Subject:	**Tunnel Gravity Flow Capacity Analysis (Final Draft)**
Project feature:	Pumping Plant
Prepared for:	California Department of Water Resources (DWR) / Delta Conveyance Office (DCO)
Prepared by:	Delta Conveyance Design and Construction Authority (DCA)
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1. Purpose

The purpose of this technical memorandum (TM) is to perform a gravity flow capacity analysis of the Delta Conveyance Project (Project) to evaluate the hydraulic conditions that establish gravity flows between the Sacramento River Intakes and the Southern Forebay. This analysis was conducted for the Project's Central and Eastern corridor options. Achievable gravity flows associated with the static head conditions between the maximum and minimum water surface elevations (WSEs) at the Sacramento River and the Southern Forebay, respectively, were determined based on the conceptual level design of the Project's hydraulic structures and configuration associated with each tunnel alignment corridor.

1.1 Background

The Project design flow capacity of 3,000 to 7,500 cubic feet per second (cfs) has been established by the DCO. Within this established range of flows, a systemwide hydraulics and capacity analysis of the tunnel diameter options was performed for three specific design flow options of 4,500, 6,000 and 7,500 cfs. The recommended tunnel inside diameter (ID) at each design flow capacity option is described in the Capacity Analysis for Preliminary Tunnel Diameter Selection TM (DCA, 2021a) and are summarized as follows:

- 31-foot ID at the maximum design flow capacity of 4,500 cfs
- 36-foot ID at the maximum design flow capacity of 6,000 cfs
- 40-foot ID at the maximum design flow capacity of 7,500 cfs

For this TM, this analysis considers only the 36-foot ID tunnel sized for the maximum Project design flow capacity of 6,000 cfs.

Gravity flow through the tunnel between the intakes and the Southern Forebay could be achievable under some circumstances when the Sacramento River WSE at the intakes is sufficiently above the WSE in the Southern Forebay. Under these conditions, flow from the tunnel could bypass the South Delta Pumping Plant (Pumping Plant) and flow by gravity into the Southern Forebay through the gravity flow control structure. The gravity flow control structure would be connected to the Pumping Plant wet well influent shaft structure. The gravity flow control structure would also include flow control gates that would balance the flow rates between the intakes and the Southern Forebay.

The Pumping Plant gravity flow control structure would also include emergency overflow weir-type openings into the Southern Forebay to manage hydraulic transient-surge conditions within the tunnel due to an electrical power failure event or other emergency event that would generate a transient-surge condition during operation of the conveyance system. The emergency weir-type openings within the gravity flow control structure would automatically permit the flow of water into the Southern Forebay and maintain the internal operating pressures in the tunnel and hydraulic control structures. The Southern Forebay would include storage capacity to accommodate incoming flows associated with transient-surge events. The sizing and elevations of these facilities would be further developed during the design phase.

Figure 1 provides a schematic of the basic Project configuration, which is applicable to both the Central and Eastern corridor options.

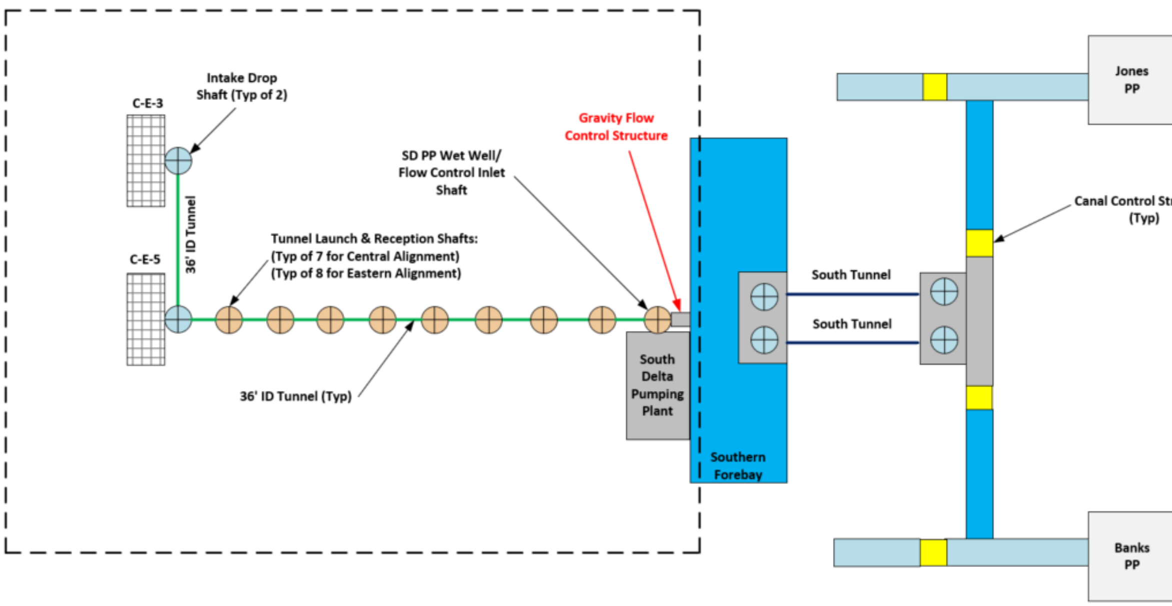

Figure 1. Delta Conveyance System Project Schematic

This evaluation was conducted between the Sacramento River Intakes (C-E-3 and C-E-5) and the Southern Forebay within the dashed boundary shown on Figure 1. The gravity flow capacity evaluation of the tunnels connecting the Southern Forebay to the existing State Water Project Harvey O. Banks Pumping Plant (Banks) and the Central Valley Project C.W. "Bill" Jones Pumping Plant (Jones) would be conducted in a subsequent TM.

The following Project configuration was considered for this evaluation:

- Central and Eastern tunnel alignment corridors
- Two intake locations on the left bank of the Sacramento River, as follows:
  - Intake C-E-3, located upstream of Hood at approximate River Mile (RM) 39.4
  - Intake C-E-5, located immediately upstream of confluence with Snodgrass Slough at approximate RM 36.8
- Tunnel connecting Intakes C-E-3 and C-E-5
- Tunnel connecting Intake C-E-5 and the gravity flow control structure at the Pumping Plant
- Tunnel shaft locations included in the analysis of the Central Corridor (between Intake C-E-5 and the Pumping Plant wet well and gravity flow control structure inlet shaft), including the following tunnel shafts:
  - Twin Cities
  - New Hope Tract

- Staten Island
- Bouldin Island
- Mandevelle Island
- Bacon Island
- Southern Forebay Inlet Structure

- Tunnel shaft locations included in the analysis of the Eastern Corridor alignment (between Intake C-E-5 and the Pumping plant wet well and gravity flow control structure inlet shaft), including the following tunnel shafts:
  - Twin Cities
  - New Hope Tract
  - Canal Ranch Tract
  - Terminous Tract
  - King Island
  - Lower Roberts Island
  - Upper Jones Tract
  - Southern Forebay Inlet Structure

2. Methodology

The methodology used to evaluate gravity flow conditions involved the following process:

- Conduct a separate, gravity flow capacity analysis for the Central and Eastern corridor options using the overall system end-to-end hydraulic model.
- Conduct the analysis using the 36-foot ID tunnel, sized for the Project design flow capacity of 6,000 cfs, for the Central and Eastern corridors and Sacramento River flow diversions at Intakes C-E-3 and C-E-5.
- Conduct the gravity flow capacity analysis with the flow control gates at the Sacramento River Intakes and within the gravity flow control structure in their fully open position to determine the maximum achievable gravity flow capacities within the range of static head operating conditions between Intakes C-E-3 and C-E-5 and the Southern Forebay. The maximum achievable flow capacities cannot exceed the maximum 0.20 foot per second (fps) approach velocities through the intake screens at each intake. If the flow approach flow velocity exceeds 0.20 fps at any intake screen, control gates would modulate to maintain the flow approach velocity to 0.20 fps. Control gates would modulate to limit the maximum head loss across the screens to a predetermined setpoint that would limit the maximum approach velocity associated with the screens to not more than 0.20 fps.

2.1 Evaluation Criteria

The following criteria were used for this analysis.

- Standard Roughness Coefficients:
  - The maximum and minimum interior equivalent roughness coefficients (Manning's n) of 0.016 and 0.014, respectively, have been assigned for the interior roughness of the segmentally lined tunnels to provide a sufficiently conservative analysis range suitable for the conceptual-level tunnel head loss analysis used to support the environmental permitting process.
  - Manning's n of 0.016 was used as the maximum standard roughness coefficient for the hydraulic analysis to evaluate the lower range of resultant tunnel gravity flow conditions due to the higher tunnel interior friction condition.

  - Manning's n of 0.014 was used as the minimum standard roughness coefficient for the hydraulic analysis to evaluate the upper range of resultant tunnel gravity flow conditions due to the lower tunnel interior friction condition.
- Governing Equations and Modeling Approach:
  - The intakes, connecting conduits, sediment basin, tunnel, and hydraulic control structures were modeled using Innovyze's InfoWorks Integrated Catchment Modeling (ICM) software. The modeling approach and governing equations are defined in the Hydraulic Analysis Criteria TM (DCA, 2021b).
  - Assignment of minor loss coefficients within the hydraulic model used the InfoWorks' standard rating curves for loss coefficients. Resulting losses were reviewed for reasonableness and adjusted as deemed appropriate.

2.2 Assumptions and Boundary Conditions

Basic assumptions and boundary conditions for this analysis:

- Alignment of tunnels (Central and Eastern) and locations of the intakes (C-E-3 and C-E-5), shafts, Pumping Plant gravity flow control structure, and Southern Forebay, as presented in the Project concept drawings (May 2020 preliminary version).
- Tunnel ID between the intakes and Southern Forebay would be 36 feet.
- Tunnel ID between C-E-3 and C-E-5 would be 36 feet.
- ID of Intakes C-E-3 and C-E-5 drop shafts of 83 feet.
- ID of Pumping Plant wet well and gravity flow structure inlet shaft of 115 feet.
- ID of tunnel shafts for both the Central and Eastern corridors (between Intake C-E-5 and the Pumping Plant wet well and gravity flow structure inlet shaft) of 70 feet.
- Intakes C-E-3 and C-E-5 were modeled with plate-type screens in their clean condition.
- Design flow sequence of operation at the Sacramento River Intakes, as follows:
  - For total diversion flows of 0 to 2,250 cfs, use only Intake C-E-3.
  - For total diversion flows of 2,250 to 4,500 cfs, Intake C-E-3 would divert up to 2,250 cfs, and then Intake C-E-5 would begin to divert flows up to 2,250 cfs.
  - For total diversion flows of 4,500 to 6,000 cfs, Intakes C-E-3 and C-E-5 diversions would increase up to the maximum diversion rate of 3,000 cfs, each.
- Sacramento River Elevations (North American Vertical Datum of 1988 [NAVD88]) assumed for the steady-state gravity flow analysis as follows:
  - Minimum of 3.72 and maximum of 27.3 feet at Intake C-E-3
  - Minimum of 3.61 and maximum of 26.3 feet at Intake C-E-5
- Southern Forebay WSEs (NAVD88) assumed for the steady-state gravity flow analysis as follows:
  - Minimum of 0.0 and maximum of 17.5 feet

2.3 Tools

2.3.1 Conveyance System Hydraulic Model

Hydraulic models for each system were constructed using InfoWorks ICM software. The model configuration consisted of the following components:

- Sacramento River Intakes C-E-3 and C-E-5, including inlet structures, screens, control gates, sediment basins, and tunnel drop shafts
- Pumping Plant wet well inlet and gravity flow and surge overflow structure
- Tunnel system (including remaining tunnel shafts) connecting the intakes to the Pumping Plant wet well and gravity flow and surge overflow structure
- Southern Forebay gravity flow inlet basin (where flow enters the Southern Forebay from the gravity flow and surge overflow structure)

3. Analysis and Evaluation

3.1 Gravity Flow Analysis

In accordance with the methodology and criteria described, a steady-state, gravity flow capacity analysis was performed between Intakes C-E-3 and C-E-5, to the Southern Forebay for the Central and Eastern corridor options, respectively. Gravity flow system head curves were developed by the InfoWorks ICM model between Intake C-E-3 and the Southern Forebay using the 36-foot ID tunnel (sized for a design flow capacity of 6,000 cfs for the Project) and the highest and lowest friction factors (Manning's n of 0.014 and 0.016) to establish the full envelope of potential gravity flows from highest to lowest between the intakes and the Southern Forebay.

To establish the maximum potential gravity flow conditions for each system head curve:

- Sacramento River diversion flows were permitted to simultaneously enter the tunnel through Intakes C-E-3 and C-E-5.
- All flow control gates within Intakes C-E-3 and C-E-5, and the gravity flow control structure at the Pumping Plant were simulated in their fully open positions for all flows within the maximum flow approach velocity allowed of 0.2 fps through the intake screens.

Figures 2 through 5 show the range of gravity flow capacities calculated through the 36-foot ID tunnel for the Central and Eastern corridor alignments at static head conditions developed between the Sacramento River WSE at the intakes and the WSE at the Southern Forebay. Figures 2 and 3 apply to the Central Corridor and were calculated using a minimum and maximum Manning's n of 0.014 and 0.016, respectively. Figures 4 and 5 apply to the Eastern Corridor and were also calculated using Manning's friction factors of 0.014 and 0.016, respectively. Figures 2 through 5 provide the achievable gravity flow capacity curves through the tunnel system between a minimum WSE of 0.0 foot and the maximum normal operating WSE of 17.5 feet at the Southern Forebay (capacity curves shown at 2.5-foot intervals), plotted against a Sacramento River WSE range between the low river WSE at Intake C-E-3 of 3.72 feet up to the extreme river high WSE of 27.3 feet (shown between the dashed horizontal lines).

Based on the information shown on Figures 2 through 5, achievable gravity flow conditions through each corridor (shown on the x-axis of each graph) can be determined by locating the intersection of the specific tunnel gravity flow curves at the desired Southern Forebay WSE (shown as colored curves at Southern Forebay WSE increments of 2.5 feet) and Sacramento River WSEs (shown on the y-axis of the graph). The Sacramento River WSEs at the extreme maximum and minimum (27.3 and 3.72 feet) are shown in the graphs as horizontal dashed lines. Figures 2 through 5 can be used to estimate achievable gravity flow conditions in the Central or Eastern Corridor alignments at any Sacramento River and Southern Forebay WSEs within the defined criteria and boundary conditions.

3.1.1 Gravity Flow Analysis of the Central Tunnel Corridor Alignment

Figure 2 shows the range of achievable gravity flows for the Central Corridor based on a 36-foot ID tunnel with capacity curves developed with a Manning's n of 0.014. These gravity flow curves were developed with the minimum friction factor and represent the maximum achievable gravity flows associated with this analysis.

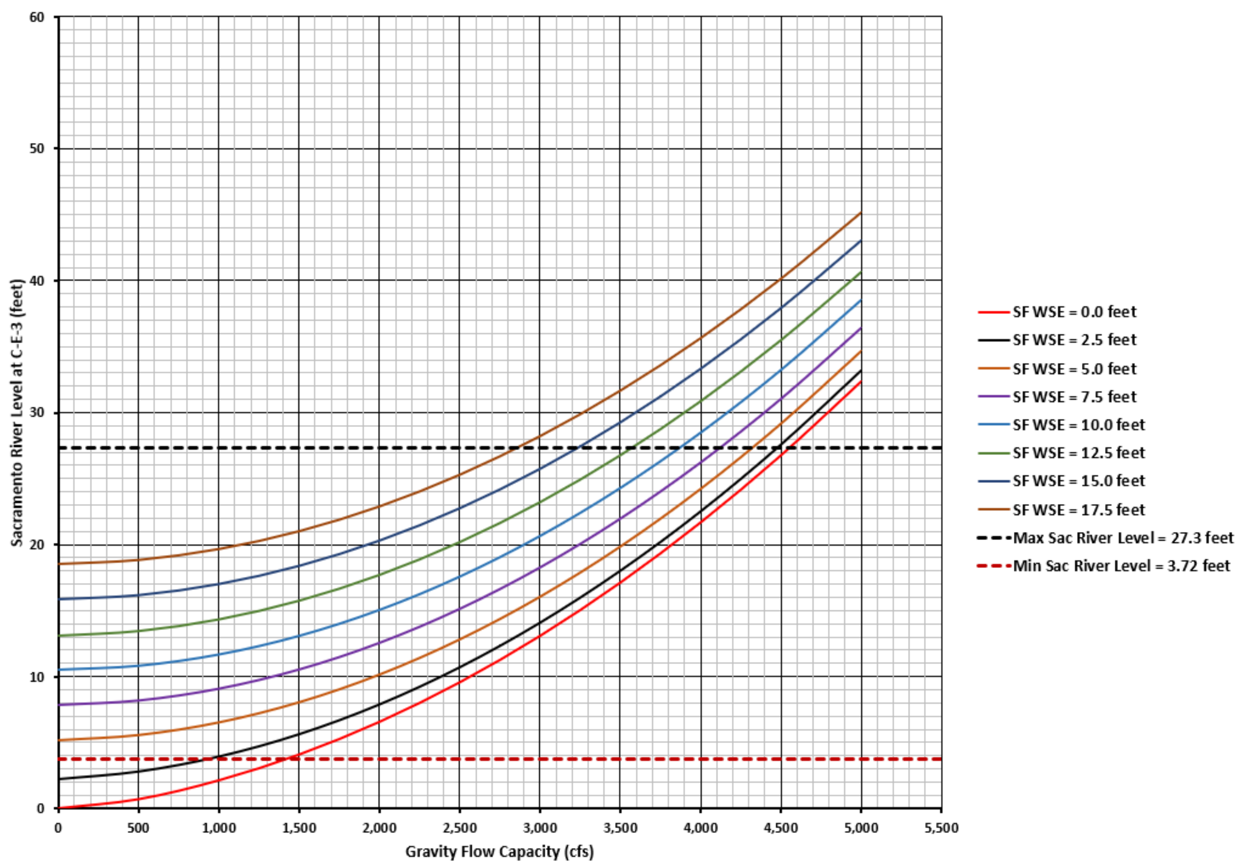

Figure 2. Gravity Flow Capacity Curves for the 36-foot ID Tunnel (Central Corridor) with Manning's n = 0.014

As shown on Figure 2, when the Sacramento River is at the extreme maximum elevation of 27.3 feet at Intake C-E-3, and the Southern Forebay WSE would be at 5.0 feet (minimum normal Southern Forebay WSE), the maximum achievable gravity flow is shown as 4,300 cfs. This capacity was determined by finding the intersection of the gravity flow capacity curve identified as "SF WSE = 5.0 feet" and the maximum Sacramento River level (shown as a black horizontal dashed line) of 27.3 feet. When the Sacramento River is at the maximum elevation of 27.3 feet, and the Southern Forebay WSE is at 17.5 feet (maximum normal Southern Forebay WSE), the maximum gravity flow achievable would be 2,800 cfs. This capacity is determined by finding the intersection of the gravity flow capacity curve identified as "SF WSE = 17.5 feet" and the maximum Sacramento River level of 27.3 feet.

When the Sacramento River is at the extreme minimum elevation of 3.72 feet at Intake C-E-3, no gravity flow could be achieved within the Southern Forebay's operating water surface range of 17.5 to 5.0 feet. Gravity flow capacities greater than 950 cfs would occur when the Southern Forebay WSE would be below 2.5 feet.

Figure 3 shows the range of achievable gravity flows for the Central Corridor based on a 36-foot ID tunnel with capacity curves developed with a Manning's n of 0.016. These gravity flow curves were developed with the maximum friction factor and represent the minimum achievable gravity flows associated with this analysis.

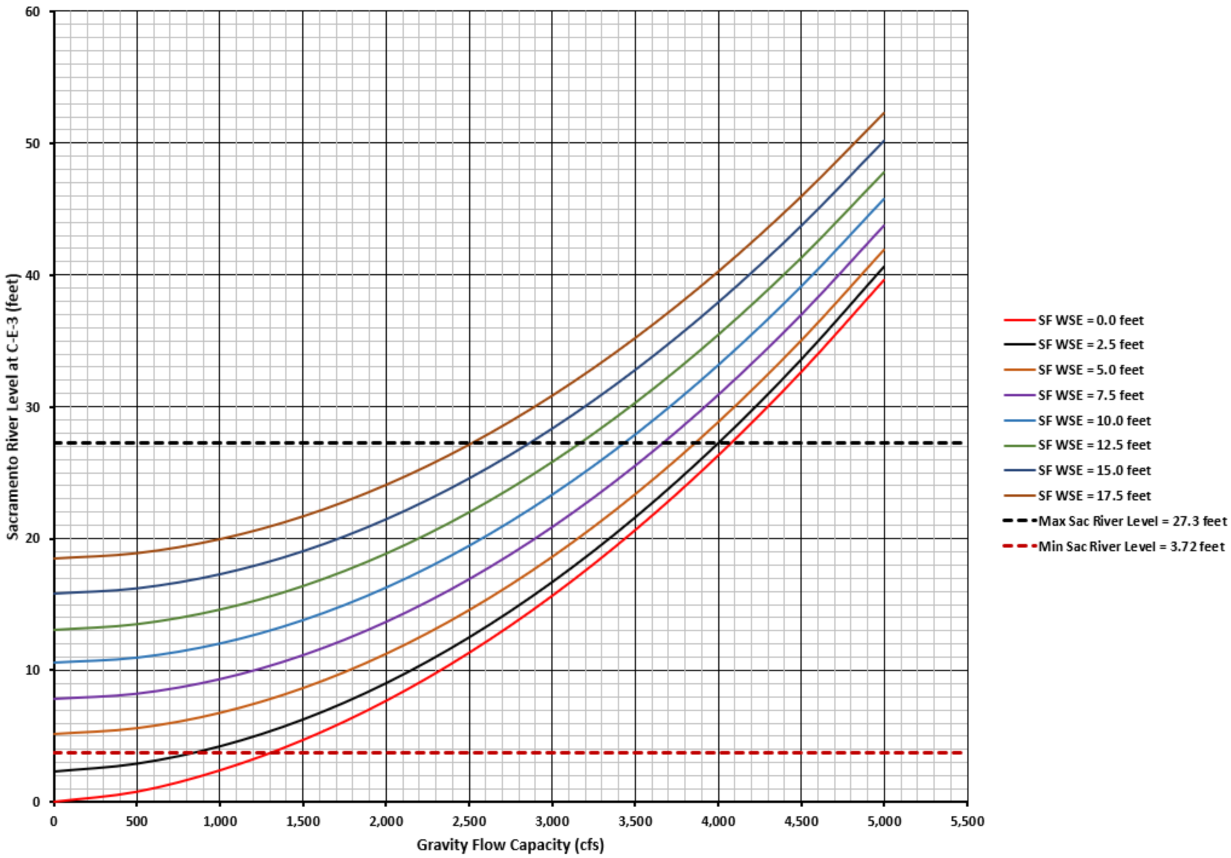

Figure 3. Gravity Flow Capacity Curves for the 36-foot ID Tunnel (Central Corridor) with Manning's n = 0.016

As shown on Figure 3, when the Sacramento River is at the extreme maximum elevation of 27.3 feet at Intake C-E-3, and the Southern Forebay WSE is at 5.0 feet (minimum normal Southern Forebay WSE), the maximum achievable gravity flow would be 3,900 cfs. When the Sacramento River is at the maximum elevation of 27.3 feet, and the Southern Forebay WSE is at 17.5 feet (maximum normal Southern Forebay WSE), the maximum gravity flow achievable would be 2,500 cfs.

When the Sacramento River is at the extreme minimum elevation of 3.72 feet at Intake C-E-3, no gravity flow could be achieved within the Southern Forebay's operating water surface range of 17.5 to 5.0 feet. Gravity flow capacities above 800 cfs would occur when the Southern Forebay WSE would be below 2.5 feet.

3.1.2 Gravity Flow Analysis of the Eastern Tunnel Corridor Alignment

Figure 4 shows the range of achievable gravity flows for the Eastern Corridor based on a 36-foot ID tunnel with capacity curves developed with a Manning's n of 0.014. These gravity flow curves were developed with the minimum friction factor and represent the maximum achievable gravity flows associated with this analysis.

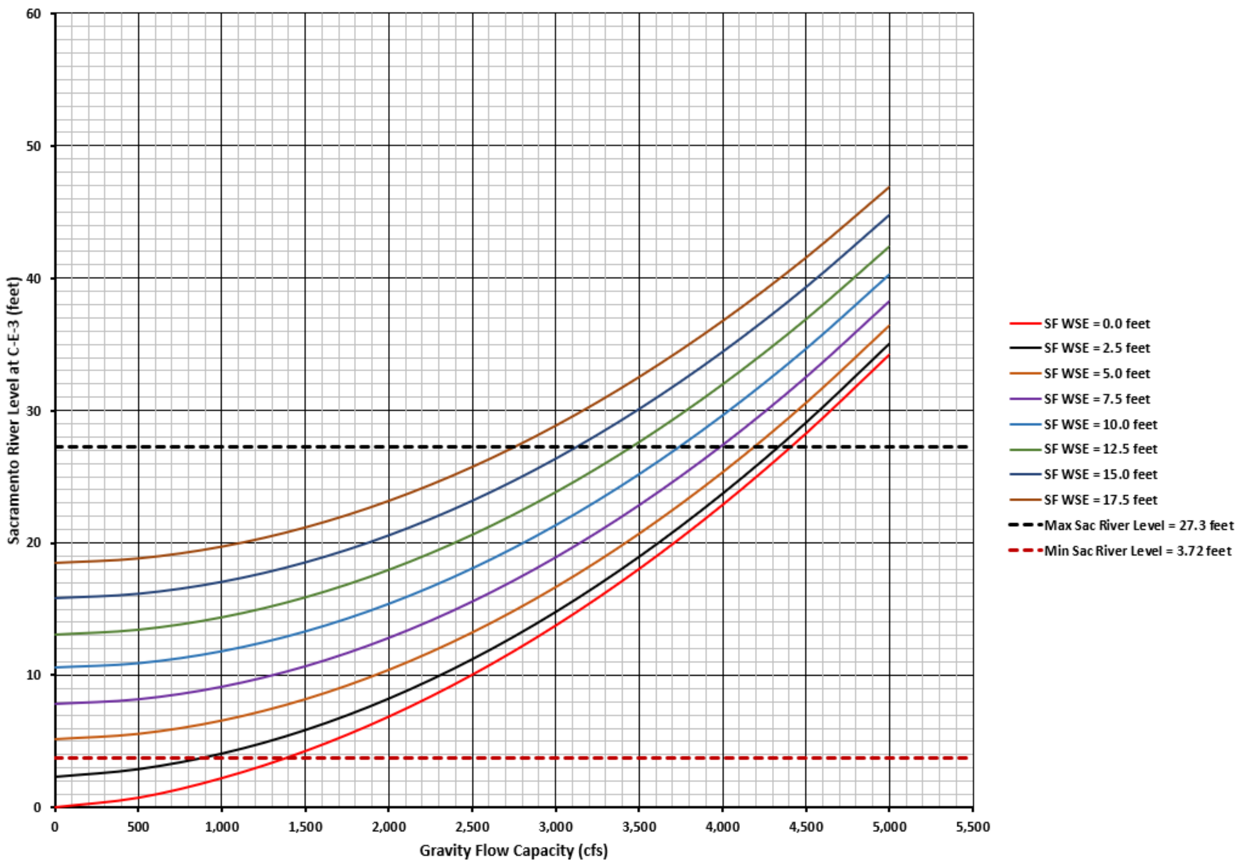

Figure 4. Gravity Flow Capacity Curves for the 36-foot ID Tunnel (Eastern Corridor) with Manning's n = 0.014

As shown on Figure 4, when the Sacramento River is at the extreme maximum elevation of 27.3 feet at Intake C-E-3, and the Southern Forebay WSE is at 5.0 feet (minimum normal Southern Forebay WSE), the maximum achievable gravity flow would be 4,200 cfs. When the Sacramento River is at the maximum elevation of 27.3 feet, and the Southern Forebay WSE is at 17.5 feet (maximum normal Southern Forebay WSE), the maximum gravity flow achievable would be 2,700 cfs.

When the Sacramento River is at the extreme minimum elevation of 3.72 feet at Intake C-E-3, no gravity flow could be achieved within the Southern Forebay's operating water surface range of 17.5 to 5.0 feet. Gravity flow capacities greater than 900 cfs occur when the Southern Forebay WSE would be below about 2.5 feet.

Figure 5 shows the range of achievable gravity flows for the Eastern Corridor based on a 36-foot ID tunnel with capacity curves developed with a Manning's n of 0.016. These gravity flow curves were developed with the maximum friction factor and represent the minimum achievable gravity flows associated with this analysis.

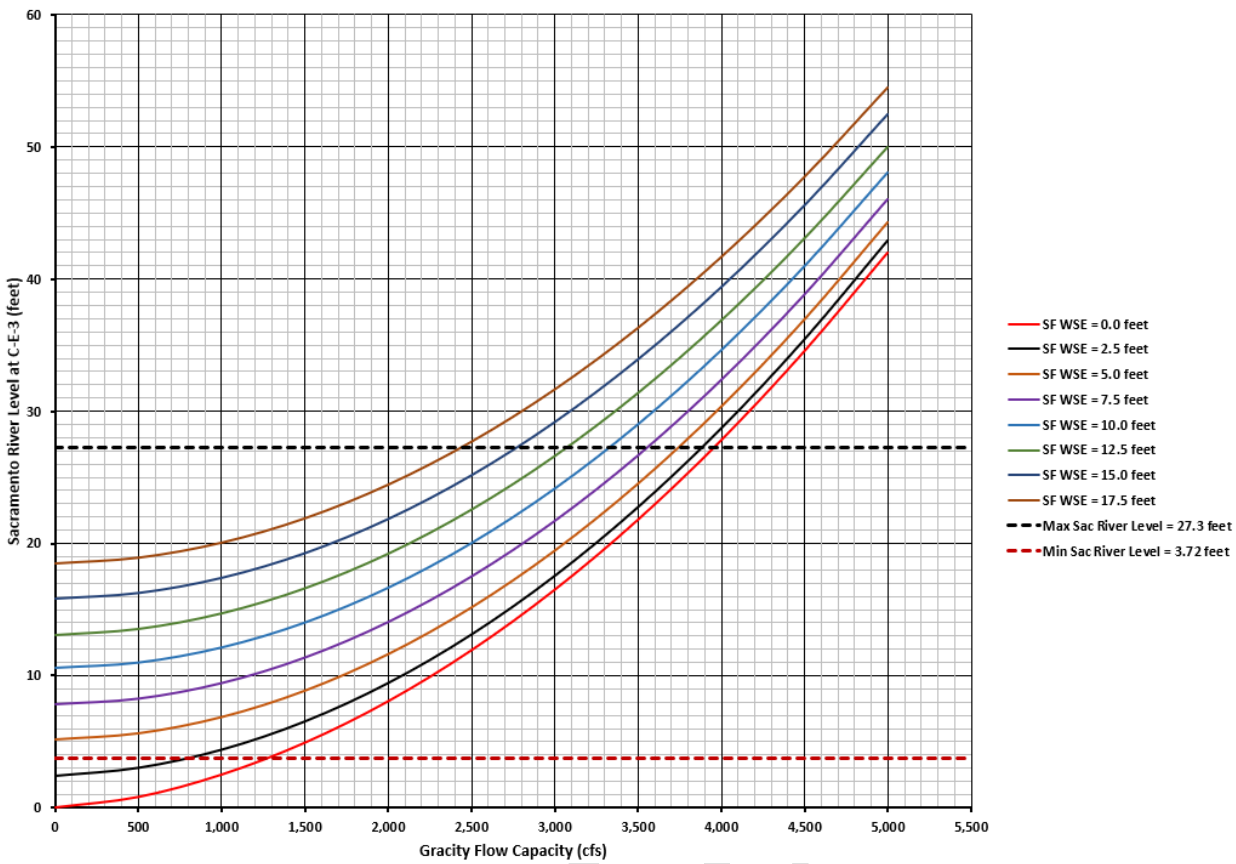

Figure 5. Gravity Flow Capacity Curves for the 36-foot ID Tunnel (Eastern Corridor) with Manning's n = 0.016

As shown on Figure 5, when the Sacramento River is at the extreme maximum elevation of 27.3 feet at Intake C-E-3 and the Southern Forebay WSE is at 5.0 feet (minimum normal Southern Forebay WSE), the maximum achievable gravity flow would be 3,750 cfs. When the Sacramento River is at the maximum elevation of 27.3 feet, and the Southern Forebay WSE is at 17.5 feet (maximum normal Southern Forebay WSE), the maximum gravity flow achievable would be 2,400 cfs.

When the Sacramento River is at the extreme minimum elevation of 3.72 feet at Intake C-E-3, no gravity flow could be achieved within the Southern Forebay's operating water surface range of 17.5 to 5.0 feet. Gravity flow capacities greater than 780 cfs occur when the Southern Forebay WSE would be below about 2.5 feet.

3.1.3 Comparison of the Central and Eastern Corridors Gravity Flow Capacities

Table 1 compares the achievable gravity flow capacity ranges of the Central and Eastern corridors with the Sacramento River levels at Intake C-E-3 between the maximum of 27.3 feet to the minimum of 3.72 feet and the Southern Forebay operating WSE between 17.5 feet maximum to 5.0 feet minimum.

Table 1. Gravity Flow Comparison between the Central and Eastern Corridors

River WSE (feet)	Southern Forebay WSE(feet)	Central Corridor Gravity Flow (cfs)		Eastern Corridor Gravity Flow (cfs)	
		Manning's n = 0.014	Manning's n = 0.016	Manning's n = 0.014	Manning's n = 0.016
27.3	5.0	4,300	2,800	4,200	2,700
27.3	17.5	3,900	2,500	3,750	2,400
20.0	5.0	3,500	3,150	3,400	3,050
20.0	17.5	1,100	1,000	1,075	950
15.0	5.0	2,850	2,500	2,750	2,475
10.0	5.0	1,950	1,790	1,900	1,700
3.72	2.5	950	800	900	780

As shown in Table 1, achievable gravity flows established within the Central corridor would generally be about 100 cfs higher than gravity flows generated within the Eastern corridor with similar static head and tunnel friction factor conditions.

Results shown in Table 1 indicate with a Sacramento River WSE of 27.3 feet and WSE within the Southern Forebay of 5.0 feet, the maximum achievable gravity flow at the lowest friction factor for the tunnel would be 4,300 cfs in the Central corridor. Under identical boundary conditions, a maximum gravity flow of 4,200 cfs would occur for the Eastern corridor. At the same static head conditions and with the highest friction factor for the tunnel, the maximum gravity flow in the Central and Eastern corridors would be 2,800 cfs and 2,700 cfs, respectively.

Results further indicate that with a Sacramento River level of 3.72 feet and a WSE in the Southern Forebay of 2.5 feet (which is below the normal minimum level of 5.0 feet), the maximum achievable gravity flow with the lowest friction factor for the tunnel would be 950 cfs and 900 cfs for the Central and Eastern corridors, respectively. With the same static head conditions and with the highest friction factor for the tunnel, the maximum gravity flow would be 800 and 780 cfs for the Central and Eastern corridors, respectively.

Control gates within Intakes C-E-3 and C-E-5 remained in their fully open positions for the entire range of achievable gravity flow conditions for each tunnel alignment corridor as flow approach velocities at each intake screen system never exceeded 0.20 fps.

4. Conclusions

The maximum achievable gravity flows established within the Central corridor would generally be about 100 cfs higher than within the Eastern corridor with the same static head and tunnel friction factor conditions. The maximum achievable gravity flow capacities would be less than the Project design flow capacity of 6,000 cfs for all cases evaluated in this TM. When desired diversions would be greater than the maximum achievable gravity flows at each corresponding static head condition, the Pumping Plant could not be bypassed.

5. References

Delta Conveyance Design and Construction Authority (DCA). 2021a. Capacity Analysis for Preliminary Tunnel Diameter Selection Technical Memorandum. Final Draft.

Delta Conveyance Design and Construction Authority (DCA). 2021b. Hydraulic Capacity Analysis Technical Memorandum. Final Draft.

6. Document History and Quality Assurance

Reviewers listed have completed an internal quality review check and approval process for deliverable documents that is consistent with procedures and directives identified by the Engineering Design Manager (EDM) and the DCA.

Approval Names and Roles

Prepared by	Internal Quality Control review by	Consistency review by	Approved for submission by
Tony Naimey / EDM Pumping Plant Lead	Ted Davis / QC Reviewer	Gwen Buchholz / EDM Environmental Consultant	Terry Krause / EDM Project Manager

This interim document is considered preliminary and was prepared under the responsible charge of Anthony M. Naimey, California Professional Engineering License M28450.

Note to Reader

This is an early foundational technical document. Contents therefore reflect the timeframe associated with submission of the initial and final drafts. Only minor editorial and document date revisions have been made to the current Conformed Final Draft for Administrative Draft Engineering Project Report version.