Hydraulic Laboratory Report HL-2018-01

Columbia Canal Pumping Plant Intake Hydraulic Model Study – San Joaquin River Restoration Program

Mid-Pacific Region
San Joaquin River Restoration Program
Reach 2B

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
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**ABSTRACT**

As part of the San Joaquin River Restoration Program, Reach 2B, a new intake structure and pumping plant were proposed to pump water from the Mendota Pool to the Columbia Canal. Due to the large design flow rate and non-standard intake design to accommodate potential sediment loads and reduce the footprint, a hydraulic model study was performed. The purpose of the study was to ensure that the hydraulic performance of the intake design met criteria established by the Hydraulic Institute and Reclamation Design Standards. A numerical model was used as an initial analysis to identify the most viable design, which was then studied in a 1:5.079 (model : prototype) physical model. Two modifications to this intake design were proposed to avoid subsurface and surface vortices approaching the pump bells. The modified intake design meets Hydraulic Institute and Reclamation Design Standards should the new intake structure be implemented as part of the overall project.

**SUBJECT TERMS**
Pump Intake, pump plant, pump, Hydraulic Institute Standard
Hydraulic Laboratory Report HL-2018-01

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The many rotation and other engineers who performed the many rounds of physical model testing.

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Cover Photos: 3D rendering and physical model of Columbia Canal Pumping Plant Intake Structure.
FIGURES

Figure 1 Extents of pump intake structure model study. ................................................................. 3

Figure 2. Conceptual 3D drawings of a combined sump intake design (left) and individual pump bays (right). Flow enters the intake from the rectangular siphon on the left and discharges through the pumps on the right. ................................................................. 5

Figure 3. Layout of combined sump intake design and pump configuration. Flow is from left to right. ........................................................................................................... 6

Figure 4. Final construction of a combined sump intake design. Flow enters at left and flows to the right through the vertical turbine pumps. ........................................................................ 8

Figure 5. Acrylic pump bells and piping of the six vertical turbine pumps................................. 8

Figure 6. Schematic of swirl meter used to measure the swirl angle of the flow entering the pump (ANSI/HI 9.2-2012, 2012). ......................................................................................... 10

Figure 7. Pitot tubes in piping above the pump bells for axial velocity measurements. .......... 11

Figure 8. Locations of axial velocity measurements shown within the cross-section of the throat (reduced diameter at end of transition) of the pump bell................................. 11

Figure 9. Comparison of velocity in ft/s entering the pump bay under the baffle wall comparing combined sump bay (left) and individual sump bays (right). .................................................. 12

Figure 10. Comparison of velocity in ft/s, 2 ft upstream of the centerline of the large pump between combined sump bay (left) and individual sump bays (right). ......................... 12

Figure 11. Comparison of velocity in ft/s at the approximate centerline of the pumps for combined sump bay (left) and configuration individual sump bays (right). ......................... 12

Figure 12. Comparison of velocity in ft/s 1 ft above the invert for combined sump bay (left) and individual sump bays (right). .................................................................................................. 13

Figure 13. Comparison of Q-Criterion (1/s²) 1 ft above the invert for combined sump bay (left) and individual sump bays (right). .................................................................................................. 13

Figure 14. Submerged vortex from the sump floor directly beneath the bell of pump 5........... 14

Figure 15. Free surface vortex formed during single operation of pump 5. Looking up at the vortex and water surface through right wall. Saw dust was placed on the surface to observe flow patterns. Circulation is counter clock-wise when looking down from the top. ....... 16

Figure 16. Dye core of free surface vortex entering the bell of pump 5................................. 16

Figure 17. Floor splitter plates (modification A6) proposed for small pumps 1 and 6 (top) and large pumps 2-5 (bottom). Dimensions shown are for the prototype. ......................... 18
Figure 18. Proposed vertical flow deflectors to prevent surface vortex formation. .................... 19

Figure 19. Comparison of the average swirl angle measured in each pump for modifications compared to the baseline geometry................................................................. 20

Figure 20. Plan view of proposed design options Combined Sump Bay (left) and individual pump bays (right). Flow is from bottom to top................................................................. 25

Figure 21. Sectional drawings of the Combined Sump Bay intake design (no pump bells shown). Flow is from left to right in the transverse section.................................................. 26

Figure 22. Sequence of Model construction on the floor of the Hydraulics Lab in Denver, CO. 28

Figure 23. Acrylic pump bells and piping ready for testing with the proposed floor splitter plates under each pump bell................................................................. 29

Figure 24. Physical model of the combined sump intake. Flow enters the intake from the rectangular siphon on the left and discharges through the six pumps on the right.............. 29

Figure 25. 3D rendering of Configuration A1 (baseline geometry, no modifications). .............. 31

Figure 26. 3D rendering of Configuration A2 below each pump bell (concrete elongated pyramids). .................................................................................................................. 31

Figure 27. 3D rendering of Configuration A3 below each pump bell (concrete cone mounds)... 32

Figure 28. 3D rendering of Configuration A4 below each pump bell (concrete center splitter - sloped pyramids).................................................................................................................. 32

Figure 29. 3D rendering of Configuration A4 below each pump bell (Floor splitter wall – 6-inch concrete).................................................................................................................. 33

Figure 30. 3D rendering of Configuration A5 below each pump bell (Floor splitter plate – ½ inch steel plate). .................................................................................................................. 33
TABLES

Table 1. Summary of modifications tested to improve hydraulic conditions of the combined sump bay design................................................................. 17

Table 2. Normalized axial velocities and normalized standard deviations measured for Pumps 4-6.............................................................................. 21

Table 3. Summary of test matrix used for initial evaluation of modifications which included visual flow observations and swirl angle measurements. These tests were followed by an acceptance test of final modification A6 which included axial velocity measurements. ..... 35
List of Symbols

d = diameter of the pump casing, same as the throat of the pump bell (ft)

D = diameter of the pump bell (ft)

θ = angle of the swirl of the flow within the pump casing (degrees)

u = axial velocity within the pump casing (ft/s)

n = revolutions/second of the swirl meter used to measure θ (-)

Q = volumetric flowrate (ft³/s)
Executive Summary

As part of the San Joaquin River Restoration Program (SJRRP), a new pumping plant and intake structure were proposed to pump water from the Mendota Pool to the Columbia Canal. Due to the large design flow rate and non-standard intake design to accommodate potential sediment loads and reduce the footprint, a hydraulic model study was performed in Reclamation’s Hydraulics Laboratory in 2017. A hybrid approach was taken utilizing both a Computational Fluid Dynamics (CFD) and a Physical Model to expedite design decisions and verify acceptable hydraulic performance of the final design. The following results, conclusions, and recommendations were made for the final intake design:

- Two initial intake design options were considered, both of which were intended to potentially reduce maintenance with sediment loads. Both options (similar in design but with different geometries and footprints) were compared using a CFD model. Results indicated that the hydraulic conditions approaching the pump bells were very similar for both options. These hydraulic conditions created high vorticity directly beneath the pump bells that would likely require localized modifications to the geometry. The design option with the smallest footprint was chosen to be pursued in the physical model due to no apparent advantages in hydraulic conditions of one option over the other. Also there was a high likelihood of correcting adverse approach conditions with simple modifications near the entrance to the pump bell without major changes in overall geometry.

- The physical model of the baseline intake design (smallest footprint chosen from CFD results) produced two hydraulic conditions that were problematic. The first was submerged vortices originating from the floor beneath the pump bell which produced excessive swirl entering the pump. This was seen in every pump bell for most operating conditions. The second problem was a type 4 free surface vortex seen only at single operation of either Pumps 2 or 5.

- The submerged vortices were mitigated by installing a thin splitter plate directly beneath the bell of all six pumps. These splitters effectively disrupted the vortex and helped straighten the flow entering the pump bell and throat.

- For the free surface vortex, two effective options were determined. First was writing the Standard Operating Procedure to avoid the condition of 50 ft³/s with only Pump 2 or 5. This flow could instead be achieved by either single operation of Pump 3 or 4, or a combination of multiple pumps. The second option was to add vertical flow deflectors to the downstream side of the baffle wall to prevent the vortex from forming.

- These simple modifications are recommended for this particular intake design to meet H.I. criteria. They will provide satisfactory hydraulic performance of this pump intake under all operating conditions and water surface elevations expected in the intake.
Background

As part of the San Joaquin River Restoration Program (SJRRP), Project Reach 2B, a new pumping plant and intake structure were proposed to pump water from the Mendota Pool to the Columbia Canal (Figure 1). The new pumping plant would replace the existing one, located upstream in Reach 2B of the San Joaquin River. The new location of the pumping plant was required to meet contractual water diversion points in the Mendota Pool, which would be cut-off following completion of the other SJRRP projects. This project, including the new intake structure, siphon, pumping plant, and delivery to the Columbia Canal, would be constructed first to prevent loss of service to the Columbia Canal Company during subsequent construction periods. When all other construction was complete, the existing pumping plant would be decommissioned. This project, and the SJRRP, are mandatory actions required under Public Law 111-11 and the San Joaquin River Restoration Settlement Act of 2004. These two laws provide the justification and authorization to study, design, construct, and operate SJRRP projects.

Due to the large design flow rate and non-standard intake design to accommodate potential sediment loads and reduce the footprint, a hydraulic model study of the new pump intake structure was performed in Reclamation’s Hydraulics Laboratory in 2017. In late 2017, near the completion of model testing, the decision was made to exclude the new pumping plant as part of the overall plan for the SJRRP. Reclamation’s Hydraulics Lab staff were instructed to complete and document the model study, which was brought to a level of approximately 30% of Final Design. This was done as a means to record the design and modeling effort made for this project, as well as to retain important findings should a similar pump intake design be proposed in the future.
Figure 1 Extents of pump intake structure model study.
Introduction

The main purpose of this study was to ensure that the hydraulic performance of the intake design was acceptable according to Reclamation Design Standards that are based on criteria established by the Hydraulic Institute (H.I.) 9.8-2012 for Pump Intake Design (ANSI/HI 9.2-2012, 2012). This information would then provide guidance to TSC’s Plant Structures (86-68120) and Hydraulic Equipment (86-68420) design groups in their development of the final design of the Columbia Canal pumping plant.

Reclamation follows the H.I. standards to ensure acceptable hydraulic intake conditions to achieve specified pump efficiencies, resolve conflicts between manufacturer and owner regarding hydraulic design/operation, and increase the longevity of pumping equipment to the extent possible. Physical model studies help ensure acceptable hydraulic performance and may reduce design footprint whenever compliance with H.I. standards is not possible due to unusual site requirements, space limitations, unusually large discharges, or significant construction costs. According to the H.I. Standard, there are several conditions that require a physical model study. The intake design evaluated in this study requires physical modeling based on two of them:

- The sump geometry deviates from those provided in the H.I. standard
- The overall intake flow is greater than 100,000 gal/min (223 ft³/s).

Given the unique intake geometry designed to facilitate sediment loads and a total design flow of 250 ft³/s the physical model study of the Columbia Canal pump intake design was needed to satisfy both of these requirements.

Model Study Objectives

- Verify that hydraulic conditions in the pump intake structure will allow for acceptable pump performance according to Hydraulic Institute Standard 9.8
  - Ensure acceptable uniformity of approach flow conditions
  - Prevent vortex formation that may cause pump vibrations or other conditions detrimental to pump performance and service life
  - Provide adequate velocity distribution and minimize velocity fluctuation within the pump bell
- Identify potential modifications to the intake design that could potentially reduce footprint or cost of the project and improve constructability

Scope Limitations

- Model extents included only the pump intake structure, pump bell inlets, and outlets from the rectangular siphon.
- Model extents did not include the siphon, scaled pumps or discharge piping to the Columbia Canal.
Proposed Intake Design

Two design options were initially proposed for the intake geometry of the Columbia Canal Pumping Plant. Both were designed to handle sediment-laden flows with a baffle wall and flow vanes that forced the flow down to the entrance of the pump bells where sediment may remain suspended and discharged, thus reducing maintenance of the intake structure. One design included a combined sump with no physical division of the pump bells and the other included individual bays for each pump and required a larger footprint (Figure 2).

![Conceptual 3D drawings of a combined sump intake design (left) and individual pump bays (right). Flow enters the intake from the rectangular siphon on the left and discharges through the pumps on the right.](image)

Both options included six vertical turbine pumps capable of discharging a total of 250 ft³/s. Pumps 1 and 6 were designed for 25 ft³/s each and Pumps 2 – 5, 50 ft³/s each as shown in Figure 3, which also shows the pump bell diameter (D) for each pump. The bell diameters chosen for this study (36-inch for small pumps and 45.25-inch for large pumps) represent the median size bell diameter for this flow range from several pump manufacturers.
Experimental Approach

A hybrid approach with both numerical and physical modeling was used to study the intake structure design options. Both designs were modeled using CFD to determine the most viable option that could then be studied with a physical model. This approach allowed more than one option to be considered and reduced the time and cost of physical model construction and testing.

Numerical Model

For this study, the CFD model was used to provide an initial comparison of the design options and not for a comprehensive analysis of final results. Velocity magnitudes and the Q-Criterion (Flow Science Inc., 2012) of both options were compared to indicate velocity distributions and potential for turbulence and vortex formation. Initial numerical results were verified and finalized with the physical model of the most viable intake design option.

FLOW-3D, a commercially available CFD software package by Flow Science Inc. was used for all CFD simulations due to its ability to accurately track free surfaces. FLOW-3D utilizes the Reynolds-averaged Navier-Stokes (RANS) equations to solve for fluid flow. Modifications to the standard RANS equations include algorithms to track the water surface and flow around geometric objects (Hirt and Nichols, 1981; Flow Science, 2012; Hirt and Sicilian, 1985; Hirt, 1992).

The CFD model was configured using prototype dimensions to avoid size-scale effects and to simplify comparison between the model, physical conditions and design dimensions. The model was configured in three dimensions.

A 3D geometry file of both design options was imported into FLOW3D as a stereo lithography file. The geometry was overlaid with a computational grid having cells 0.25-ft cubed in the x
(streamwise), y, and z (vertical) direction. A second nested computational grid was located near the pump bells with cells 0.125-ft cubed, to better resolve the pump bell curvature and flow patterns entering the bells. Optimization of the grid resolution was not completed for this study; it is expected however that reducing the cell size would not result in drastic changes to the simulation results.

The inflow boundary (-x) was set to match the prototype flow rates by specifying an approximate, uniformly distributed discharge for each simulation. Wall boundary conditions were applied along both sides of the numerical model (+y), the floor (-z) and the back of the simulation (+x) was set as a no-slip boundary condition. The top (+z) boundary was set as a pressure boundary with gauge pressure equal to zero. The fluid exited the simulation through mass source objects located within the pump bells to provide flows similar to that which would draw water into the pumps.

Turbulence was modeled using the Renormalized Group theory (RNG) because it more accurately describes low intensity turbulent flows and flows with strong shear regions using fewer computations than other methods (Flow Science, 2012).

**Physical Model**

The combined sump bay design was selected for physical modeling in the hydraulics laboratory. Details regarding this decision are given in the Results section.

**Model Design and Construction**

The physical model was designed and sized according to Froude scaling laws since gravity is the dominant force acting on the open channel flows within the intake structure. A model to prototype scale ratio of 1:5.079 ($L_r = 5.079$) was selected to allow for the use of commercially available acrylic pipe for the pump casings, resulting in the following Froude scale relationships:

- **Geometry** – 1 : $L_r$
- **Discharge** – 1 : $L_r^{5/2}$
- **Velocity** – 1 : $L_r^{1/2}$
- **Time** – 1 : $L_r^{1/2}$

Flows at this size-scale result in a minimum Reynolds number of $6.57 \times 10^4$ and minimum Weber number of 567 based on pump bell diameter as the critical length dimension. Both of these parameters are greater than the minimum required by H.I. standards for physical modeling (ANSI/HI 9.2-2012) and are sufficiently high to neglect viscous and surface tension effects at the model scale.

The exterior and floor of the model intake structure were constructed out of structural lumber and marine-coated plywood sheeting (Figure 4). Both side and downstream walls were sheeted with clear acrylic panel for visualization. Interior features such as the baffle wall and flow vanes were made out of expanded PVC sheets. The pump bells were machined out of clear acrylic and
attached to acrylic tubes to represent the vertical pump casings (Figure 5) and allowed for flow visualization within each pump bell. Each bell and tube were connected to a separate PVC pipe for individual operation and flow control. Additional photographs of model construction are shown in Appendix B.

Figure 4. Final construction of a combined sump intake design. Flow enters at left and flows to the right through the vertical turbine pumps.

Figure 5. Acrylic pump bells and piping of the six vertical turbine pumps.
Testing and Instrumentation

Flow was provided to the model by the hydraulic lab’s closed-loop pumping system which includes a 240,000 gallon sump, four 100 hp pumps, and calibrated venturi flowmeters accurate to ±0.25%. Each of the six model pumps were operated individually as siphons with the individual discharges controlled with downstream PVC gate valves. Each pump flow rate was measured individually with an acoustic flow meter (accurate to ±2%). Water surface elevations in the intake structure upstream and downstream of the baffle wall were measured using ultrasonic water level sensors (MassaSonic) in separate stilling wells. These measurements were checked periodically using a Venier point gage accurate to 0.001-inch.

All combinations of pump operations were tested assuming 25 ft³/s for the small pumps and 50 ft³/s for the large ones. The majority of testing occurred at the minimum water surface elevation of 152.64-ft assuming it to be the worst case condition for vortices and flow irregularities. A select number of tests were repeated at the maximum water surface elevation of 154.44-ft for verification. The actual test matrix is shown in Appendix D.

Initial testing was performed using flow visualization to identify adverse flow conditions such as vortex formation. This allowed comparisons to be made of various configurations of modified geometry for improved hydraulic performance. Flow visualization techniques included colored dye, neutrally buoyant beads, and saw dust particles on the free surface which were documented with video.

The intensity of flow rotation entering the pump was quantified by measuring the swirl angle (ANSI/HI 9.2-2012). A rotometer (swirl meter) was installed in each pump (Figure 6) and used to determine the swirl angle of the flow entering the pump according to Eq. 1. A long-term (10 minutes) swirl angle of less than 5° was required for the design to meet H.I. standards.

\[
\theta = \tan^{-1}\left(\frac{ndn}{u}\right) \quad \text{Eq. (1)}
\]

Where:

\(\theta\) = swirl angle (degrees)

\(u\) = average axial velocity at the swirl meter (ft/s, estimated from pump discharge and \(d\)).

\(d\) = diameter of the pipe at the swirl meter (ft)

\(n\) = revolutions/second of the swirl meter
Uniform axial velocities were also required to meet acceptance standards. These were measured at 16 different locations within the throat of the pump bell using Dwyer pitot tubes (1/8-inch diameter) as shown in Figures 7 and 8. Axial velocities within the throat were required to not deviate more than 10% from the overall average (normalized velocities between 0.90 and 1.10). Also, the standard deviation were required to be less than 10% of the individual time-averaged signal. Axial velocity testing was performed for verification only for the worst case operating condition on the final design modification.
Figure 7. Pitot tubes in piping above the pump bells for axial velocity measurements.

Figure 8. Locations of axial velocity measurements shown within the cross-section of the throat (reduced diameter at end of transition) of the pump bell.
Results

Numerical Modeling

Velocity magnitudes and flow distribution were compared for both designs. Figures 9 through 11 show results of both intake designs at multiple vertical cross-sections. The contours show velocities looking downstream in the range of 0-5 ft/s. There is no clear distinction between the two designs. Both seem to provide a well distributed flow approaching the pump bells.

Figure 9. Comparison of velocity in ft/s entering the pump bay under the baffle wall comparing combined sump bay (left) and individual sump bays (right).

Figure 10. Comparison of velocity in ft/s, 2 ft upstream of the centerline of the large pump between combined sump bay (left) and individual sump bays (right).

Figure 11. Comparison of velocity in ft/s at the approximate centerline of the pumps for combined sump bay (left) and configuration individual sump bays (right).
Figure 12 is a horizontal cross-section displaying magnitude velocities near the invert where flow enters the pump bells. Again, both designs provide a uniform approach flow which produces velocities that are approximately the same in each pump bell.

Figure 12. Comparison of velocity in ft/s 1 ft above the invert for combined sump bay (left) and individual sump bays (right).

Figure 13 identifies potential vortex issues for both intake designs. The Q-Criterion (related to vorticity and indicates the potential for vortex formation) (Flow Science Inc., 2012) is shown in the horizontal cross-section just below the pump bells. These results suggest there is a potential for a submerged vortex to form off the floor into the bell of the pumps. The contour plots in Figure 13 suggest there is a greater potential for submerged vortices to occur in the combined sump bay although they could form in the individual bay design as well.
Based on these initial numerical results the decision was made to pursue the combined sump intake design for the physical model. This was justified since there were no significant differences in approach flow and general hydraulic conditions between the two design options. While there was a potential for submerged vortex formation with the combined sump design, there seemed to be a high likelihood of correcting these with modifications to the geometry. In addition, the combined sump design was desirable due to the smaller footprint and reduced construction cost.

**Physical Modeling**

**Initial Design**

The initial combined sump intake design (baseline geometry) was tested in the physical model and produced results similar to those from the CFD model. Using flow visualization, general flow distribution from the baffle wall and flow vanes seemed reasonable and approach flow to the pump bells appeared to be uniform. Due to the layout of the pumps flow conditions were symmetrical from one side to the other as expected. However, two conditions were identified that were problematic.

The first was the formation of submerged vortices directly beneath the pump bells, similar to those shown in the CFD model. These formed beneath all six pump bells for most operating conditions but were most pronounced at the full design flow of 250 ft³/s with all six pumps operating. Figure 14 shows a submerged vortex brought out with dye injection.
The second problem was a strong free surface vortex that formed when either pump 2 or 5 were operated individually. Though the total intake discharge was relatively low (50 ft³/s), the bulk of the flow had to cross over to one side setting up a large slow moving eddy which transformed into a type 4 surface vortex (Figures 15 and 16). Surface vortices did not appear at any other operating conditions. This was likely due to the close proximity of the side wall to break up circulation for pumps 1 and 6 and not enough lateral flow movement to produce sufficient circulation for pumps 3 and 4.

Figure 14. Submerged vortex from the sump floor directly beneath the bell of pump 5.
Figure 15. Free surface vortex formed during single operation of pump 5. Looking up at the vortex and water surface through right wall. Saw dust was placed on the surface to observe flow patterns. Circulation is counter clockwise when looking down from the top.

Figure 16. Dye core of free surface vortex entering the bell of pump 5.
**Modifications for subsurface vortices**

Multiple modifications were tested to prevent submerged vortices near the pump bell. Table 1 outlines the configurations that were considered and tested to break up flow rotation and prevent vortex formation. Each configuration was evaluated based on visual observations using dye and neutrally buoyant beads as well as measuring the swirl angle within the pump casings. All modifications are shown in Appendix C.

All of the modifications, with the exception of A3 (cone mounds) significantly improved flow conditions entering the pump bells. The decision for final design then became a question of constructability and maintenance. Modification A6 (floor splitter plate) was chosen as the modification for final design. It is to be built out of ½ or ¾-inch steel plate for simple construction and can easily be removed and reinstalled as needed for maintenance. Prototype dimensions are shown in Figure 17.

Table 1. Summary of modifications tested to improve hydraulic conditions of the combined sump bay design.

<table>
<thead>
<tr>
<th>Configuration</th>
<th>Modified Geometry</th>
<th>Description</th>
<th>Conclusions</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>baseline design</td>
<td>combined sump bay with no individual pump walls or features beneath pump bells</td>
<td>Not effective due to excessive swirl and submerged vortex action from floor directly beneath pump bells</td>
</tr>
<tr>
<td>A2</td>
<td>Elongated pyramid</td>
<td>Elongated splitter with triangular cross-section on floor directly beneath pump bells</td>
<td>Effective but complicated concrete construction due to geometry</td>
</tr>
<tr>
<td>A3</td>
<td>Cone mounds</td>
<td>Half sphere on floor directly beneath pump bells</td>
<td>Not effective, modeled in CFD only, not included in physical model testing</td>
</tr>
<tr>
<td>A4</td>
<td>Center Splitter</td>
<td>Sloped pyramid, 0.3D high, 2D long on floor directly beneath pump bells</td>
<td>Effective but complicated concrete construction due to geometry</td>
</tr>
<tr>
<td>A5</td>
<td>Floor splitter wall</td>
<td>0.35D high, 2.5D long, 6-inch thick wall on floor directly beneath pump bells. To be constructed of concrete</td>
<td>Effective but pushing limits of minimum concrete wall thickness</td>
</tr>
<tr>
<td>A6</td>
<td>Floor splitter plate</td>
<td>0.35D high, 2.5D long, 0.5-0.75 inch thick wall on floor directly beneath pump bells. To be constructed of stainless or galvanized steel plate</td>
<td>Effective and most simple/cost effective option for construction and maintenance.</td>
</tr>
</tbody>
</table>
Figure 17. Floor splitter plates (modification A6) proposed for small pumps 1 and 6 (top) and large pumps 2-5 (bottom). Dimensions shown are for the prototype.

**Modifications for free surface vortex**

Two options were identified to prevent problems with the free surface vortex. The first is to avoid the condition by simply removing single operation of Pump 2 or 5 from the Standard Operating Procedure. Given the operational flexibility of this pumping plant, a discharge of 50 ft³/s could be achieved by either single operation of Pump 3 or 4, or a combination of multiple pumps.

The second option is to install vertical flow deflectors to the downstream side of the baffle wall as shown in Figure 18. These deflectors should be placed 1.5-2 pump bell diameters (large D = 45.25-inch) from the side walls as shown. Doing so breaks up flow circulation and prevents the surface vortex from forming. Prototype deflectors should be at least 15-inches wide and should run the full height of the baffle wall.
Figure 18. Proposed vertical flow deflectors to prevent surface vortex formation.
Acceptance Tests
Acceptance testing was performed with modification A6 (floor splitter plate) as the final design. This testing included prevention of vortex formation, swirl angles less than 5°, and uniform axial velocities within the pump bell. Vortex prevention was demonstrated using flow visualization as previously discussed. Figure 19 compares swirl angle results for several of the configurations tested, and shows that final modification A6 is well below the maximum allowable swirl for all six pumps.

Figure 19. Comparison of the average swirl angle measured in each pump for modifications compared to the baseline geometry.
Results from axial velocity measurements are shown in Table 2. Axial velocity measurements were only made at the full discharge of 250 ft³/s which was the operating scenario that produced the worst hydraulic conditions. Due to symmetry of the flow with six pumps, measurements were only made in Pumps 4-6 which were assumed to be the same as Pumps 1-3.

Normalized velocities from each of the sixteen locations were all within 10% of the average with the exception of one (location 1.4 of Pump 4). It is uncertain why the velocity at this location was so high when all others were uniform. It could be due to difficulty in obtaining the exact same condition in the physical model for the multiple test setups needed for velocity measurements at all sixteen locations. Standard deviations of each measurement were all well within the criteria of 10% of the time average. Results from axial testing help confirm the uniform approach flow into the pumps as observed visually and are considered acceptable according to the H.I. standard.

<table>
<thead>
<tr>
<th>Test Location</th>
<th>PUMP 4</th>
<th>PUMP 5</th>
<th>PUMP 6</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Normalized Velocity</td>
<td>Normalized Standard Deviation</td>
<td>Normalized Velocity</td>
</tr>
<tr>
<td>1.1</td>
<td>0.98</td>
<td>1.7%</td>
<td>1.00</td>
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<td>1.2</td>
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<td>1.00</td>
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<tr>
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<td>0.98</td>
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<tr>
<td>1.6</td>
<td>0.98</td>
<td>1.4%</td>
<td>1.00</td>
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<tr>
<td>1.7</td>
<td>0.99</td>
<td>1.6%</td>
<td>1.00</td>
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<td>1.8</td>
<td>0.97</td>
<td>1.9%</td>
<td>0.99</td>
</tr>
<tr>
<td>2.1</td>
<td>1.00</td>
<td>1.8%</td>
<td>1.08</td>
</tr>
<tr>
<td>2.2</td>
<td>0.96</td>
<td>1.3%</td>
<td>0.95</td>
</tr>
<tr>
<td>2.3</td>
<td>0.97</td>
<td>1.7%</td>
<td>0.99</td>
</tr>
<tr>
<td>2.4</td>
<td>0.96</td>
<td>1.5%</td>
<td>0.95</td>
</tr>
<tr>
<td>2.5</td>
<td>0.96</td>
<td>1.9%</td>
<td>0.95</td>
</tr>
<tr>
<td>2.6</td>
<td>0.94</td>
<td>2.4%</td>
<td>0.99</td>
</tr>
<tr>
<td>2.7</td>
<td>1.02</td>
<td>2.8%</td>
<td>1.08</td>
</tr>
<tr>
<td>2.8</td>
<td>1.00</td>
<td>1.8%</td>
<td>1.06</td>
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</table>
Conclusions and Recommendations

A hybrid approach was taken by utilizing both Computational Fluid Dynamics modeling (CFD) and physical modeling to study and verify acceptable hydraulic performance of the Columbia Canal Pump Intake design. After testing the original baseline design and several modifications, the following conclusions and recommendations were made for the final intake design:

- Two initial intake design options were considered, both of which were intended to potentially reduce maintenance with sediment loads. Both options (similar in design but with different geometries and footprints) were compared using a CFD model. Results indicated that the hydraulic conditions approaching the pump bells were very similar for both options. These hydraulic conditions created high vorticity directly beneath the pump bells that would likely require localized modifications to the geometry. The design option with the smallest footprint was chosen for the physical model due to no apparent advantages in hydraulic conditions of one option over the other. Also there was a high likelihood of correcting adverse approach conditions with simple modifications near the entrance to the pump bell without drastic changes in overall geometry.

- The physical model of the baseline intake design (smallest footprint chosen from CFD results) produced two hydraulic conditions that were problematic. The first was submerged vortices originating from the floor beneath the pump bell which produced excessive swirl entering the pump. This was seen in every pump bell at the majority of operating conditions. The second problem was a type 4 free surface vortex seen only at single operation of Pumps 2 and 5.

- The submerged vortices were mitigated by installing a thin splitter plate directly on the floor beneath the bell of all six pumps. These splitters effectively disrupted the vortex and helped straighten the flow entering the pump bell and throat.

- For the free surface vortex, two effective options were determined. First was writing the Standard Operating Procedure to avoid the condition of 50 ft³/s with only Pump 2 or 5. This flow could instead be achieved by either single operation of Pump 3 or 4, or a combination of multiple pumps. The second option is to add vertical flow deflectors to the downstream side of the baffle wall to break up flow circulation and prevent the vortex from forming.

- These simple modifications meet the objectives of this study and are recommended for this particular intake design to meet H.I. criteria. They will provide satisfactory hydraulic performance of this pump intake under all operating conditions and water surface elevations expected in the intake.
References


Appendix A: Drawings
Figure 20. Plan view of proposed design options Combined Sump Bay (left) and individual pump bays (right). Flow is from bottom to top.
Figure 21. Sectional drawings of the Combined Sump Bay intake design (no pump bells shown). Flow is from left to right in the transverse section.
Appendix B: Photographs of Physical Model
Figure 22. Sequence of Model construction on the floor of the Hydraulics Lab in Denver, CO.
Figure 23. Acrylic pump bells and piping ready for testing with the proposed floor splitter plates under each pump bell.

Figure 24. Physical model of the combined sump intake. Flow enters the intake from the rectangular siphon on the left and discharges through the six pumps on the right.
Appendix C: Drawings of Modifications
Figure 25. 3D rendering of Configuration A1 (baseline geometry, no modifications).

Figure 26. 3D rendering of Configuration A2 below each pump bell (concrete elongated pyramids).
Figure 27. 3D rendering of Configuration A3 below each pump bell (concrete cone mounds).

Figure 28. 3D rendering of Configuration A4 below each pump bell (concrete center splitter - sloped pyramids).
Figure 29. 3D rendering of Configuration A4 below each pump bell (Floor splitter wall – 6-inch concrete).

Figure 30. 3D rendering of Configuration A5 below each pump bell (Floor splitter plate – ½ inch steel plate).
Appendix D: Physical Modeling Test Matrix
Table 3. Summary of test matrix used for initial evaluation of modifications which included visual flow observations and swirl angle measurements. These tests were followed by an acceptance test of final modification A6 which included axial velocity measurements.

<table>
<thead>
<tr>
<th>Test Number</th>
<th>Pumps Operating (green)</th>
<th>Total Discharge</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>Baseline Condition; Vortex on floor was visible under all pumps. Worst condition.</td>
</tr>
<tr>
<td>2</td>
<td>1 2 3 4 5 6</td>
<td>125 cfs</td>
<td>Baseline Condition; Slight to moderate vortex under all pumps.</td>
</tr>
<tr>
<td>3</td>
<td>1 2 3 4 5 6</td>
<td>100 cfs</td>
<td>Baseline Condition; Tight vortex under the tested pumps.</td>
</tr>
<tr>
<td>4</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>Baseline Condition; Slight vortex that appeared and disappeared. Surface vortex type 4 was present.</td>
</tr>
<tr>
<td>5</td>
<td>1 2 3 4 5 6</td>
<td>100 cfs</td>
<td>Baseline Condition; Vortex on floor that would occasionally become tight.</td>
</tr>
<tr>
<td>6</td>
<td>1 2 3 4 5 6</td>
<td>100 cfs</td>
<td>Baseline Condition; Moderate vortex from the bottom. Dye moved in rather quickly and was not stagnant in the vicinity of the pump.</td>
</tr>
<tr>
<td>7</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>Baseline Condition; Occasional vortex at bottom. Flow within a decent range, including in the corner goes into the pump.</td>
</tr>
<tr>
<td>8</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>Center Splitter P4, P5, P6; Flow came in from the two sides of the splitter and combined in pump. The flow came in fairly uniform. Some passed above the pump. Surface dimples were present.</td>
</tr>
<tr>
<td>9</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>Center Splitter P4, P5, P6; Flow came in from the two sides of the splitter and combined in pump. The flow came in fairly uniform. Surface vortex type 4 was present.</td>
</tr>
<tr>
<td>10</td>
<td>1 2 3 4 5 6</td>
<td>125 cfs</td>
<td>Center Splitter P4, P5, P6; Splitter broke up the flow in order to prevent a vortex on the bottom. Flow came in uniformly. Saw dust was used in order to better see the surface swirls. Surface swirls tended to begin at a pump and work their way away.</td>
</tr>
<tr>
<td>11</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>Center Splitter P4, P5, P6; Splitter broke up the flow in order to prevent a vortex on the bottom. Flow came in uniformly. Surface vortex type 4 was present.</td>
</tr>
<tr>
<td>12</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>Center Splitter P4, P5, P6; A surface vortex appeared after about 15 minutes at Up W.S. Elevation of around 152.64 ft. This helps to prove symmetry among the 6 pumps as a vortex also appeared at Pump 5 with similar testing conditions.</td>
</tr>
<tr>
<td>13</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>Floor Plate P1, P2, P3 / Center Splitter P4, P5, P6; Flow was split by the floor plate. Flow would separate and reform in the pump. Flow above the bell downstream of the pump tended to flow up rather than into the pump.</td>
</tr>
<tr>
<td>14</td>
<td>1 2 3 4 5 6</td>
<td>125 cfs</td>
<td>Floor Plate P1, P2, P3 / Center Splitter P4, P5, P6; Flow was split by the floor plate. Flow would separate and reform in the pump. Flow above the bell downstream of the pump tended to flow up rather than into the pump.</td>
</tr>
<tr>
<td>15</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>Floor Plate P1, P2, P3 / Center Splitter P4, P5, P6; Flow was split by the floor plate. Flow would separate and reform in the pump. A surface vortex type 4 formed as the box was filling with water. Once the water level was at the desired elevation, no surface vortex appeared over a 45 minute time span. Surface rotation was present.</td>
</tr>
<tr>
<td>Test Number</td>
<td>Pumps Operating (green)</td>
<td>Total Discharge</td>
<td>Notes</td>
</tr>
<tr>
<td>-------------</td>
<td>------------------------</td>
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</tr>
<tr>
<td>16</td>
<td>1 2 3 4 5 6</td>
<td>25 cfs</td>
<td>Floor Plate P1, P2, P3 / Center Splitter P4, P5, P6; Flow was split by the floor plate. Flow would separate and reform in the pump.</td>
</tr>
<tr>
<td>17</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>Floor Plate P1, P2, P3 / Center Splitter P4, P5, P6; Informal test using beads to record flow under Pump 3 and Pump 4.</td>
</tr>
<tr>
<td>18</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>Baseline Condition; Vortex Type 3 present at El. 152.90ft, Vortex Type 2 present at El. 152.99ft, Vortex Type 1 present at El. 153.10ft.</td>
</tr>
<tr>
<td>19</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>1/8&quot; Floor Plate P4, P6 / 1-9/16&quot; Floor Plate P1, P3; Swirl could be seen from each side of the swirl plates. The 1/8&quot; floor plate appeared to have less swirl overall than the 1-9/16&quot; plate.</td>
</tr>
<tr>
<td>20</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>1/8&quot; Floor Plate P4, P6 / 1-9/16&quot; Floor Plate P1, P3; Informal test used to see dye flow for Pump 6. P6 had swirl across the top of the plate.</td>
</tr>
<tr>
<td>21</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>1/8&quot; Floor Plate P4, P6 / 1-9/16&quot; Floor Plate P1, P3; Informal test used to see dye flow for P6 and P1. Slight swirl across top of plate in both cases. Flow generally good.</td>
</tr>
<tr>
<td>22</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>1/8&quot; Floor Plate under all Pumps. Swirl meters for P3 and P5. Flow would separate and reform in the pump. No vortices were noticed. Small amounts of dye rarely went over the floor plate and created a small rotation on the other side of the plate</td>
</tr>
<tr>
<td>23</td>
<td>1 2 3 4 5 6</td>
<td>125 cfs</td>
<td>1/8&quot; Floor Plate under all Pumps. Swirl meters for P3 and P5. Flow would separate and reform in the pump. No vortices were noticed. Small amounts of dye rarely went over the floor plate and created a small rotation on the other side of the plate</td>
</tr>
<tr>
<td>24</td>
<td>1 2 3 4 5 6</td>
<td>100 cfs</td>
<td>1/8&quot; Floor Plate under all Pumps. Swirl meters for P3 and P5. Flow would separate and reform in the pump. No vortices were noticed. Small amounts of dye rarely went over the floor plate and created a small rotation on the other side of the plate</td>
</tr>
<tr>
<td>25</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>1/8&quot; Floor Plate under all pumps. Flow would separate and reform in the pump. Surface vortex appeared for about 30s as the water was rising to the minimum water surface elevation. Once the water level was at the desired elevation, no surface vortex appeared over a 45 minute time span. Surface rotation was present.</td>
</tr>
<tr>
<td>Test Number</td>
<td>Pumps Operating (green)</td>
<td>Total Discharge</td>
<td>Notes</td>
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<tr>
<td>26</td>
<td>1 2 3 4 5 6</td>
<td>100 cfs</td>
<td>1/8” Floor Plate under all pumps. Flow was split by the floor plate. Flow would separate and reform in the pump. No vortices were noticed. Small amounts of dye rarely went over the floor plate and created a small rotation on the other side of the plate. Q = 50.1 cfs, Up W.S. = 152.68ft, Dn W.S. = 152.64ft</td>
</tr>
<tr>
<td>27</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>1/8” Floor Plate under all pumps. Informal test to observe Vortex Type 3 at surface. When a board was placed in the water at the back wall and the side closest to the vortex, it would disappear</td>
</tr>
<tr>
<td>28</td>
<td>1 2 3 4 5 6</td>
<td>100 cfs</td>
<td>1/8” Floor Plate under all pumps. Flow was split by the floor plate. Flow would separate and reform in the pump. Occasional wall vortex formed. Small amounts of dye occasionally went over the floor plate and created a small rotation on the other side of the plate.</td>
</tr>
<tr>
<td>29</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>1/8” Floor Plate under all pumps. Flow was split by the floor plate. Flow would separate and reform in the pump. Q = 49.9 cfs, Up W.S. = 152.70ft, Dn W.S. = 152.71ft</td>
</tr>
<tr>
<td>30</td>
<td>1 2 3 4 5 6</td>
<td>50 cfs</td>
<td>1/8” Floor Plate under all pumps. Flow was split by the floor plate. Flow would separate and reform in the pump. Small amounts of dye occasionally went over the floor plate and created a small rotation on the other side of the plate. Q = 24.9cfs, Up WS = 152.66ft, Dn WS = 152.67 ft</td>
</tr>
<tr>
<td>31</td>
<td>1 2 3 4 5 6</td>
<td>250 cfs</td>
<td>1/8” Floor Plate with cross splitters under P1 and P2. 1/8” Floor Plate under P3-P6. Flow was split by the floor plate. Flow would separate and reform in the pump. Small amounts of dye occasionally went over the floor plate and created a small rotation on the other side of the plate. Q = 24.8cfs, Up WS = 152.66ft, Dn WS = 152.37 ft</td>
</tr>
<tr>
<td>32</td>
<td>1 2 3</td>
<td>125 cfs</td>
<td>1/8” Floor Plate with cross splitters under P1 and P2. 1/8” Floor Plate under P3-P6. Flow was split by the floor plate. Flow would separate and reform in the pump. Q = 24.9cfs, Up WS = 152.63ft, Dn WS = 152.60 ft</td>
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<tr>
<td>33</td>
<td>1 2</td>
<td>75 cfs</td>
<td>1/8” Floor Plate with cross splitters under P1 and P2. Flow was split by the floor plate. Flow would separate and reform in the pump</td>
</tr>
<tr>
<td>34</td>
<td>2</td>
<td>50 cfs</td>
<td>1/8” Floor Plate with cross splitters under P1 and P2. Flow was split by the floor plate. Flow would separate and reform in the pump</td>
</tr>
<tr>
<td>35</td>
<td>1</td>
<td>25 cfs</td>
<td>1/8” Floor Plate with cross splitters under P1 and P2. Flow was split by the floor plate. Flow would separate and reform in the pump</td>
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