 15.42

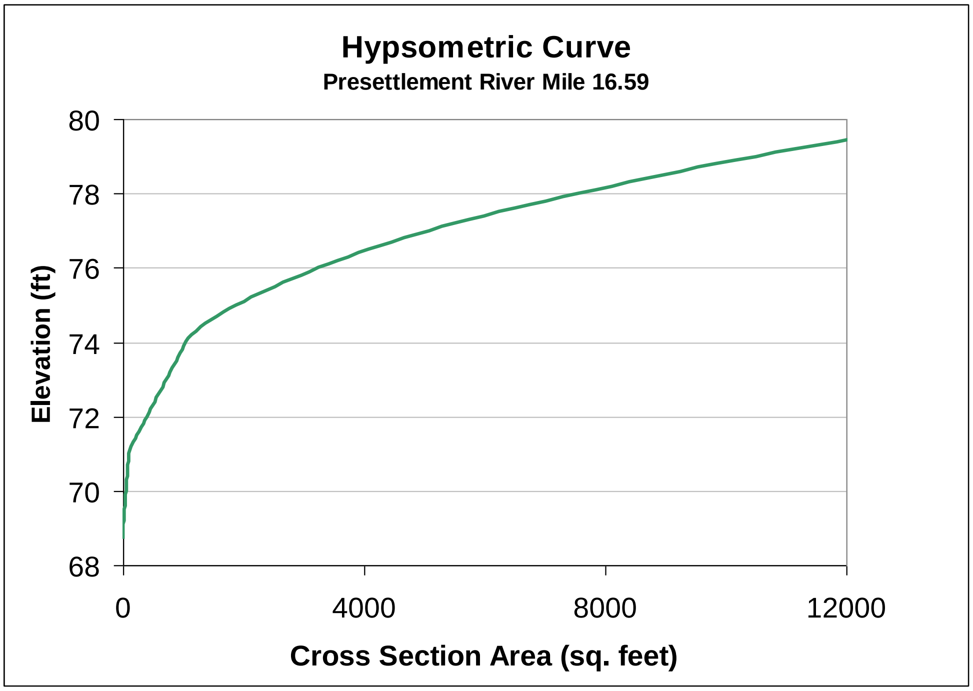

Figure 51. Hypsometric Curve at Pre-settlement River Mile 16.59

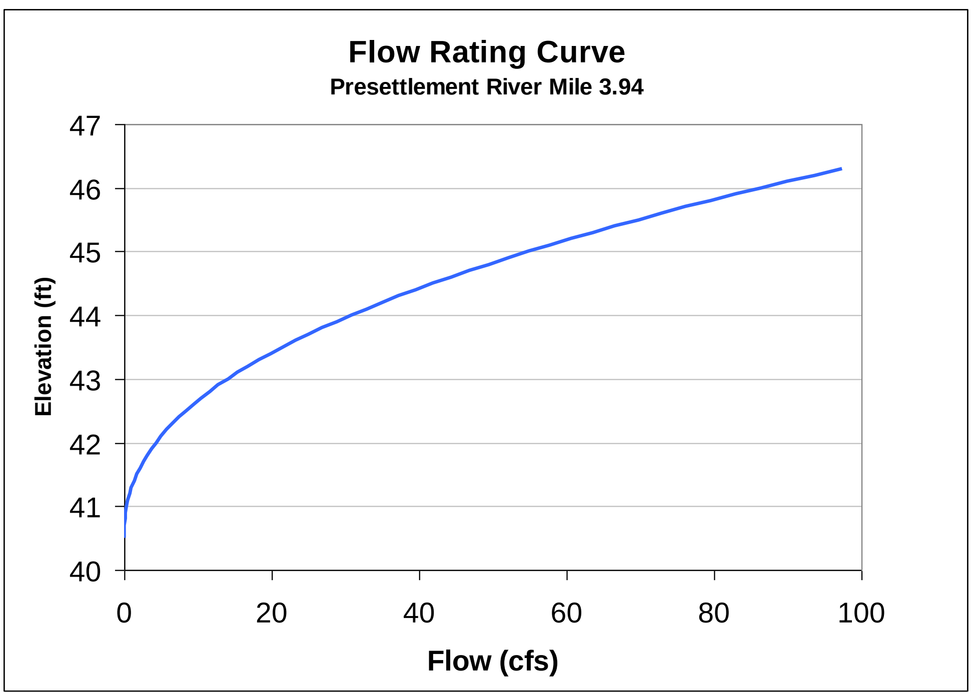

Figure 52. Flow Rating Curve at Pre-settlement River Mile 3.94

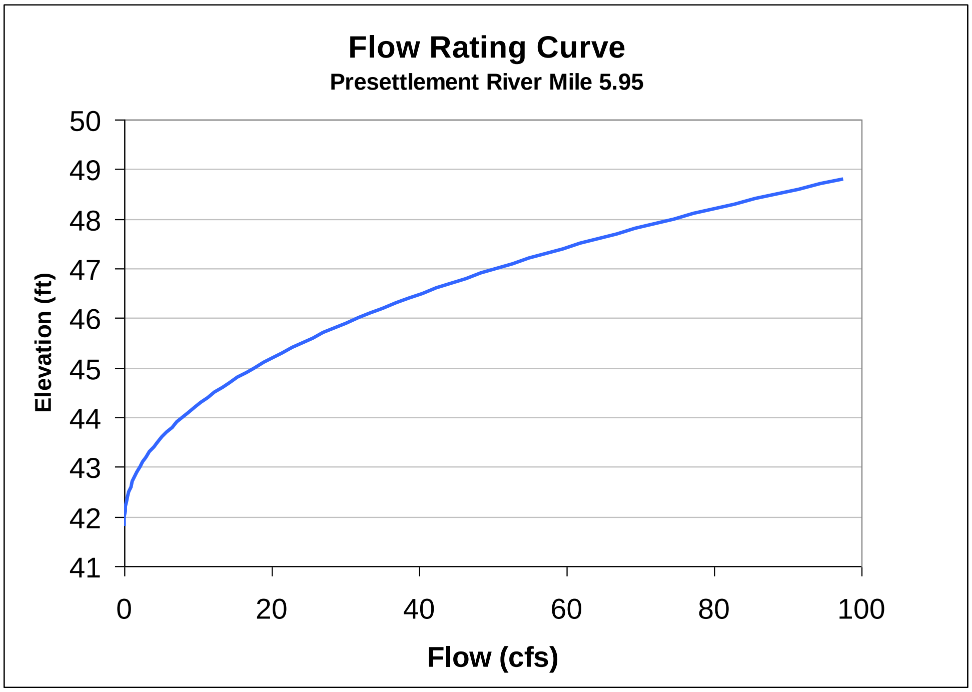

Figure 53. Flow Rating Curve at Pre-settlement River Mile 5.95

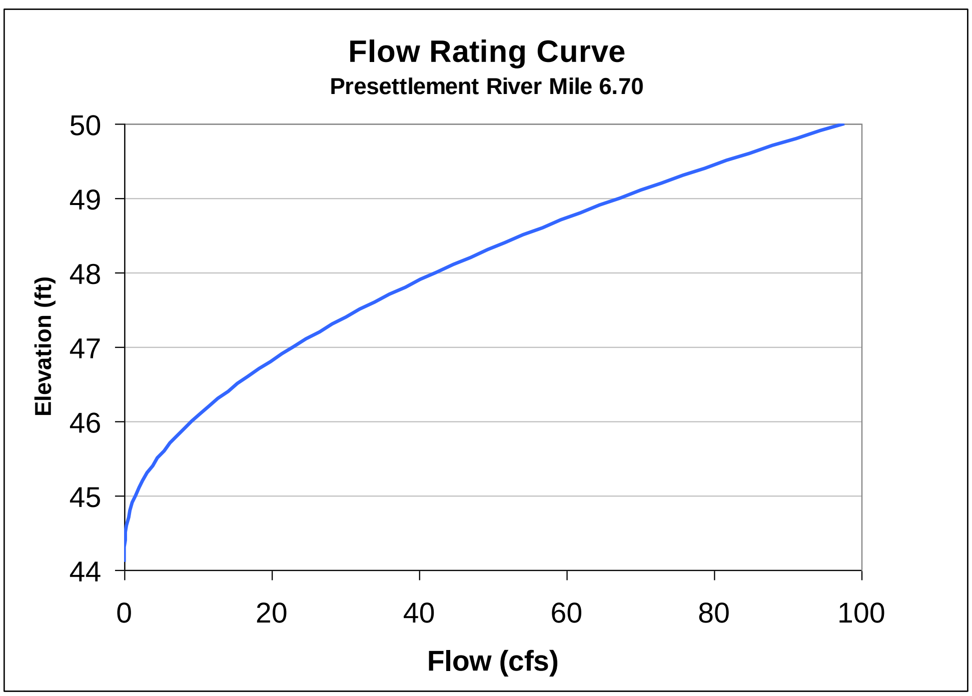

Figure 54. Flow Rating Curve at Pre-settlement River Mile 6.70

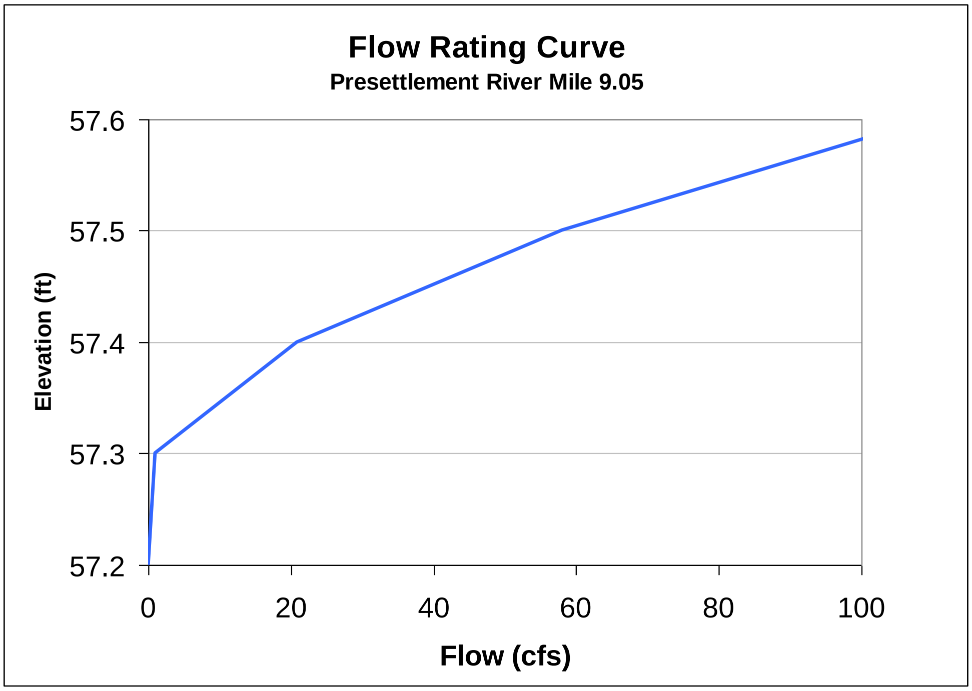

Figure 55. Flow Rating Curve at Pre-settlement River Mile 9.05

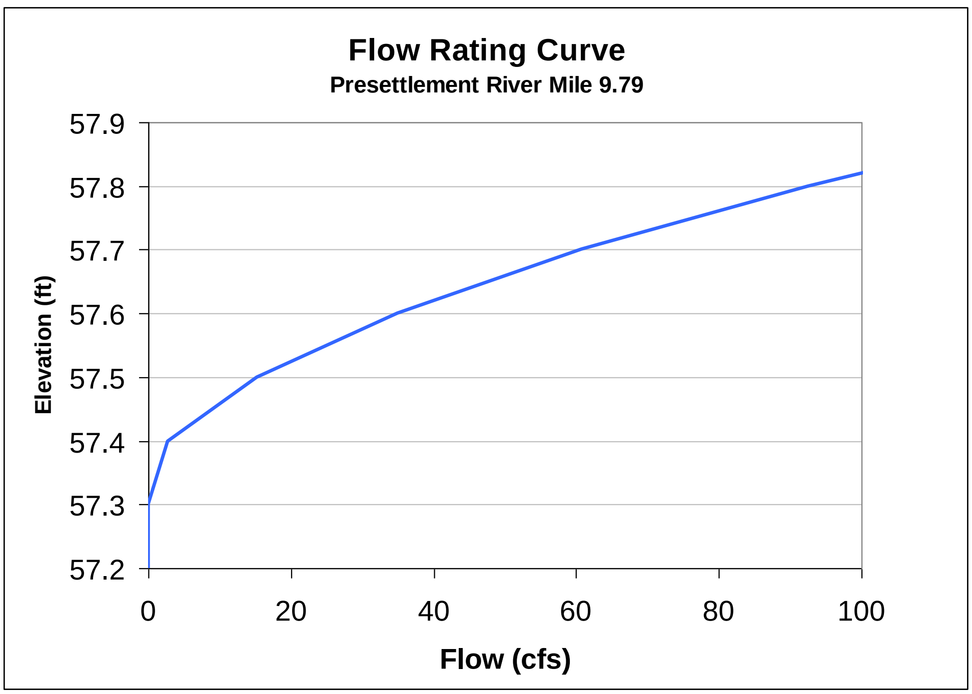

Figure 56. Flow Rating Curve at Pre-settlement River Mile 9.79

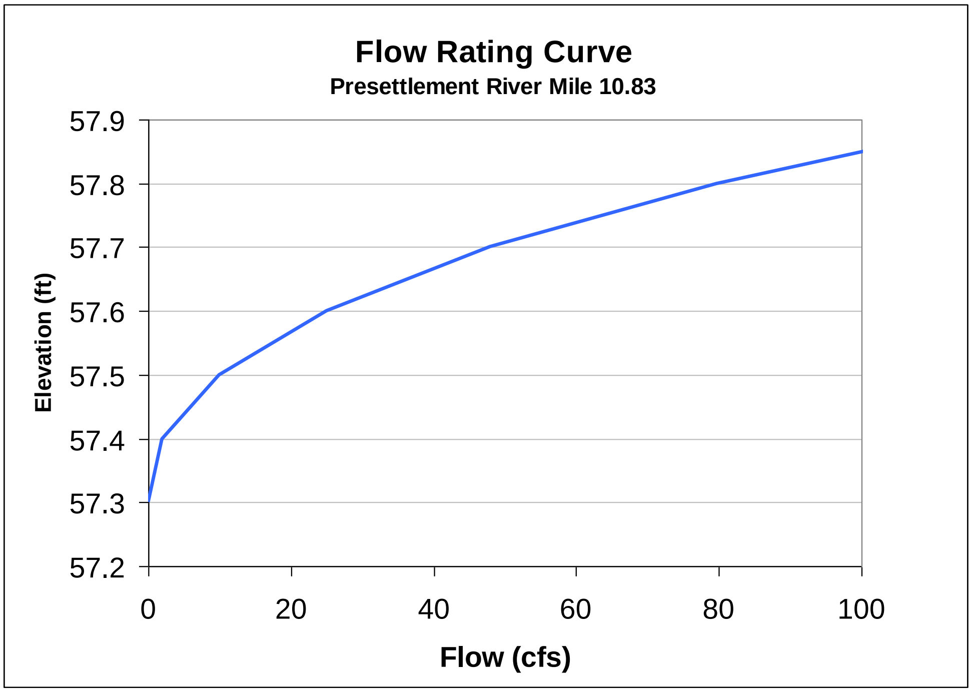

Figure 57. Flow Rating Curve at Pre-settlement River Mile 10.83

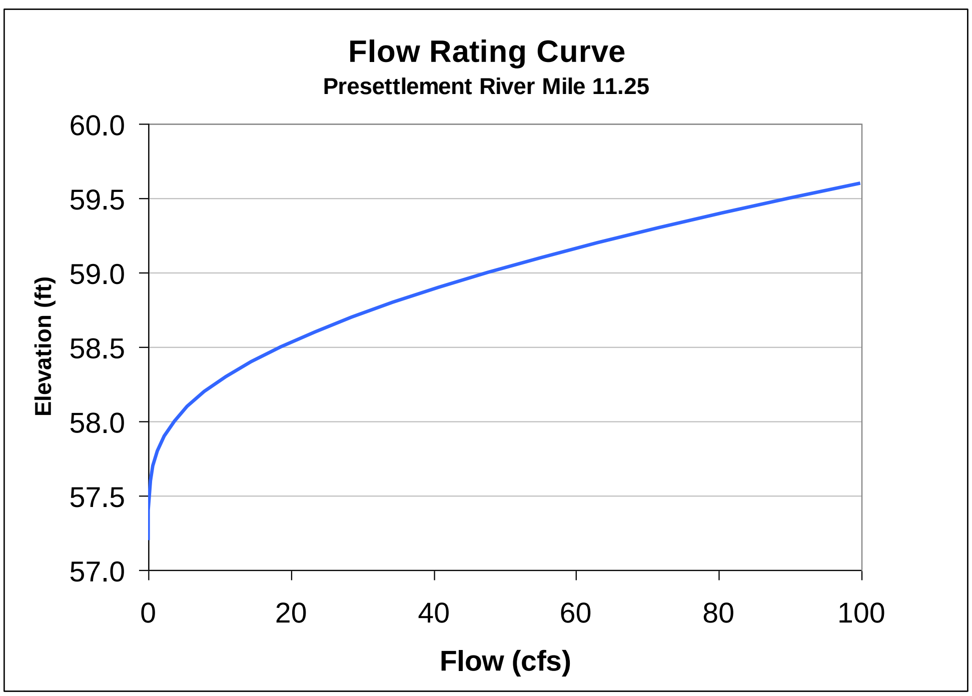

Figure 58. Flow Rating Curve at Pre-settlement River Mile 11.25

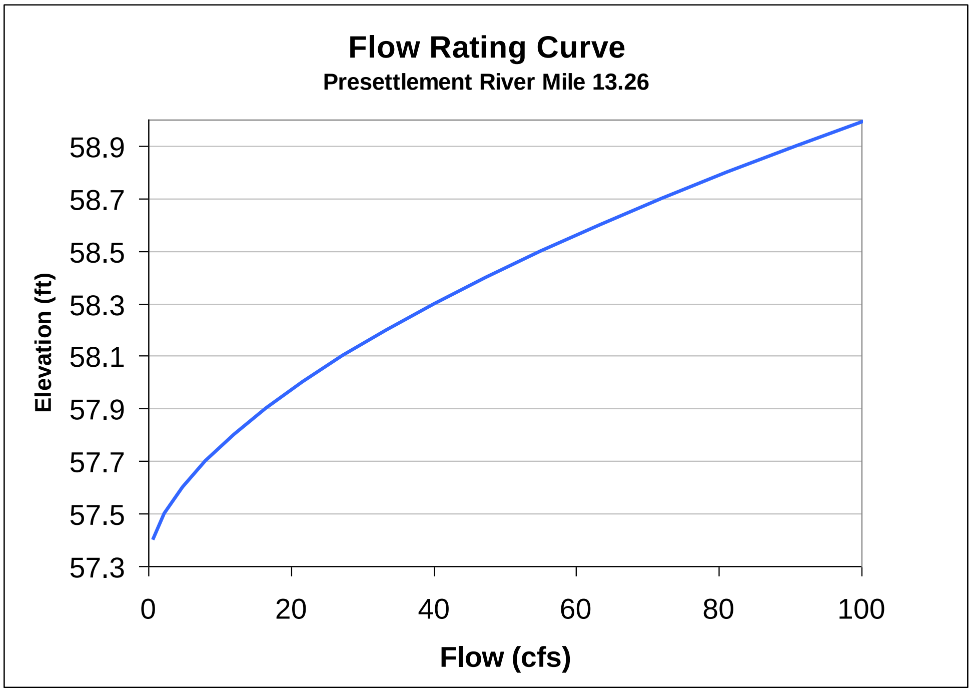

Figure 59. Flow Rating Curve at Pre-settlement River Mile 13.26

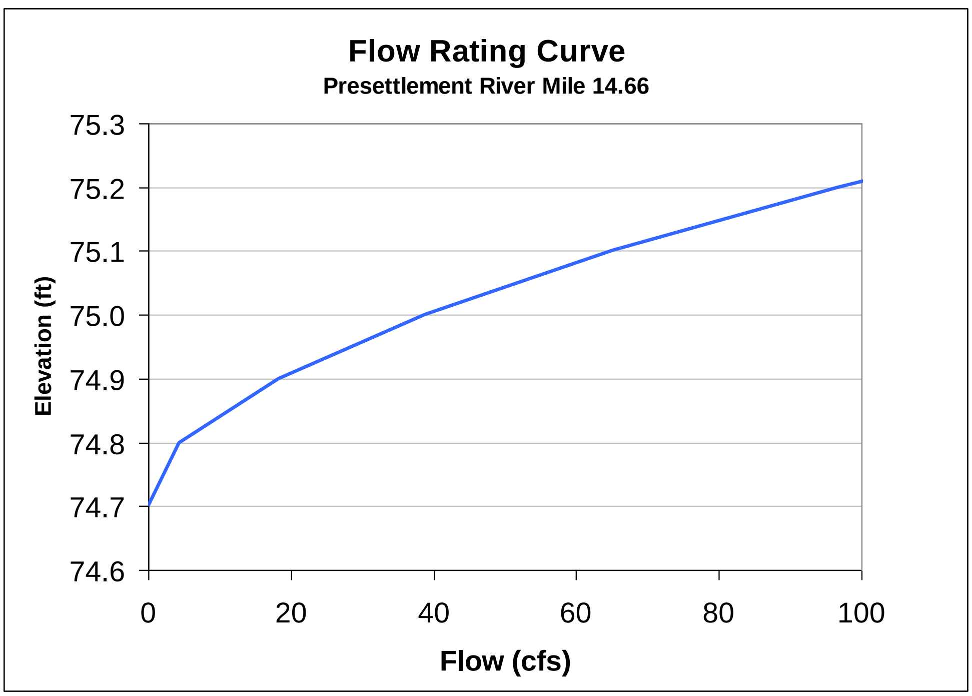

Figure 60. Flow Rating Curve at Pre-settlement River Mile 14.66

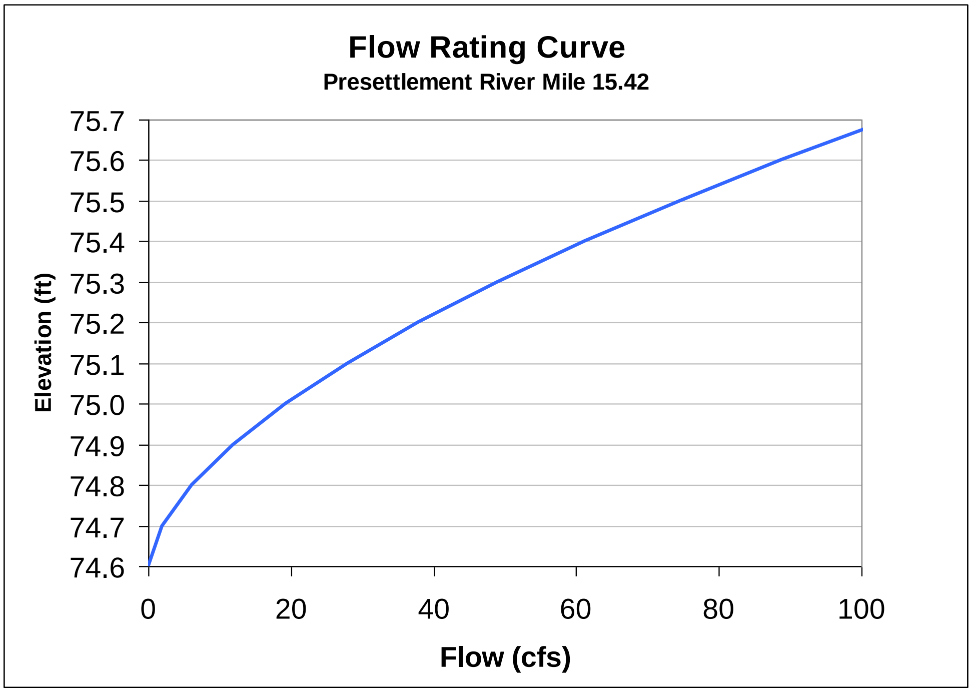

Figure 61. Flow Rating Curve at Pre-settlement River Mile 15.42

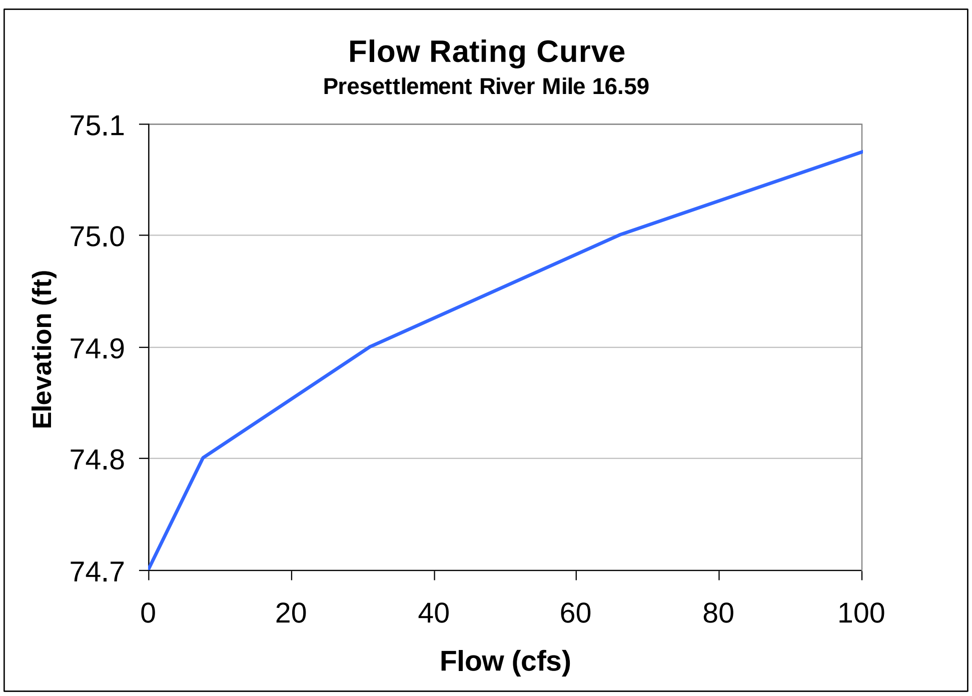

Figure 62. Flow Rating Curve at Pre-settlement River Mile 16.59