Appendix B

Evaluation of the Effect of Subsidence on Flow Capacity in the Chowchilla and Eastside Bypasses, and Reach 4A of the San Joaquin River

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SAN JOAQUIN RIVER
RESTORATION PROGRAM

San Joaquin River Restoration Program

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California Department of Water Resources
Division of Integrated Regional Water Management
South Central Region Office

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Acronyms and Abbreviations

cfs	cubic feet per second
DWR	California Department of Water Resources
EBCS	Eastside Bypass Control Structure
HEC-RAS	Hydrologic Engineering Center's River Analysis System
Highway	State Route
LiDAR	Light Detection and Ranging
MESB	Middle Eastside Bypass
O&M Manual	Operation and Maintenance Manual for the Lower San Joaquin River Flood Control Project
Reclamation	U.S. Bureau of Reclamation
SGMA	Sustainable Groundwater Management Act
SJRRP	San Joaquin River Restoration Program
SSCC	Sand Slough Connector Channel
UESB	Upper Eastside Bypass
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

Introduction

This study presents the change in levee freeboard and flow capacity in the Chowchilla and Eastside bypasses and Reach 4A of the San Joaquin River that has occurred between 2008 and 2016, and makes projections on potential changes in freeboard and capacity related to continuing subsidence through 2026. This report provides an update to the initial study, *Evaluation of the Effect of Subsidence on Flow Capacity in the Chowchilla and Eastside Bypasses*, performed in 2013 by the California Department of Water Resources (DWR), South Central Region Office. The initial study was done to evaluate effects of ground subsidence on flow capacity in the Chowchilla and Eastside bypasses between the San Joaquin River at the Chowchilla Bifurcation Structure and the Eastside Bypass Control Structure (EBCS) (Figure 1). It focused on assessing the effects of ground subsidence between 2008 and 2011, and then estimated possible future effects to 2016. This current study updates the 2016 projected capacity results based on recent levee survey data and extends the estimated effects of continued subsidence to 2026. The study also includes capacity estimates for Reach 4A of the San Joaquin River.

The goal of this study is to provide a planning tool for use by the San Joaquin River Restoration Program (SJRRP) in identifying potential effects on the design and implementation of the projects to achieve the goals of the program. The information may also assist the flood agencies in informing and planning future flood operations and maintenance, as well as regional planning efforts as part of the Central Valley Flood Protection Plan. Using the data collected by various agencies, this study provides a general picture of flow capacity and the effect of subsidence on the ability of the system to convey flood flows. The conclusions presented in this study are planning-level estimates of the potential maximum flow capacities that can be conveyed using hydraulic design criteria. But, this study does not consider the potential capacity limitations related to levee performance and sediment transport. The study also does not evaluate the effects of flow capacity if subsidence rates are different than historical rates. Further work in these areas may be necessary prior to the development of site-specific actions to address the effects of subsidence shown in this report.

Background

The flood control bypasses that parallel the San Joaquin River include the Chowchilla, Eastside and Mariposa bypasses. They are part of the Lower San Joaquin River Flood Control Project. The design flow capacities and operating rules used in this evaluation for the bypasses and tributaries are based on the Operation and Maintenance Manual (O&M Manual) (Reclamation Board 1967) for the Lower San Joaquin River Flood Control Project. Based on the initial study, the Sand Slough interchange area, where flows from the San Joaquin River converge with flows from the Eastside Bypass, was determined to be the critical location for flow capacity effects related to subsidence (California Department of Water Resources 2013). As a result, the 0.3-mile Sand Slough Connector Channel (SSCC) is separated out from the bypass for this study. Reach 4A of the San Joaquin River was also added because of its vicinity to the critical area. Reach 4A is a 14-mile stretch of the San Joaquin River that runs from Sack Dam to Sand Slough. Reach 4A is connected to the Eastside Bypass through the SSCC.

Subsidence in the San Joaquin Valley is the downward shift or sinking of the ground that is primarily caused by pumping from the deep, confined aquifer. The effect of subsidence can change conveyance channel slopes. That 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 U.S. Army Corps of Engineers (USACE), DWR, the U.S. Bureau of Reclamation (Reclamation), and the U.S. Geological Survey (USGS). One of those studies within the project area is the *Sacramento-San Joaquin Comprehensive Study* completed by USACE in 2002. This study highlighted the observed areas of subsidence, and provided historic rates based on previous surveys. The areas of greatest documented subsidence occur at various control structures located along the river, including Mendota Dam, Sack Dam, the Reach 4B1 Headworks, and Sand Slough Control Structure.

In recent years, subsidence appears to be greatest along the Chowchilla and the Eastside bypasses between Road 9 and Sand Slough Control Structure. Ground control surveys conducted in 2010 to confirm the 2008 Light Detection and Ranging (LiDAR) data 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 among 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. But, the surveys show similar subsidence trends compared to the previous data collection efforts.

Based on Reclamation's bi-annual surveys, the subsidence trends have continued through 2017. Since DWR's initial study in 2013, California's Central Valley experienced some of the driest years on record. During the drought of 2012–2016, locations along the Eastside Bypass experienced subsidence rates as much as 1-foot per year (San Joaquin River Restoration Program 2015). In 2017, the Central Valley experienced one of the wettest years on record. The subsidence rate in 2017 decreased to nearly half of the annual rates recorded during the drought (San Joaquin River Restoration Program 2017). If more wet years occur in the future, the subsidence rates will continue to be lower than during the drought. Furthermore, in 2014, the State of California passed the Sustainable Groundwater Management Act (SGMA), which plans for the "management, and use of groundwater in a manner that can be maintained during the planning and implementation horizon without causing undesirable results" (California Department of Water Resources 2018a). In addition to the efforts related to SGMA, local officials and landowners are working together to increase groundwater recharge opportunities and reduce groundwater pumping by securing future surface water supplies. Consequently, the amount of subsidence will likely be reduced significantly with the implementation of the SGMA and other local efforts.

Assumptions and Limitations

This study was performed to provide a planning-level understanding of the effects of subsidence on flow capacities of the San Joaquin River and flood bypasses that are within the areas showing significant subsidence. In performing this study, there were several assumptions made, and limitations of the data identified, that may affect the results provided in the study. The following assumptions and limitations apply to this study:

1. Subsidence rates between 2008 and 2016 were estimated using the DWR 2008 LiDAR and DWR 2016 top of levee surveys. Subsidence rates calculated in this study vary slightly from the rates presented by Reclamation from its control point surveys. Individual differences in

calculated subsidence rates may be a function of when the survey was conducted and which survey methods were employed, including data density and how the data is averaged. DWR did not attempt to determine the source of any discrepancies between the different studies, but for the purposes of this investigation, the results of the two surveys appear to be consistent. The differences are not deemed to be significant. Projected subsidence rates between 2016 and 2026 were estimated from Reclamation control point surveys taken between December 2011 and December 2017 (Figure 2). This rate was used because it was determined that these years were a better representation of the region's variable hydrologic cycle to estimate the future effects of ground subsidence between 2016 to 2026.

2. Subsidence was assumed to be uniform across each channel cross-section. The topographic surveys in 2016 show some variance between the left and right levee which resulted in slight differences in subsidence rates. But, these differences were deemed insignificant and the average subsidence rate of the two levees were used for each cross-section. DWR subsidence rates may also be slightly underestimated (approximately 0.3 foot of total subsidence) because of a levee-crown rocking project in the Middle Eastside Bypass (MESB). In 2011, the left levee of the MESB was raised from the Merced National Wildlife Refuge weirs to the EBCS. In 2015, the right levee of the MESB was raised from Dan McNamara Road to the EBCS (Tetra Tech 2017). But, these differences were not deemed to be significant, as DWR's subsidence rates generally fell within the range of Reclamation's rates.
3. Sediment transport was not considered in this study. Actual flow capacities may differ in areas of significant sediment deposition and erosion in the channel. Specifically, the flood of 2017 may have created sedimentation patterns that are not represented in the model topography. Furthermore, the topographic data used in this study does show the excavation of as much as 30,000 cubic yards of sediment from the channel near El Nido Road in 2016. Sediment deposition and excavation may affect the capacity results provided in this study.
4. Design 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, 4 feet of freeboard for the bypass channels, and 3 feet of freeboard for the San Joaquin River. Levee freeboard is defined as the height of the top of the levee above the design water level.
5. Flow 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 that add to downstream flows below the channel segment that would reduce the capacity in the channel upstream. The backwater conditions can significantly affect the flow capacities in Reach 4A and the Upper Eastside Bypass (UESB). The assumed concurrent tributary inflows are shown in Table 1.
6. The analysis and findings in this study were based solely on a hydraulic comparison of the computed water-surface profiles and levee freeboard elevations. The analysis did not consider levee seepage and stability, levee erosion, and other potential failures.
7. The data and results from 2008 were taken from DWR's 2013 study and used for discussion purposes in this updated study. This study did not assess the reason for any differences between the 2008 capacity and design flow capacity.

Table 1 Tributary Inflows Creating Backwater Conditions (in cfs)

Tributary	Tributary Design Flow
Chowchilla Bypass	
Fresno River	5,000
Eastside Bypass	
Berenda Slough	2,000
Ash Slough	5,000
San Joaquin River (Reach 4A)	4,500
San Joaquin River	
Eastside Bypass	12,000

Note: cfs = cubic feet per second

Topography

Table 2 summarizes the subsidence rates developed by both DWR and Reclamation at key structures along the river and bypasses. The DWR subsidence rates (2008–2016) were estimated based on a comparison of top of levee profiles from the 2008 LiDAR and the 2016 levee surveys (Figures 3, 4, and 5). These rates match reasonably well with the Reclamation data, though they are slightly higher along the Eastside Bypass between Road 9 to State Route (Highway) 152. General differences in subsidence rates could be a result of the time frames that the data was taken, as well as the accuracy and geographical coverage of the data. For example, the annual subsidence rate calculated by Reclamation near Road 9 was 0.13 foot/year from July 2017 to December 2017, but 0.48 foot/year from December 2016 to December 2017. Additionally, the DWR 2016 surveys collected additional data points that may better represent subsidence in areas where there are few control points in the Reclamation surveys. For example, in the immediate vicinity of the bypass, the Reclamation subsidence rates are based on 11 surveyed control points, whereas the DWR estimated subsidence rates are based on approximately 2,900 survey points collected at 100- to 200-foot intervals. Both rates were applied to this study. The DWR rates (2008–2016) were used to update the modeled geometry to reflect current subsidence in 2016. Reclamation’s rates (2011–2017) were used to project the model to 2026. Reclamation’s lower rates were used to predict subsidence in the future because the rate of future subsidence is anticipated to decrease with the implementation of SGMA and better management practices by local landowners.

Hydraulic Analysis and Results

The hydraulic study summarized in this report was completed as two separate evaluations. The first was to estimate the change in freeboard that has occurred from recent subsidence, and may occur in the future as a result of ongoing subsidence. The second evaluation included translating those changes in freeboard into changes in flow capacity. The following section summarizes the hydraulic model development, study methodology, and the results of the two evaluations.

Model Development

This study was conducted using validated Hydrologic Engineering Center’s River Analysis System (HEC-RAS) baseline models of the river and flood bypasses with 2008 topography, and 2010–2011 bathymetry where available. The model geometry was then updated to 2016, based on the DWR top of

Table 2 Ground Subsidence Rates along the Chowchilla and Eastside Bypasses and Reach 4A

Reach	Key Structures	Reclamation (2017)	Reclamation (2011–2017)	DWR (2008–2016)
		ft/year	ft/year	ft/year
Chowchilla Bypass	Avenue 7	0.11	0.16	0.18
	Avenue 14	0.52	0.48	0.54
Upper Eastside Bypass	Road 9	0.47	0.50	0.63
	Triangle T	0.32	0.45	0.59
	Avenue 18 1/2	0.32	0.47	0.57
	Road 4	0.35	0.48	0.95
	Avenue 21	0.27	0.45	0.69
	Highway 152	0.15	0.41	0.64
	Washington Road Bridge	0.02	0.38	0.48
Middle Eastside Bypass	Sand Slough Vicinity	0.00	0.37	0.40
	Merced National Wildlife Refuge Weirs	0.00	0.24	0.27
	Sandy Mush Road	0.00	0.22	0.17
	Hayfield Bridge	0.00	0.21	0.20
Reach 4A	Downstream of Sack Dam	0.17	0.36	0.42
	Highway 152	0.17	0.38	0.38
	Sand Slough Patrol Bridge	0.00	0.38	0.38

Note: DWR = California Department of Water Resources, ft/year = feet per year

levee surveys. In updating the model geometry, the 2008 cross-sections were adjusted based on the total subsidence measured between the 2008 LiDAR and 2016 surveys.

The model was then validated using water surface elevation surveys conducted in February 2017. High flows measured in February 2017 provided a reliable data set of flows that were close to design flows for the system, including a measured flow of 9,200 cfs at the downstream end of the UESB, 12,800 cfs at the upstream end of the MESB, and 3,300 cfs at the downstream end of Reach 4A. Through this validation effort, most of the model results were within 1 foot of surveyed water levels in Reach 4A and within 0.5 foot in the bypass (California Department of Water Resources 2018b). DWR deemed these results to be reasonable for this study and made no changes to the models beyond the topography. It should be noted that ±1 foot within Reach 4A, and ±0.5 foot within the bypasses, could result in as much as 400 cfs and 1,000 cfs difference in flow capacity, respectively.

The model geometry was further modified to reflect future subsidence conditions in 2026. For 2026 conditions, the model was adjusted to reflect the amount of subsidence that is projected to occur between 2016 and 2026, using Reclamation's average annual rates from 2011 to 2017. No other changes were made in the model to simulate the 2026 water levels.

Freeboard Analysis and Results

The hydraulic models were used to evaluate freeboard on the river and flood bypass levees using flood design flow capacity rates published in the O&M Manual. The design flows for Reach 4A, and the Chowchilla and Eastside bypasses were input into the models to generate water surface elevations and evaluate freeboard under 2016 and 2026 topographic conditions. The freeboard analysis and results for each reach are provided in Figures 6 through 11, which include 2008 results from the initial study (except for Reach 4A which was not included in the previous study). These figures show the lowest elevation between the left and right levee profiles for each cross section, and the modeled freeboard for the flood capacity flows based on the run-of-the-river scenario for 2008, 2016, and 2026. Because changes in topography represent the only difference between the models, changes in freeboard are the direct result of subsidence. The results generally show that because the ground is subsiding at different rates along the channel, it tends to steepen and flatten out some segments of the channel, which results in an increase and decrease in freeboard, respectively. The following sections describe the modeled freeboard for the design flow for 2008, 2016, and 2026 conditions, and if each reach meets the 4-foot design freeboard for the bypasses and a 3-foot design freeboard for the San Joaquin River as defined in the O&M Manual.

Chowchilla and Upper Eastside Bypasses

For the Chowchilla Bypass and UESB, Figure 6 shows water surface profiles for the design flow based on run-of-the-river and the lowest elevation of the left and right levee profiles for each cross section. The freeboard amounts for 2008, 2016, and 2026 are shown in Figure 7. Generally, the bypass channel slope between Ash Slough and Road 4, and upstream of the Fresno River confluence, is steepening. The increase in slope results in an increase of freeboard of as much as 1.0 foot in these channels between 2008 to 2016, showing a minimum freeboard of 5.7 feet. That increase in freeboard is predicted to continue by another 0.5 foot by 2026. In all, these channels show freeboard amounts between 5 feet and 10 feet, which is greater than the 4-foot design freeboard.

In the segment from Road 4 to Sand Slough, the flattening out of the channel slope has resulted in an increased water depth, resulting in reduced freeboards. The channel between Road 4 and Avenue 21 shows a decrease of as much as 1.5 feet in freeboard between 2008 to 2016. A smaller decrease is shown between 2016 to 2026 when the freeboard is predicted to be further reduced by approximately 0.2 foot. The smaller decrease is the result of using Reclamation's lower subsidence rates that projected the model's topography to 2026. But, the decreasing freeboard is still of concern as the length of levee that encroaches the freeboard criteria of 4 feet continues to increase. The critical area of the channel is between West Washington Road to Sand Slough where the minimum freeboard is approximately 1.4 feet in 2016, which may potentially be decreased to 0.7 foot by 2026.

Middle Eastside Bypass

For the MESB, Figure 8 shows profiles for the design flow based on run-of-the-river and the lowest elevation of the left and right levee profiles for each cross section. The freeboard amounts for 2008, 2016, and 2026 are shown in Figure 9. Along this stretch of the bypass, freeboard was reduced as much as 1.0 foot between 2008 to 2016. It is predicted to be further reduced as much as another 1.0 foot by 2026. The two critical channel areas, where the design flow encroaches the freeboard criteria of 4 feet, occur downstream of the SSCC and just upstream of the Lower Merced Wildlife Refuge weir (Figure 9). In 2016, approximately 160 feet of the left levee, upstream from the Lower Merced Wildlife Refuge weir, encroached on design freeboard. But, the more critical channel length is downstream of Sand Slough, as design freeboard was encroached for approximately 1.0 mile on the left levee and 1.5 miles on the right levee. In 2026, the length of the critical channel area upstream of the Lower Merced Wildlife Refuge weir increased to approximately 0.5 mile. In 2026, the lengths of the critical areas downstream from Sand Slough increased to 2.5 miles for both levees. The minimum freeboard in the Middle Eastside Bypass in 2026 is 1.9 feet.

Reach 4A and Sand Slough Connector Channel

Figure 10 shows profiles for the design flow based on run-of-the-river and the lowest elevation of the left and right levee profiles for each cross section in Reach 4A and the SSCC. The freeboard amounts for 2016 and 2026 are shown in Figure 11 (2008 is not shown because Reach 4A was not evaluated in the DWR 2013 study). In Reach 4A, freeboard increased for a short segment upstream of Highway 152, but the results generally show a decrease in freeboard for the remainder of the reach. The critical channel location where the design flow encroaches the 3-foot design freeboard occurs approximately 2.5 miles downstream of Sack Dam. Freeboard at this critical location is expected to be 2.2 feet in 2026, a reduction of approximately 0.5 feet from 2016, because of future ground subsidence. Freeboard at the SSCC is also expected to be reduced by 0.5 foot between 2016 to 2026, showing a minimum freeboard of 5.5 feet for the run-of-the-river scenario.

Flow Capacity Analysis and Results

The previous section discussed the effect of subsidence on design flow freeboard, as determined by the hydraulic models. In this analysis, the same models were used to estimate the flow capacity in each channel for 2008, 2016, and 2026 conditions at the 4-foot and 3-foot design freeboard for the bypasses and river, respectively. Assuming typical flood routing, as described in the O&M Manual, a range of flows up to the flood design flows were run in the river and bypasses for two conditions: run-of-the-river, and maximum backwater effects at the Sand Slough interchange area. The backwater analysis can significantly affect the flow capacity upstream of Sand Slough. In Reach 4A and SSCC, the capacity is affected when assuming a concurrent flow of 12,000 cfs from the bypass; in the UESB, the capacity is affected when assuming a concurrent flow of 4,500 cfs from Reach 4A.

The flow capacity for each channel segment was then determined 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 comprise of one or more individual cross sections. These areas would limit the amount of flow that could be conveyed in the channel at the design freeboard. It should be noted that aside from these critical areas, the remainder of the channel will likely convey flood design flows within the design freeboard. Estimated flow capacities for each segment within the study area are summarized in Table 3. The table includes results for 2008 and 2011 that were evaluated in the DWR 2013 study.

Chowchilla and Upper Eastside Bypasses

The flow capacity of the bypasses depends greatly on the quantity of tributary inflows and flow routing at Sand Slough and the EBCS. In this analysis, flow capacity upstream of Ash Slough will still convey published flood design flows within design freeboard for the run-of-the-river and backwater conditions. But, in the Eastside Bypass downstream of Ash Slough, flow capacity is less than the reported flood design flow. The flow capacity in the Eastside Bypass from Ash Slough to Sand Slough was 12,500 cfs in 2008 for the run-of-the-river condition at design freeboard, 5,000 cfs less than published design flows.

Table 3 Estimated Flow Capacity in Reach 4A and the Chowchilla and Eastside Bypasses based on Freeboard Criteria (in cfs)

Channel Segment	Flood Design Flow[a]	2008[b]	2011[b]	2016	2026
Chowchilla Bypass					
Bifurcation Structure to Fresno River	5,500	>5,500	>5,500	>5,500	>5,500
Eastside Bypass					
Fresno River to Berenda Slough	10,000	>10,000	>10,000	>10,000	>10,000
Berenda Slough to Ash Slough	12,000	>12,000	>12,000	>12,000	>12,000
Ash Slough to Sand Slough	17,500	9,500[c] – 12,500	7,500[c] – 11,500	5,700[c] – 9,500	3,400[c] - 7,500
Sand Slough to Mariposa Bypass[d]	16,500	16,000	14,500	12,500	9,800
San Joaquin River					
Reach 4A	4,500	ND	ND	3,700[e] – 4,300	2,500[e] – 3,800
Sand Slough Connector Channel	ND	ND	ND	2,100[e] – > 4,500	0[e] – > 4,500

Notes: cfs = cubic feet per second, ND = not determined as part of this study

[a] Referenced from the Lower San Joaquin River Flood Control Project Operation and Maintenance Manual.

[b] Results obtained from a previous study done by DWR in 2013.

[c] Reduced capacity assumes contribution of 4,500 cfs from Reach 4A of the San Joaquin River (creating backwater conditions).

[d] Capacity assumes diversions into the Mariposa Bypass based on the O&M Manual operating rules.

[e] Reduced capacity assumes contribution of 12,000 cfs through the Bypass Channel (creating backwater conditions).

Under backwater conditions, assuming concurrent tributary inflows from the San Joaquin River, the capacity is reduced to 9,500 cfs. Though no data exist on the reason for these decreases, it is assumed that subsidence and sediment deposition are significant factors in this reduction from design flood flows.

In 2016, subsidence reduced the flow capacity between Ash Slough and Sand Slough to 9,500 cfs at the design freeboard, a decrease of 3,000 cfs from 2008. This decreased capacity was based on the run-of-the-river condition shown in Figure 12. When flood flows enter the Eastside Bypass from Reach 4A of the San Joaquin River at Sand Slough, the added flows create higher backwater conditions. The backwater increases the water surface elevation within this stretch of bypass, further reducing the capacity from 9,500 cfs to 5,700 cfs (Figure 13). By 2026, the run-of-the-river capacity is projected to decrease an additional 2,000 cfs, allowing 7,500 cfs in the bypass at the design freeboard (Figure 14). When considering inflows from Reach 4A, the capacity within this segment may be further reduced to 3,400 cfs (Figure 15). This is a significant reduction from the flood design flow of 17,500 cfs in this segment of the bypass, and is likely because of recent and historical subsidence.

Middle Eastside Bypass

In the Eastside Bypass from Sand Slough to the EBCS, the flow capacity was 16,000 cfs in 2008, a 500 cfs reduction from the flood design flow of 16,500 cfs (California Department of Water Resources 2013). Between 2008 and 2016 the capacity was reduced by approximately 3,500 cfs, to 12,500 cfs. The capacity will decrease another 2,700 cfs with continued subsidence. It is expected to be 9,800 cfs by 2026. The section of the Middle Eastside Bypass with the lowest capacity is just downstream of Sand Slough (Figures 16 and 17).

Reach 4A and Sand Slough Connector Channel

The design flow along this reach is 4,500 cfs. Figure 18 shows the modeled capacity in Reach 4A was 4,300 cfs in 2016, based on the run-of-the-river condition, with the critical channel area located approximately 2.5 miles downstream of Sack Dam. When considering backwater conditions, assuming a maximum allowable flow of 12,000 cfs coming through the UESB, the water surface elevation in 2016 increases in the reach as far upstream as Highway 152. Because of the increased water surface elevation, the critical channel location occurs between Highway 152 and the SSCC (Figure 19) which reduces the capacity in Reach 4A to 3,700 cfs. The backwater condition also effects the SSCC in which the 2016 capacity is reduced from a run-of-the-river capacity that exceeds flood design flow to a capacity of 2,100 cfs.

By 2026, the capacity in Reach 4A, based on the run-of-the-river condition, is projected to be 3,800 cfs at the critical channel location as shown in Figure 20. When considering backwater, the capacity is reduced to 2,500 cfs (Figure 21). The flow coming from Reach 4A would be reduced even further because of constraints in the SSCC under the backwater condition. As shown in Figure 21, backwater from flows in the bypass alone (no inflows from Reach 4A) were projected to encroach into the design freeboard in the SSCC, allowing no additional flow capacity under the design freeboard.

Conclusion and Next Steps

The results of this hydraulic analysis show that portions of the bypasses and Reach 4A currently do not meet the reported flood design flow capacity. Subsidence documented since 2008 has affected the ability of the river and bypasses to convey flows, and in some locations has significantly reduced capacities. If future subsidence occurs at current rates, capacities would be further reduced, which could change the way the flood system is operated. The channels within the Sand Slough area appear to be most significantly affected by subsidence. Considering backwater conditions, the 2016 capacity in the UESB is 5,700 cfs, a loss of as much as 70 percent of its design flow capacity. The loss in capacity is expected to increase by 2026 when the capacity is projected to be 3,400 cfs, a reduction of 80 percent from its design flow capacity.

The same trend is seen in the MESB and Reach 4A. In the MESB, the 2016 capacity is 12,500 cfs, a loss of 25 percent from its design flow capacity; in 2026, the capacity will be reduced by 40 percent to 9,800 cfs. Considering backwater conditions, currently Reach 4A has a capacity of 2,100 cfs, a reduction of 50 percent from its design flow capacity. Furthermore, the reach may not be able to convey any flows at its design freeboard by 2026 because of limitations at the SSCC. It is important to restate that these reported reduced capacities are the result of flows exceeding the 3-foot and 4-foot design freeboard at a single cross-section, or small segments within each channel segment. A majority of each channel can convey flood design flows within the design freeboard. It should also be noted that the Lower San

Joaquin Levee District will operate the system to reduce the risk of flood damages in the system. This may mean encroaching on freeboard during high-flow events to increase the conveyance in these channels.

DWR and Reclamation will continue to conduct monitoring and analysis that could provide a better understanding of the future rates of subsidence and the effect on future flow capacities. Periodic topographic and water-surface profile surveys could be conducted to monitor the rate of subsidence at the bypasses and the river. It is also recommended that additional modeling with updated bathymetric surveys of the Sand Slough area be completed to better understand the hydraulic characteristics and associated effects on capacity. Because the hydraulic analysis does not include the impact of future sediment deposition, it may not fully represent the overall effect caused by subsidence. DWR and Reclamation are completing sediment transport studies to better understand how subsidence is affecting sedimentation patterns and flow capacity. In addition, efforts to reduce subsidence is currently ongoing, including the implementation of SGMA, and various water supply projects by landowners and local agencies to reduce pumping from the deeper aquifer, a cause of ground subsidence. Both efforts could reduce subsidence in the area and benefit flood operations and actions of the SJRRP.

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Figure 1 **Study Area**

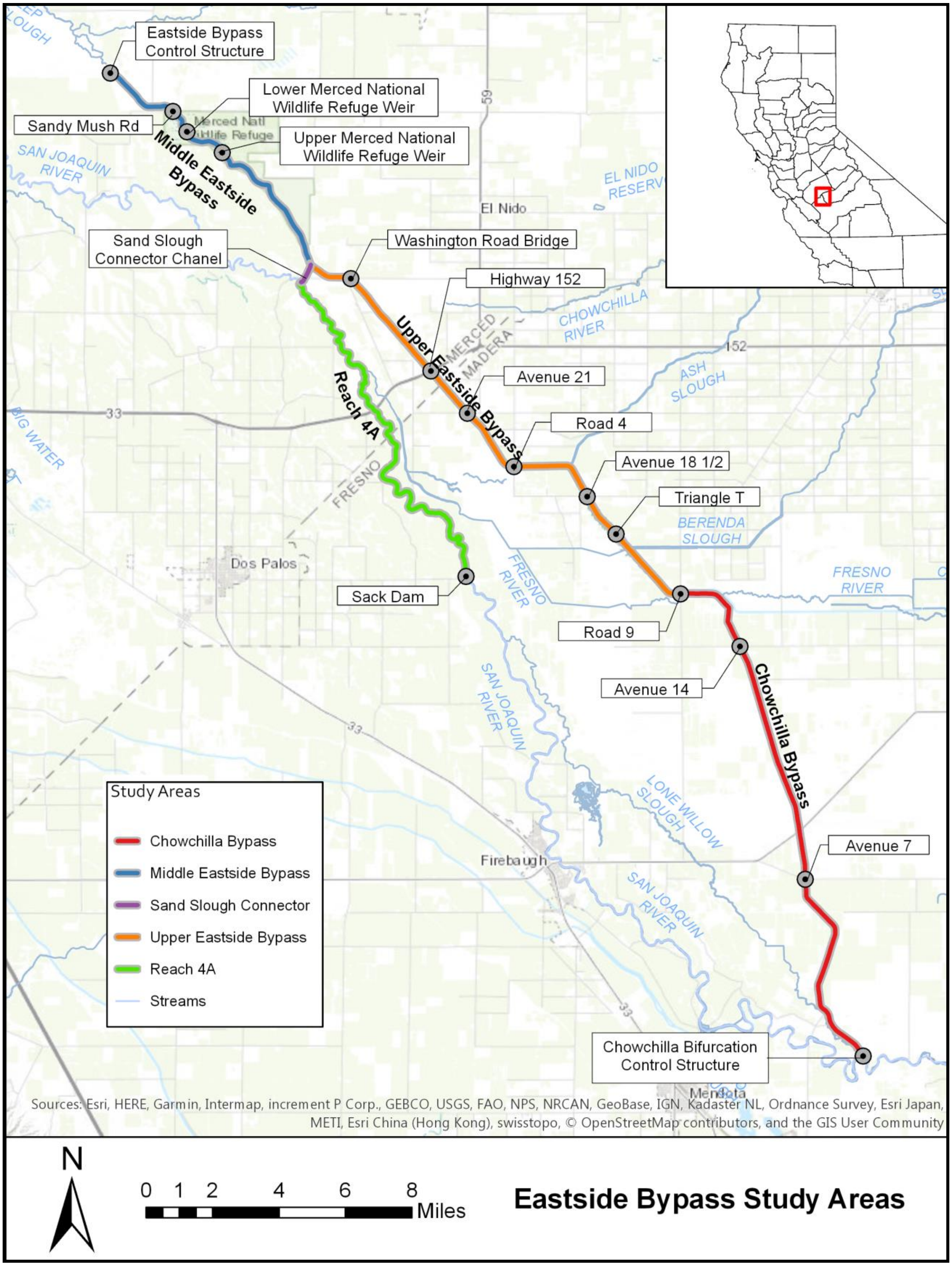


Figure 2 U.S. Bureau of Reclamation's Subsidence Rates from 2011 to 2017

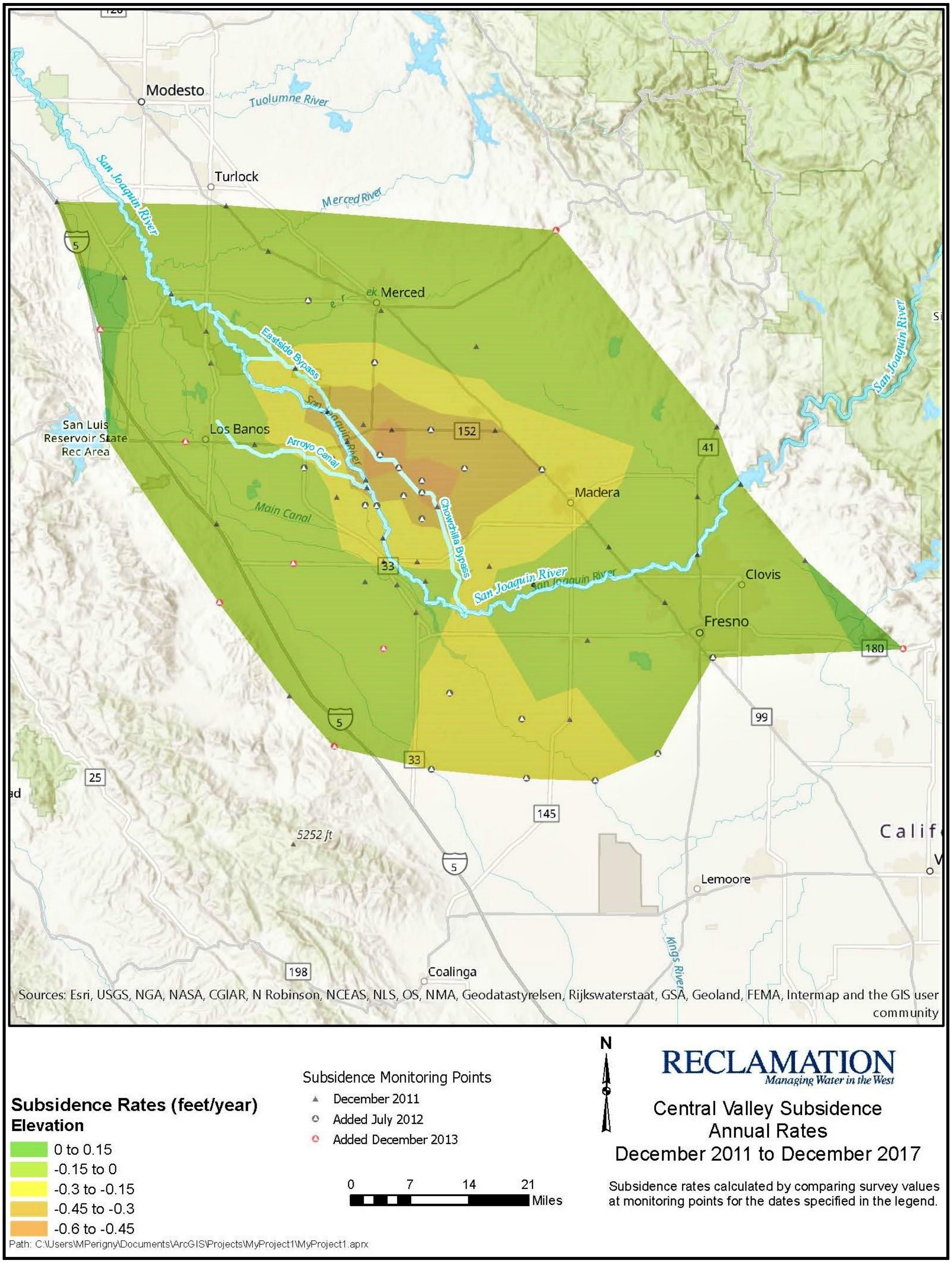


Figure 3 Ground Subsidence along the Chowchilla and Eastside Bypasses from the Chowchilla Bifurcation Structure to Sand Slough (2008–2016)

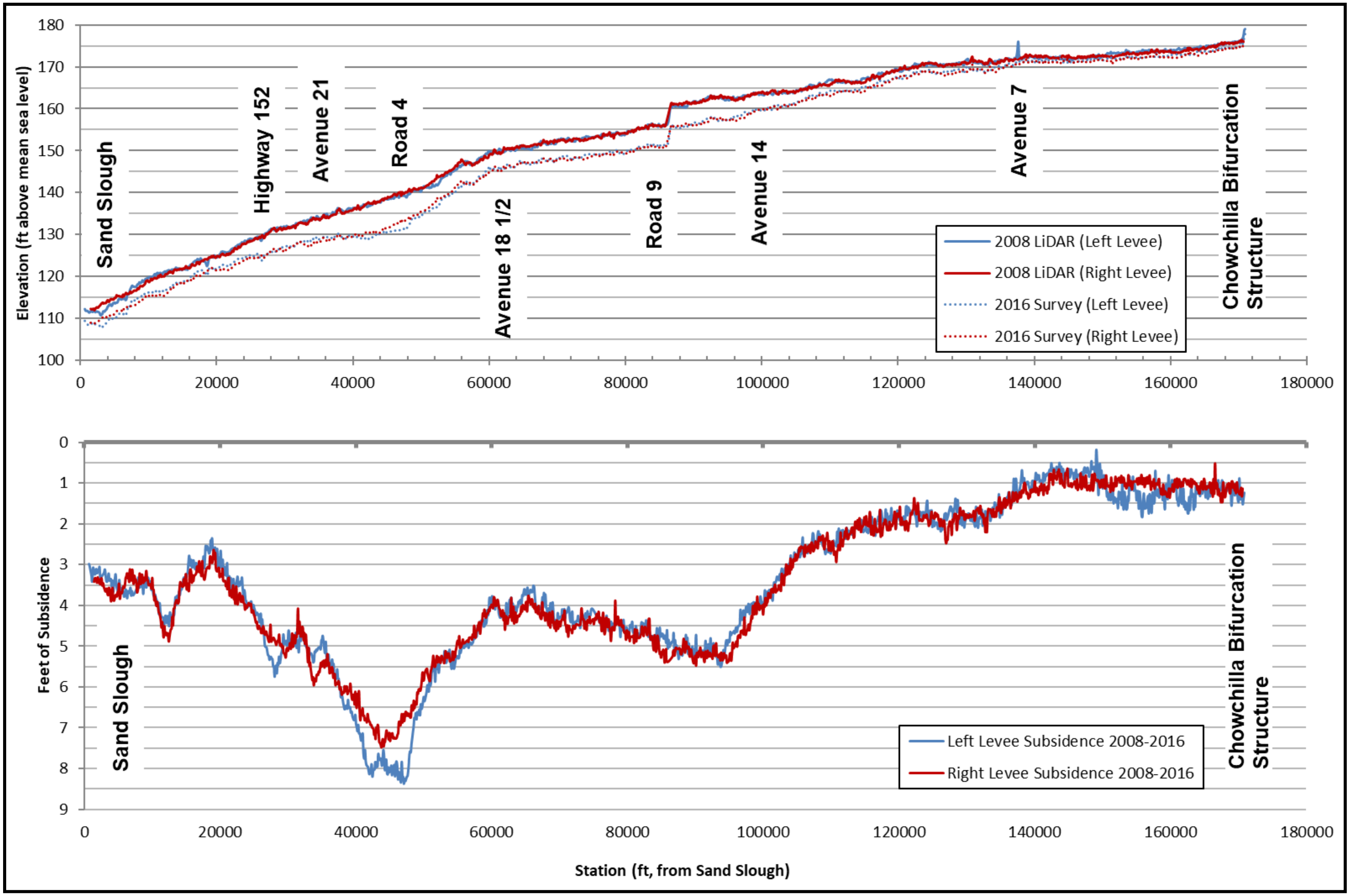


Figure 4 Ground Subsidence along the Eastside Bypass from Sand Slough to the Eastside Bypass Control Structure (2008–2016)

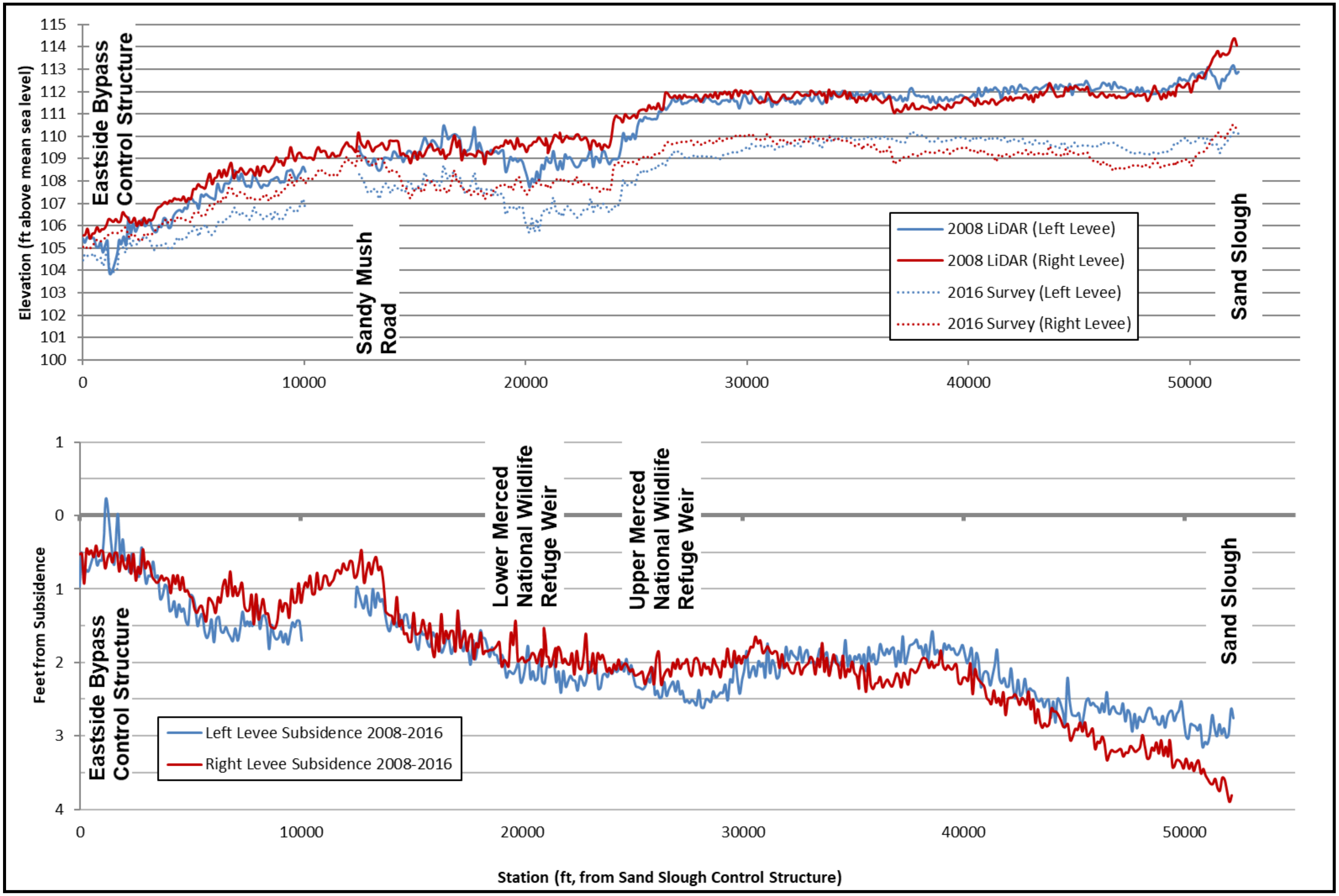


Figure 5 **Ground Subsidence along Reach 4A of the San Joaquin River (2008–2016)**

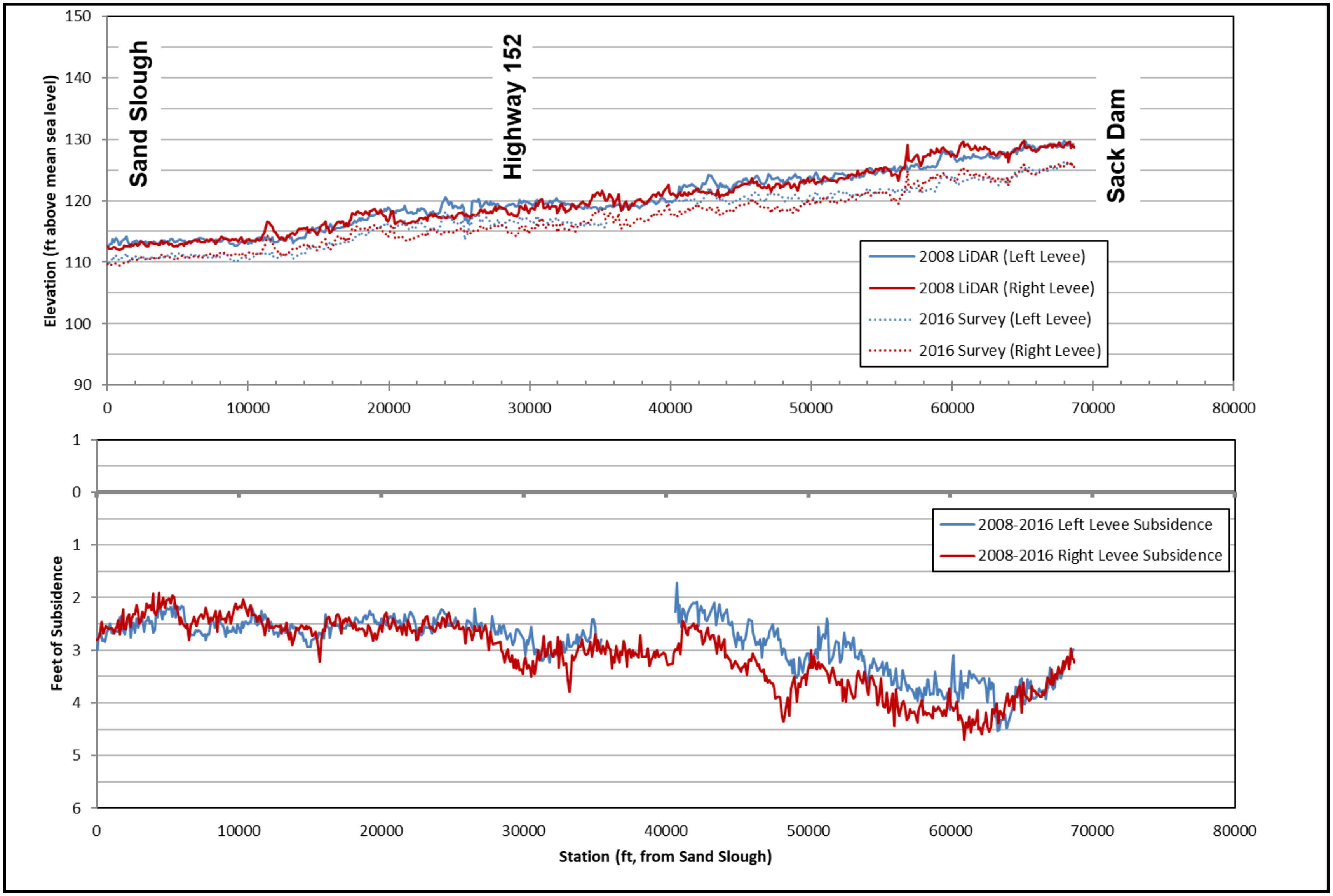


Figure 6 **Design Flow Profile under 2008, 2016, and 2026 Run-of-the-River Conditions in the Chowchilla and Eastside Bypasses from the Chowchilla Bifurcation Structure to Sand Slough**

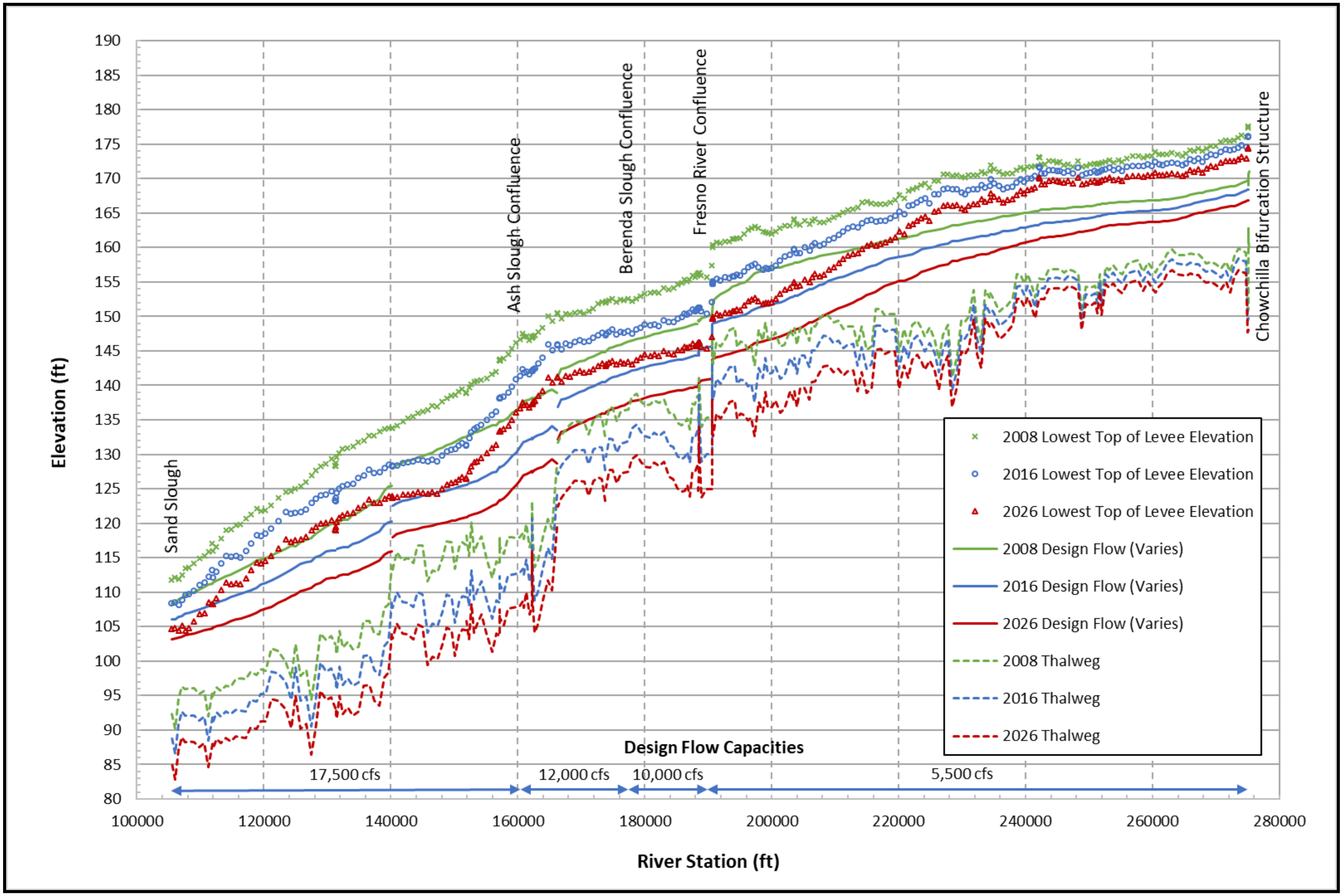


Figure 7 Freeboard Conditions under 2008, 2016, and 2026 Run-of-the-River Conditions in Chowchilla and Eastside Bypasses from the Chowchilla Bifurcation Structure to Sand Slough, based on Design Flow Capacities

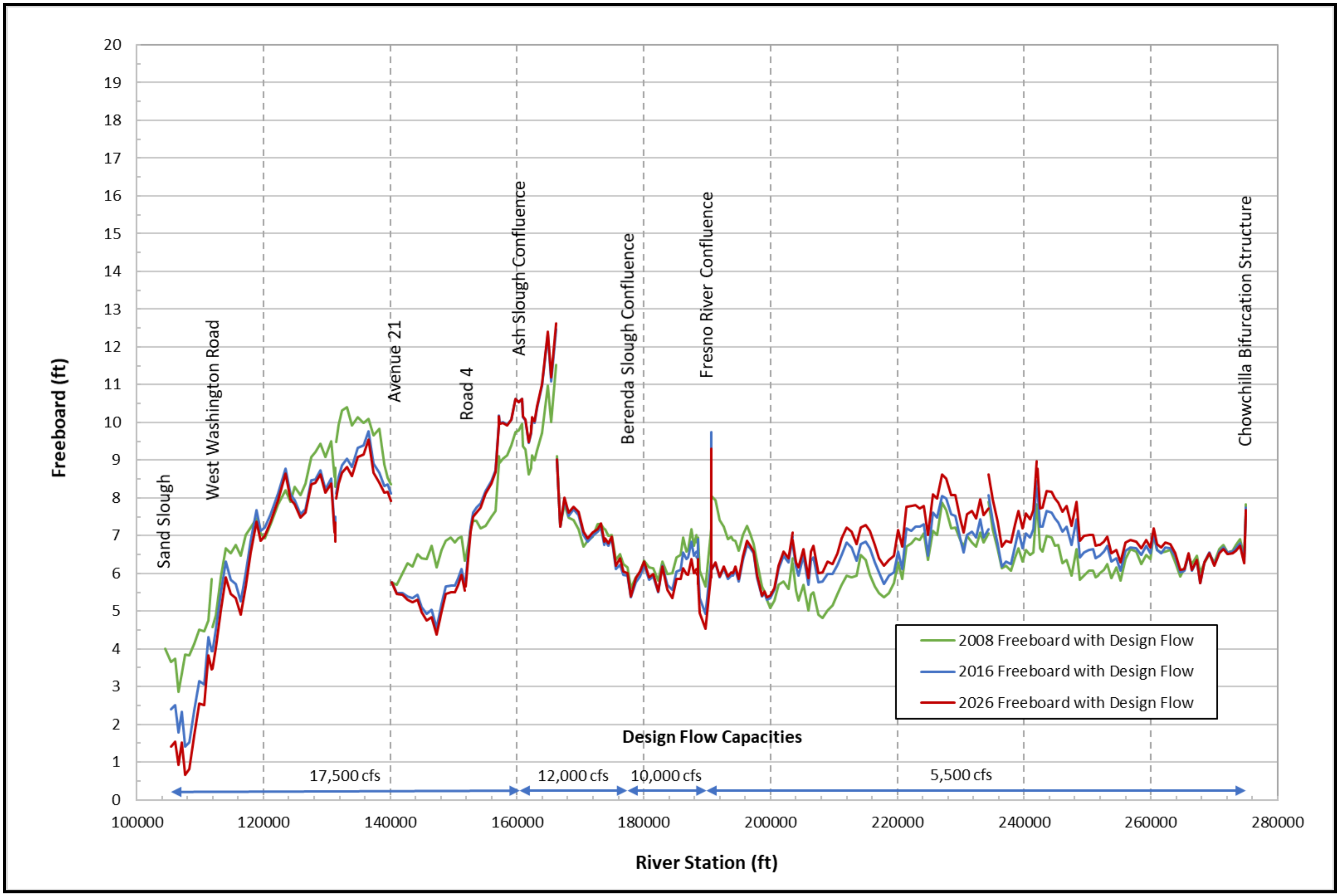


Figure 8 **Design Flow Profile under 2008, 2016, and 2026 Run-of-the-River Conditions in the Eastside Bypass from Sand Slough to the Eastside Bypass Control Structure**

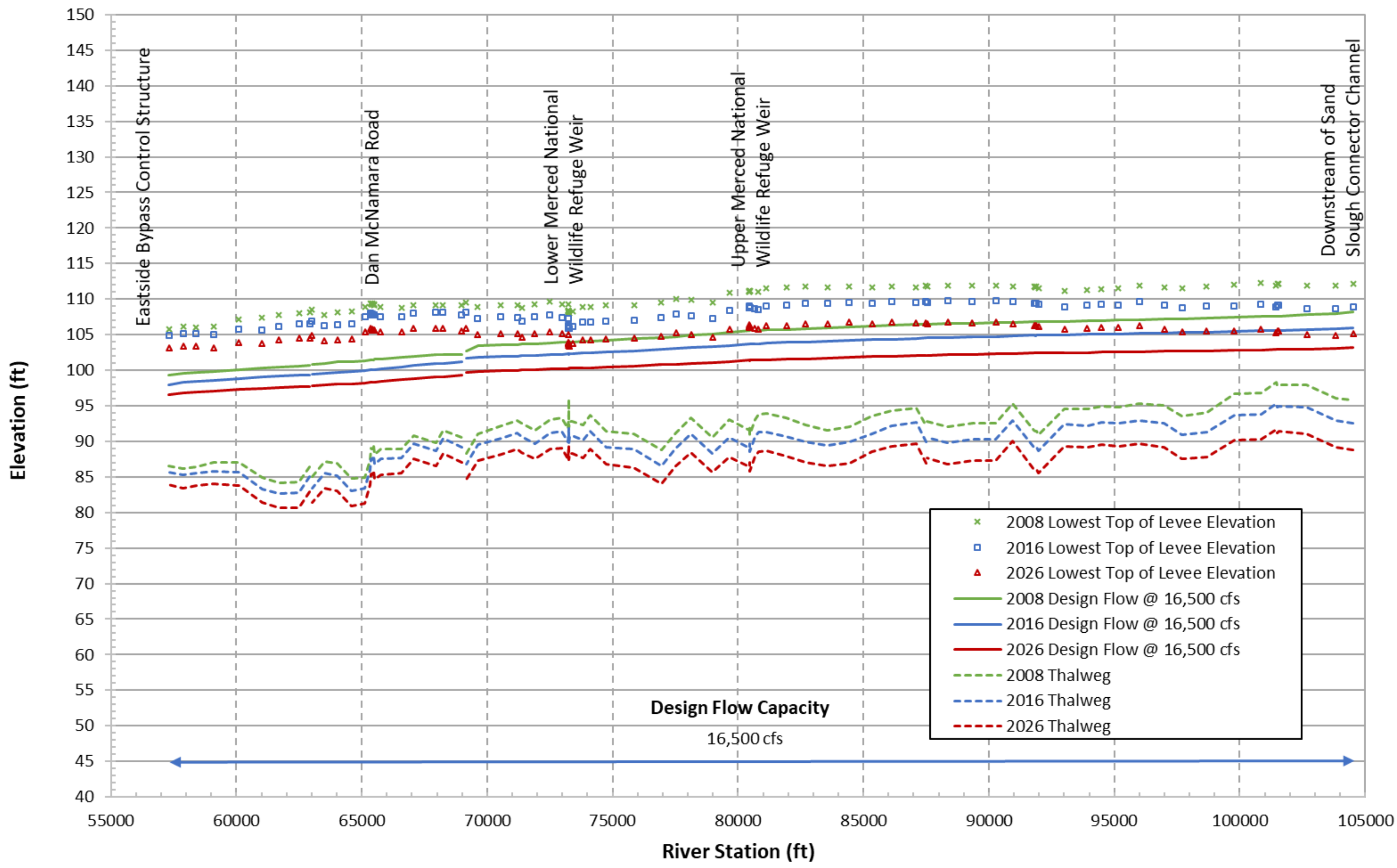


Figure 9 Freeboard Conditions for 2008, 2016 and 2026 Run-of-the-River Conditions for Eastside Bypass from Sand Slough to the Eastside Bypass Control Structure, based on Design Flow Capacities

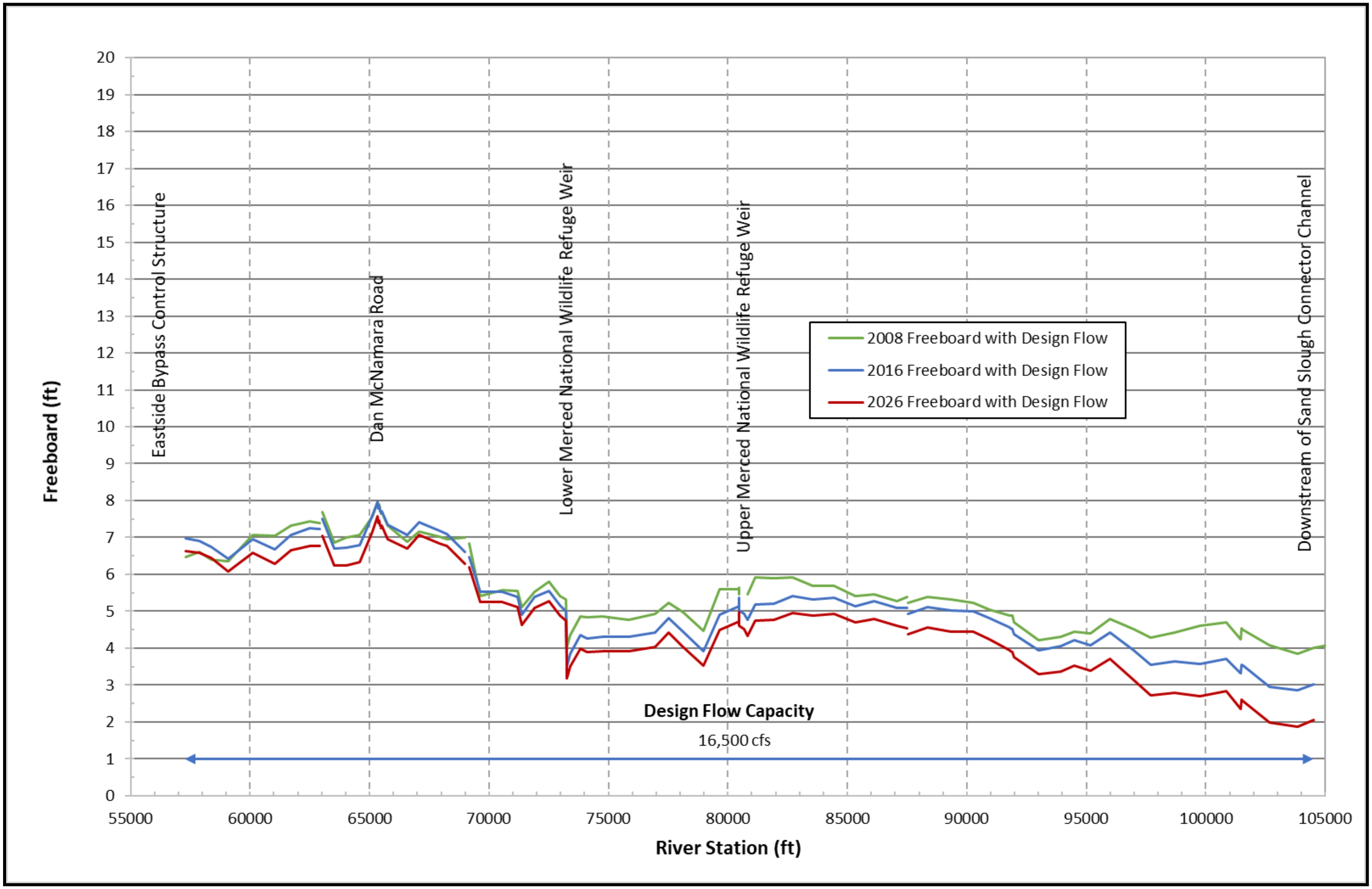


Figure 10 **Design Flow Profile under 2016 and 2026 Run-of-the-River Conditions in Reach 4A of the San Joaquin River**

Figure 11 Freeboard Conditions for 2016 and 2026 Run-of-the-River Conditions for Reach 4A of the San Joaquin River based on Design Flow Capacities

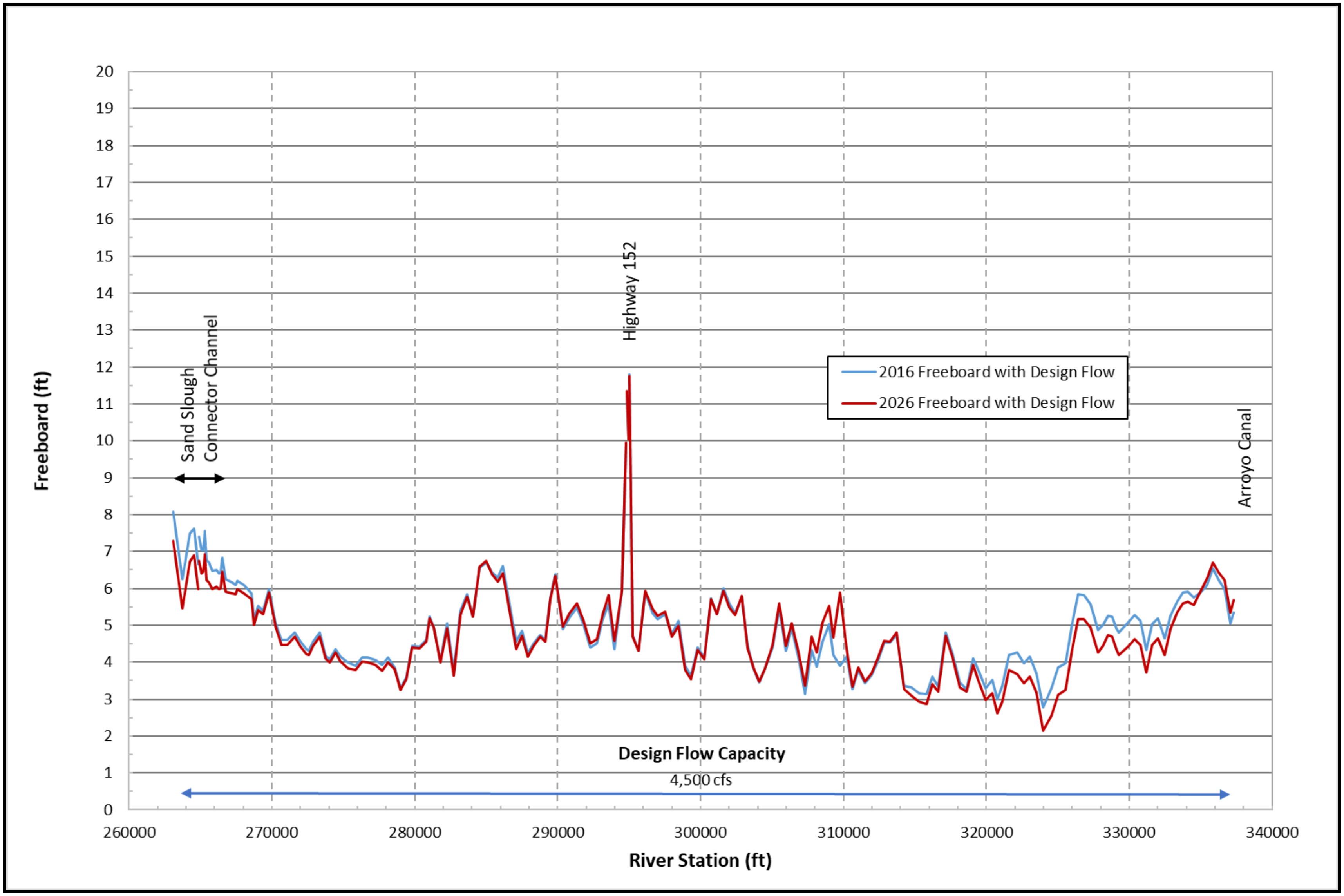


Figure 12 Water Surface Profile for 2016 Run-of-the-River Condition for the Chowchilla and Eastside Bypasses from the Chowchilla Bifurcation Structure to Sand Slough

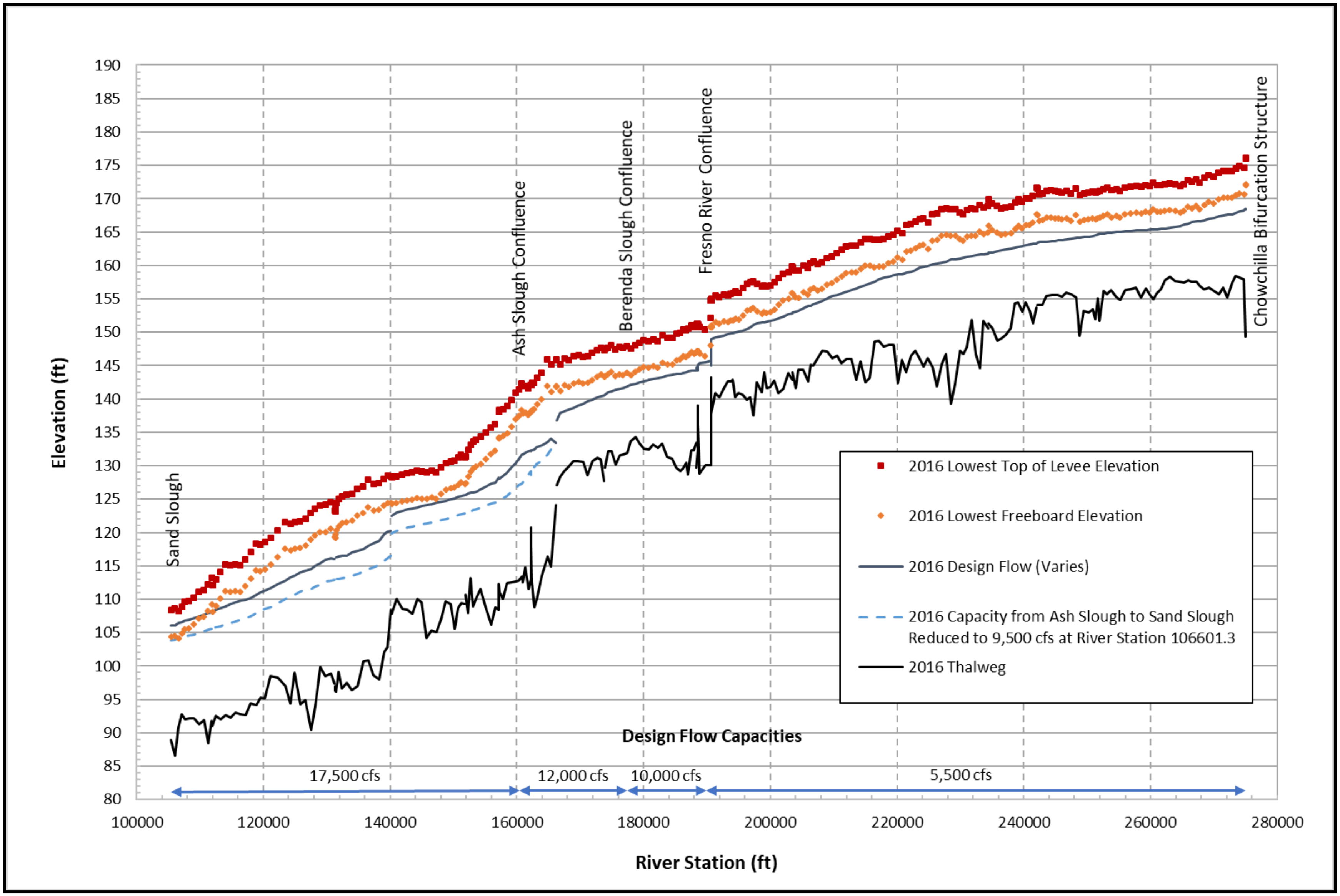


Figure 13 Water Surface Profile for 2016 Backwater Condition for the Eastside Bypass from the Ash Slough Confluence to Sand Slough

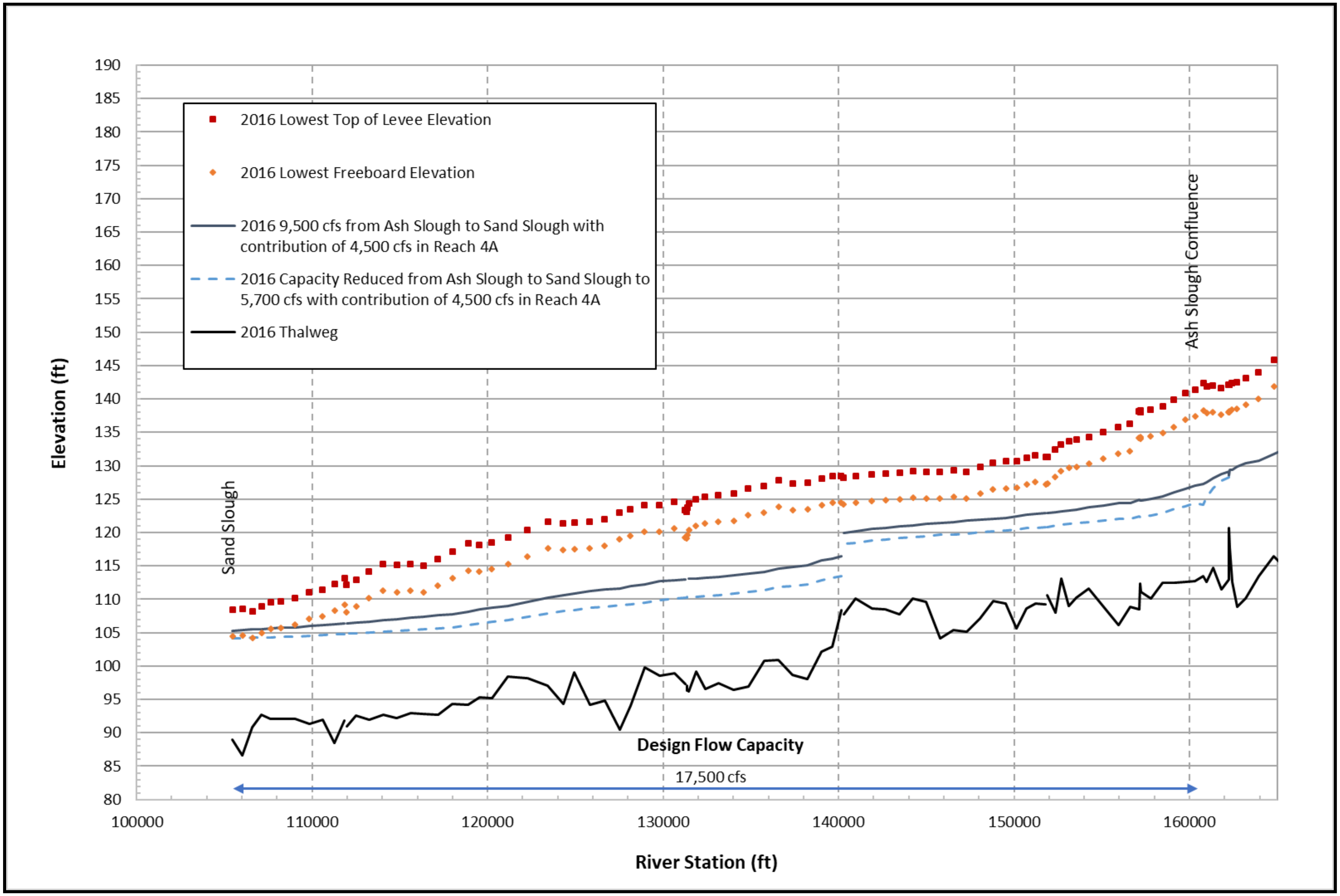


Figure 14 Water Surface Profile for 2026 Run-of-the-River Condition for the Chowchilla and Eastside Bypasses from Chowchilla Bifurcation Structure to Sand Slough

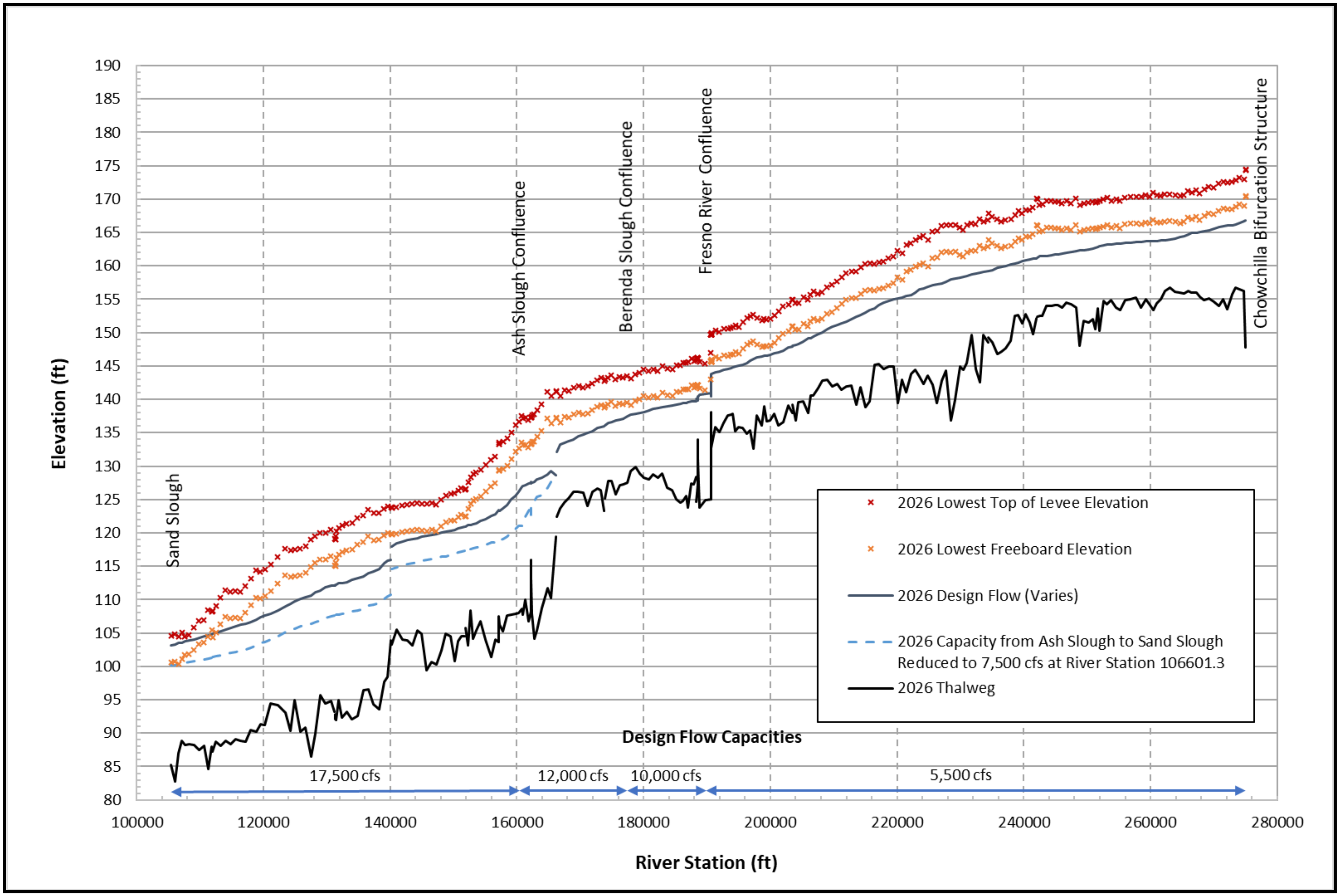


Figure 15 Water Surface Profile for 2026 Backwater Condition for the Eastside Bypass from the Ash Slough Confluence to Sand Slough

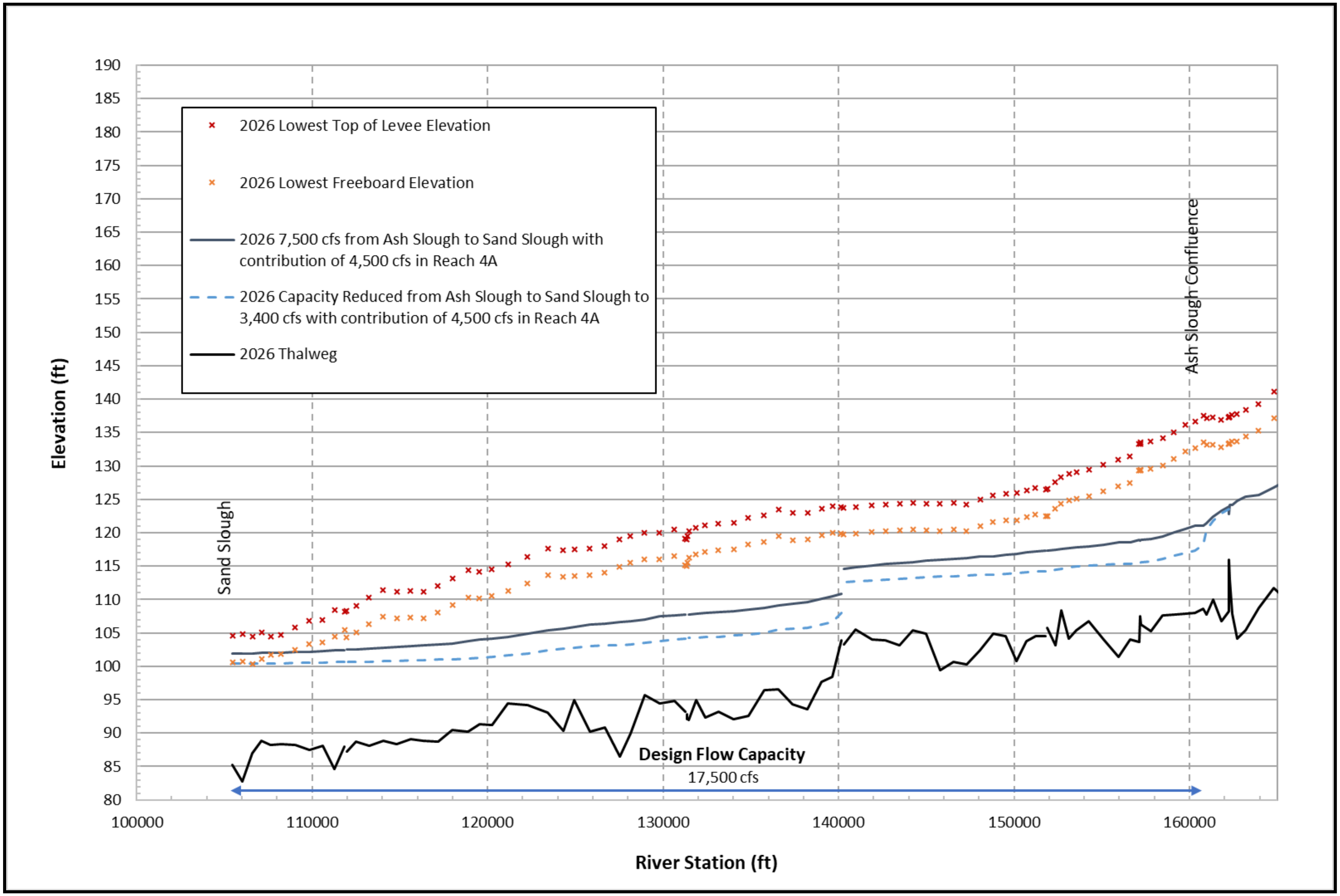


Figure 16 Water Surface Profile for 2016 Run-of-the-River Condition for the Eastside Bypass from Sand Slough to the Eastside Bypass Control Structure

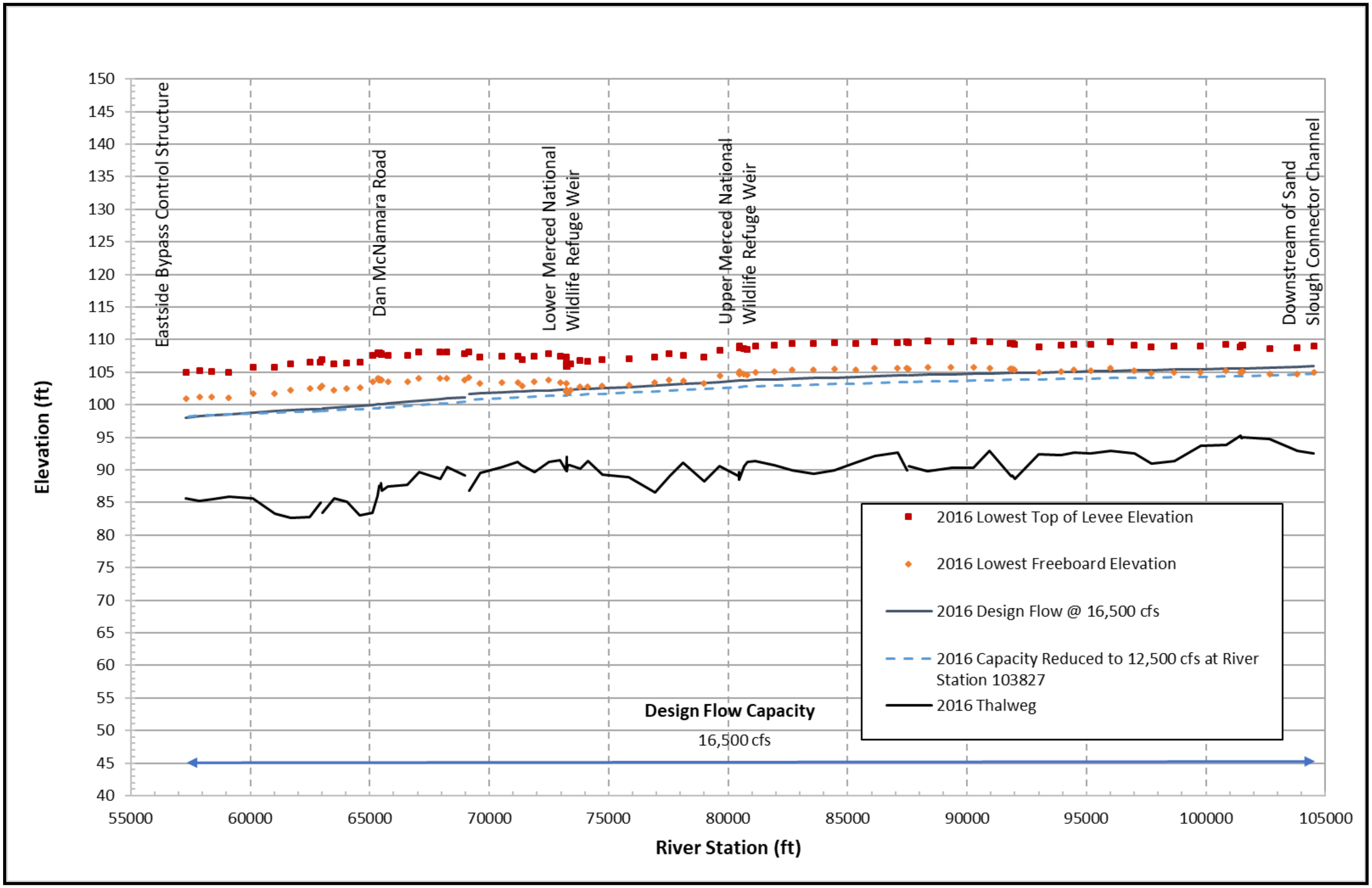


Figure 17 Water Surface Profile for 2026 Run-of-the-River Condition for the Eastside Bypass from Sand Slough to the Eastside Bypass Control Structure

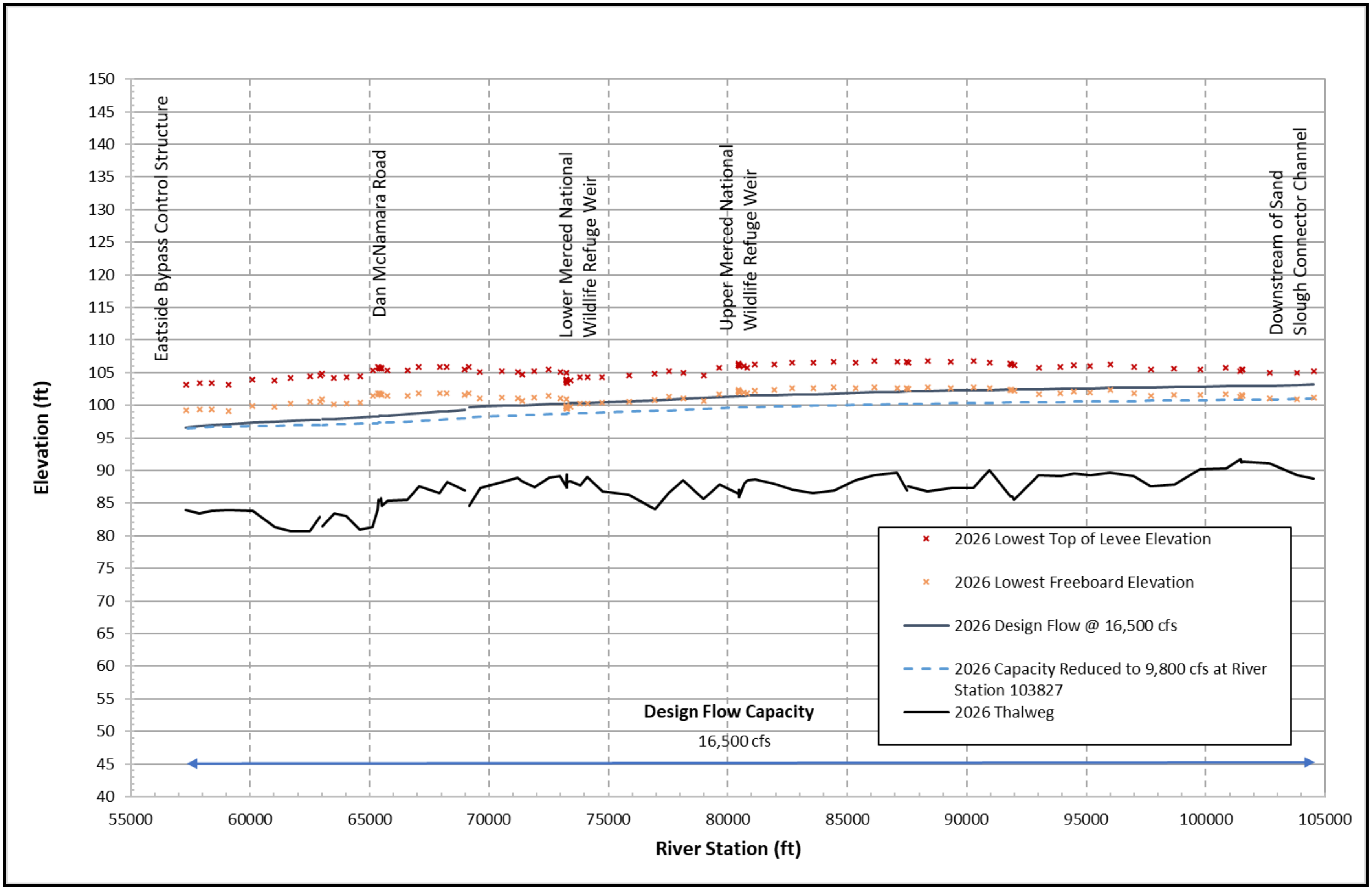


Figure 18 Water Surface Profile for 2016 Run-of-the-River Condition for Reach 4A from Arroyo Canal to Sand Slough

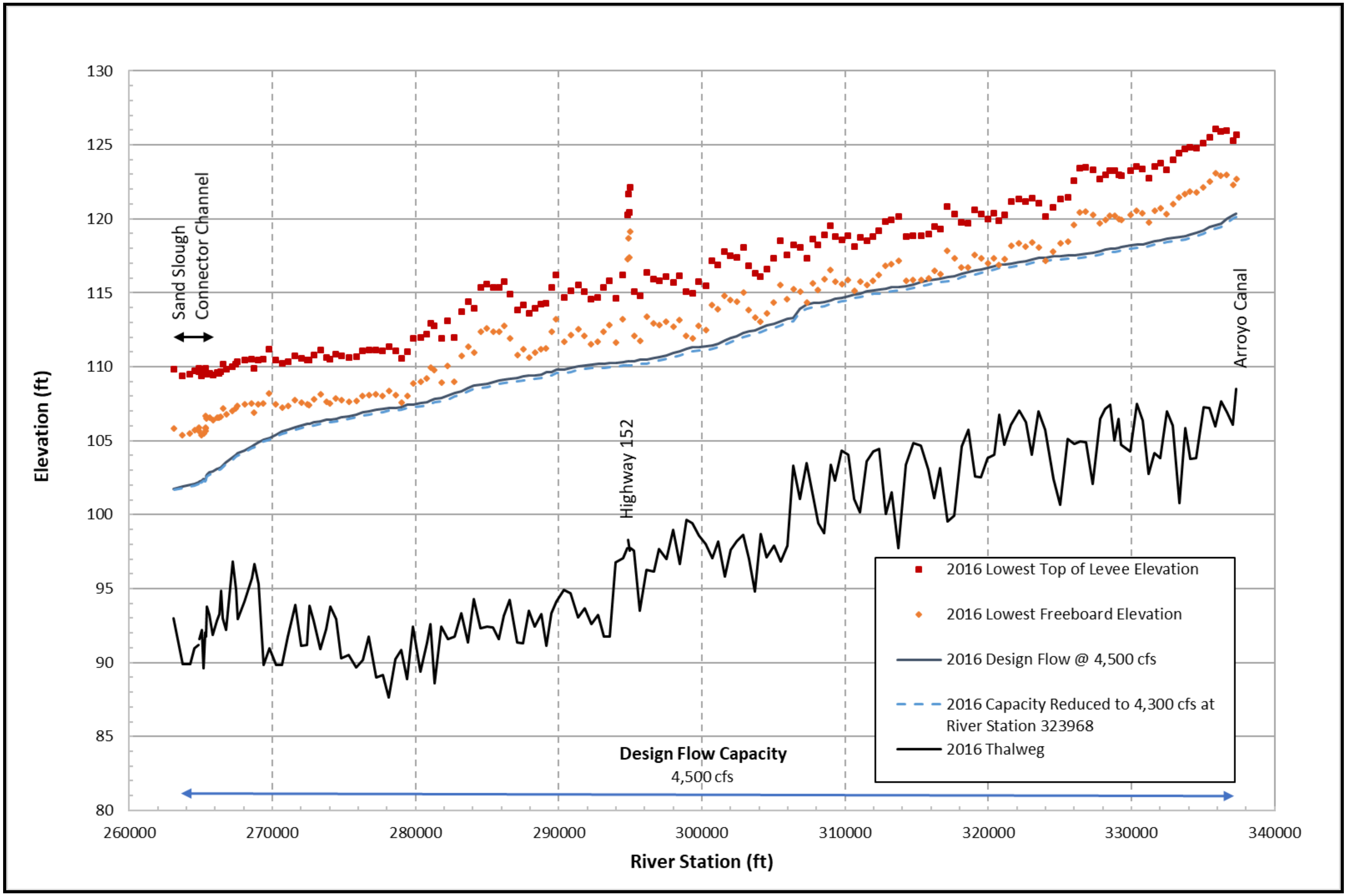


Figure 19 Water Surface Profile for 2016 Backwater Condition for Reach 4A from Highway 152 to Sand Slough

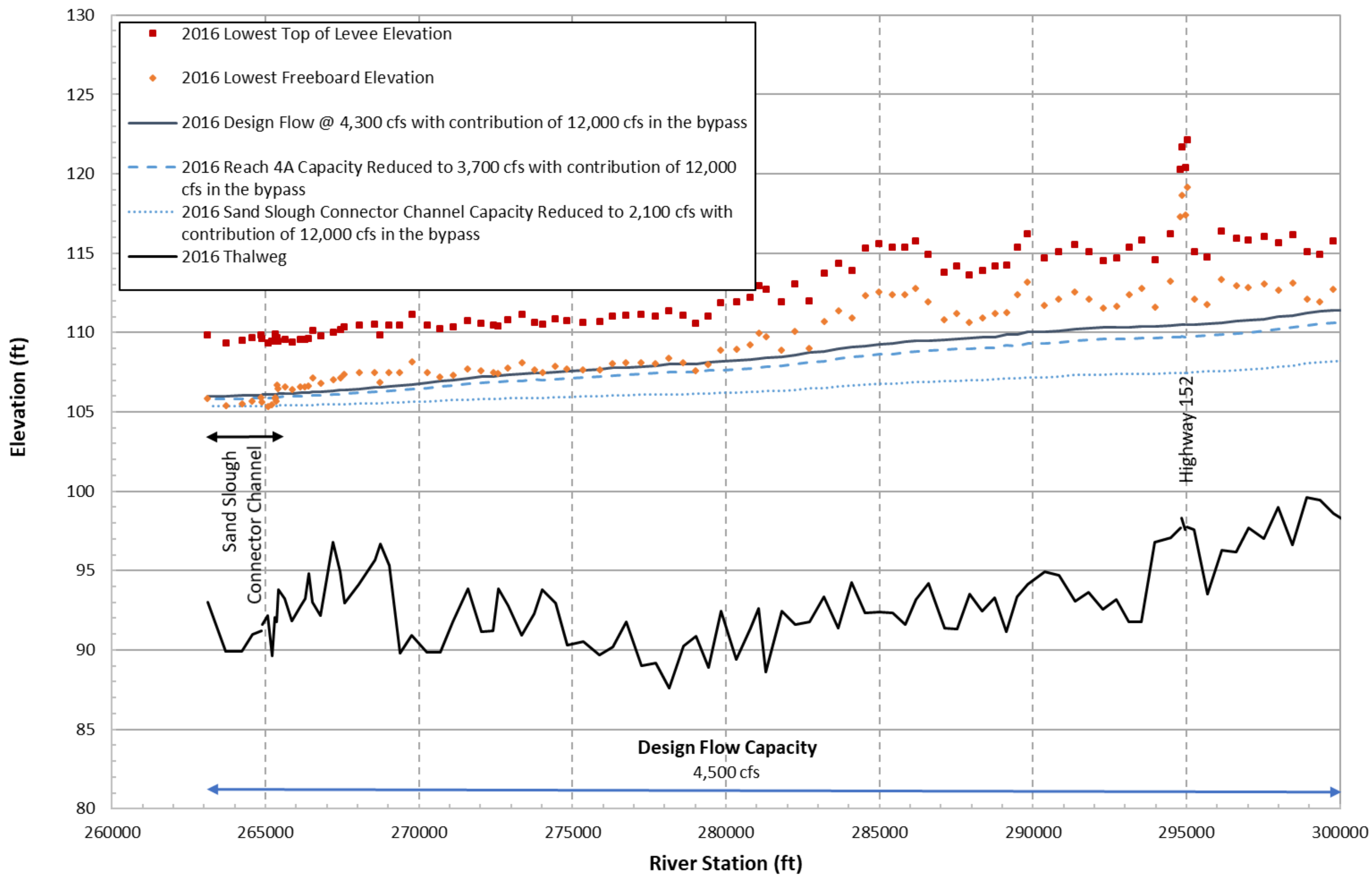


Figure 20 **Water Surface Profile for 2026 Run-of-the-River Condition for Reach 4A from Arroyo Canal to Sand Slough**

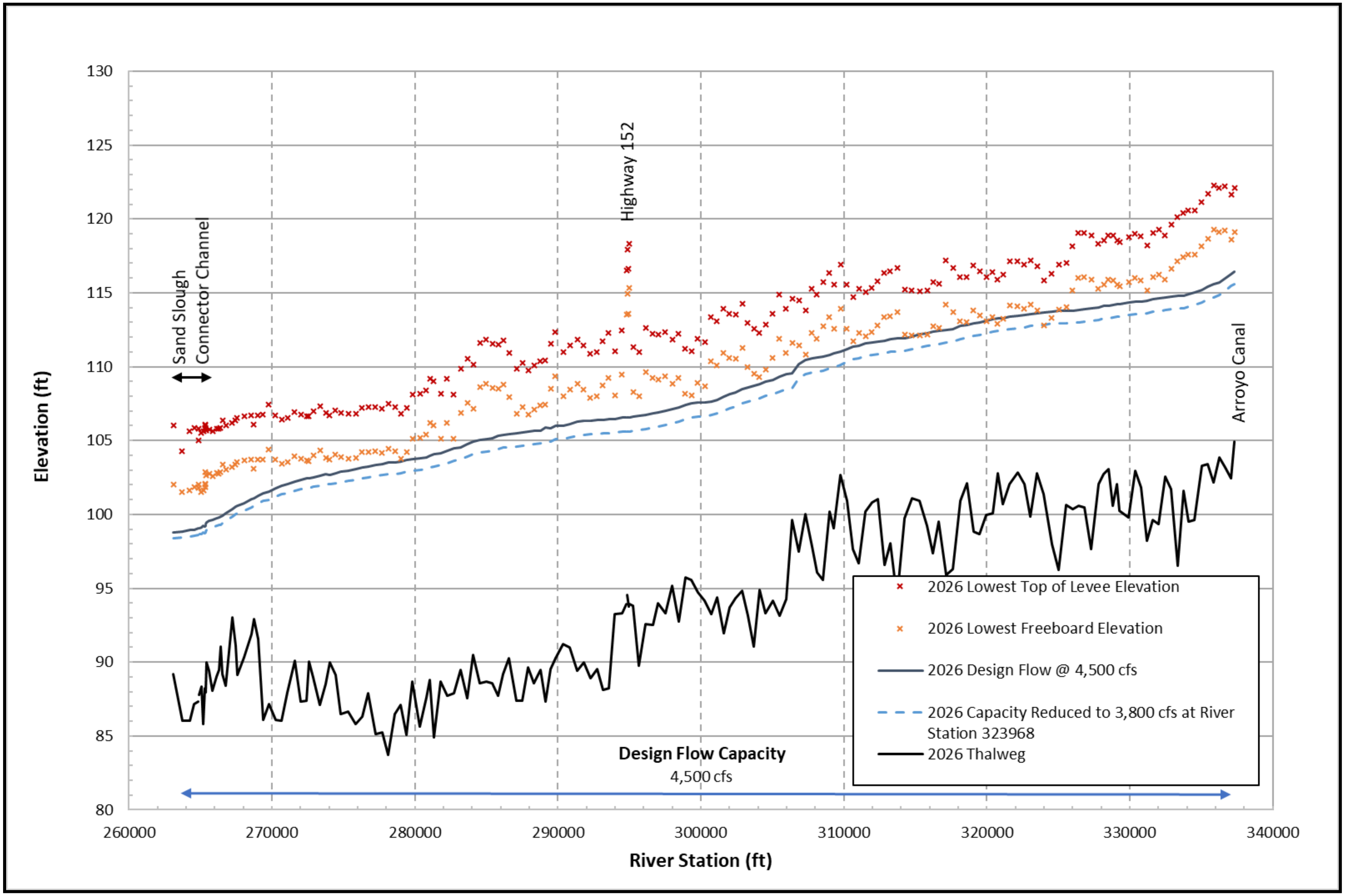
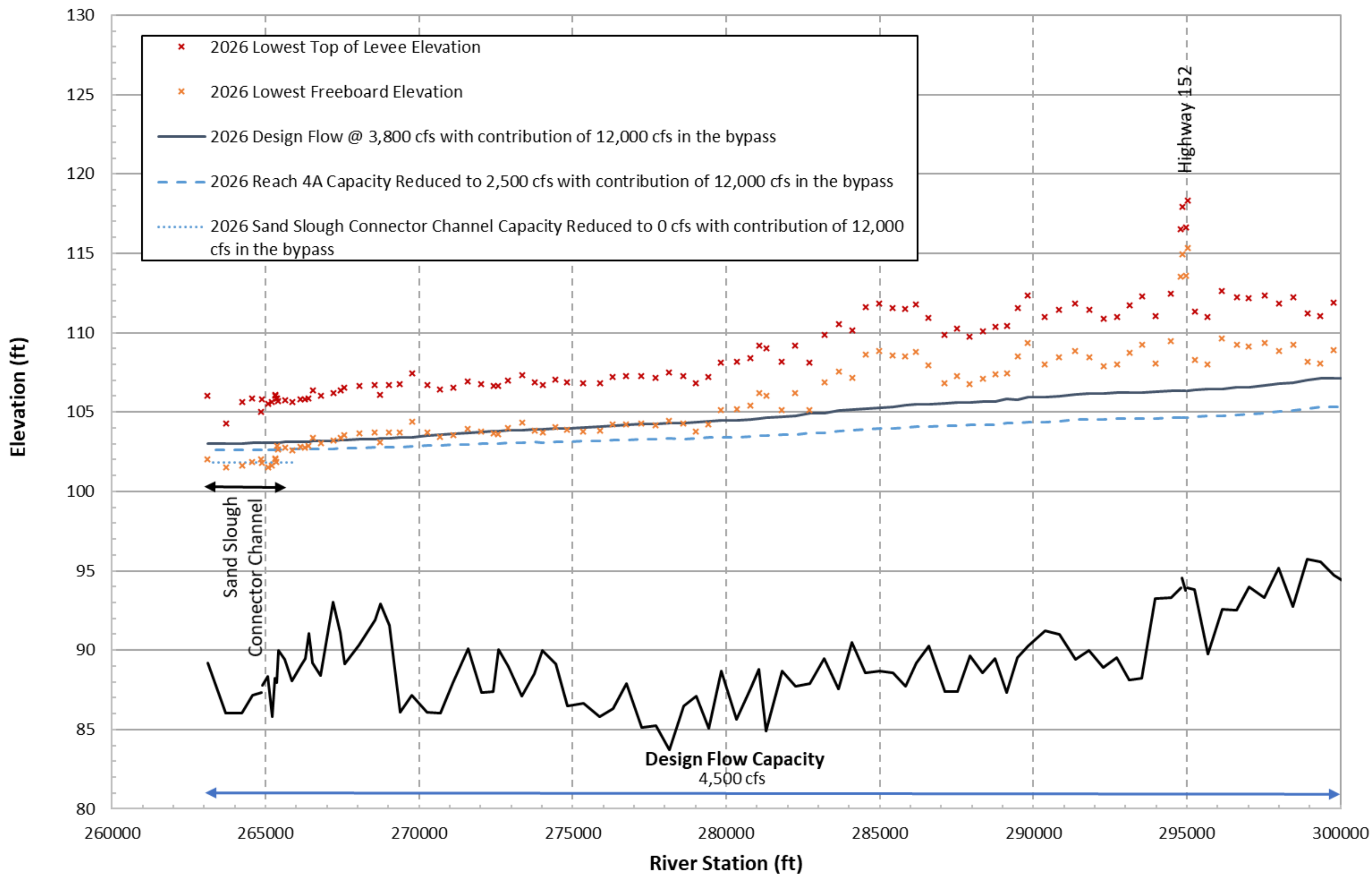


Figure 21 Water Surface Profile for 2026 Backwater Condition for Reach 4A from Highway 152 to Sand Slough



DEPARTMENT OF WATER RESOURCES

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