Appendix C

Evaluation of the Effects of Subsidence and Sediment Transport on Channel Capacity in the Eastside Bypass and Reach 4A of the San Joaquin River

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California Department of Water Resources
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Introduction

This study was performed to evaluate the effects of subsidence and sediment transport on channel capacity in the Upper and Middle Eastside Bypass, and Reach 4A of the San Joaquin River (**Figure 1**). The evaluation looks at the effects of subsidence and flows released from Friant Dam under the San Joaquin River Restoration Program (SJRRP), herein called *Restoration Flows*, on design freeboard capacity to the year 2029. The work was done using two hypothetical flow records representing dry and wet water year periods as “bookends”, that could represent future “near-term” conditions prior to the implementation of the Reach 4B, Eastside Bypass, and Mariposa Bypass Channel and Structural Improvements Project (Reach 4B Project).

The study was performed on the channels in which subsidence and sediment transport will likely have the greatest effect on channel capacity within the Restoration Area. Reach 4A of the San Joaquin River is a 14 mile stretch of the San Joaquin River that runs from Sack Dam to Sand Slough. The Eastside Bypass parallels the San Joaquin River and is part of the Lower San Joaquin River Flood Control Project. The Eastside Bypass is connected to Reach 4A through a short 0.3-mile segment of the bypass system called the Sand Slough Connector Channel (SSCC). The design flow capacities and operating rules used in this evaluation are based on the Operation and Maintenance Manual (O&M Manual) (Reclamation Board, 1967) for the Lower San Joaquin River Flood Control Project.

Using the data collected by various agencies, this study provides a general picture of flow capacity and the effect of subsidence and sediment transport on the ability of the system to convey flood flows. This study is intended to help decision makers for the SJRRP understand the potential need to reduce Restoration Flows or implement sediment removal projects due to reduced channel capacity. The conclusions presented in this study are planning level estimates of the potential maximum flow capacities that can be conveyed using hydraulic design criteria. However, this study does not consider the potential capacity limitations related to levee performance or evaluate the effects of channel capacity if subsidence rates are different than recent historical rates. Further work in these areas may be necessary prior to the development of site-specific actions to address channel capacities shown in this report.

Background

Subsidence, which is the downward shift or sinking of the ground, can change conveyance channel slopes, and has the potential to affect the flow capacity of channels and flow control structures, change sediment transport behavior, and reduce the ability of the flood and river systems to perform as designed. Subsidence has occurred throughout the San Joaquin Valley and to varying degrees along the San Joaquin River and flood bypass channels. Various studies and mapping efforts that identify the extent and magnitude of subsidence have been completed by the United States Army Corps of Engineers (USACE), DWR, the Bureau of Reclamation (Reclamation), and the US Geological Survey (USGS). One of those studies within the project area is the *Sacramento-San Joaquin Comprehensive Study* completed by the USACE in 2002. This study highlighted the observed areas of subsidence, and provided historic rates based on previous surveys. The study showed areas of greatest documented subsidence occur at various control structures located along the river, which includes Mendota Dam, Sack Dam, the Reach 4B1 Headworks and Sand Slough Control Structure.

In recent years, subsidence appears to be greatest in areas along the Chowchilla and the Eastside Bypass between Road 9 and Sand Slough Control Structure. Ground control surveys conducted in 2010 and compared to 2008 LiDAR control surveys, showed an area of extreme subsidence rates occurring near the Eastside and Chowchilla Bypasses between 2008 and 2010. Topographic data collected by USGS using Interferogram data between 2008 and 2010 confirmed the findings. In 2012, the SJRRP formed a subsidence coordination group to help address and study the effects of subsidence and to share information between landowners, SJRRP stakeholders, and government agencies. As a result of this coordination, the SJRRP conducts bi-annual surveys of the SJRRP Geodetic Control Network to monitor subsidence. These Reclamation-led bi-annual surveys show that subsidence rates vary along the bypass depending on season, year type, and land use. However, the surveys show similar subsidence trends compared to the previous data collection efforts. The subsidence trends have continued through 2017 based on Reclamation’s bi-annual surveys.

Sediment transport can also effect channel capacities. Subsidence can change the slope of channels and increase or decrease the ability of the channel to convey sediment. Furthermore, the addition of Restoration Flows in the system can also increase the amount of sediment that is transported through the channels that can deposit in channels and reduce flow capacity. Sediment deposition has historically been an issue in the areas around Sand Slough where historical subsidence and the natural slope of the lands have reduced slopes in the channels and created significant areas of deposition. In the early 1980s, the USACE found that the capacity of the Eastside Bypass was reduced to between 6,000 to 7,000 cubic-feet-per-second (cfs), a significant reduction of its 16,500 cfs design flow capacity.

Two significant sediment removal projects have been completed in the Sand Slough area of the bypass including a Channel Clearing project performed by the USACE between November 1984 and February 1985. The project removed about 1 million cubic yards of sediment in the bypass for about 2 miles of the channel downstream of Sand Slough; approximately 30% of the design capacity was restored as a result of the project (USACE, 1985). Another project, completed by Reclamation for the SJRRP in 2016, removed about 40,000 cubic yards around the El Nido Road crossing to reduce water levels in the bypass. If the pattern of subsidence continues, the area around Sand Slough will continue to see significant sediment deposition within the channel of the Eastside Bypass and Reach 4A. This sediment deposition can significantly reduce channel capacity.

Sediment Transport Model Development

In performing the evaluation, HEC-RAS models were adjusted to incorporate subsidence and sediment transport within the study area to develop model geometries that represent current (2016) and future channel conditions based on the ongoing subsidence that is affecting the study reach. The following describes the methodology for the development of the sediment transport model for this analysis.

Model Geometry

This analysis required modeling of the Chowchilla Bypass, Upper and Middle Eastside Bypasses, and Reach 4A. Reach 4A was added to the model network to provide additional information regarding the supply of sediment to the Bypass system. Models for each of these river and Bypass segments were initially developed based on 2008 LiDAR elevations, but the geometry in the models were subsequently updated to reflect October 2013 elevations based on levee profile surveys (Tetra Tech, 2015a). The various model segments were combined to form a single network model, which provided direct connections for downstream water-surface elevation boundary conditions as well as the direct supply of sediment from one segment to the other.

The model geometry was modified at two structures in the Middle Eastside Bypass (MESB). The Merced National Wildlife Refuge Weirs were modeled such that all boards were removed. This was done to remove any influence on sediment transport as a result of the backwater conditions created by the weirs. Additionally, the higher ground elevations associated with the Dan McNamara crossing were removed and the channel graded to smooth the profile (**Figure 2**). These modifications are included as part of the proposed SJRRP's Eastside Bypass Improvements Project.

Geometry Subsidence Adjustments

As mentioned above, the available geometry in the models were based on the October 2013 timeframe. Because the "near-term" hydrologic simulations (described in more detail below) start on a simulated date of March 1, 2016, it was necessary to bring the October 2013 version of the model geometry up to the simulation start date condition. To accomplish this, the total adjustment needed to represent the cumulative subsidence from October 2013 to December 2015 was first determined. Once the subsidence for that timeframe was calculated, that total amount was prorated for the additional period from December 2015 to March 2016 to sync with the estimated simulation start date.

Figure 3 shows the project area and the December 2011 to December 2015 annual subsidence rates published by Reclamation that were used to compute the first component of subsidence between October 2013 and December 2015. Data in yearly December-to-December increments are also available, which were used as discussed below. Elevation changes for each of the approximately 70 control points used to develop this map were obtained from the published data. The "Free Adjusted" or minimally constrained points were used per recommendations from the San Joaquin River Restoration Program website (http://www.restoresjr.net/monitoring-data/subsidence-monitoring/; SJRRP, 2015). Data for these control points were used to directly compute the total amount of subsidence for the period between December 2013 and December 2015. However, since the existing hydraulic models are based on an October 2013 condition (i.e., a few months prior to the December 2013 timeframe indicated by Reclamation's data), the additional amount of subsidence between October and December 2013 was calculated by prorating Reclamation's measured December 2012 to December 2013 annual rate for each control point for approximately 2.5 months of the year. With that addition, the total subsidence component within the measured timeframe between October 2013 and December 2015 was computed.

To account for the additional subsidence that is likely to have occurred between December 2015 and the March 1, 2016 model start date, an additional 2.5 months of subsidence was estimated by extrapolating the resultant computed long-term (October 2013 to December 2015) rate by an additional 2.5 months. A Triangulated Irregular Network (TIN) surface was then created using ArcGIS based on the total amount of subsidence at the control points. **Figure 4** shows the TIN surface representing the total subsidence amounts for the October 2013 to March 2016 time frame. A profile of the resultant total subsidence adjustment along each of the channel segments is shown in **Figure 5** to adjust the model to the March 2016 time frame.

To account for future subsidence up to the year 2029, an annual rate was determined from previously surveyed control data. It was assumed that subsidence will continue in the immediate future (13-year time period) at the same rate as the recent past (2011 to 2015). Annual rates that were applied over the 13-year simulation ranged spatially from 0.174 to 0.716 feet/year. **Figure 6** shows the total subsidence that was estimated to occur by the end of the 13-year simulation. At the beginning of the 13-year simulation the average channel slope in the MESB is 0.000155 feet/feet and in Reach 4A the average channel slope is 0.000217 feet/feet. After the 13-year simulation, subsidence has reduced the average channel slope in the MESB to 0.000101 feet/feet and increased the average channel slope in Reach 4A to 0.000232 feet/feet.

Sediment Transport Modeling Methodology

In 2014 Tetra Tech developed a mobile bed sediment-transport model of the Chowchilla and Eastside Bypasses using HEC-6T (Tetra Tech, 2015b). As part of this current analysis, the HEC-6T model was used as a guide to develop a mobile bed sediment-transport model using HEC-RAS (USACE, 2016) in order to have a more useful and user-friendly end product. The HEC-RAS version of the model was developed by using the model geometry (cross-sectional geometry, bank stations, reach lengths, hydraulic roughness and coefficients of expansion and contraction) from the source HEC-RAS models described above. Sediment data used in the HEC-6T model were coded into the HEC-RAS model, including the gradation of the resident bed material [bed sediment reservoir (BSR)], the width and depth of the BSR, rating curves defining the load and gradation of upstream and tributary loads by discharge, erosion and deposition limits, and cohesive sediment erosion/deposition parameters.

Sediment-transport computational controls were also entered into the sediment dataset and included specification of the Engelund-Hansen sediment-transport function, the Exner 7 sorting method, and the “Report 12” fall velocity computation method. Hydrologic data (i.e. flow records) were based on the Riverware data described below, and computation intervals were informed from the HEC-6T modeling (Tetra Tech, 2015b). These data include the upstream flow series for both the Chowchilla Bypass and Reach 4A, and flow series for the Fresno River, Ash Slough, and Sand Slough tributary inflows. The Fresno River and Ash Slough tributary sediment inflows are input into the sediment-transport model as rating curves, which were developed for the HEC-6T model (Tetra Tech, 2015b). These rating curves may slightly overestimate the amount of sediment transported into the Bypass for a given discharge because the available hydraulic models used to develop the rating curves did not account for backwater conditions in the Bypass. Other required model input from the HEC-6T model that were used to inform the HEC-RAS model development included hydraulic weighting parameters (no weight given to the upstream and downstream cross sections), the number of bed exchange iterations per time step (30), specification of the average energy slope for use in the sediment-transport equation, and the method for computing the steady-state friction slope (HEC-6 slope-averaging method).

Sediment Gradations

Sediment gradations along the Chowchilla and Eastside Bypasses were developed from bed-material samples collected by Tetra Tech in 2013 (Tetra Tech, 2015b), and sediment gradations along Reach 4A were characterized based on bed-material samples collected by Reclamation (SJRRP, 2008) (**Figure 7**). The equilibrium load method was chosen for the upstream boundary condition of Reach 4A and the Chowchilla Bypass because this method computes the equilibrium sediment-transport capacity for each time step and introduces the loads into the next cross section as a time series. This method accounts for the variation in the inflowing hydrographs associated with Restoration Flows. In Reach 4A, the upstream model boundary is located immediately downstream from Sack Dam, which has a greater sediment-transport capacity than the portion of the river immediately upstream of Sack Dam because of the associated backwater conditions. Although the upstream sediment supply in the Reach 4A model does not specifically account for any channel downcutting from the upstream Reach 2B Project, it is assumed that any additional sediment that might be delivered from the Reach 2B downcutting will be deposited along Reach 3 and upstream of Sack Dam, resulting in a negligible change in sediment supply to Reach 4A. This assumption is consistent with the conclusions determined by Reclamation in their analysis of the Reach 2B project (Reclamation, 2017).

Hydrology and Design Flows

In performing this study, four separate 13-year hydrologic periods were developed to represent dry and wet periods under flow operations without Restoration Flows (herein denoted as existing) and Restoration Flow conditions. The model was then executed using these four separate hydrologic periods to simulate the possible hydrology over the period between 2016 and 2029. These simulations were modeled with the mobile-bed sediment transport models to generate 2029 geometry for each hydrologic scenario that could be used to determine the flood design flow capacity in each channel. The following describes the hydrology and flood design flows used in the study.

Hydrology

Results from Reclamation's Riverware® model were used to develop the hydrologic simulations (Reclamation, 2012). This model simulates flows under with full Restoration Flow and without Restoration Flow conditions over an 83-year period from Water Year 1922 (WY1922) to WY2003. In general, annual flow volumes are greater under Restoration flows, even though the magnitude of flood flow events are less. Results from the simulation of Alternative 2A that routes all Restoration Flows down the Middle Eastside Bypass were used, along with the results from the simulation of existing (i.e. no Restoration Flow) conditions. In order to be consistent with the near-term project intent of directing flows in the MESB downstream into the Lower Eastside Bypass (LESB), one variation from the Alternative 2A routing that was applied to the sediment-transport modeling was the assumption that all flows would continue into the LESB. One limitation of using the full Restoration Flows for this analysis is that the model geometry does not portray the channel grading and levee setbacks, which are a part of the Reach 4B Project, and would likely be constructed prior to actually releasing full Restoration Flows. An interim restoration hydrograph has not yet been developed and may be different due to changes in operational rules for Flood and Restoration flows. Furthermore, full Restoration Flow operational rules and corresponding flood flows in the mainstem and tributaries are also only unknown at this time. Because of these unknowns in the Riverware® model, the predicted amount of flow contribution, and thus, associated sediment contributions, from the tributaries are uncertain. This was especially apparent with the Fresno River inflows under Restoration-Wet conditions, which appear much greater than would actually occur (personal correspondence between Blair Greimann, Reclamation and Chadwick Moore, Reclamation). The Fresno River flow uncertainties do not appear to have an impact on the studies reaches, but would need to be further refined if looking at channel capacity in the bypass above Ash Slough.

The Alternative 2A results were first used to classify the Year Type based on the Restoration Flow Schedules presented in the Stair-Step Allocations in Settlement Exhibit B (**Figure 8**). Because the Restoration Flow schedules extend from March 1 to the end of February, the Riverware® record was first segregated into “Restoration Years” (instead of Water Years) that extend from March 1 of the current year to the end of February in the following year. The portions of the Riverware® record prior to March 1, 1922, at the beginning of the record and after February 28, 2003, at the end of the record were not included in the assessment because these portions do not represent complete Restoration Years, which leaves a record of 81 years.

The Restoration Year Type classification was based on the simulated Friant Dam release. If the release did not meet or exceed the targeted flow schedule, that year was classified as the next drier Year Type. Once classified, the 13-year period with the highest number of Wet and Normal Wet Year Types was identified, along with the 13-year period with the highest number of Critical Low and Critical High Year Types (**Figure 9**). Multiple different 13-year periods had the highest number of Wet and Normal Wet Year Types, and multiple different 13-year periods had the highest number of Critical Low and Critical High Year Types. As a result, the cumulative release volume over each 13-year period was used as a second scoring criteria. Of those 13-year periods that had the highest number of Wet and Normal Wet Year Types, the 13-year period with the largest release volume was selected as the recommended wet period (Restoration Year 1974 to Restoration Year 1986; **Figure 10**). Similarly, of those 13-year periods that had the highest number of Critical Low and Critical High Year Types, the 13-year period with the smallest release volume was selected for use as the recommended dry period (Restoration Year 1923 to Restoration Year 1935; **Figure 10**). These same wet and dry periods were also used for existing (without Full Restoration Flow) conditions, since consistent simulation periods is desirable to compare the effects of with Full Restoration flow conditions. The four hydrological scenarios used to evaluate channel capacity represent dry and wet periods for existing and Restoration Flow routing are shown as Scenarios 2-5 in **Table 2**. Scenario 1 represents starting geometry conditions (i.e. 2016) prior to running any of the four hydrologic scenarios.

Table 2. Scenarios considered for 2016 starting conditions and near-term future conditions channel capacity analysis

Scenario*	Geometry/Hydrology
1	2016 Starting Conditions
2	2029 Dry – Existing Operations
3	2029 Dry – Restoration Flows
4	2029 Wet – Existing Operations
5	2029 Wet – Restoration Flows

*Scenarios 2-5 also include subsidence adjustments.

Design Flows and Boundary Conditions

As indicated in Table 2 above, five different model geometries were used to evaluate flood capacities. Scenario 1 represents current conditions (i.e. March 2016 geometry condition) before running any hydrologic, subsidence, or sediment-transport simulations. Scenarios 2 through 5 account for the various hydrologic scenarios, subsidence, and sediment-transport. The five selected model geometry conditions described above were used to model fixed-bed conditions in order to determine the channel capacities at the design freeboard for each channel segment.

This analysis specifically focused on identifying the maximum (or limiting) discharge that can be conveyed through each reach associated with the water-surface elevation that does not exceed the design levee freeboard elevation at any location within the reach. **Table 3** shows the design flows used in this analysis. These flows were taken directly from the O&M Manual and assume maximum tributary inflows. The study also assumes the initial 8,500 cubic-feet-per-second (cfs) in the Eastside Bypass would be diverted into the Mariposa Bypass as described in the O&M Manual. Design flow capacity is based on the design specifications of four feet of freeboard for the bypass channels and three feet of freeboard for the San Joaquin River (Reclamation Board, 1967). Levee freeboard is defined as the height of the top of the levee above the design water level.

In evaluating channel capacity, a range of flows up to the design capacity was run for each reach of the bypass system and river. Channel capacities were evaluated for two conditions: a run-of-the-river condition in which there are no concurrent tributary flows, and a backwater condition in which there are concurrent flows in tributary channels. The tributary inflows would add to downstream flows below the channel segment and raise water surface elevations which would reduce the capacity in the channel upstream. The maximum inflow as designated by the design flood flow for each of the tributaries was assumed to occur concurrently with the flood peak in the mainstem. The backwater conditions created by the addition of the tributary inflows can significantly affect the channel capacities in Reach 4A and the Upper Eastside Bypass (UESB).

Table 3. Flood Design Capacities

Channel Segment	Flood Design Flow (cfs)
Upper Eastside Bypass	
Ash Slough to Sand Slough	17,500
Middle Eastside Bypass	
Sand Slough to Mariposa Bypass	16,500
San Joaquin River	
Reach 4A	4,500
Sand Slough Connector Channel	not available

Results

Channel capacities were evaluated for five different model geometries. These included the March 2016 geometry that were used as the starting condition for all the sediment transport simulations representing existing conditions, and the four end-of-sediment-transport-run geometries that also account for estimated future subsidence and the four different hydrologic records. The channel capacity for each cross section in the model is based on a levee freeboard of 4 feet in the Bypass and 3 feet in the River. The capacity for each channel segment was then determined for both the run-of-the-river and backwater conditions, and defined as the maximum flow (up to the flood design flow) that would not exceed the freeboard criteria at the most critical cross section. Critical cross sections occur at different locations throughout each channel segment, most of which are comprised of a single or small number of individual cross sections. These areas would limit the amount of flow that could be conveyed in the channel at the design freeboard. However, it should be noted that aside from these critical areas, some of which may not be representative of the rest of the channel, the remainder of the channel will likely convey flood design flows within the design freeboard.

The starting condition run was developed to provide a comparison of the current conditions geometry (2016) with the future channel geometry changes that would result from subsidence and sediment deposition and erosion patterns from routing floods and Restoration Flows over the 13-year wet and dry periods. All future geometry scenarios included a total amount of subsidence estimated for the year 2029 based on rates corresponding to the most recent estimates by Reclamation for the SJRRP (SJRRP, 2015). The 2029 runs were made assuming the full amount of subsidence had occurred at the start of the runs, effectively providing a conservative estimate of the subsidence effects.

The four hydrological scenarios represent dry and wet periods for existing and Restoration Flow routing. As discussed previously, the purpose of this sediment-transport modeling is to evaluate the effects of subsidence and the restoration conditions hydrology on channel capacity within the bypasses and Reach 4A. All variations in the flows associated with four hydrologic conditions will affect the distribution and magnitude of flows, changing the sediment loading within these channels (**Figure 11**). For example, under existing conditions the volume of water leaving the UESB is much greater than the volume of water coming out of Reach 4A and the SSCC. Under these conditions, higher sediment loads are delivered from the UESB than the SSCC and Reach 4A. However, the

UESB also tends to have a higher transport capacity than Reach 4A. So when Restoration Flows route more of the water through Reach 4A and the SSCC, a somewhat similar volume of water entering the MESB results in a lesser volume of sediment. It is important to note that the changes to sediment loading under the various scenarios do not necessarily translate to significant changes in aggradation or degradation trends because some reaches show similar trends regardless of the hydrologic condition (i.e. effects are attributed more to the subsidence). The implications of the sediment loading, and aggradation and degradation tendencies, under the various model scenarios on associated channel capacities are shown in **Table 4**. Capacity results are only shown for the areas where sediment deposition and capacity are a concern; the reaches surrounding the SSCC (Upper Eastside Bypass, Middle Eastside Bypass, and Reach 4A). The following sections describe the results of the predicted changes in channel capacity due to subsidence and Restoration Flows under the dry and wet year scenarios for the Upper Eastside Bypass, the Middle Eastside Bypass and Reach 4A.

Upper Eastside Bypass (lower portion between Ash Slough and Sand Slough)

In the Upper Eastside Bypass (UESB) between Ash Slough and Sand Slough, the 2016 capacity is 9,900 cfs under the run-of-the-river conditions, and 6,000 cfs with maximum backwater from tributary inflows from the San Joaquin River. This is a significant reduction from the design flows of 17,500 cfs. Under the 2029 Existing-Dry conditions, the lower portion of the UESB between Ash Slough and the Sand Slough has a limiting capacity ranging from 3,600 cfs to 7,600 cfs, respectively, for the maximum and minimum inflow from Reach 4A of the San Joaquin River. Under the 2029 Restoration-Dry conditions, capacities do not change much more as they are only slightly reduced to 3,500 cfs and 7,500 cfs for the maximum and minimum inflows from the Reach 4A, respectively. The capacities for both Dry 2029 conditions are a significant reduction from 2016 conditions. Under Wet 2029 conditions, the reductions are even greater and the limiting capacity with Existing-Wet conditions range from 1,500 cfs to 5,000 cfs, for maximum and minimum contributions from the San Joaquin River, respectively. However, the reduction is slightly less for the Restoration-Wet conditions as capacities are 2,500 cfs and 6,000 cfs, for maximum and minimum contributions from the Reach 4A, respectively. The critical area of the channel limiting the flow capacity is the downstream 2 miles of the channel. All of the results for the Upper Eastside Bypass are shown in **Figures 12 through 15**.

Table 4. Channel capacities in the San Joaquin River and Eastside Bypass based on Design Freeboard Criteria (cfs)

Bypass Segment	Flood Design Flow	2016 Starting Conditions	2029 Dry Year Scenario		2029 Wet Year Scenario	
			Existing	Restoration	Existing	Restoration
Eastside Bypass						
Ash Slough to Sand Slough	17,500	**6,000[a]-9,900**	**3,600[a]-7,600**	**3,500[a]-7,500**	**1,500[a]-5,000**	**2,500[a]-6,000**
Sand Slough to Mariposa Bypass	16,500	**13,100**	**9,800**	**9,800**	**8,000**	**9,100**
San Joaquin River						
Reach 4A	4,500	**3,400[b]-4,300**	**600[b]-3,600**	**500[b]-4,100**	**<100[b]-3,800**	**<100[b]-3,700**
Sand Sough Connector Channel	unknown	<100[b]-10,500	<100[b]-8,200	<100[b]-7,800	<100[b]-6,100	<100[b]-7,000

Bold values denote capacity is below flood design flow.
a-Reduced Capacity is due to backwater conditions associated with 4,500 cfs being added from Reach 4A of the San Joaquin River.
b-Reduced Capacity is due to backwater conditions associated with 12,000 cfs being added from the Upper Eastside Bypass.

Reach 4A and Sand Slough Connector Channel

In Reach 4A, the 2016 starting run-of-the river capacity at 4,300 cfs is close to the design capacity. However, with maximum tributary inflows from the Upper Eastside Bypass, the design levee freeboard capacities were reduced to 3,400 cfs, a 25-percent reduction from design capacity. Reach 4A has a limiting capacity under the Existing-Dry conditions that ranges from 600 cfs to 3,600 cfs for maximum and zero tributary flows from the UESB, respectively (**Figures 18 through 21**). The limiting capacity in Reach 4A under Restoration-Dry conditions ranges from 500 cfs to 4,100 cfs for maximum and minimum tributary flows, respectively. Under both Existing-Dry and Restoration-Dry simulations, the majority of Reach 4A maintains a freeboard of more than 4 feet. However, there are a few discrete locations, such as near Station 3250+00 on the right levee, that have less than 4 feet of freeboard. The limiting capacity in Reach 4A with the Existing-Wet conditions run ranges from less than 100 cfs to 3,800 cfs, for maximum flood flows in the MESB and no flows from the UESB, respectively (**Figures 18 through 21**). Considering the Restoration-Wet conditions run in Reach 4A the limiting capacity ranges from less than 100 cfs to 3,700 cfs for maximum and minimum downstream flood flows, respectively. Much like the dry simulations, the predicted bed profiles in Reach 4A for both the Existing-Wet and Restoration-Wet simulations show erosion of the riffles and aggradation in the pools (**Figure 18**). Because of the nature of the equilibrium load boundary conditions, the wet year simulations have higher sediment loads entering Reach 4A than the dry year simulations, which causes more deposition in the upstream end of Reach 4A. The deposition in the upstream end of Reach 4A causes higher water-surface elevations, which reduce the freeboard.

Although no reported design capacities are available for the SSCC, the estimated 2016 capacity ranged widely from 10,500 cfs under run-of-the-river conditions to less than 100 cfs when backwatered by flood flows from the Upper Eastside Bypass. This reduction is mainly due to the bypass water-surface elevations being high enough to encroach on the 4-foot design freeboard of the SSCC. The SSCC has a limiting capacity of less than 100 cfs under all conditions if there is maximum tributary flow from the UESB. Considering no additional flood flow from the UESB, the SSCC has a capacity of about 8,200 cfs under Existing-Dry conditions and 7,800 cfs under Restoration-Dry conditions (**Figures 22 through 25**). The reduction in capacity from Existing-Dry to Restoration-Dry conditions is because the Restoration-Dry simulations result in a greater amount of deposition at the upstream end of the MESB than the Existing-Dry simulations; thus creating a slightly higher downstream water-surface elevations for the SSCC model under Restoration-Dry scenarios.

Considering no additional flood flow from the UESB under the Wet hydrologic scenarios, the SSCC has a capacity of 6,100 cfs for Existing-Wet conditions and 7,000 cfs for Restoration-Wet conditions. This increase is due to a lesser relative amount of sediment entering the MESB under Restoration conditions, but flows are still significant enough to result in lower channel bed elevations at the upper end of the MESB. These lower channel elevations cause lower water-surface elevations in the MESB, which directly impact results in the SSCC.

Summary and Conclusions

This channel capacity analysis is intended to provide information regarding predicted future channel capacities in the San Joaquin River and Eastside Bypass prior to the implementation of the Reach 4B Project. The analysis looked at changes in capacity based on geometry changes in the channel from subsidence and sediment transport from two existing and two Restoration Flow scenarios. In general, the analysis of channel capacity in the Upper and Middle Eastside Bypass and Reach 4A over the 13-year, near-term period of SJRRP implementation shows that none of the reaches within this study area can meet the flood design flow capacity within design freeboards under current or future subsidence and sediment transport conditions. This area has been historically impacted by subsidence and sediment deposition and capacities will likely continue to decrease with the continuing effects of future subsidence and local sediment transport capacities regardless of potential increases to upstream sediment supplies associated with full Restoration Flows.

The results show that subsidence is a significant factor in the change in future capacity in the channels within the Sand Slough area. This is largely due to the recent subsidence whose epicenter is mostly upstream of the study reach. This has caused a reduction of channel slopes in each reach, reducing the channel capacity due to reduced slopes and sediment carrying capacity. Sediment can also play a factor in changing channel capacities as the change in flows also change the sediment transported in a reach. As expected, the dry conditions hydrology results in much lower sediment loads than the wet conditions in all of the subreaches, directly attributable to the magnitude of flows. Compared to the existing conditions hydrology, the Restoration-Dry hydrology results in much lower sediment loads from the UESB, but higher sediment loads from Reach 4A. This occurs because a greater portion of the flows are routed through Reach 4A rather than the UESB under Restoration Flow conditions.

In the Upper Eastside Bypass, relative to existing, Restoration Flows have very little impact on the Upper Eastside Bypass channels as would be expected since Restoration Flows are not routed into the Chowchilla and Upper Eastside Bypasses. Capacities in the most downstream portion of the UESB from Ash Slough to the SSCC are less than the design capacity under existing conditions, and the sediment transport modeling indicates that the capacity limitations will continue to worsen over time. Restoration Flow hydrology does not have a significant impact on the capacities in this reach, and the capacity actually increases under the wet hydrology scenario.

Capacities in the MESB are below the design capacity under existing conditions, and the sediment transport modeling indicates that capacities will continue to decrease with subsidence and aggradation that is predicted to occur at the upstream end in the vicinity of El Nido Road. The subsidence that occurs in this reach is greater at the upstream end and reduces the slope of the reach and subsides more than the downstream end creating backwater conditions that are a significant contributing factor in the higher water surface elevations and aggradation creating a reduction in capacity. Sedimentation in the reach is also a function of the balance of the sediment supply being delivered from either the UESB or Reach 4A. Sedimentation at the upstream end of the reach is typically where the capacities are being limited. Results from the dry hydrographs show that when going from existing to Restoration Flows, changes in sediment loads are too low to significantly impact capacities. Under the wet hydrographs, the redistribution of sediment loads from the UESB to Reach 4A is noticeable, with less sediment being delivered to the MESB from

Reach 4A under Restoration conditions than from the UESB under existing conditions. This causes the Restoration-Wet conditions to have higher capacities than the Existing-Wet conditions.

The current capacity in Reach 4A is very close to the flood design flow. Sediment transport modeling indicates that there is potential for channel capacities to decrease to about 80% of the design flow under the future conditions. Results of the various sediment transport simulations indicate that the routing of Restoration-Dry flows are predicted to increase channel capacities in the reach but the Restoration-Wet flows will slightly decrease the channel capacities. The increased discharges entering Reach 4A under Restoration Flows deliver more sediment to the head of the reach, and this increase in sediment loads is shown to cause slight aggradation in the upstream-most portion of the reach (i.e., upstream of approximately Sta 3240+00). This aggradation is the driving factor for the slight reduction in channel capacity for the Restoration-Wet scenario.

In the SSCC, the Restoration Flow scenarios actually have an opposite impact on channel capacity in the reach. The Restoration-Dry scenario does not change significantly, but results do show a slightly lower channel capacity than existing, while the Restoration-Wet scenario increases the capacity in this short 0.3-mile reach. The increase in capacity for the Restoration-Wet scenario likely occurs because the water-surface elevations in the SSCC are controlled by water-surface elevations in the MESB, and the lower relative channel bed elevations that occur in the MESB under Restoration-Wet conditions directly impact results in the SSCC. The Restoration-Dry scenario is also controlled by conditions at the upper end of the MESB, and water-surface elevations just upstream of the critical capacity location in the MESB are just slightly higher under Restoration-Dry conditions (relative to Existing-Dry). This directly causes the slight capacity reduction in the SSCS. In either case, the capacity of this reach under no concurrent tributary flows is much greater than the capacity in Reach 4A so it will not be limiting. And sediment deposition plays a backseat to the backwater elevations in the bypass as these elevations show little capacity in the reach for all flow scenarios.

Previous capacity studies demonstrate that subsidence is responsible for a majority of the predicted reductions in capacity (Tetra Tech, 2015a). Furthermore, though sediment transport is predicted to further reduce capacities beyond the impacts of subsidence alone, sediment transport associated with Restoration Flows will not likely change channel capacities significantly beyond the impacts of subsidence. Assuming that subsidence is likely to continue to occur, and that the hydrology is likely to be somewhere between the Dry and Wet extremes that were evaluated, the results indicate that the capacity of Reach 4A is likely to decrease by about 12 percent regardless of existing or Restoration Flows; in the MESB, channel capacity is likely to decrease by about 34 percent (**Table 4**). The primary sedimentation issues that do occur in the MESB, are located in the upstream end of the reach near the El Nido area. This is an area that has a history of sedimentation and low-capacity issues, and it is recommended that the SJRRP continue to monitor this area and potentially develop plans to mitigate or limit future flows until capacity improvements can be made.

There are several assumptions that were made in this analysis that if refined could change the results. Future improvements to the analysis should include updating the Restoration Flow hydrology. This would include updating the RiverWare® data to include a reasonable near-term (prior to the Reach 4B Project) flow scenario which could help refine the results. Also, looking closer at the tributary inflows to better understand the impact of Restoration Flows on flood flows in these tributaries could allow the expansion of the models upstream into the Chowchilla Bypass. Lastly, continuing to better understand the potential sediment supply to Reach 4A in more detail could refine the results. However, it is likely the most significant assumption in the modeling is the future rate of subsidence. A better understanding of how subsidence will change in the future could have a significant effect on the results. In all, refinement of these data will improve the results but are not expected to change the trends, especially the trend of insignificant changes in channel capacity from sediment transport changes due to Restoration Flows.

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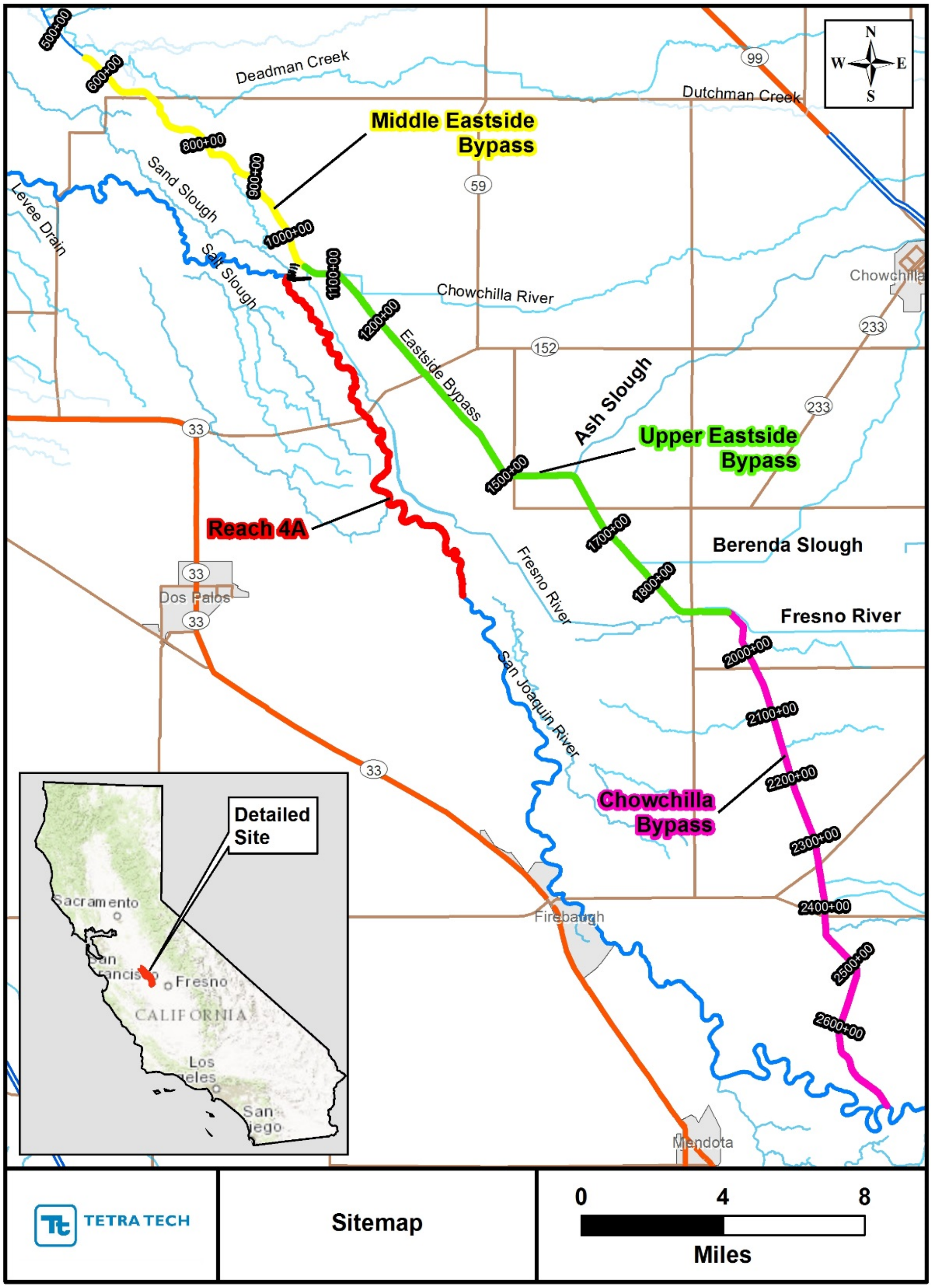

Figure 1. Planview schematic of the Bypass and San Joaquin River study area reaches.

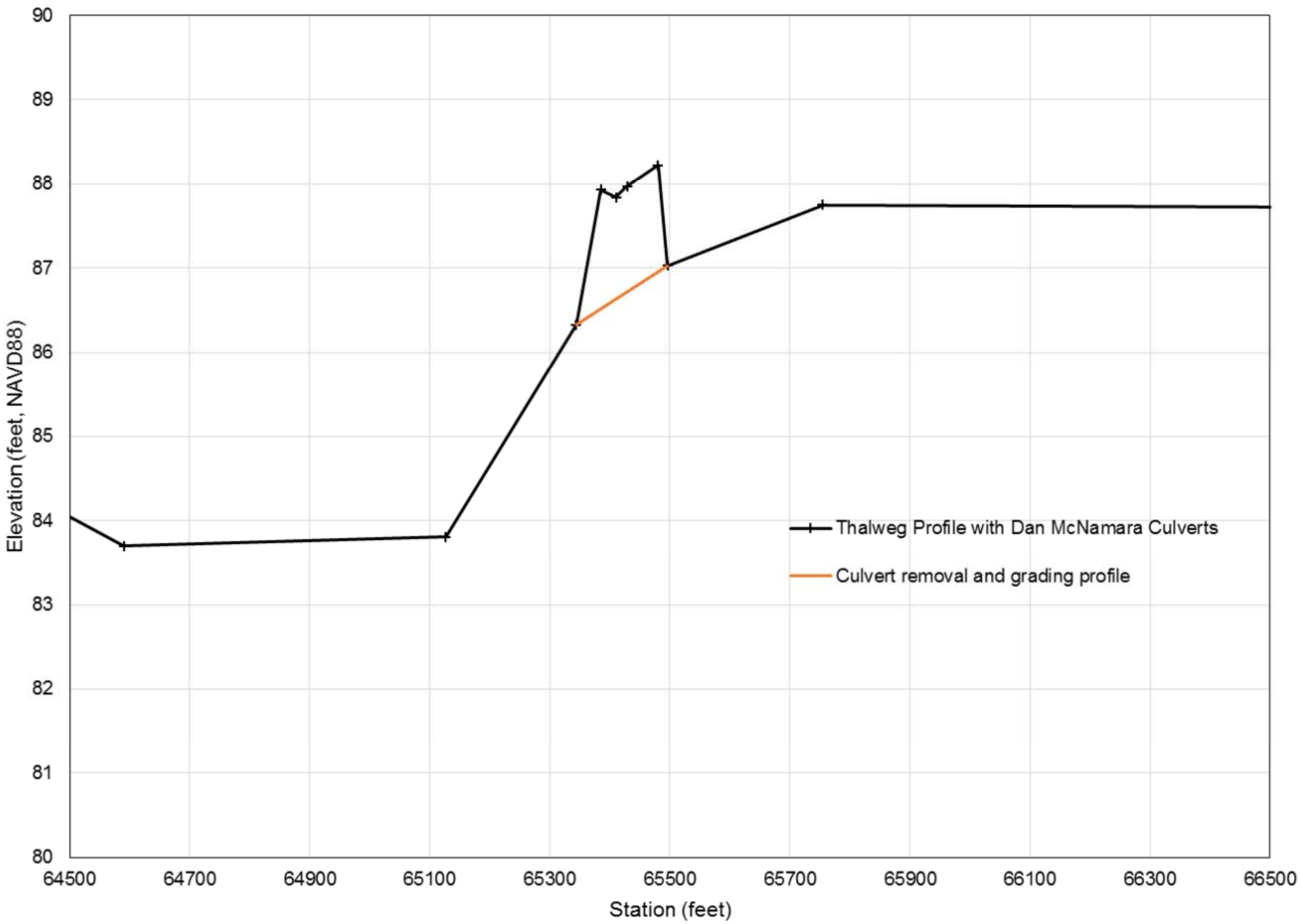

Figure 2. Channel bed profile showing removal of Dan McNamara culverts and associated minimal channel regrading.

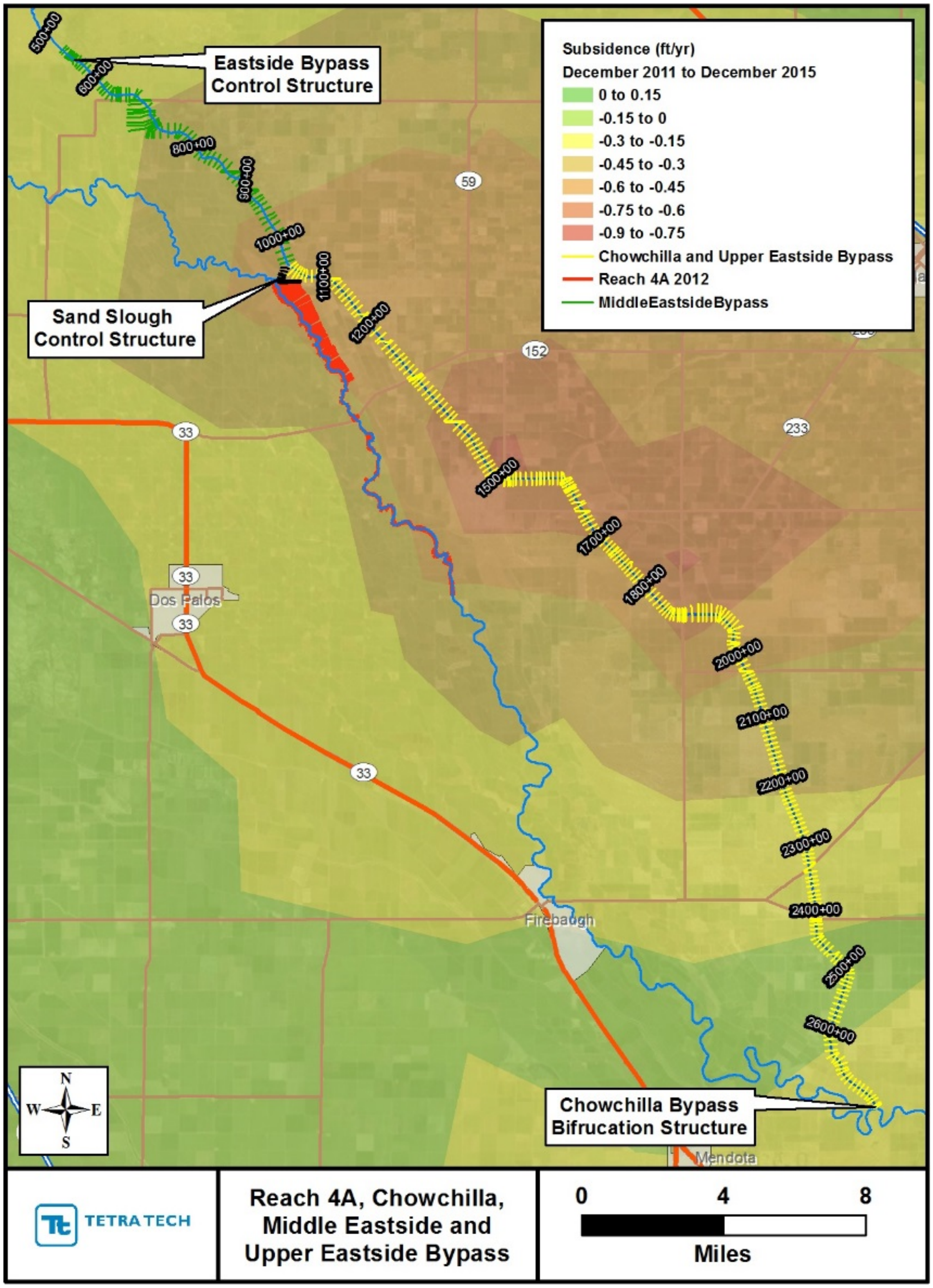

Figure 3. Subsidence rates from December 2011 to December 2015 based on elevation changes at control points collected by Reclamation.

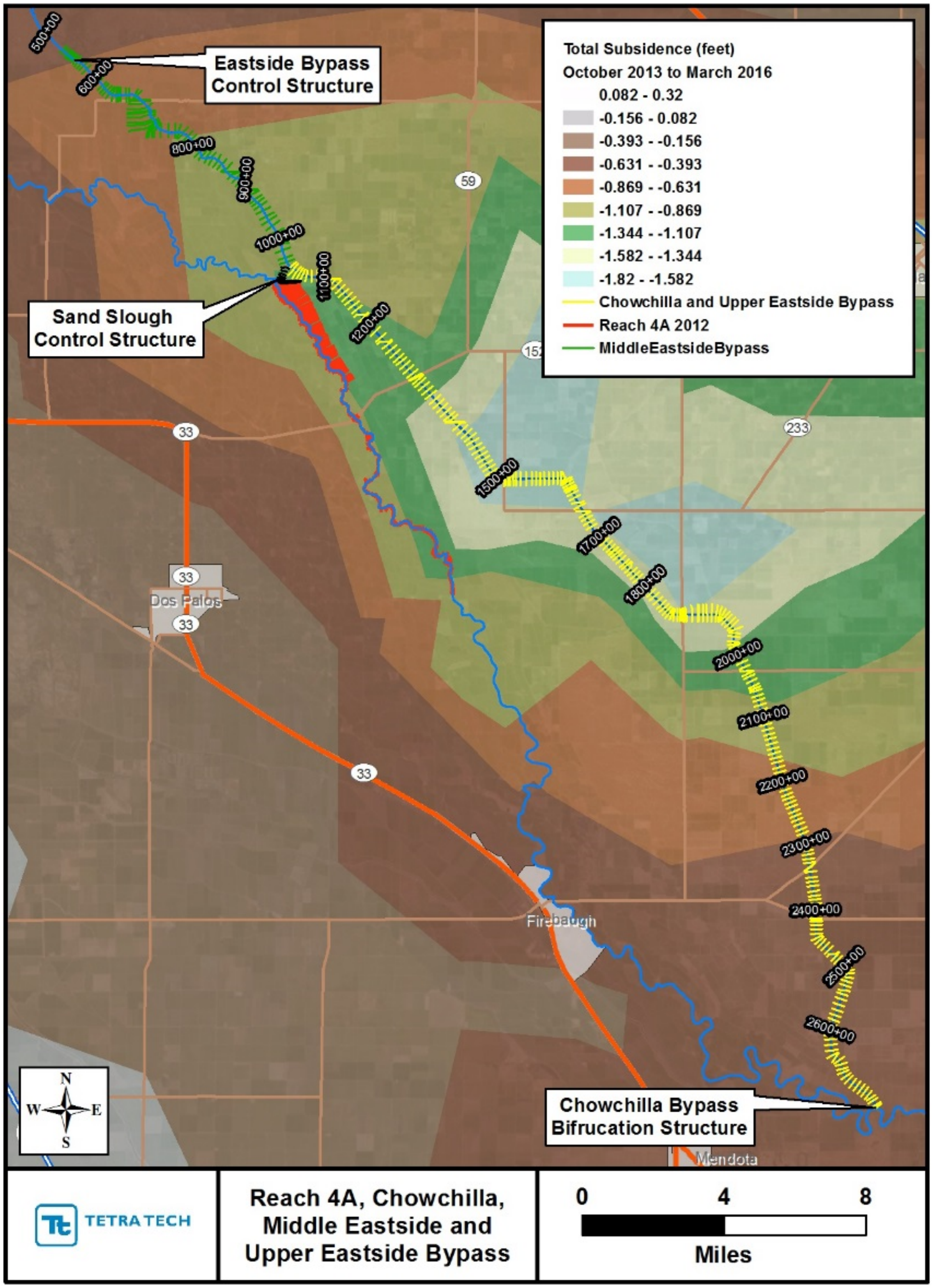

Figure 4. Total subsidence from October 2013 to March 2016 calculated from rates determined from Reclamation data.

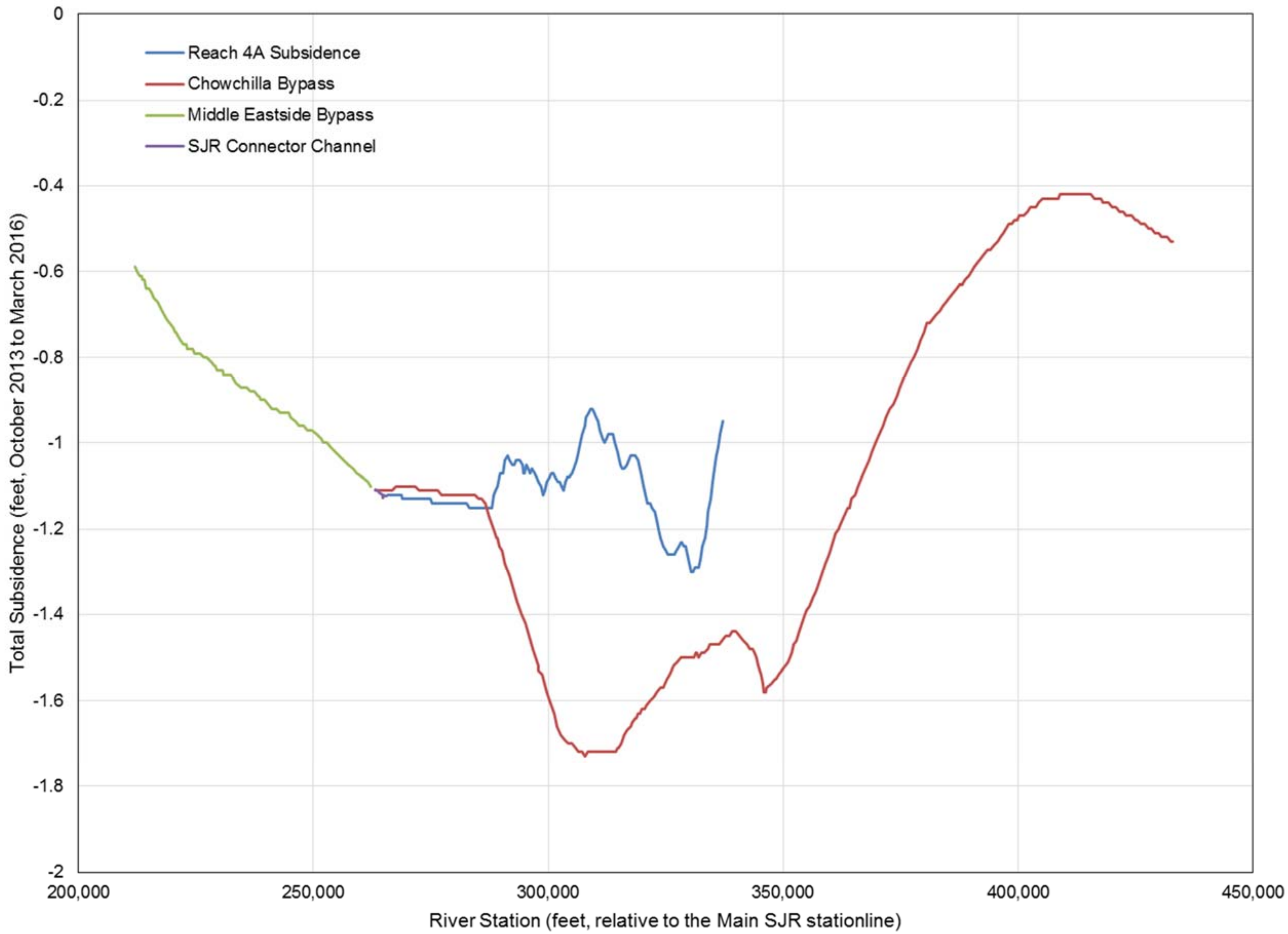

Figure 5. Total subsidence profile proposed to adjust the HEC-RAS model geometry to represent March 2016 conditions.

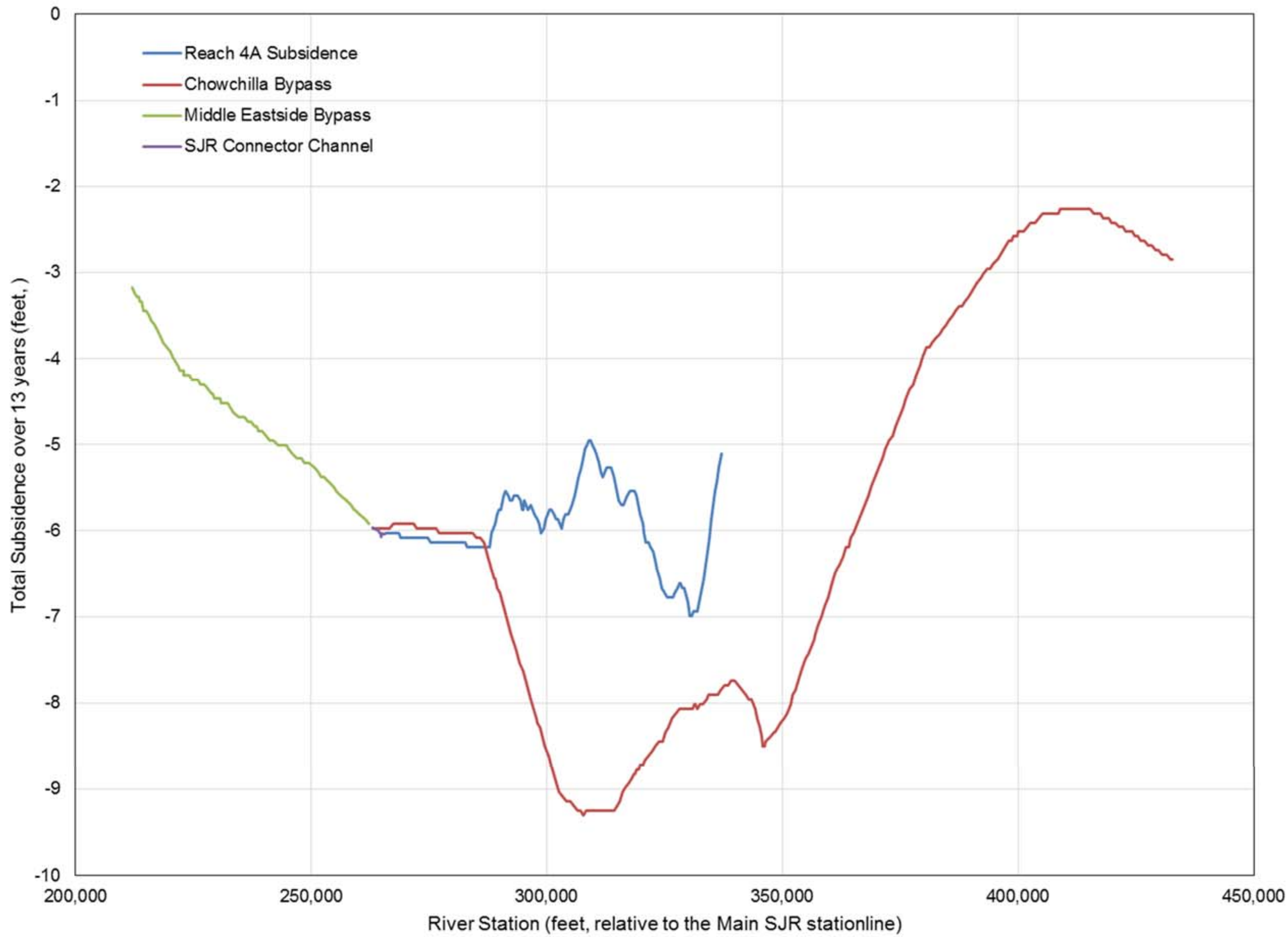

Figure 6. Total subsidence profile at the end of the 13-year simulation.

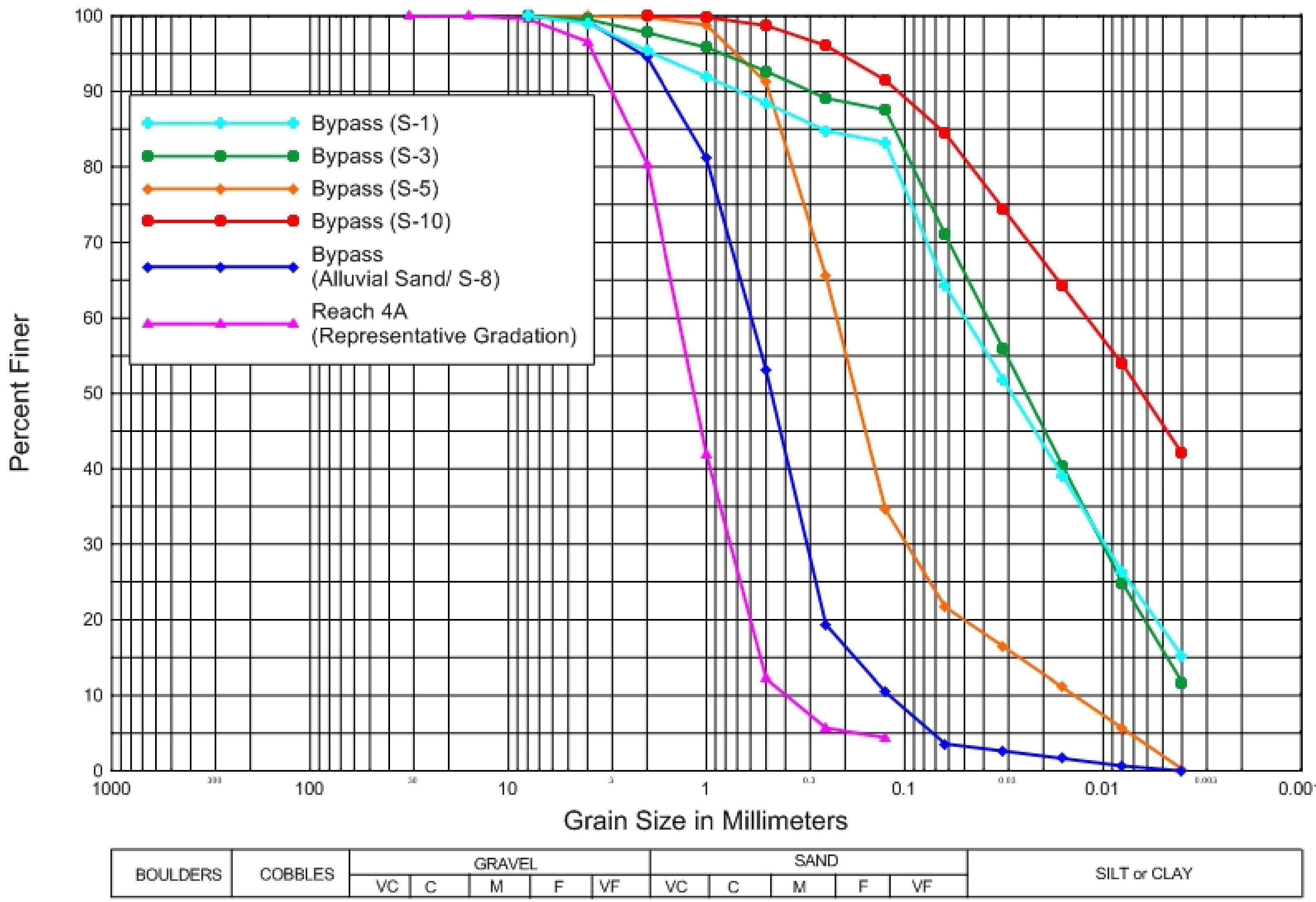

Figure 7. Bed-material sediment sample gradations used in the HEC-RAS mobile boundary model to represent the sediment along the Bypasses and Reach 4A. Note: Bypass sample numbers denoted by (S-#).

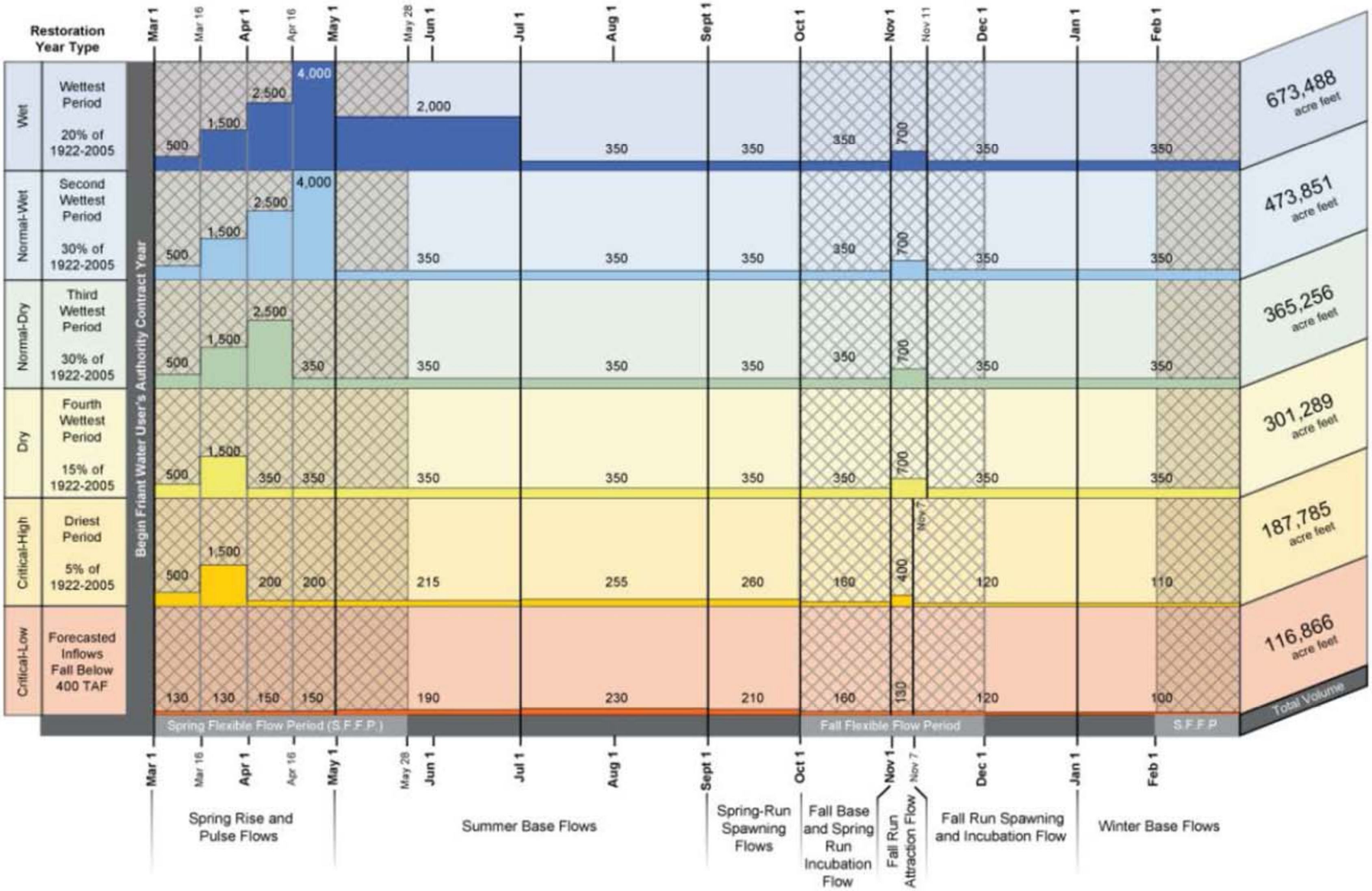

Figure 8. Restoration Flow Schedules, by Restoration Year Type, Settlement Exhibit B Stair-Step Allocations (SJRRP, 2009).

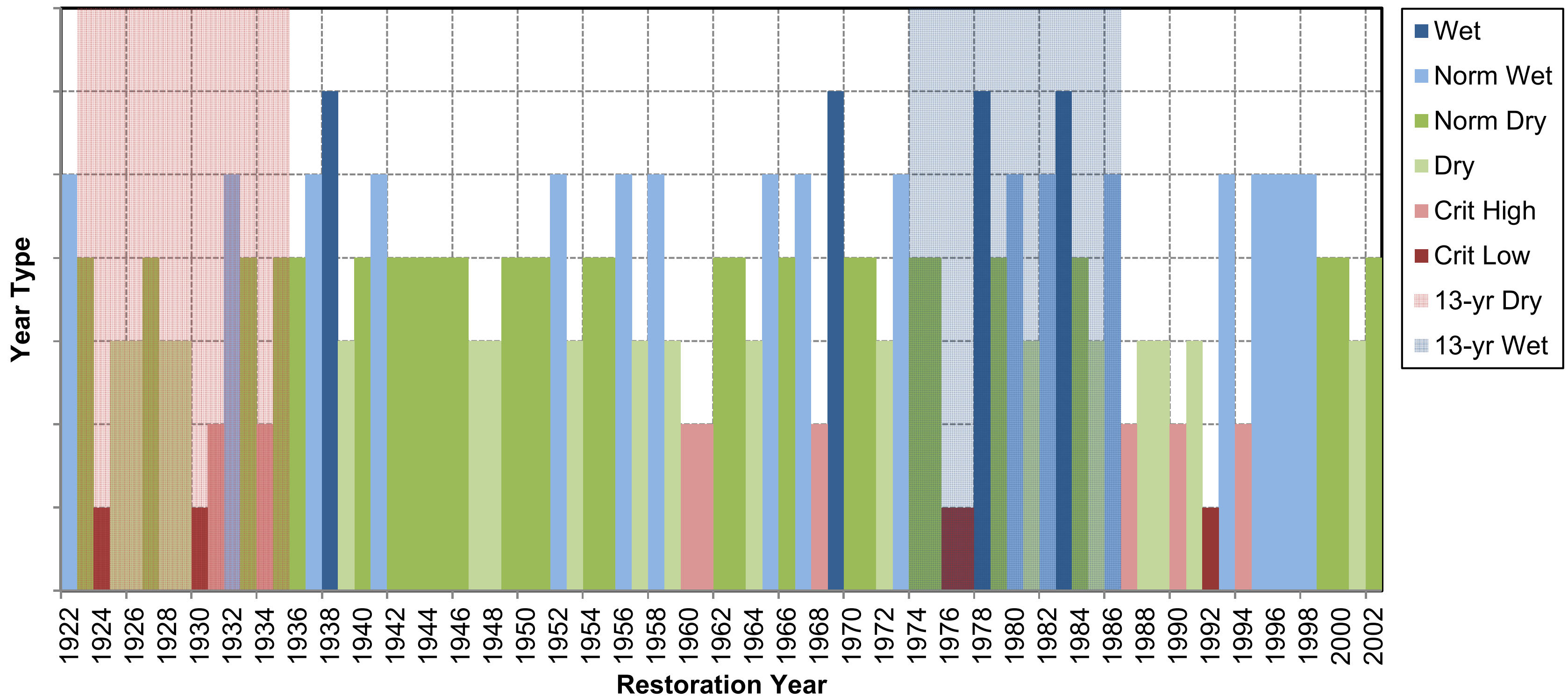

Figure 9. Restoration Year Types based on the Riverware® model results of the simulation for Restoration Alternative 2A. Also shown are the proposed 13-year periods representing dry and wet conditions.

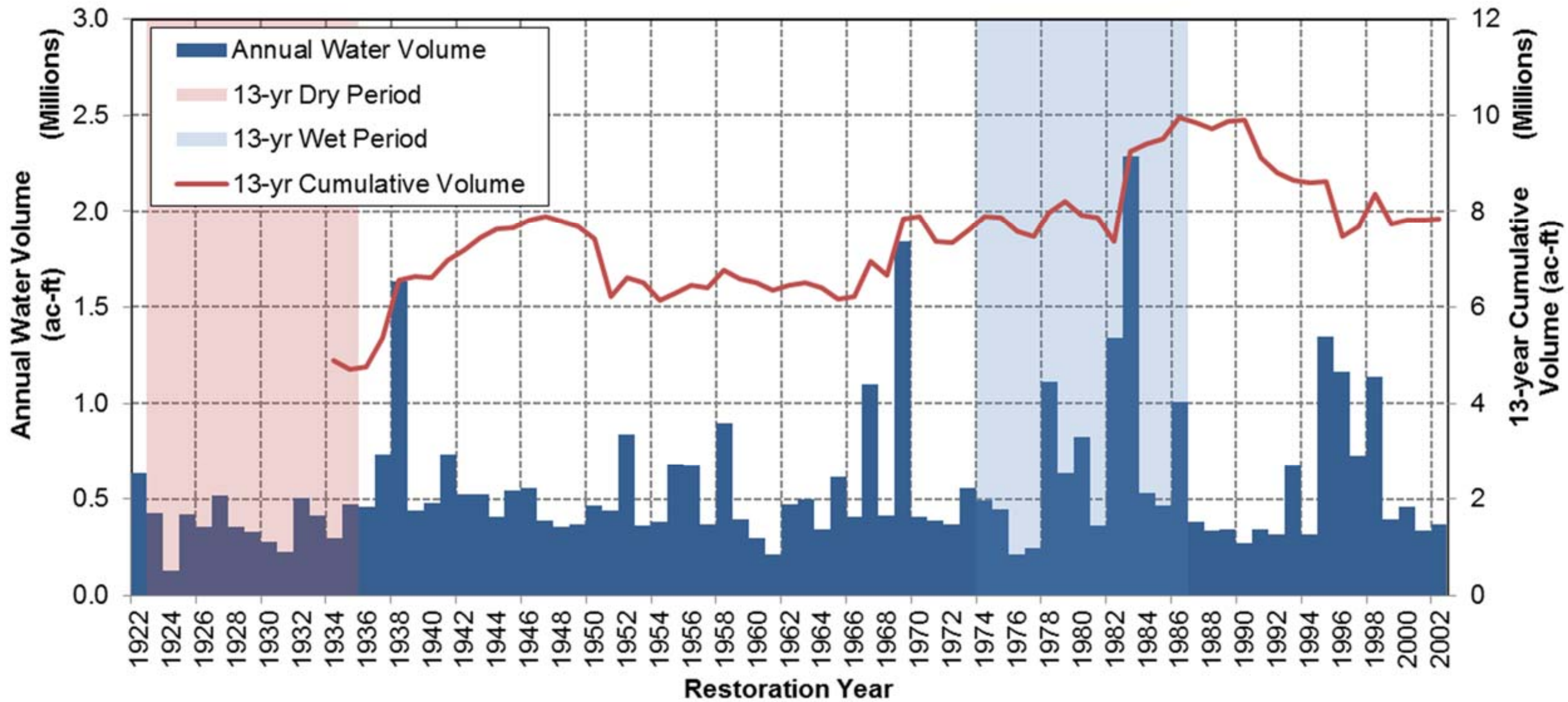

Figure 10. Annual Millerton release volumes under Restoration Alternative 2A, and the moving cumulative volume for the previous 13-years. Also shown are the proposed 13-year periods representing dry and wet conditions.

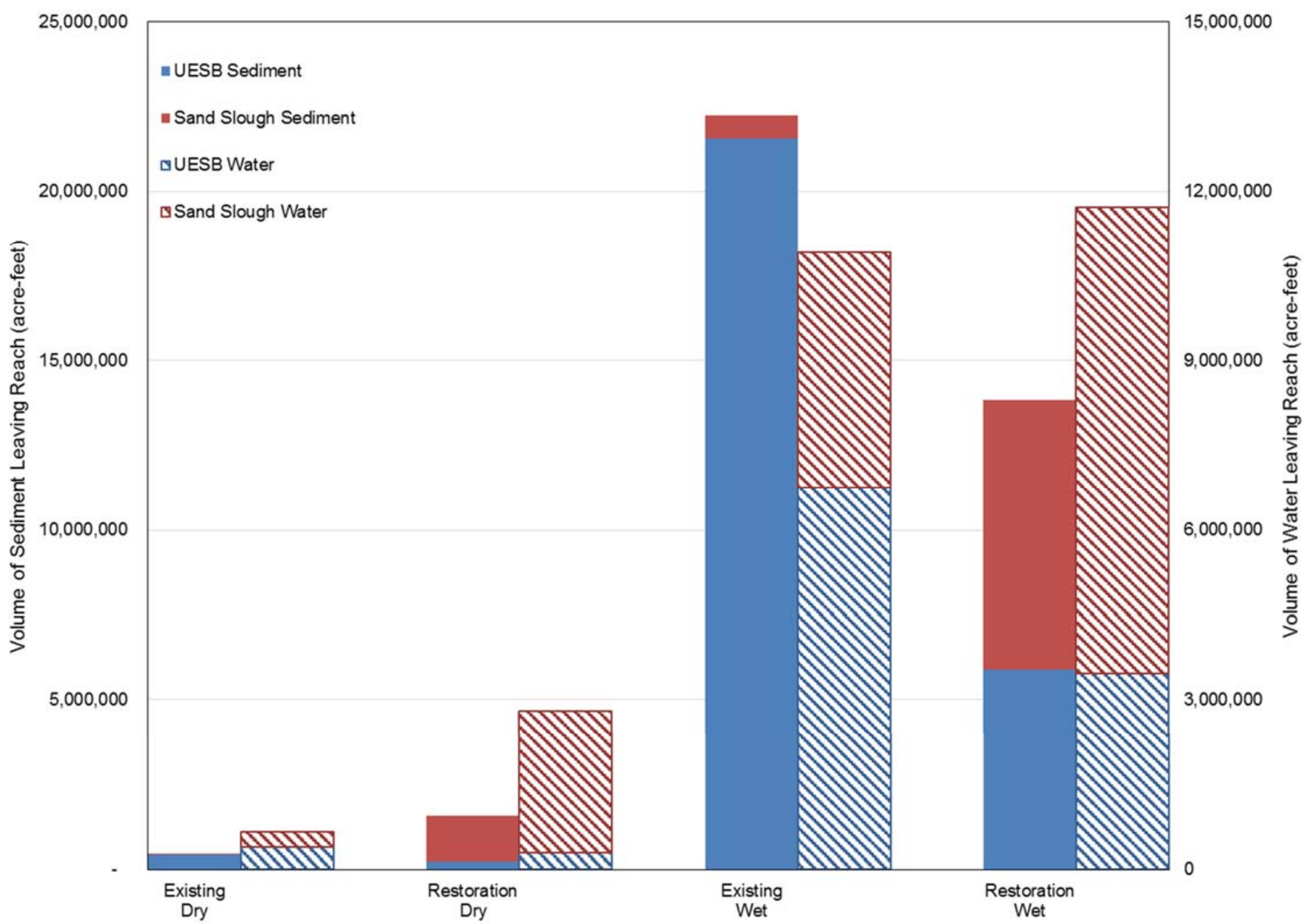

Figure 11. Cumulative volumes of sediment and water at the end of the 13-year simulation leaving the UESB and Reach 4A/Sand Slough Connector Channel.

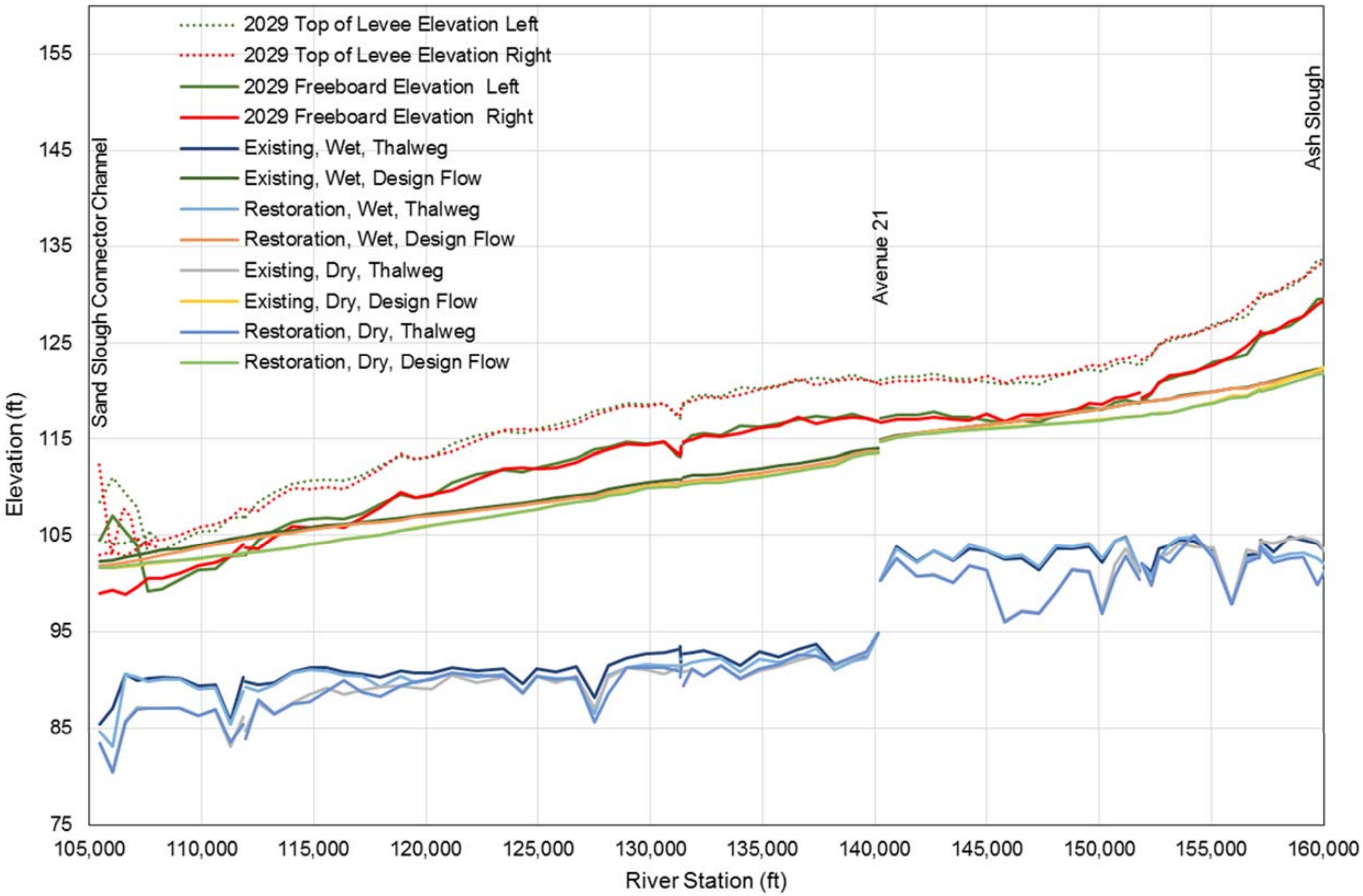

Figure 12. Upper Eastside Bypass (Ash Slough to Sand Slough) channel bed profiles and design flow (17,500 cfs) computed water-surface profiles for 2029 conditions with zero inflows from Reach 4A.

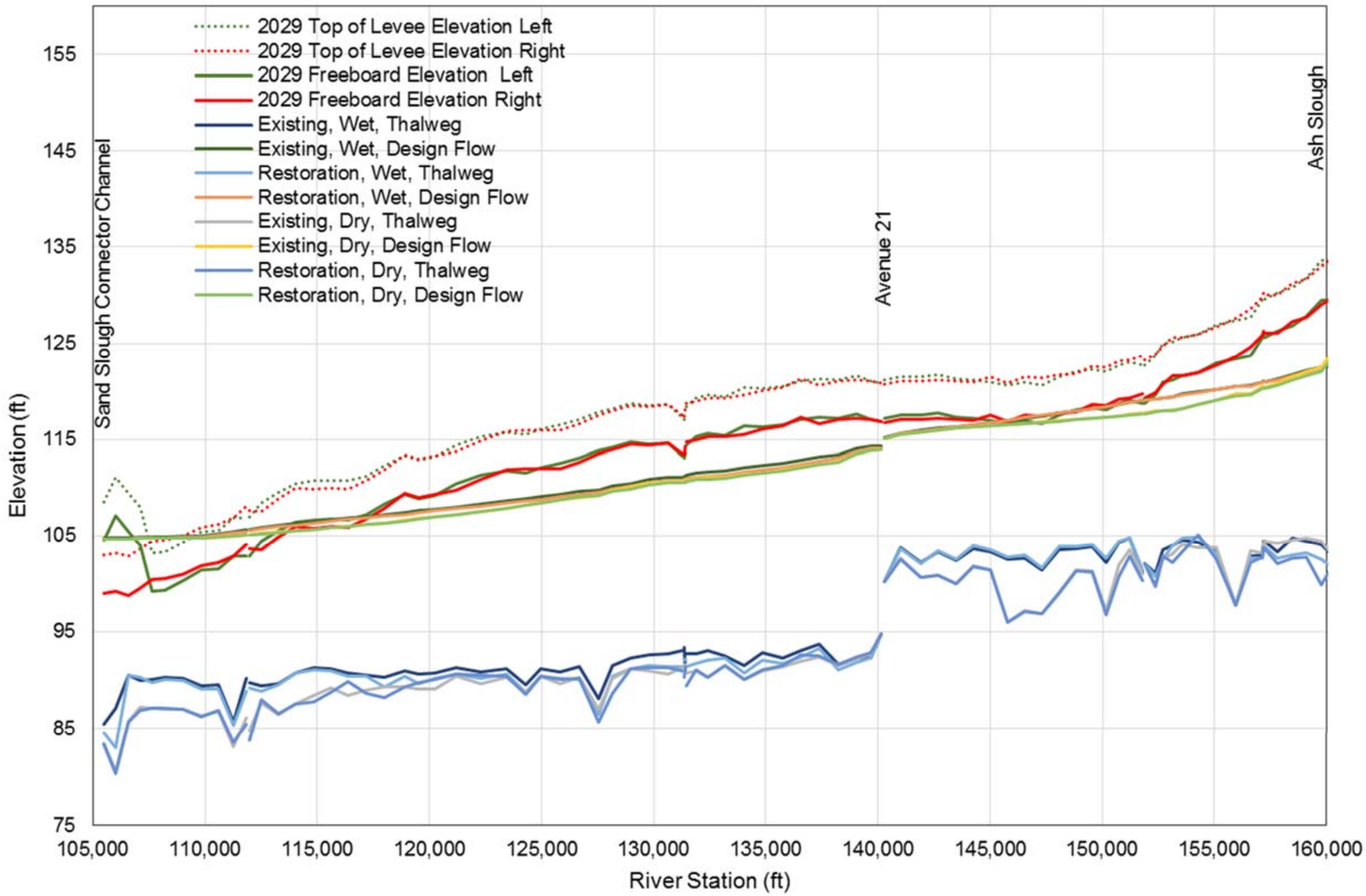

Figure 13. Upper Eastside Bypass (Ash Slough to Sand Slough) channel bed profiles and design flow (17,500 cfs) computed water-surface profiles for 2029 conditions with maximum inflows from Reach 4A.

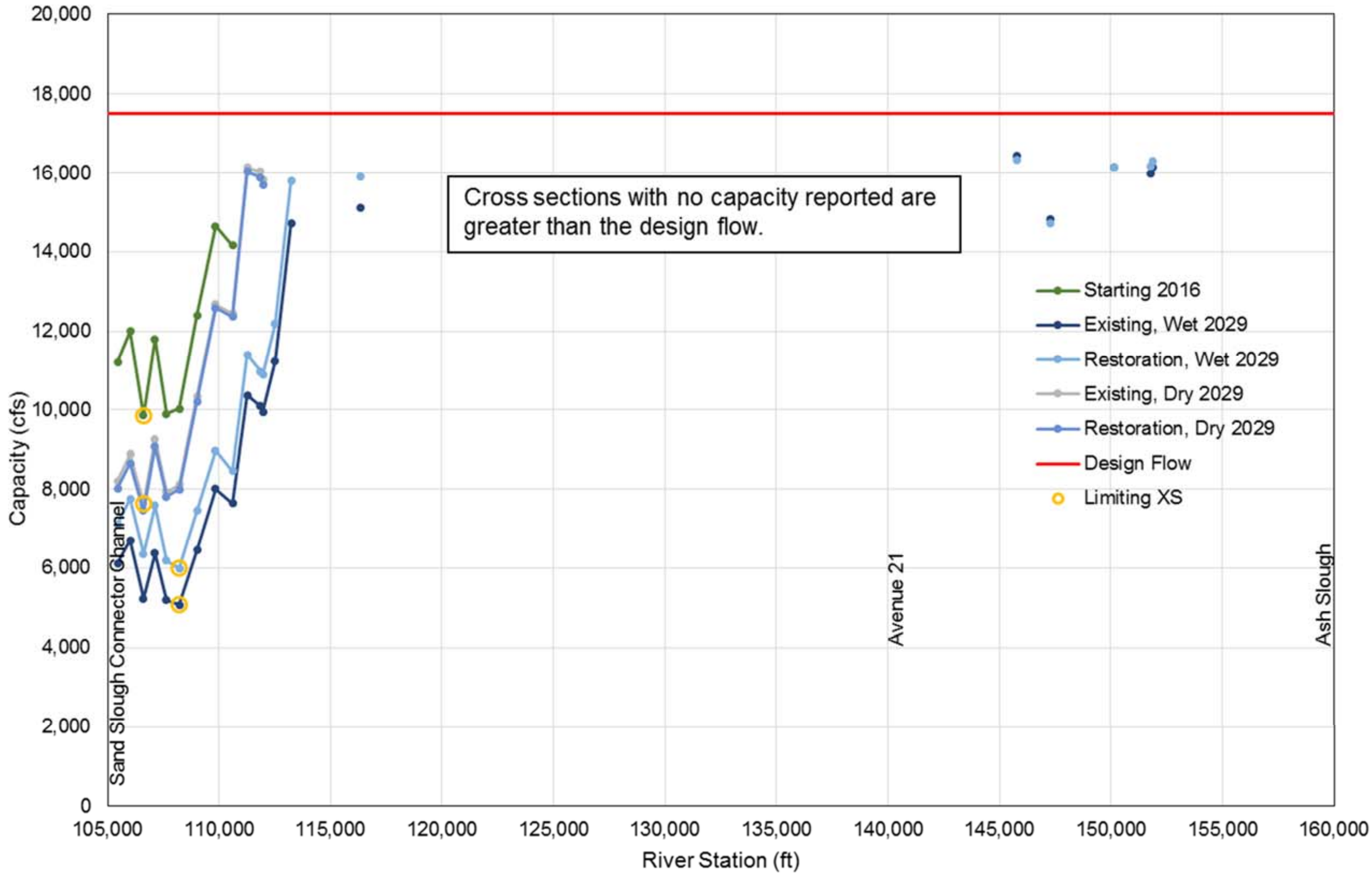

Figure 14. Limiting channel capacity for each cross section under the 2029 conditions for zero tributary inflows in the Upper Eastside Bypass (Ash Slough to Sand Slough).

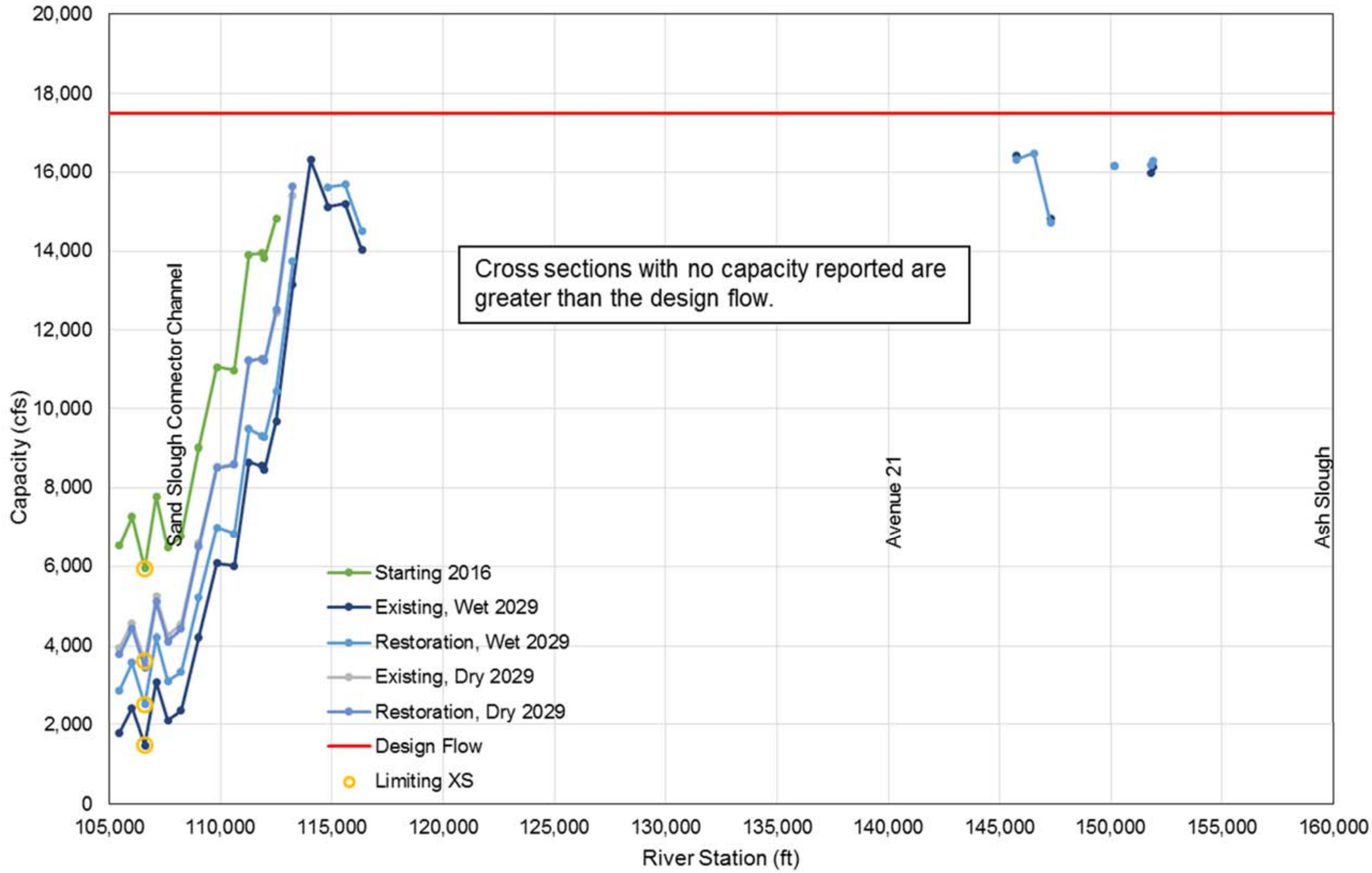

Figure 15. Limiting channel capacity for each cross section under the 2029 conditions for maximum tributary inflows in the Upper Eastside Bypass (Ash Slough to Sand Slough).

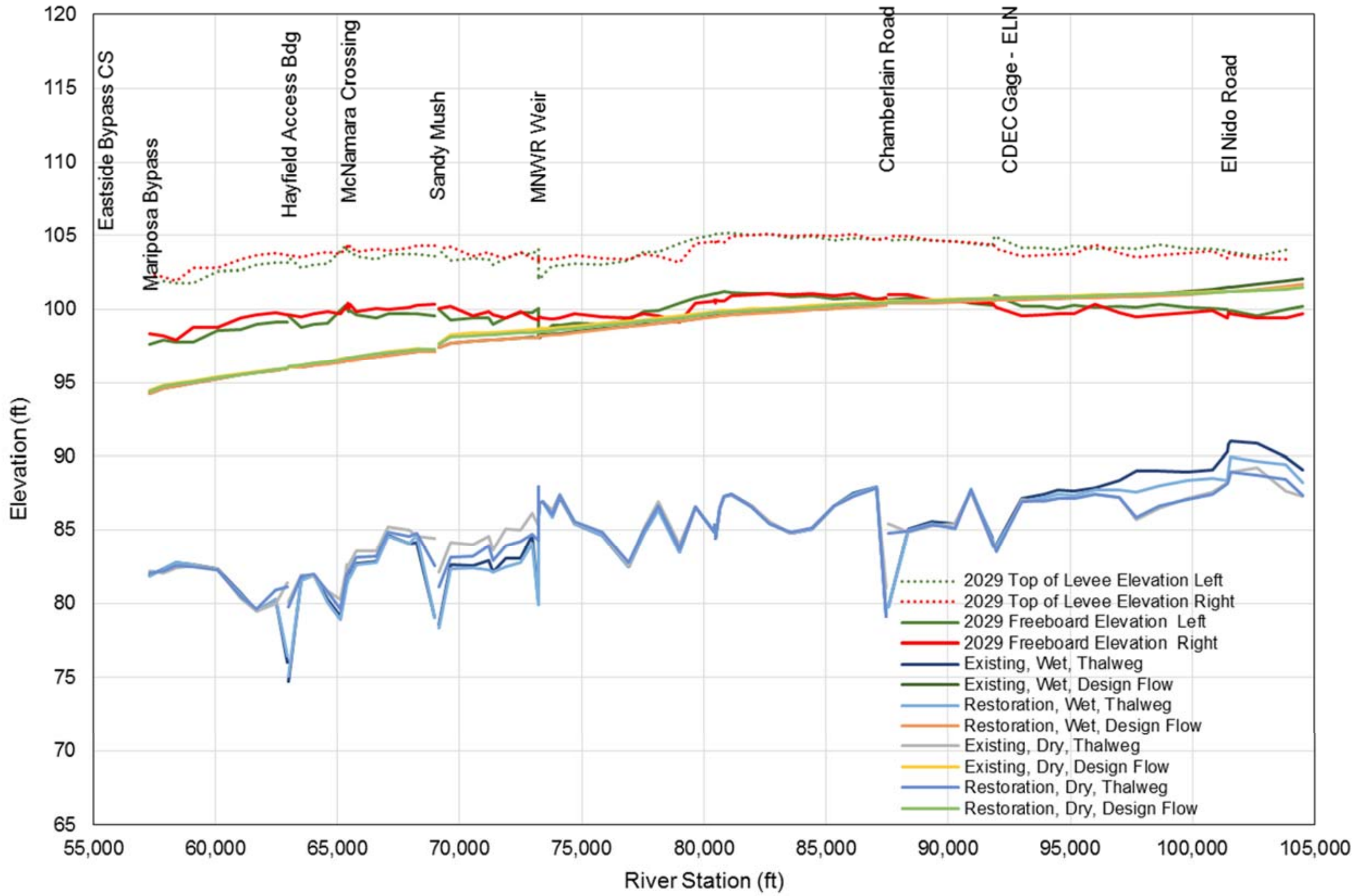

Figure 16. Middle Eastside Bypass channel bed profiles and design flow (16,500 cfs) computed water surface profiles for 2029 conditions.

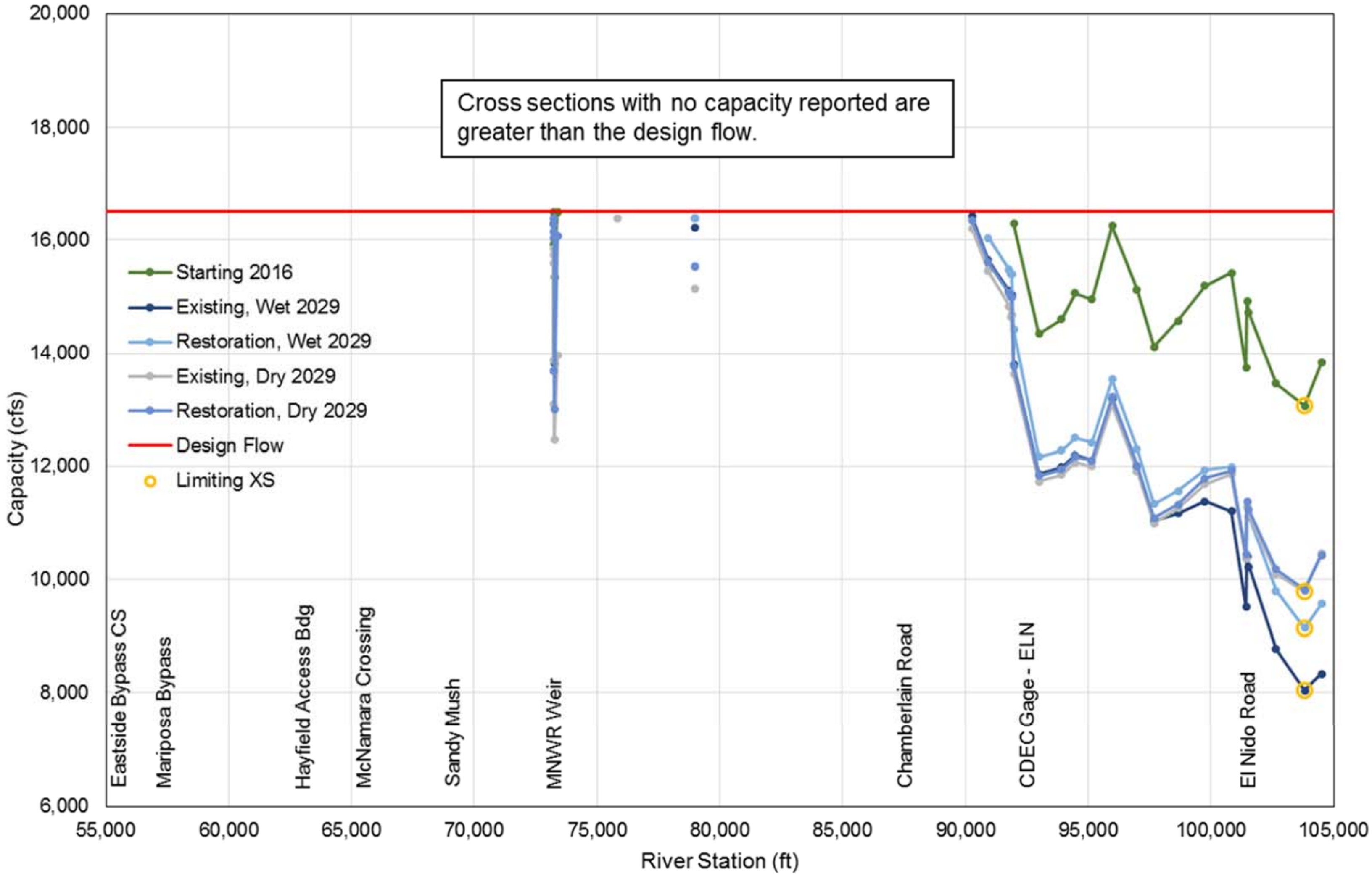

Figure 17. Limiting channel capacity for each cross section under the 2029 conditions in the Middle Eastside Bypass.

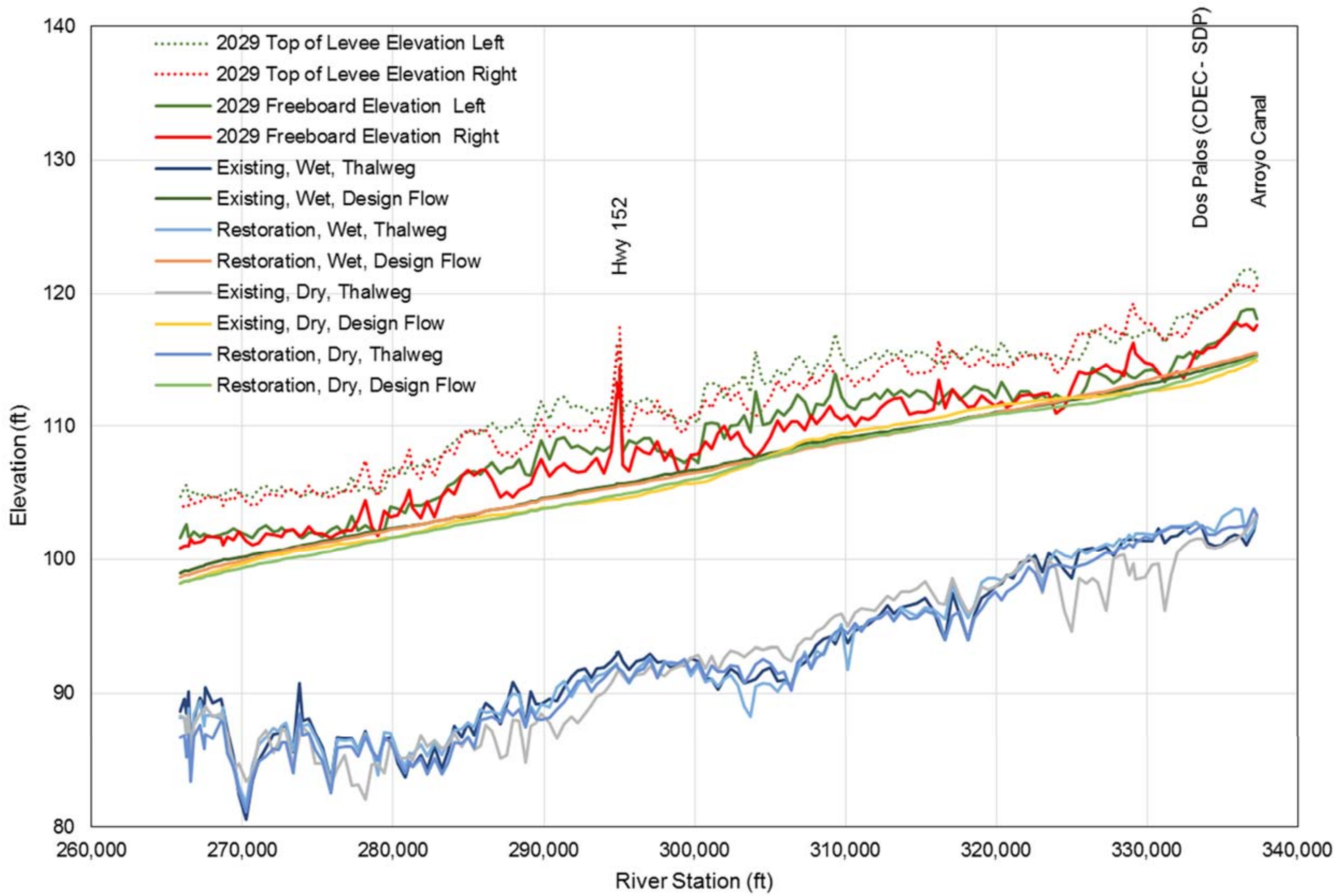

Figure 18. Reach 4A channel bed profiles and design flow (4,500 cfs) computed water-surface profiles for 2029 conditions with zero inflows from the UESB.

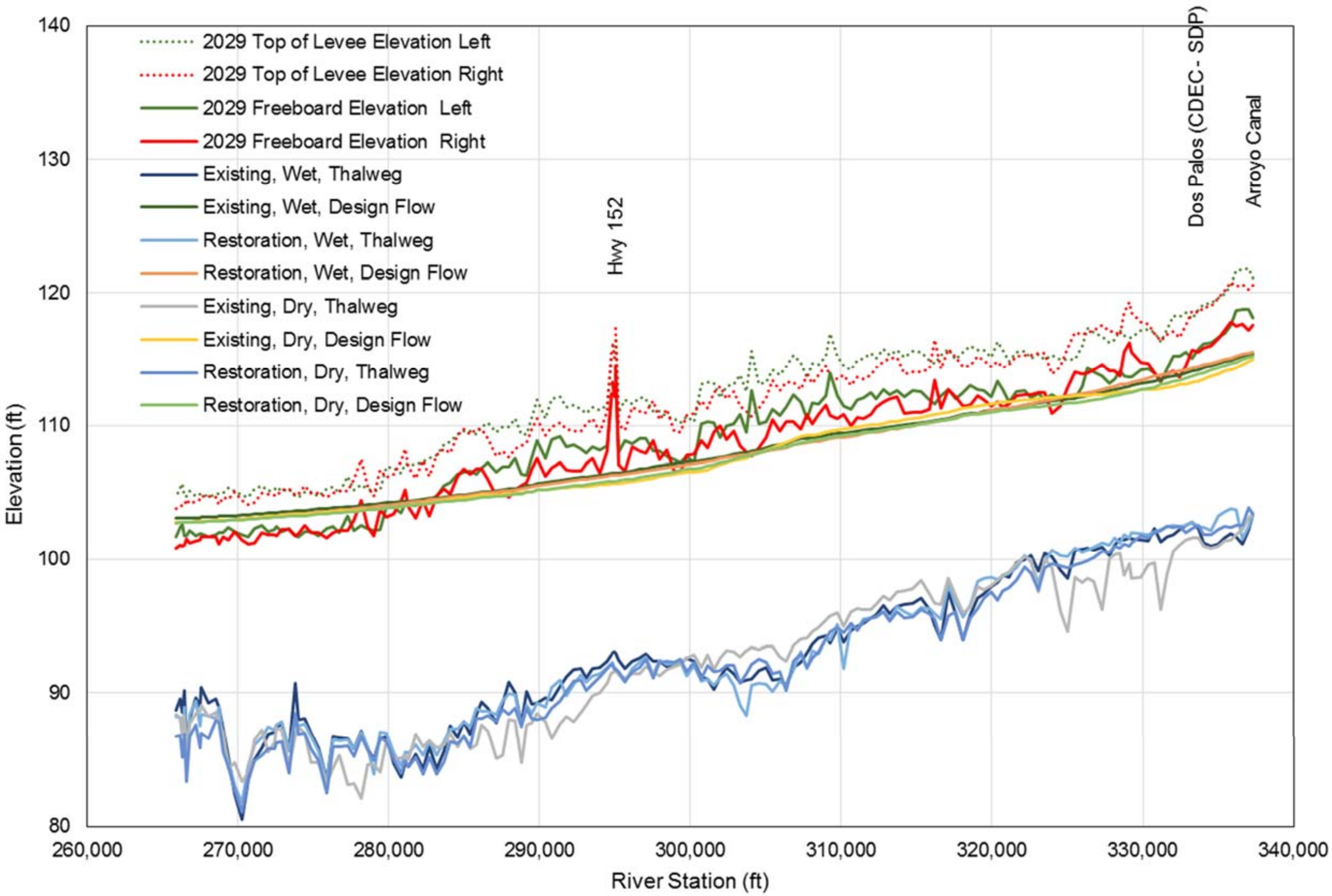

Figure 19. Reach 4A channel bed profiles and design flow (4,500 cfs) computed water-surface profiles for 2029 conditions with maximum inflows from the UESB.

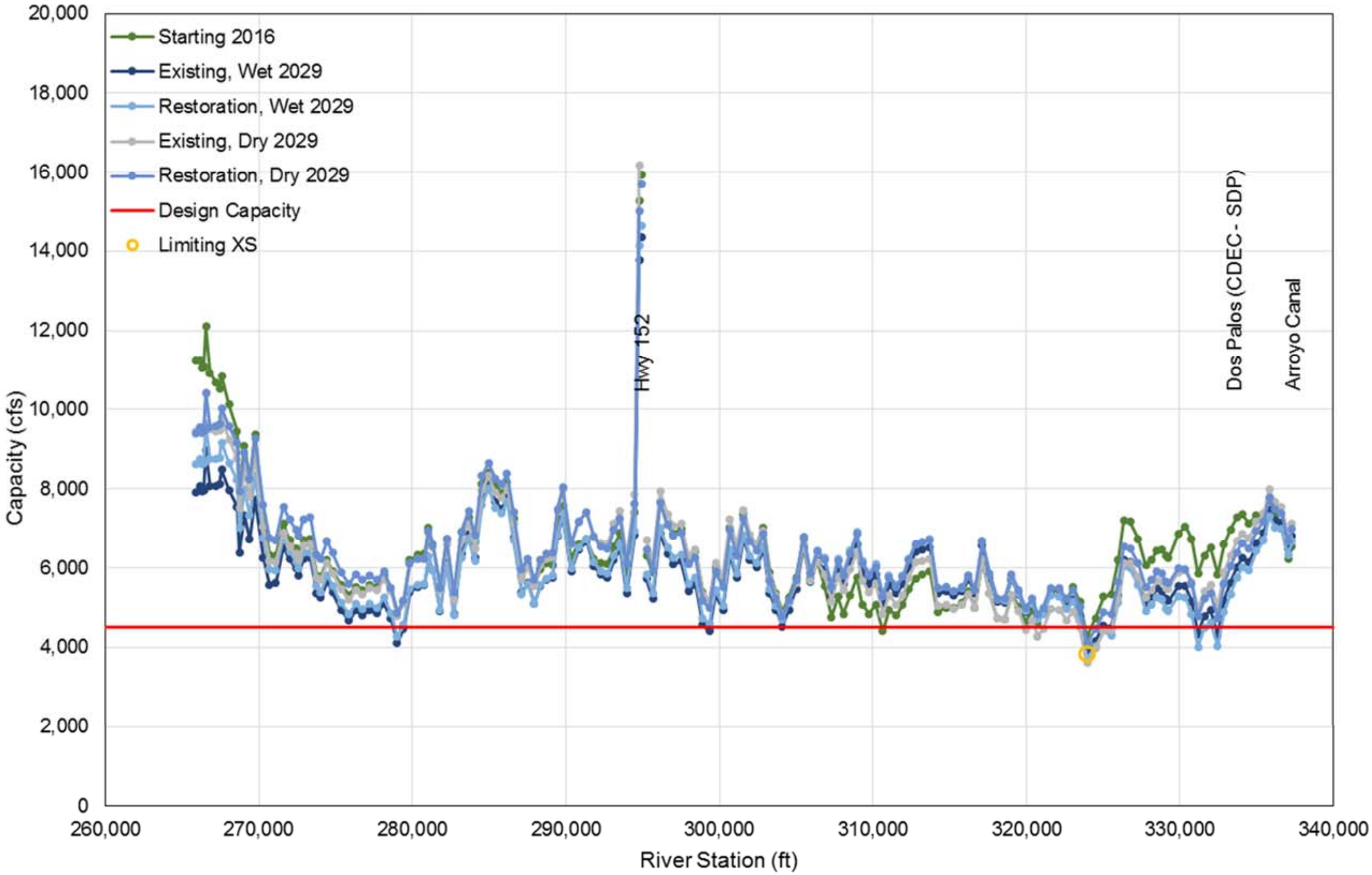

Figure 20. Limiting channel capacity at each cross section under the 2029 conditions for the zero tributary inflows in Reach 4A.

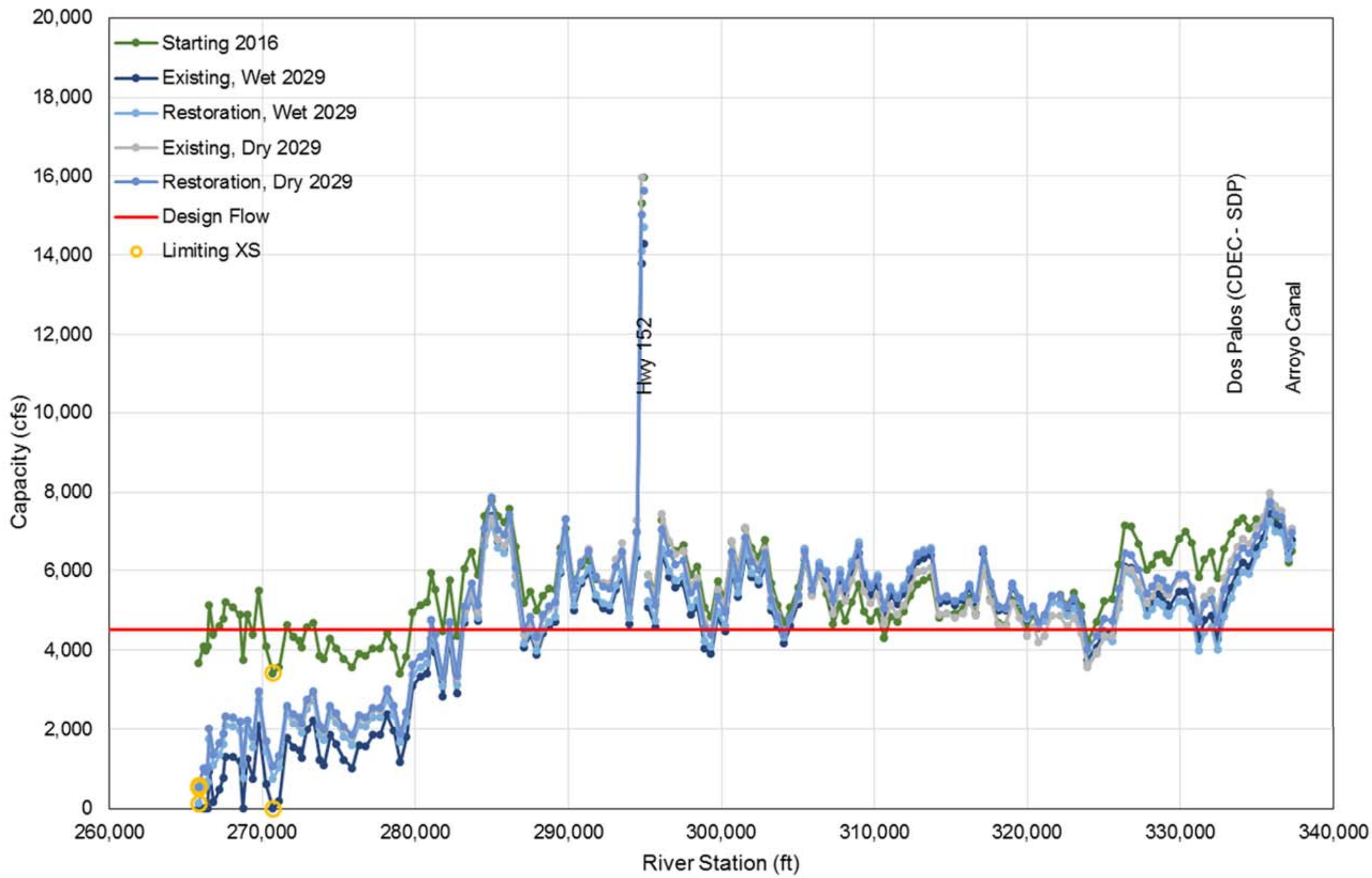

Figure 21. Limiting channel capacity at each cross section under the 2029 conditions for maximum tributary inflows in Reach 4A.

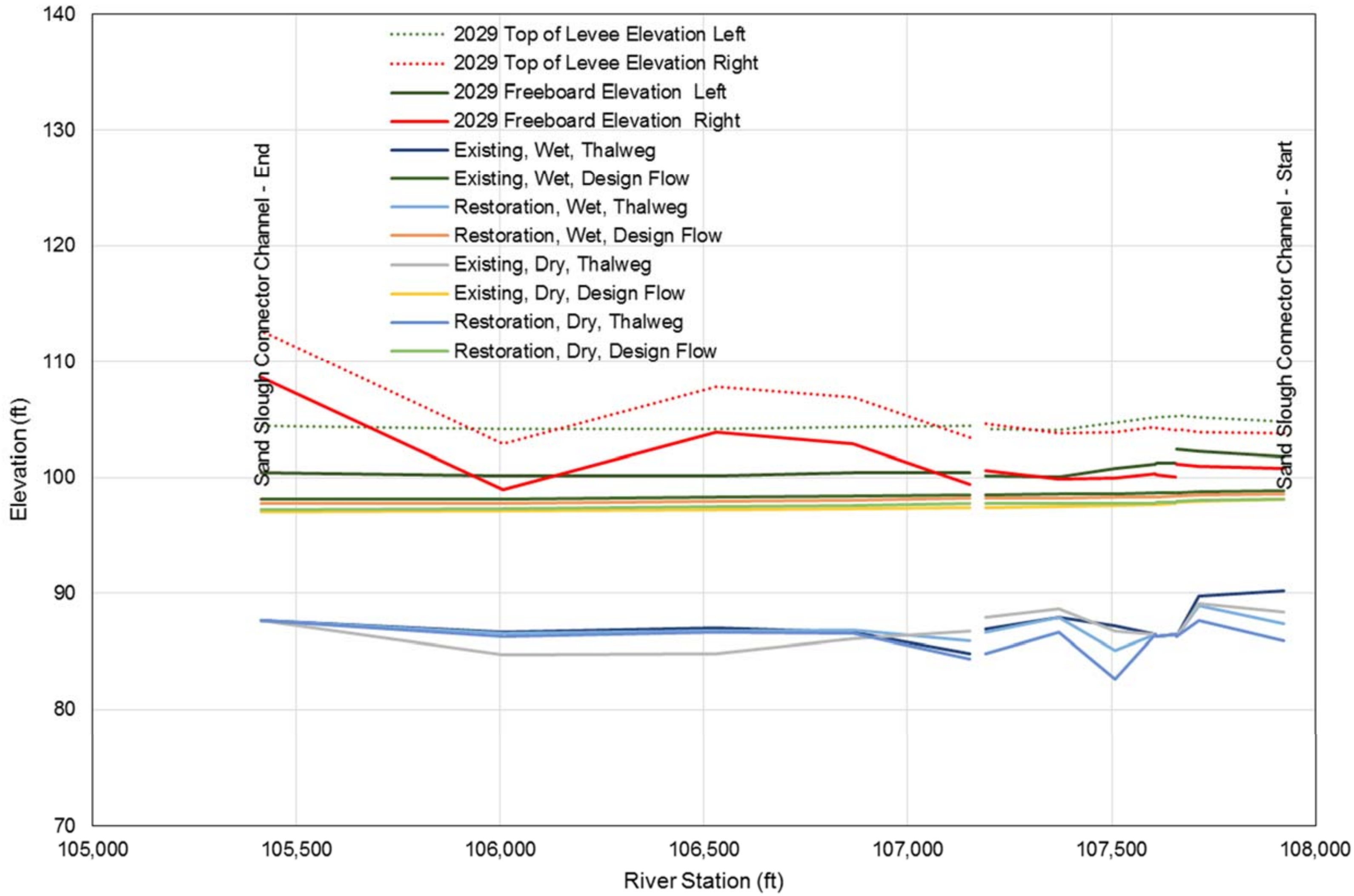

Figure 22. Sand Slough Connector Channel bed profiles and design flow (4,500 cfs) computed water-surface profiles for 2029 conditions with zero inflows from the UESB.

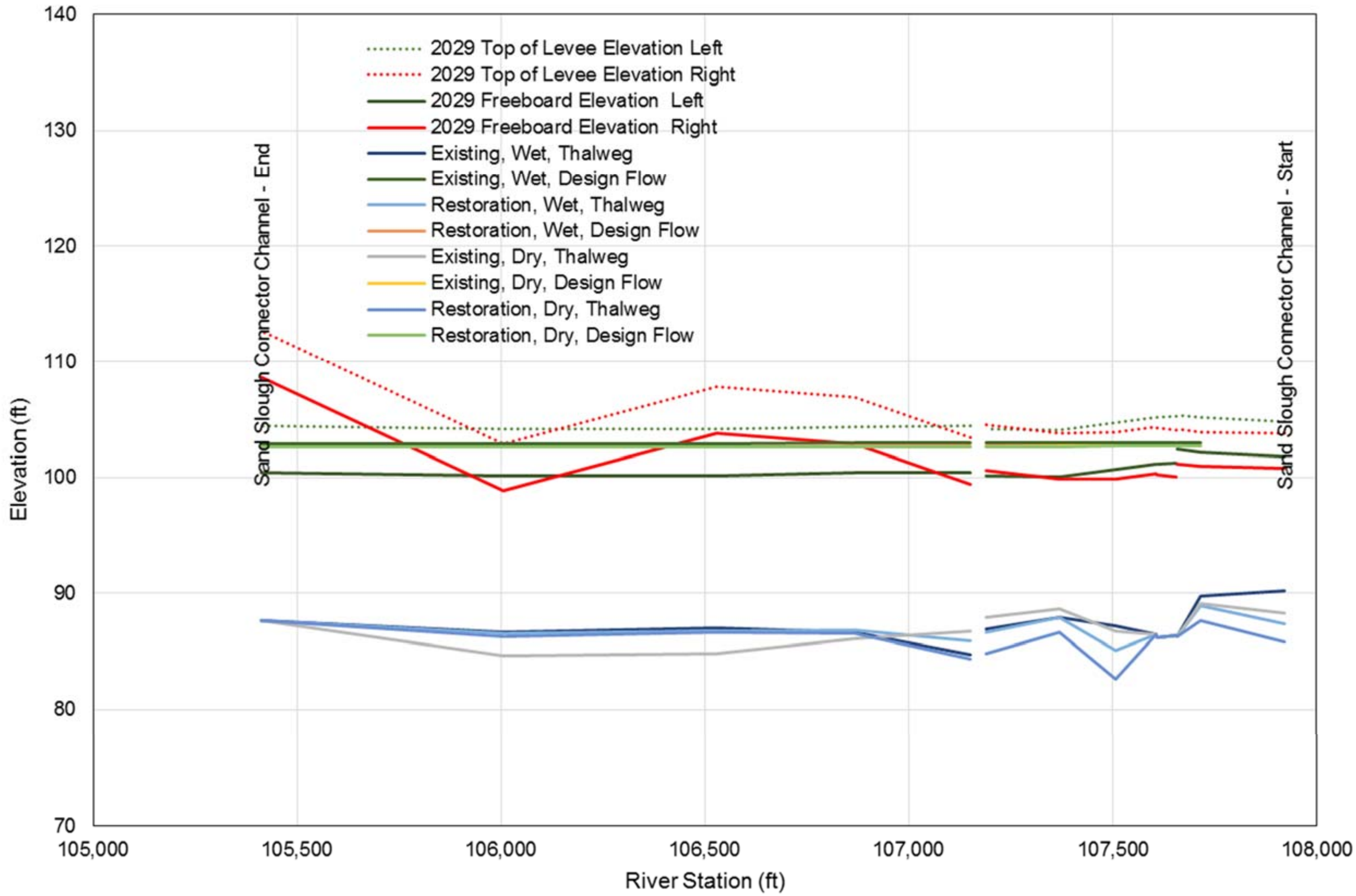

Figure 23. Sand Slough Connector Channel bed profiles and design flow computed water-surface profiles for 2029 conditions with maximum inflows from the UESB.

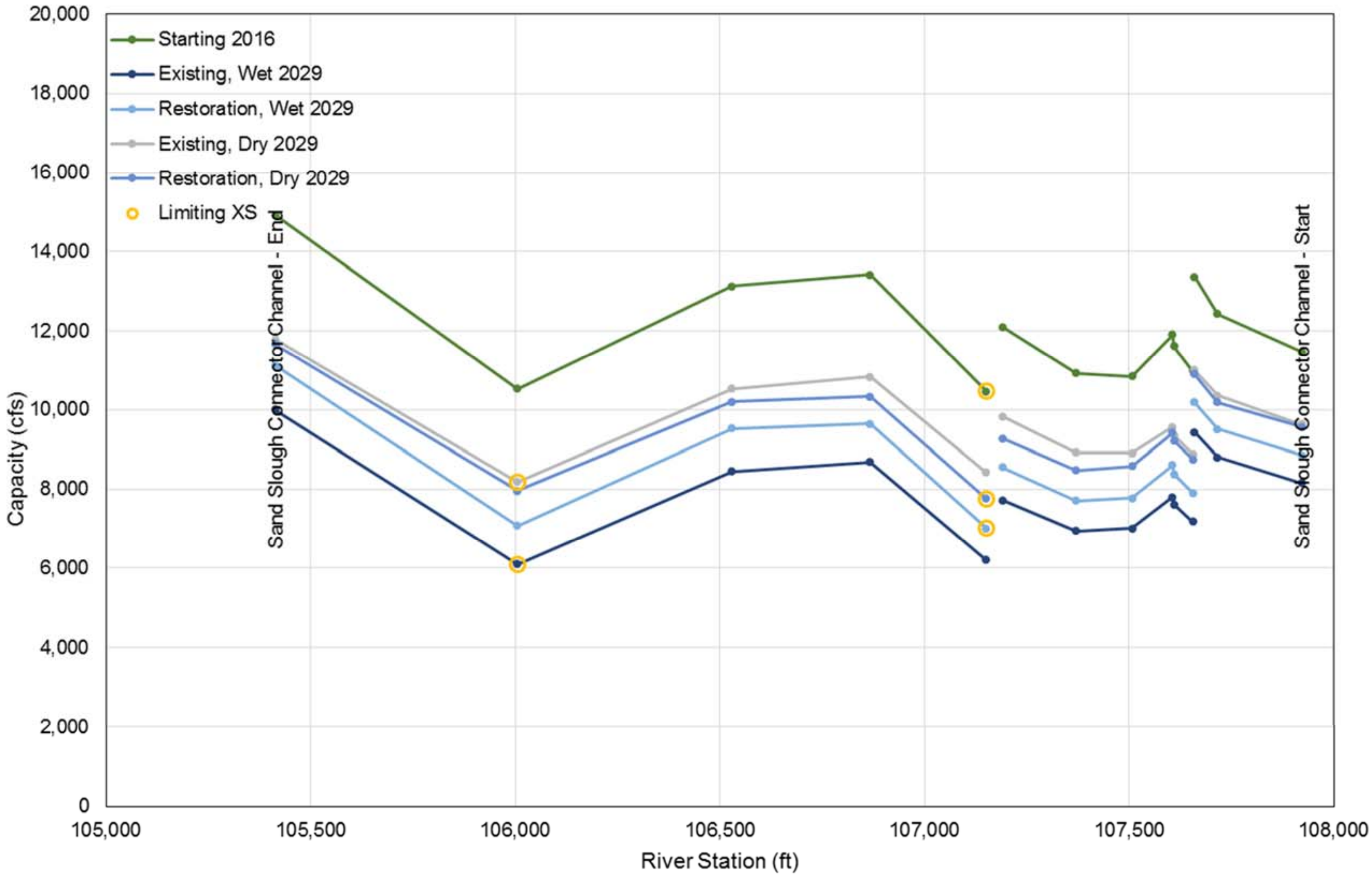

Figure 24. Limiting channel capacity at each cross section under the 2029 conditions for the zero tributary inflows in the Sand Slough Connector Channel.

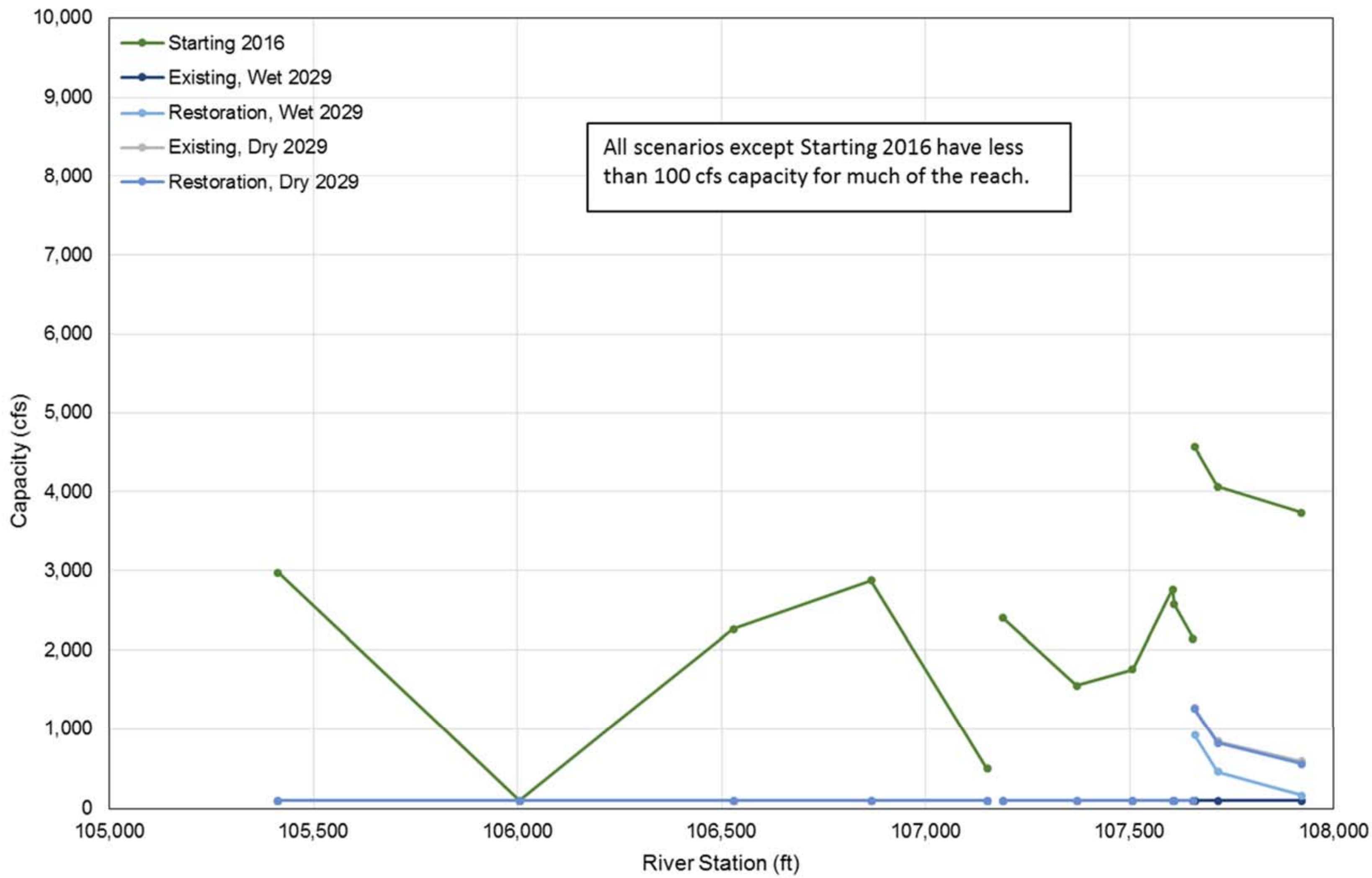

Figure 25. Limiting channel capacity at each cross section under the 2029 conditions for maximum tributary inflows in the Sand Slough Connector Channel.

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