Bonneville Spillway – High Flows and Tailwater Impacts

Laurie Ebner
July 2024

Problem Statement: The Bonneville Spillway is viewed as a "normative" route for juvenile fish passage, and the spill percentage is pushed beyond the conditions evaluated when the spillway was designed. During design, it was assumed flow would first go through the powerhouse and spill would only be initiated if the power was not needed or the powerhouse capacity was exceeded. Therefore, the tailwater associated with spill was assumed higher during design than the current operations.

Although spill is a preferred passage route at Bonneville survival has not been as high as desired and it should be noted that other routes at Bonneville have higher survival rates than the spillway.

The Bonneville Spillway CFD model has been used to provide insight into the hydraulic conditions that exist in the spillway with various spill volumes and tailwater elevations. The goal of the work is to provide insight into why survival rates are impacted at Bonneville Spillway as well as document the hydraulic impacts of spill volume versus tailwater.

Results: Tremendous insights have been gained on the hydraulic impacts associated with different spill volumes and tailwater. These insights are documented in the following report with the following key findings:

- No dam safety concerns were identified with the high spill volume and lack of tailwater support (not an expected outcome).
- TDG characteristics should be revisited based on the high spill volumes and the range of tailwater evaluated. The flow deflector jets are rarely skimming and meeting the original TDG design characteristics. CFD results are compared to available physical model results and the limitations of the physical model results are identified.
- Particles were not released in the CFD model to represent juvenile fish but streamlines have been released off of the Elevation 14 foot flow deflectors (bays 4 – 15) and the Elevation 7 foot flow deflectors (bays 1-3 and 16-18). There is a strong interaction shown in the streamlines between the deflectors of different elevations (bays 3 and 4 and bays 15 and 16).

Spillway:

The Bonneville Spillway is essentially original equipment (built in the 1920s and 1930s). The spillway concrete is original except for the addition of flow deflectors in the late 70s and early 2000s. The spillway gates are original. The gantry cranes are original. Hoists have been added over time since the 70s. But the part that fish interact with (gates and concrete surface) is original equipment. The gates and concrete are extremely rough.

Ideally, we would build new gates which would be smoother and provide better flow control. But USACE cannot install new gates on the project because they will weigh more and the spillway bridges can't take additional load.

Ogees and piers need to be cleaned up but to-date smooth surfaces require dewatering which is very expensive.

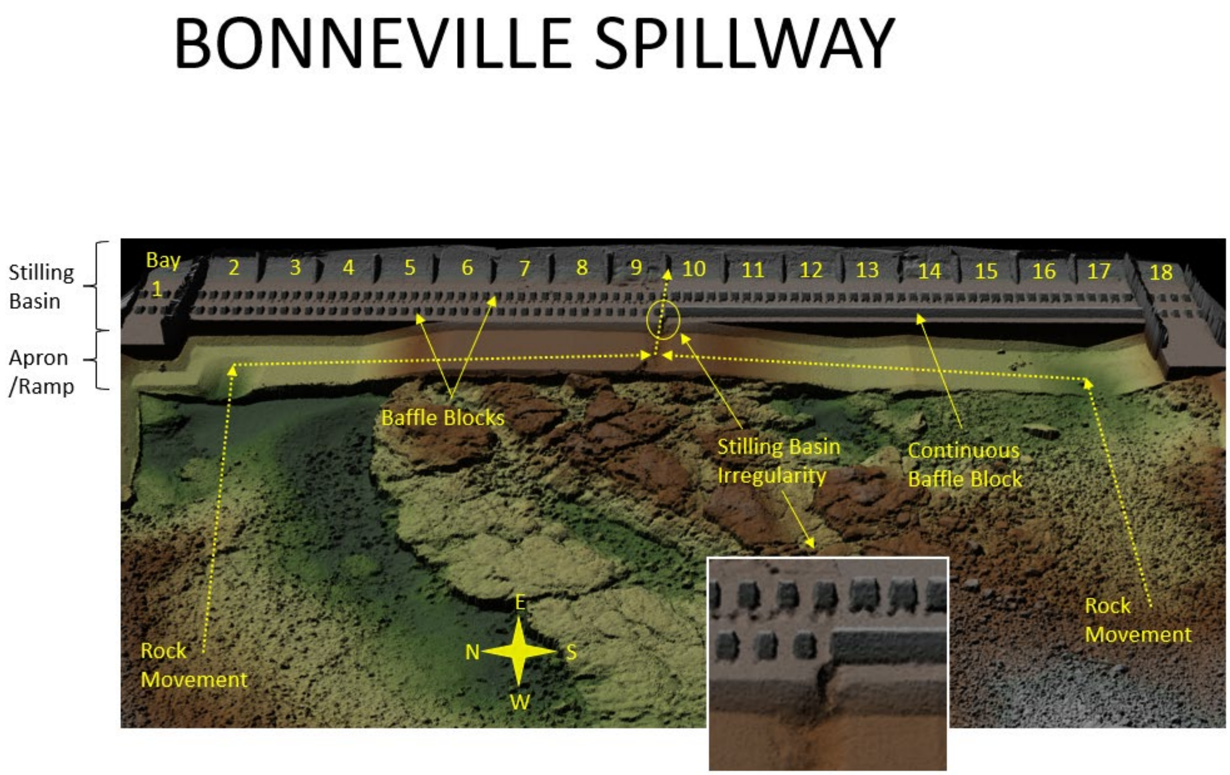

Figure 1 – Bonneville Spillway

Hydraulic Conditions:

When Bonneville was originally designed it was anticipated that the spillway would only be used when river flows exceeded the hydraulic capacity of the powerhouse. The spillway was only used during high flows but water quality standards were not met (TDG was too high). In the 70s flow deflectors were added to some bays in an attempt to meet TDG standards – the flow deflectors were at elevation 14 feet since spill only occurred at high flows (higher tailwater). In the 90s when the spillway became a preferred passage route for juvenile fish spill was occurring at lower flows (lower tailwater) and the elevation 14 foot deflectors were too high. In the 2000s elevation 7 foot flow deflectors were added to the outside bays to improve TDG performance for lower total river flows. But flood flows still need the elevation 14 foot flow deflectors.

Flow deflectors provide good TDG performance when spill volume and tailwater are at a specific conditions. The physical model results (used to design the existing flow deflectors) will be reviewed along with the CFD results. When the flow deflector is providing good TDG performance the jet skims across the surface. When the jet skims across the surface other flow has to support the jet and the flow has to come from somewhere. In the physical model the adjacent bays had deflectors at the same elevation and the flow condition at Bays 3 and 4 and Bays 15 and 16 were not modeled. In the physical model the flow that supports the jet comes from downstream and recirculates under the jet as shown in Figure 3. The CFD model shows similar results for some flow conditions but also shows some interesting interactions between adjacent bays.

Generally, we see higher velocities at lower tailwater (makes sense – same volume of water moving through less cross sectional area).

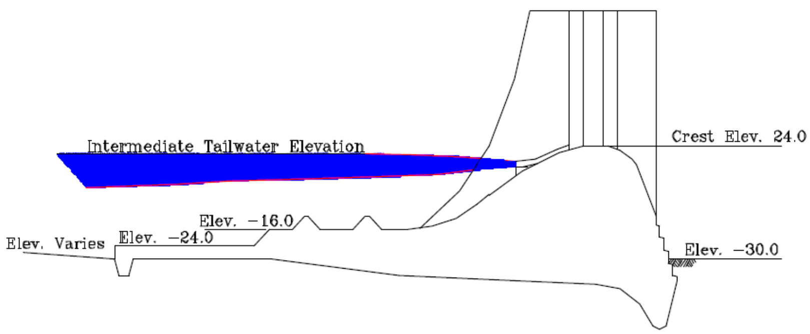

Figure 4. Cross-section of Skimming Flow

Figure 2 – Bonneville Skimming Flow

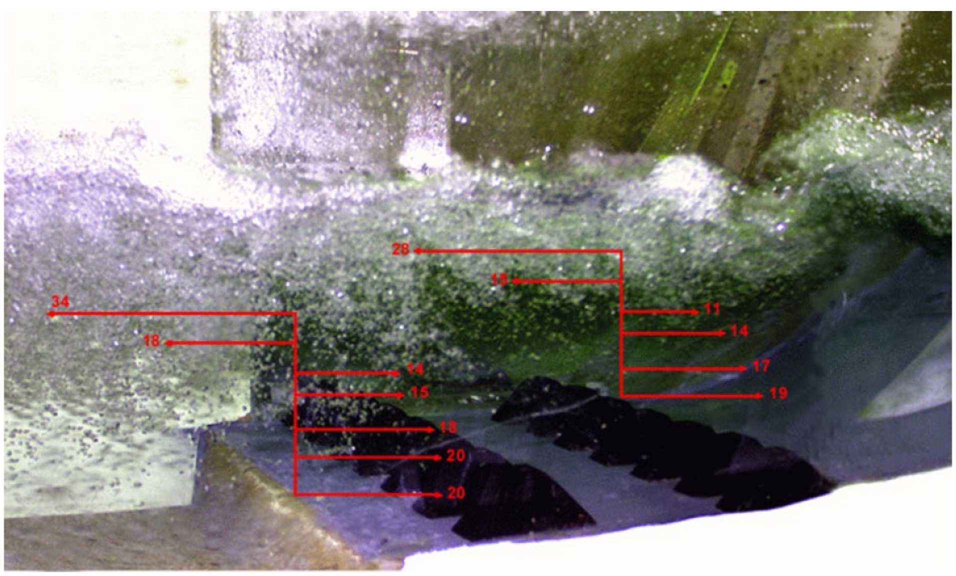

Figure 15. Skimming Surface Jet, Modified Bonneville Deflector,
6,700 cfs/bay, 1-1/2 bays, TW el -21.0, HW - 74.0

Figure 3 – Physical Model results showing flow moving upstream under the skimming jet

Tremendous time and energy has been devoted to developing spill patterns for the Bonneville Spillway. The patterns were developed in a 1:55 physical model at ERDC. The majority of the physical modeling was done in the early 2000s. The physical model needs significant remodeling/rebuilding before it could be used for additional testing.

The spill at Bonneville has changed over time – Figure 4 shows spill volume versus tailwater. The solid line is the minimum design tailwater that should exist for that particular spill volume. In recent years, Bonneville has adopted the practice of high spill volumes and low tailwater. Table 1 provides insight on how often the tailwater was too low for the spill volume.

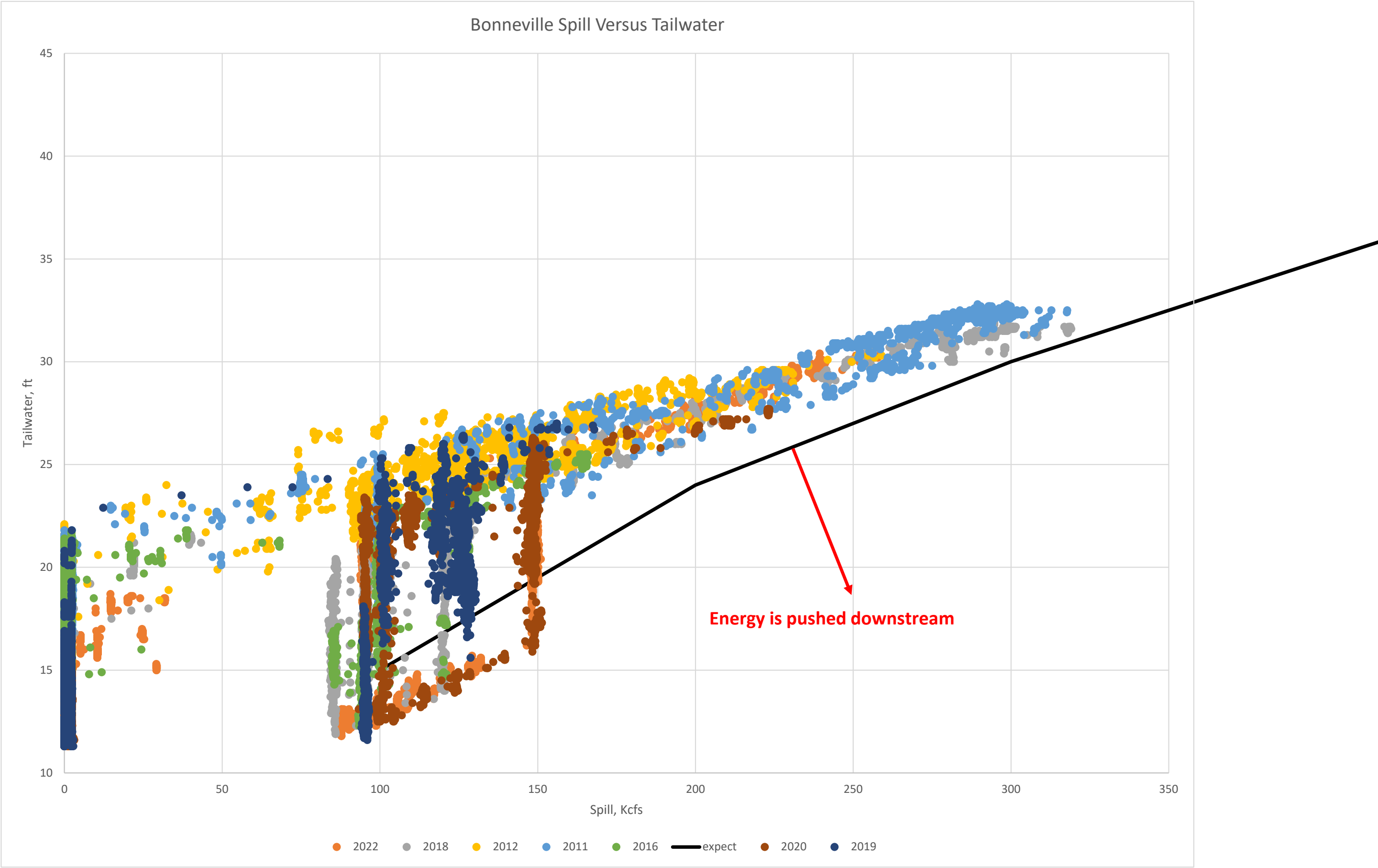

Figure 4 – Bonneville Spill Volume Versus Tailwater

When data is to the left of the solid line shown in Figure 4, the design energy dissipation is occurring in the stilling basin. When data is to the right of the line, the stilling basin is not dissipating sufficient energy and energy is pushed downstream.

Table 1 – Low Tailwater vs Spill

Spill with too low a tailwater				
Year	Hours of Low TW Spill	Hours of Spill in Year	%	
2023	2752	4416	62%	All except freshet
2022	1758	4417	40%	All except freshet
2021	3141	4417	71%	All except freshet
2020	1737	4417	39%	All except freshet
2019	2159	4417	49%	Post freshet
2018	1542	4417	35%	Post freshet
2017	1354	4417	31%	Post freshet
2016	2152	4417	49%	Post freshet
2015	3352	4417	76%	All except freshet
2014	1157	4417	26%	Post freshet
2013	1363	4417	31%	Mix
2012	457	4417	10%	Post freshet
2011	561	4417	13%	Post freshet
2010	1758	4417	40%	All except freshet

CFD Modeling:

Table 2 shows the boundary conditions of the Bonneville Spillway executed in the various CFD model runs made of the Bonneville Spillway. The lower end of the tailwater was based on the expected tailwater for the spill volume plus 35 Kcfs which is the minimum powerhouse flow. The upper end was the spill volume plus the hydraulic capacity of the powerhouses (~250 Kcfs).

Table 2 – CFD Model Runs

80 Kcfs at TW of 9, 12,15,18.9,24,28
100 Kcfs at TW of 11,15,20.3,24,29
125 Kcfs at TW of 13,15,20,21.8,25,30
150 Kcfs at TW of 14,20,23.3,25,31
200 Kcfs at TW of 17,20,25.9,30,33
Saw Tooth Pattern at 80 Kcfs TW of 18.9

An example output is shown in Figure 5. The figure shows a standard output file with the inflow, outflow, residual, Courant Number. The image of the spillway shows the surface velocity.

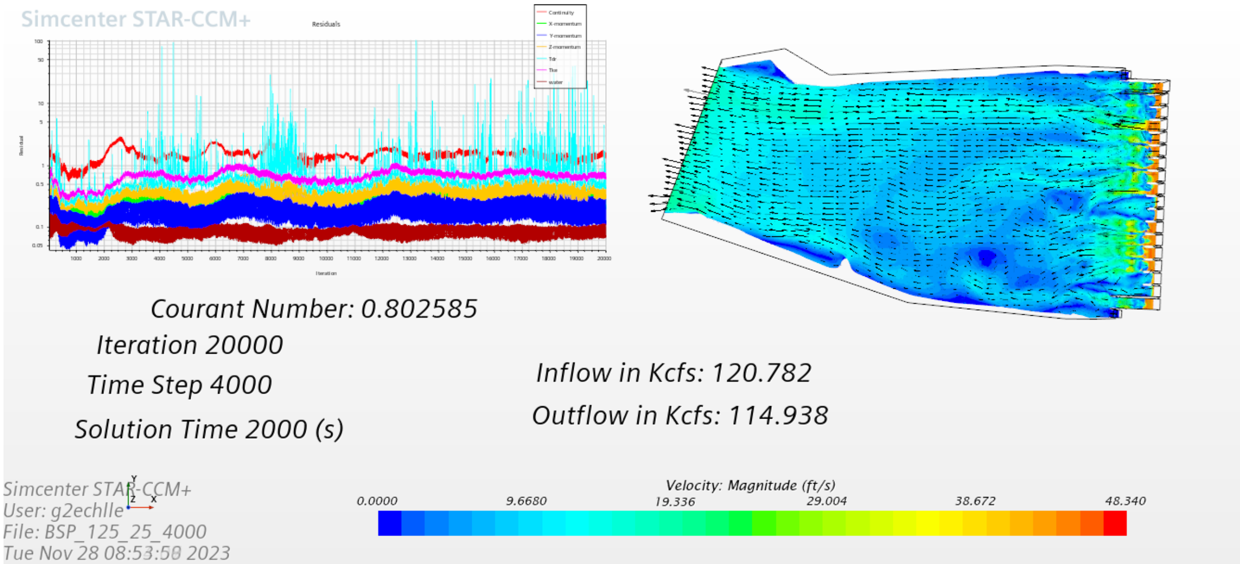

Figure 5 - CFD Model Output – 125 Kcfs Spill and 25 foot tailwater

Stilling Basin Pressure:

To evaluate the impacts on the spillway/stilling basin to high spill volumes without tailwater support the pressures on the stilling basin surfaces was probed, see Figure 6. All of the pressure plots have the same scale: – 750 psf to 4500 psf.

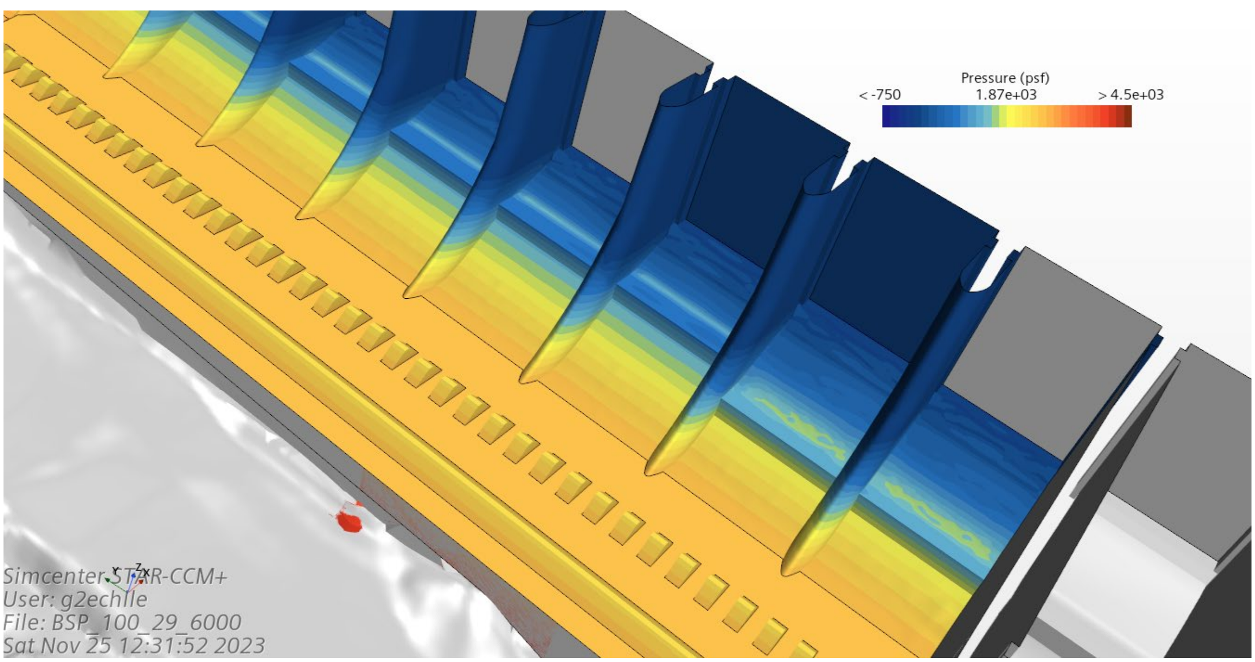

Figure 6 – Pressures on the Spillway Concrete – Results shown for 100 Kcfs Spill and a Tailwater of 29.6 feet

Figure 7 shows the same spill at a much lower tailwater (11 feet). The pressures are significantly lower at the lower tailwater scenario and cavitation damage might be initiated at the baffle blocks but it is just on the edge. The 11 foot tailwater is essentially all flow at Bonneville being routed through the spillway which is not a realistic condition. Figure 8 shows a more reasonable 100 Kcfs spill and low tailwater condition.

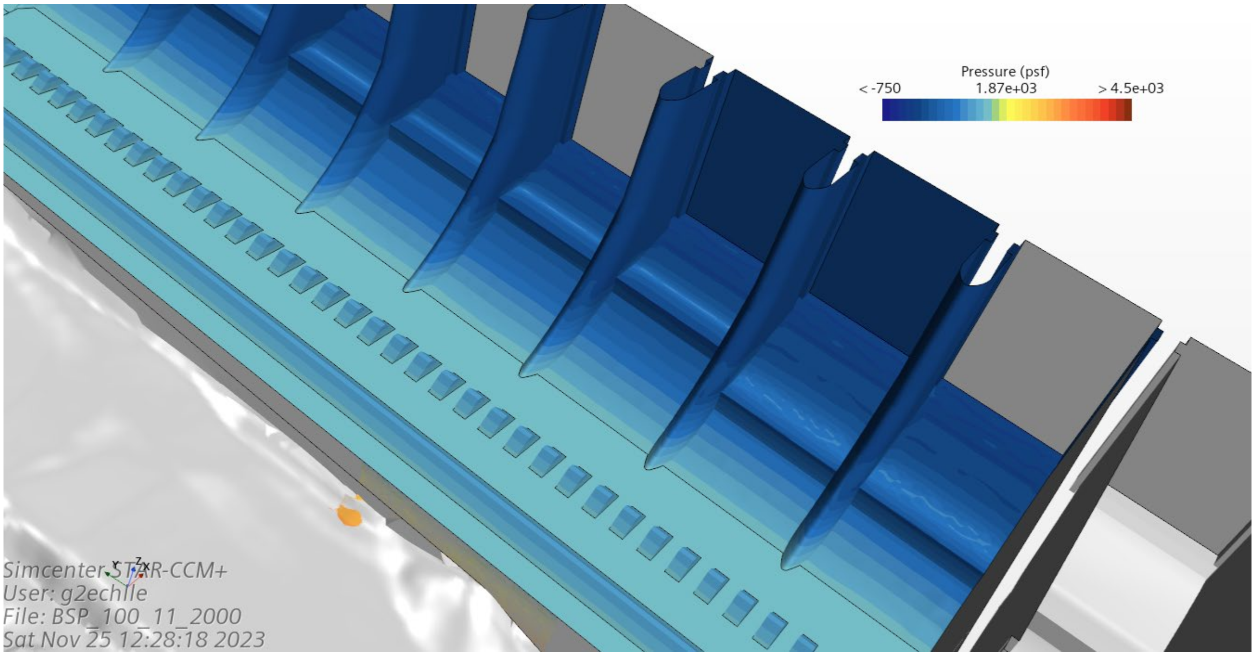

Figure 7 – Pressures on Spillway Concrete – 100 Kcfs Spill and a Tailwater of 11 feet

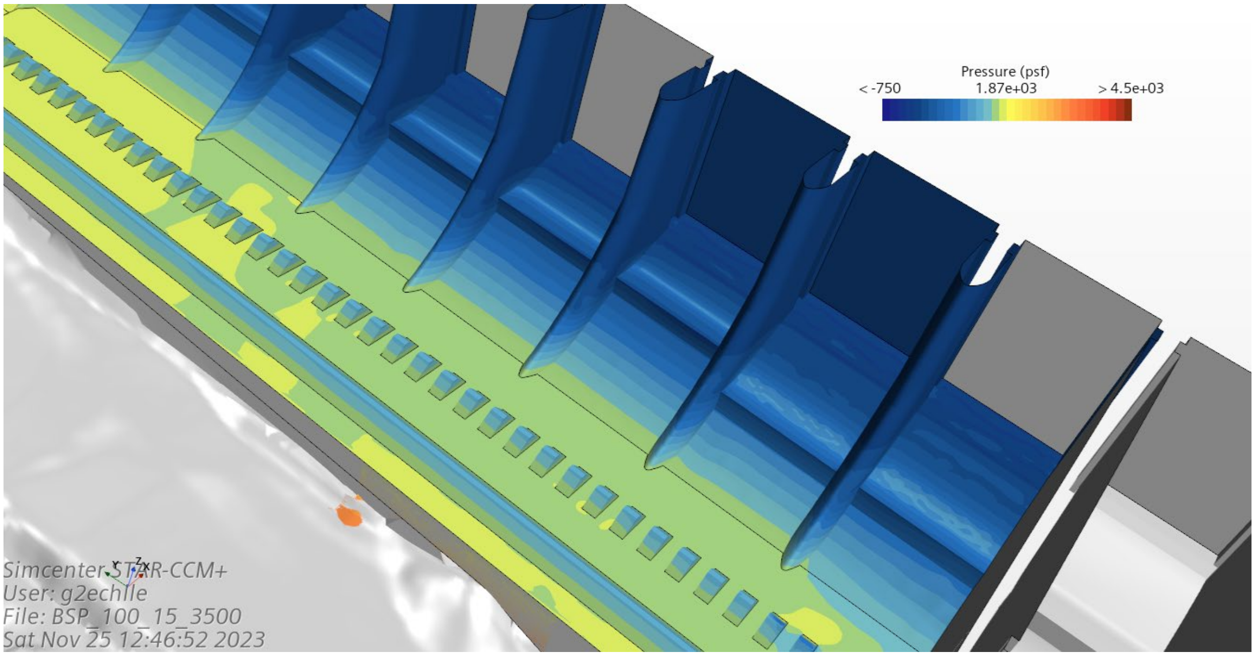

Figure 8 – Pressures on Spillway Concrete – 100 Kcfs Spill and a Tailwater at 15 feet

The range of pressures for the 200 Kcfs spill is shown in Figure 9 and Figure 10.

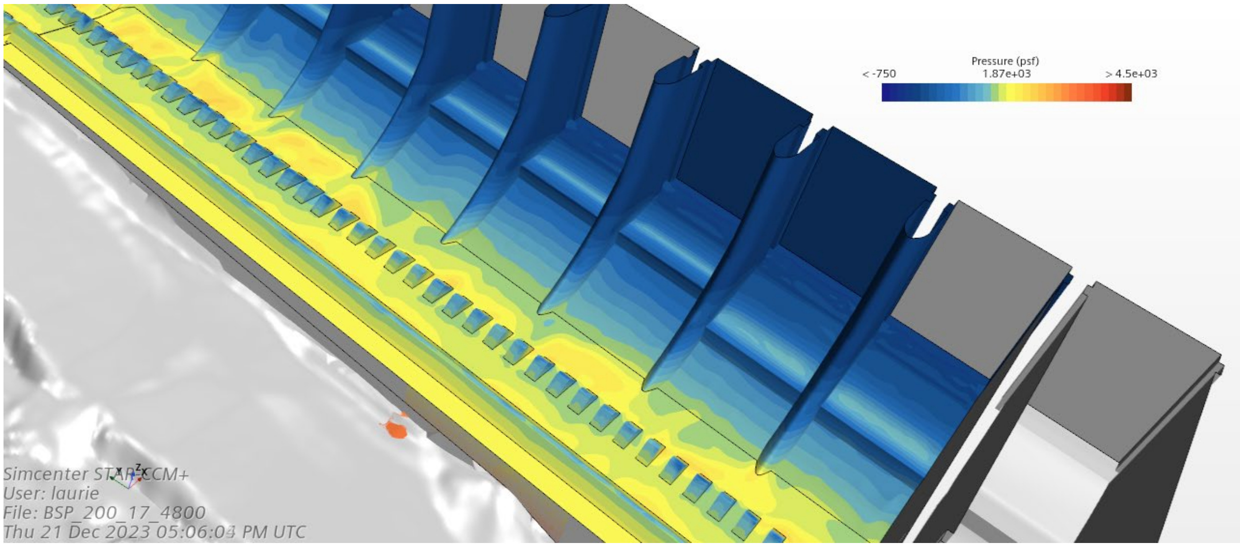

Figure 9 – Pressures on Spillway Concrete – 200 Kcfs Spill and a Tailwater at 17 feet

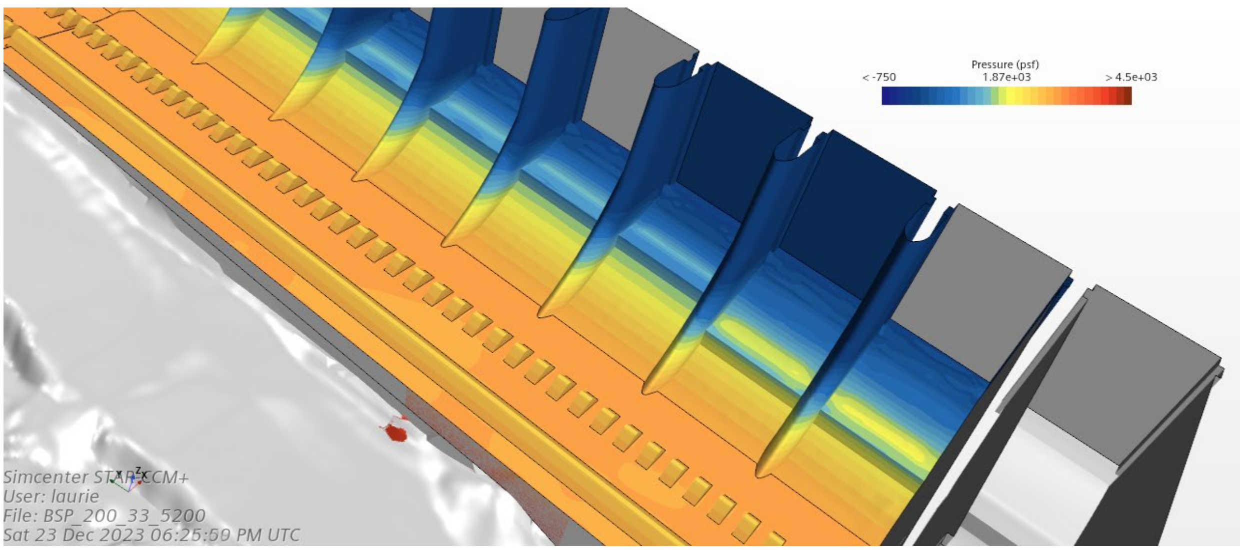

Figure 10 – Pressures on Spillway Concrete – 200 Kcfs Spill and a Tailwater of 33 feet

Results for all of the CFD runs are provided in the attached PowerPoint file. None of the CFD models executed showed stilling basin pressures that posed a dam safety risk. It had been anticipated that low pressures during high spill and low tailwater could have caused cavitation damage throughout the stilling basin, but pressures in the model runs were high enough to prevent cavitation. There were no dam safety issues associated with the flow conditions evaluated. Rocks being moved into the stilling basin and causing ball milling is still a dam safety concern and continuous monitoring is required.

TDG Characteristics:

TDG is not evaluated or predicted in this modeling effort but the characteristics of the jet off of the deflector given spill volume and different tailwater is available from the CFD results. Figure 2 shows the ideal condition for best TDG performance – the jet skims across the surface and air bubbles aren't taken to depth. If skimming flow cannot be obtained undulating flow is the next best. Figure 11 is the performance curves for the elevation 14 foot deflectors and Figure 12 is the performance curves for the elevation 7 foot deflectors. The 2023 FPP spill pattern was used in all of the CFD model runs and Table 3 provides the flow per bay. Note a saw tooth pattern at 80 Kcfs was tried – it is not the FPP spill pattern but the region was interested in what 80 Kcfs would look like with larger gate openings.

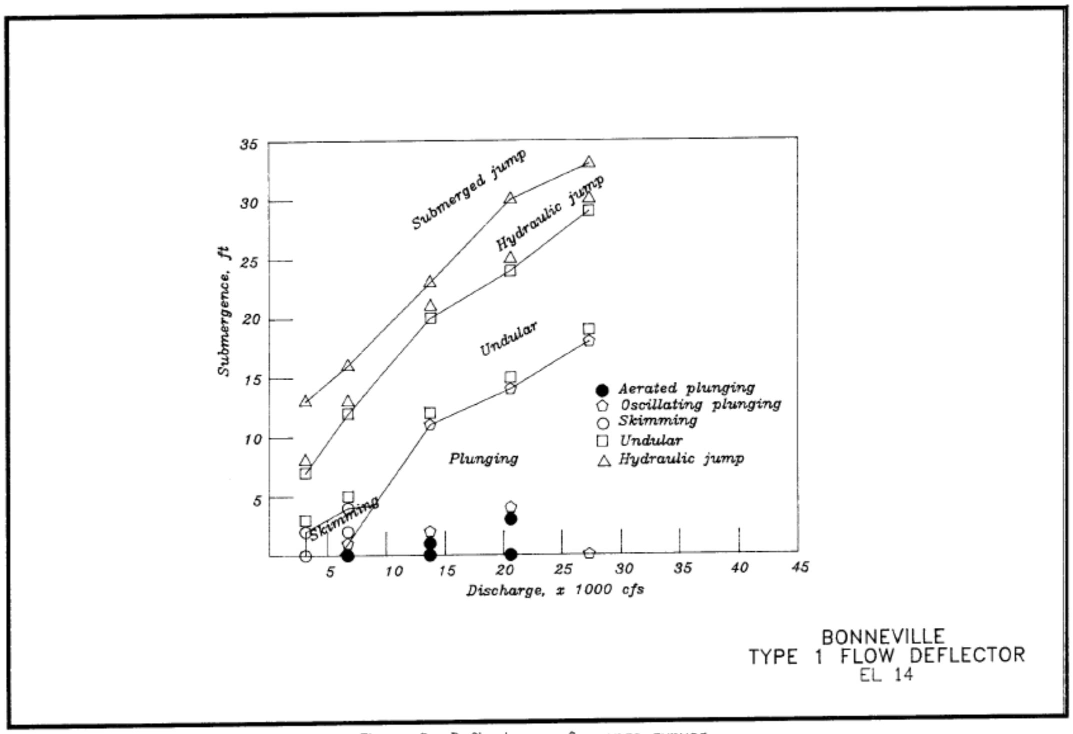

Figure 8. Deflector performance curves

Figure 11 – Bonneville Flow Deflector Performance Curves – Bays 4 - 15

Figure 6.1

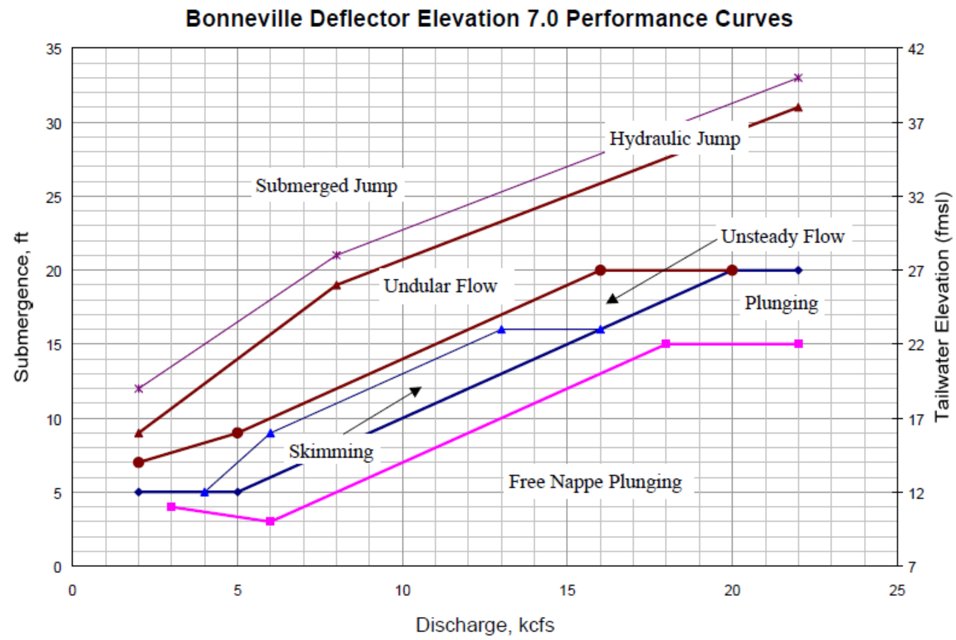

Figure 12 – Bonneville Flow Deflector Performance Curves – Bays 1-3 and 16-18

Table 3 - Spill Patterns Tested																		
1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0	13.0	14.0	15.0	16.0	17.0	18.0	Total Discharge
4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	4456	80213
8564	0	8564	0	8564	0	8564	0	5514	5514	0	8564	0	8564	0	8564	0	8564	79542
6551	6551	6551	5514	5514	5514	4456	4456	5514	4456	4456	5514	4456	5514	5514	6551	6551	6551	100183
7567	7567	7567	7567	6551	6551	6551	6551	6551	5514	5514	6551	6551	6551	6551	7567	8564	8564	124948
8564	9543	9543	8564	8564	8564	7567	7567	7567	7567	7567	7567	7567	7567	8564	9543	9543	8564	150095
8564	11447	11447	11447	11447	11447	11447	11447	11447	11447	11447	11447	11447	11447	11447	11447	11447	8564	200287

Table 4 - Flow Deflector Performance Data							
				14 foot Deflectors		7 foot Deflectors	
Spill	Min Spill per bay	Max Spill per bay	Ave Spill per bay	Min TW	Max TW	Min TW	Max TW
Kcfs	Kcfs	Kcfs	Kcfs	ft	ft	ft	ft
				Skim and Undular		Skim and Undular	
80	4456	4456	4456	17	21	12	20
100	4456	6551	5566	17	24	12	23
125	5514	8564	6942	17	26	12	26
150	7567	9543	8339	19	28	18	27
200	8564	11447	11127	19	29	19	29

Table 4 summarizes the expected results from the Performance Data (Figure 11 and Figure 12). Figure 13 shows the jets off of the flow deflectors in Bays 15 and 16 for the 100 Kcfs spill at a tailwater of 15 feet. Table 4 suggest that the 7 foot deflector should be skimming or undular and the 14 foot deflector plunging. Figure 13 does suggest that the jet off of the 7 foot deflector is on the water surface, but the flow off the 14 foot deflector is plunging.

Note: The following figures show only cells which contain at least 50% water. As a result, the highly aerated flow visible in the physical model in Figure 3, is not shown in the CFD model, since that flow is more than 50% air. These figures should be used primarily to compare CFD results to CFD results, not to TDG performance in the field.

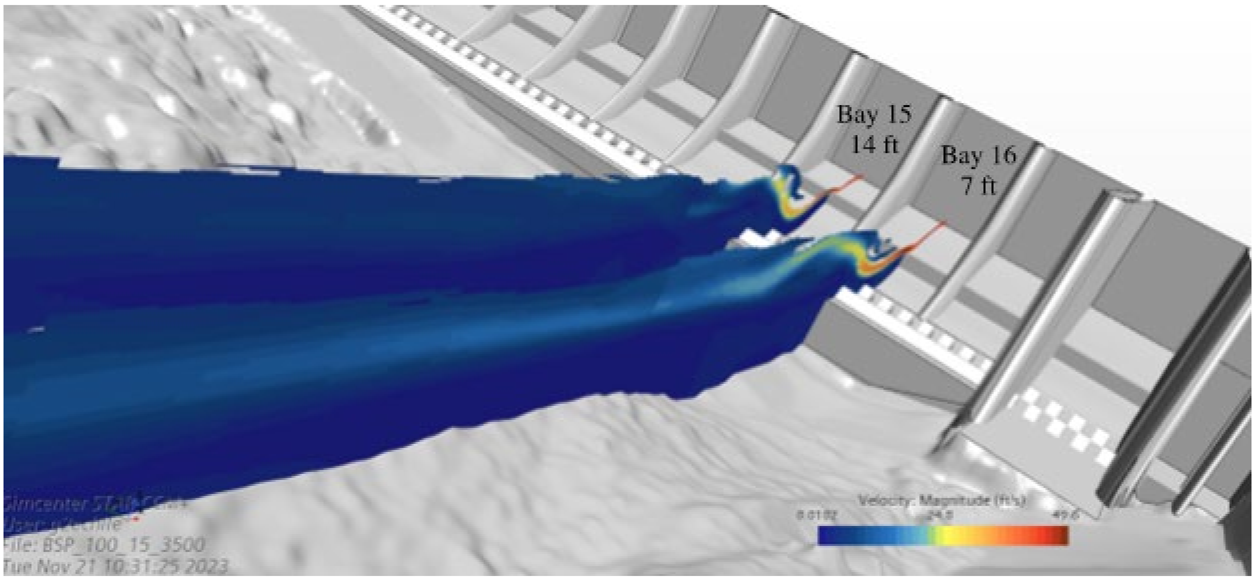

Figure 13 – Flow Deflector Jets – 100 Kcfs Spill 15 Foot Tailwater

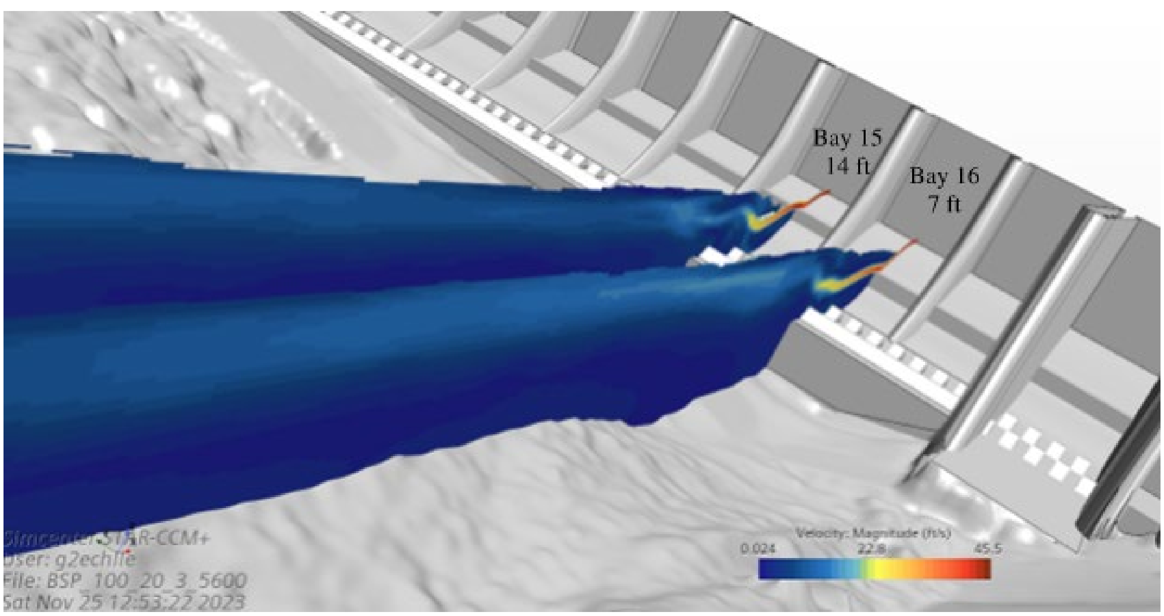

Figure 14 – Flow Deflector Jets – 100 Kcfs Spill 20.3 Foot Tailwater

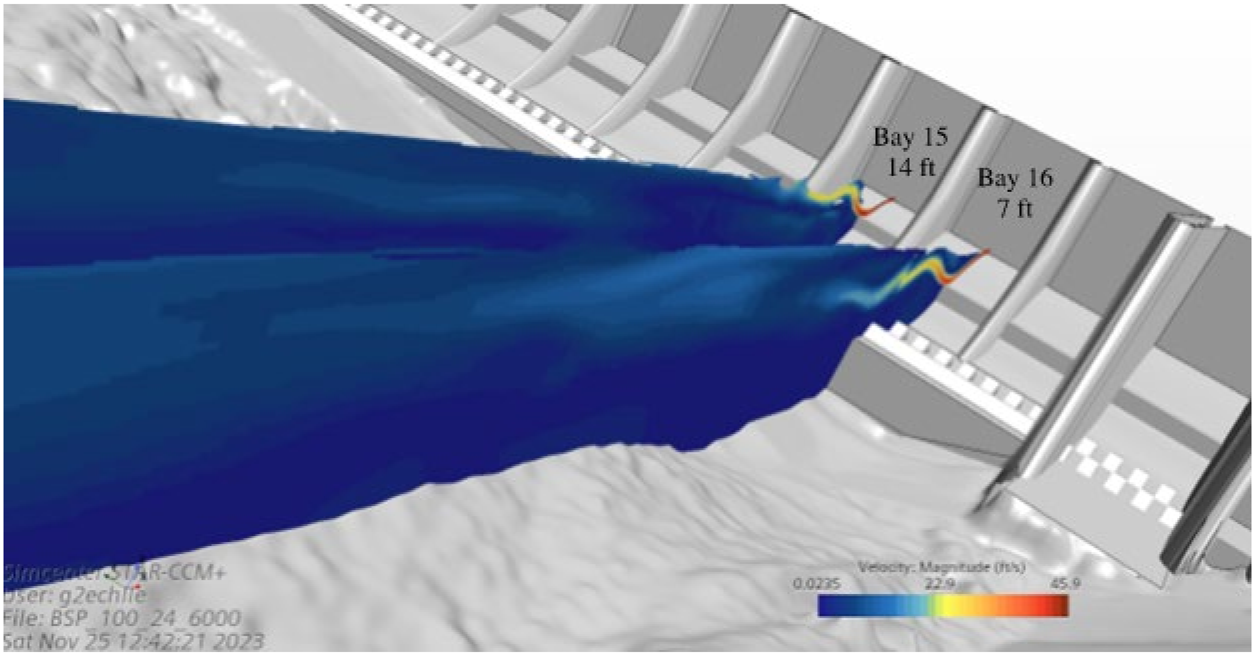

Figure 15 – Flow Deflector Jets – 100 Kcfs Spill 24 Foot Tailwater

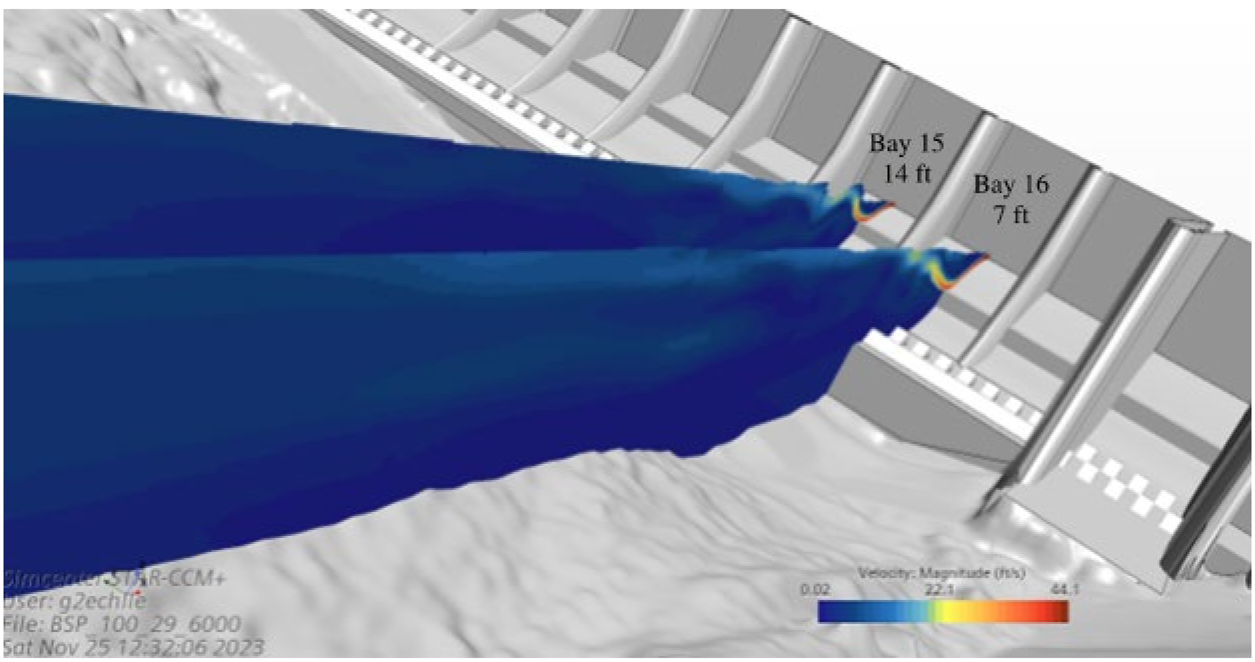

Figure 16 – Flow Deflector Jets – 100 Kcfs Spill 29 Foot Tailwater

Figure 13 through Figure 16 show flow deflector jets for 100 Kcfs spill through a range of tailwater. The 7 foot deflector appears to be in the skimming/undular flow regime for a range of tailwaters of 20.3 to 29 but at a tailwater of 29 the flow condition appears to be a hydraulic jump.

The 14 foot deflector doesn't appear to have skimming or undular flow for the tailwaters tested except for the 29 foot tailwater – but even this could be a hydraulic jump.

The PowerPoint file attached to this document has images for all of the conditions evaluated in the CFD model. Figure 17 shows a true skimming flow condition and an undular flow condition – 150 Kcfs spill and a tailwater of 20 feet. But these conditions completely change with a few more feet of tailwater – see Figure 18.

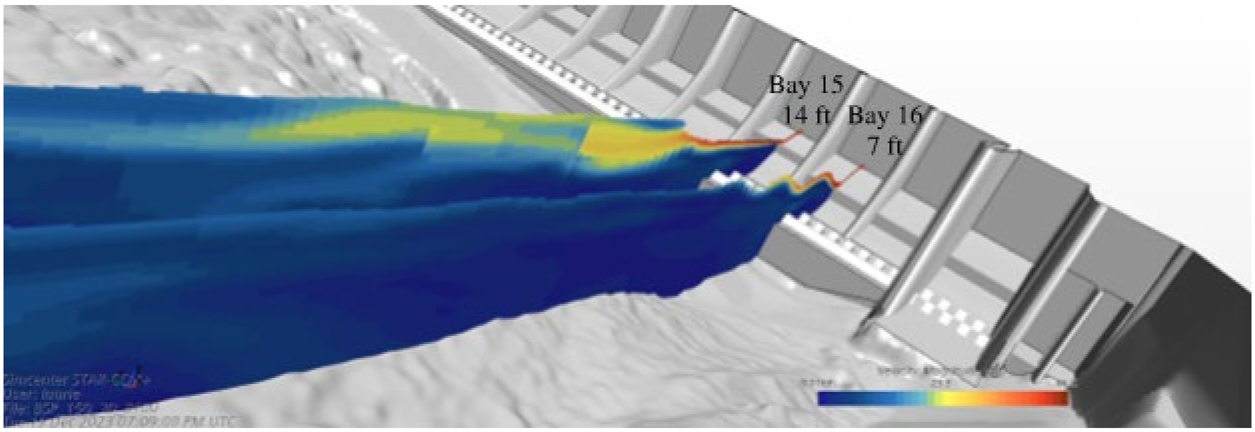

Figure 17 – Flow Deflector Jets – 150 Kcfs Spill 20 Foot Tailwater

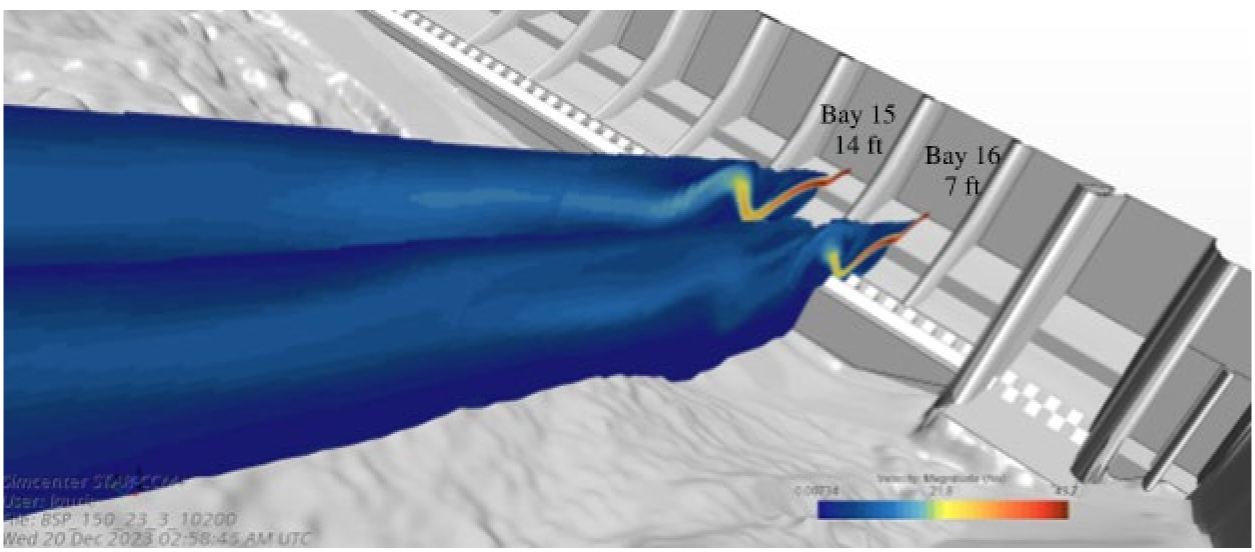

Figure 18 – Flow Deflector Jets – 150 Kcfs Spill 23.3 Foot Tailwater

Achieving the desired TDG at Bonneville is very difficult and being able to predict the TDG is even more difficult.

Juvenile Fish Passage:

Particles have not been released to represent juvenile fish – juvenile fish passage is being evaluated by looking at streamlines released at different locations in the spillway. Three zone have been created – the blue zone is in Bays 4 through 15 and is on the downstream lip of the 14 foot flow deflector, the pink zone is in Bays 1 – 3 and Bays 16 – 18 and is on the downstream lip of the 7 foot deflector and the green zone is downstream of the all of the deflectors and is the upper 10 feet of the water column (Tailwater minus 10 feet). Figure 19 shows the three zones for the 150 Kcfs spill and 23.3 foot tailwater.

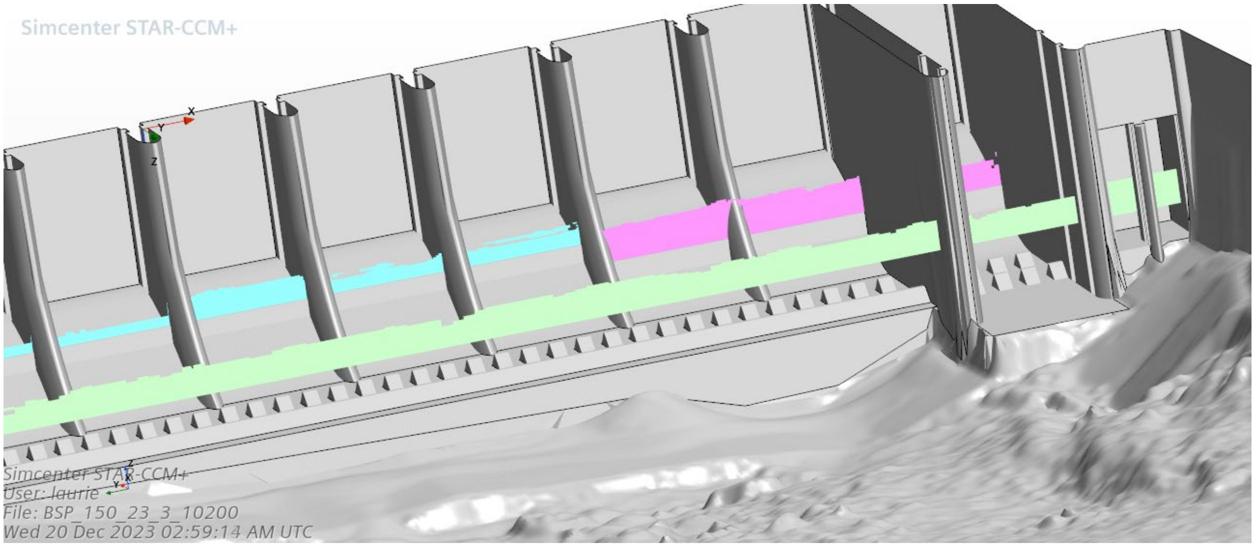

Figure 19 – Streamline release zones for 150 Kcfs spill and 23.3 ft tailwater

Figure 19 shows some fairly reasonable zones for each release but that is not always the case depending on available tailwater and spill volume, Figure 20 shows a case where the zones are very small (vertical height).

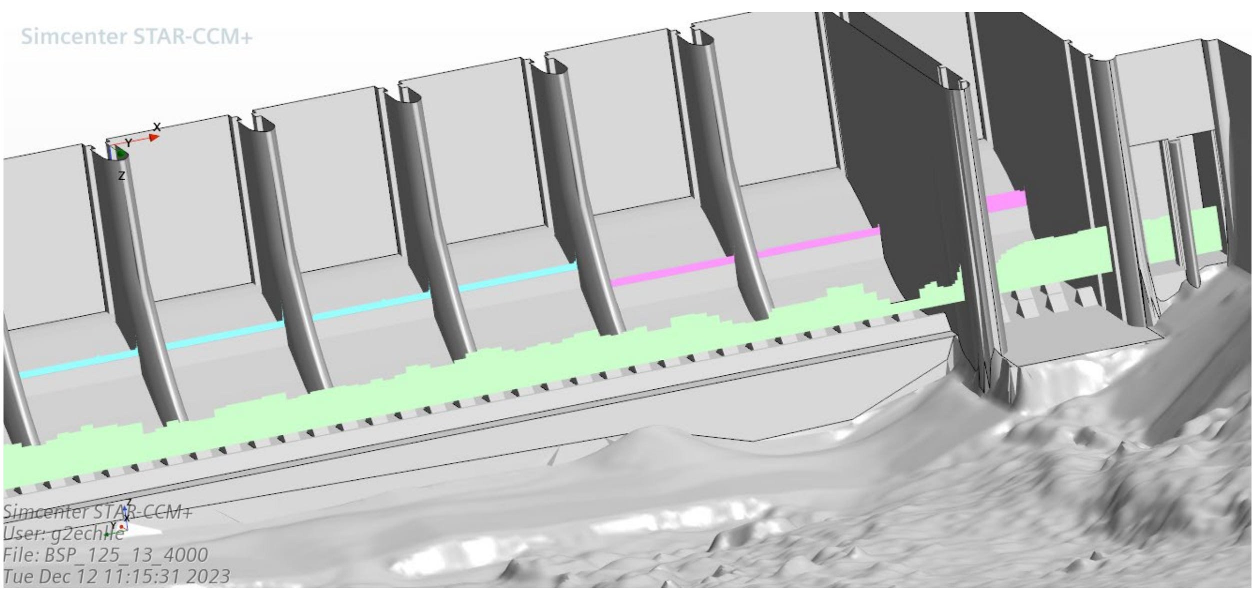

Figure 20 – Streamline release zones – 125 Kcfs Spill and a 13 foot Tailwater

Streamlines were releases in the positive flow direction – streamlines are colored to match the zone they were released from. Figure 21 shows the streamlines for a 125 Kcfs Spill and a 20 foot tailwater – from above it appears that the pink streamlines move downstream except for those that end up under the 14 foot deflectors jets. The green streamlines seem to move downstream but get caught in the eddies but where are the blue streamlines – bays 4 and 5 appear to have a good number of streamlines moving downstream but what about the other bays?

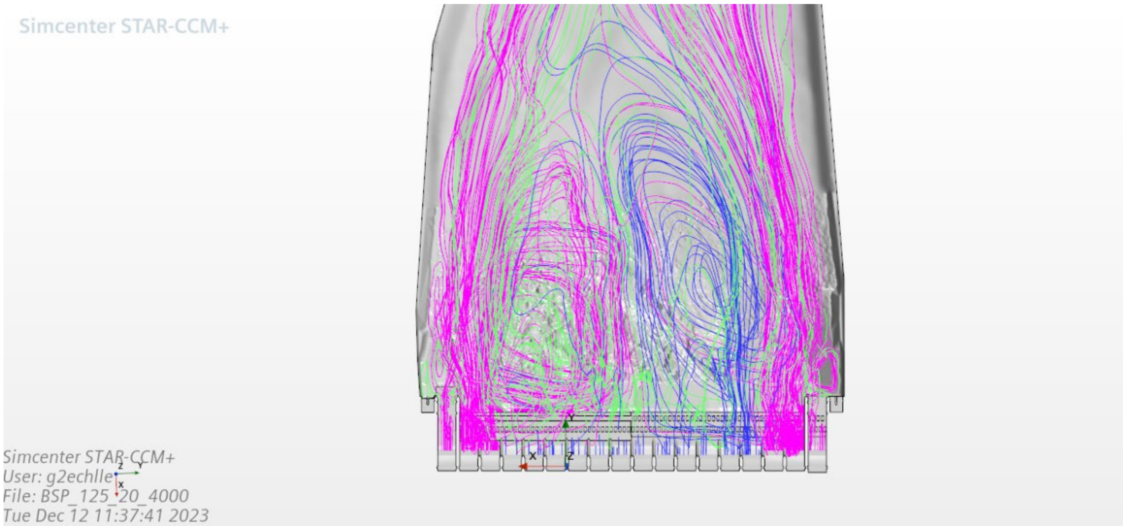

Figure 21 - Streamlines 125 Kcfs Spill and a 20 foot Tailwater

A closer look at this is shown in Figure 22. The blue streamlines are leaving the model – they are ending up in cells without sufficient water to move them. Essentially the water depth is too thin. The other thing Figure 21 points out is the movement of flow from bays 16 and 17 towards the north and supporting the elevation 14 foot flow deflector jets.

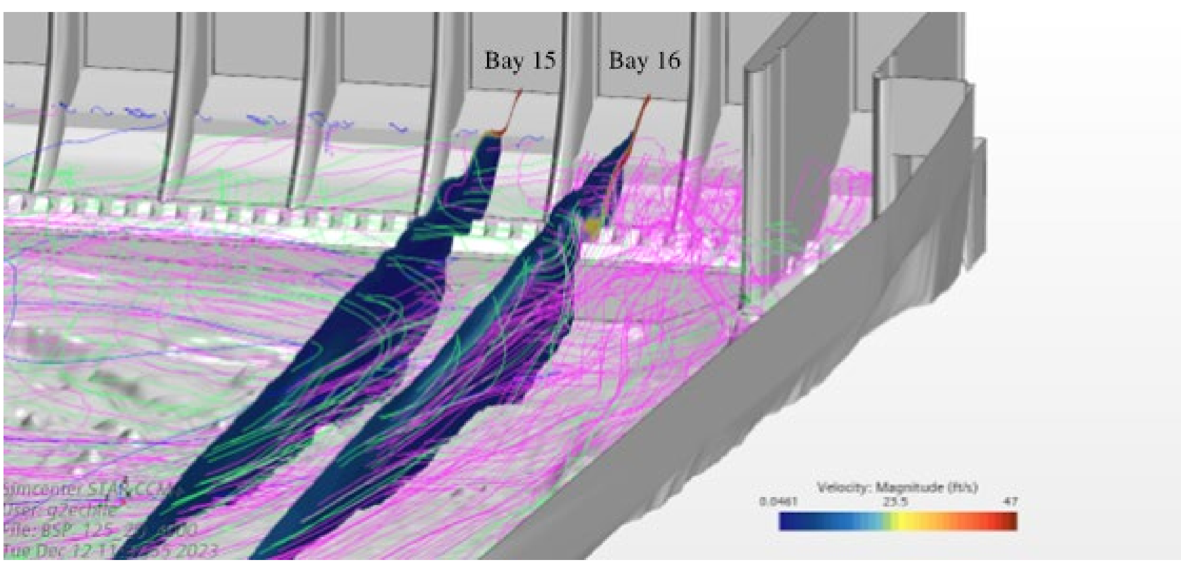

Figure 22 – Streamlines 125 Kcfs Spill and a 20 foot Tailwater side view

Images for all of the CFD model runs are in the attached PowerPoint file. Figure 23 through Figure 26 show conditions where the general movement of the streamlines was downstream.

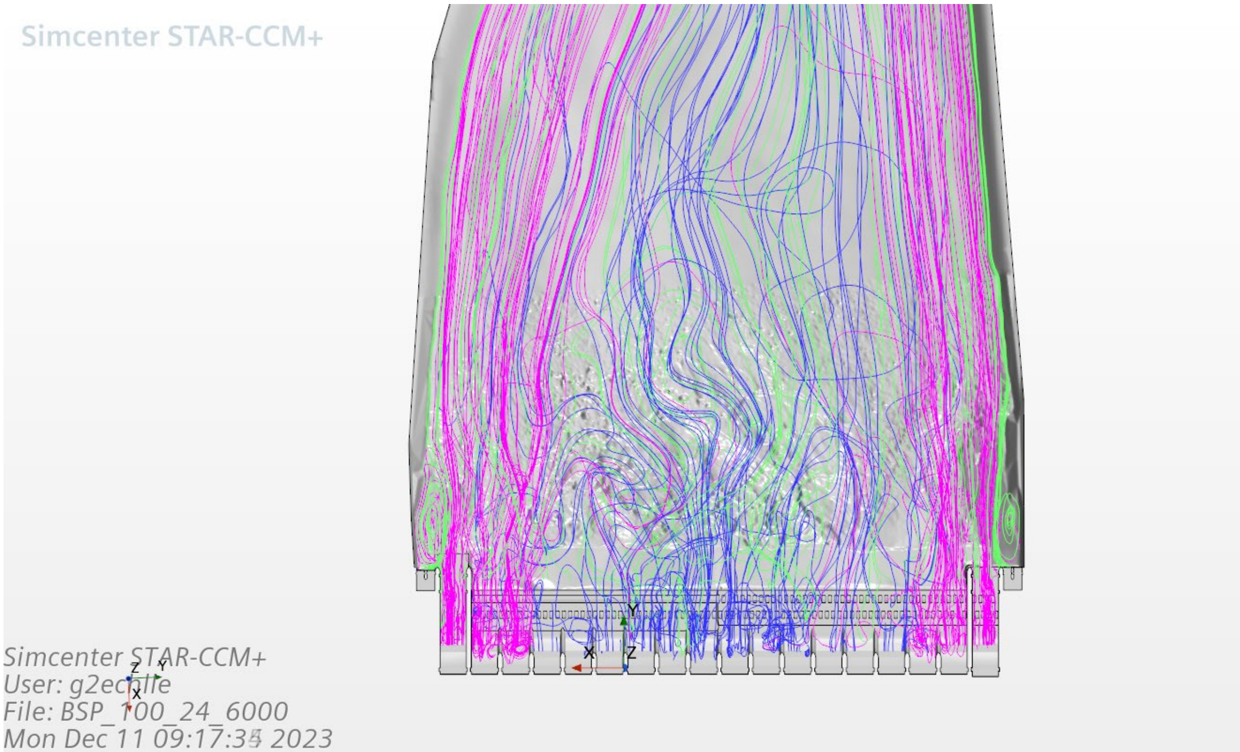

Figure 23 – Streamlines for 100 Kcfs Spill and 24 foot Tailwater

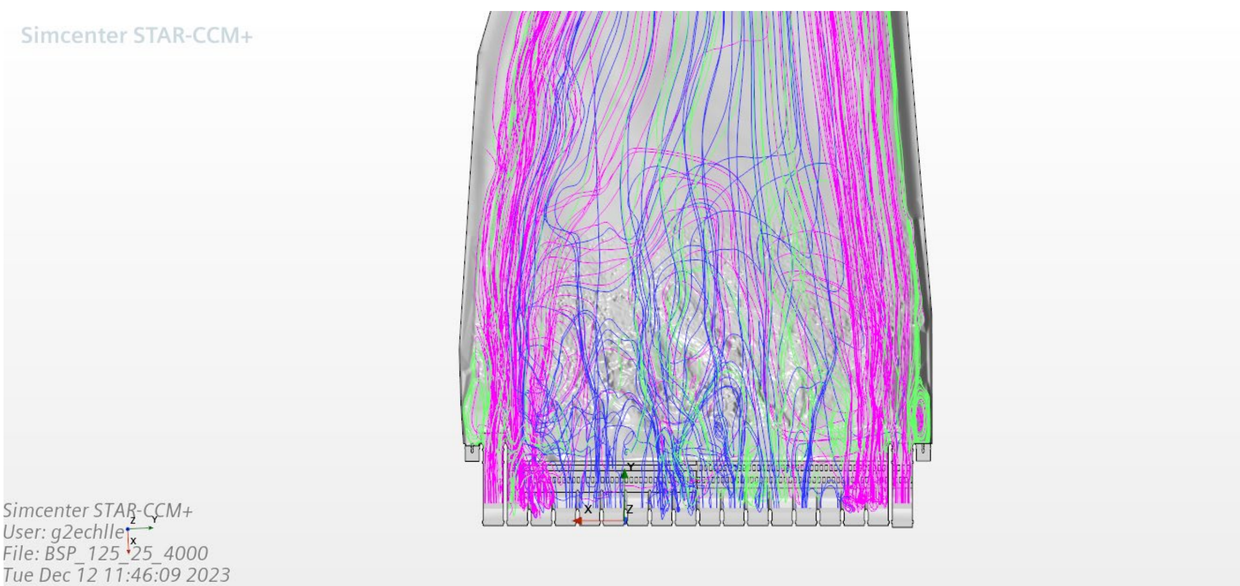

Figure 24 – Streamlines for 125 Kcfs Spill and 25 foot Tailwater

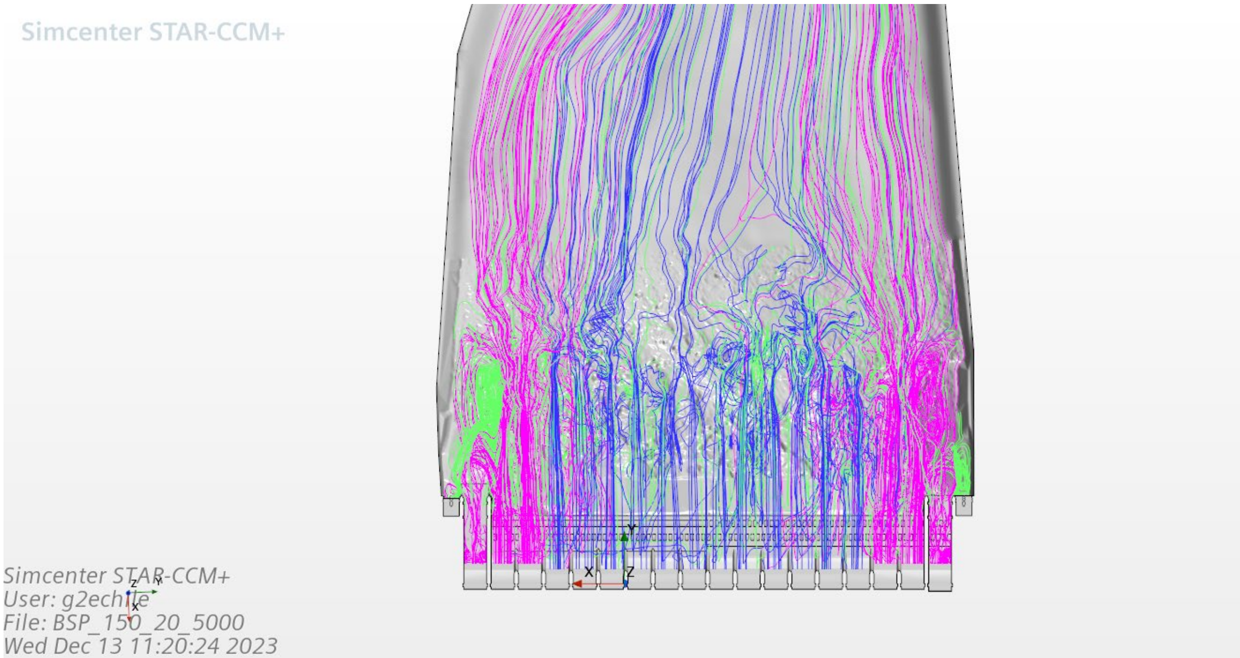

Figure 25 – Streamlines 150 Kcfs Spill and 20 foot Tailwater

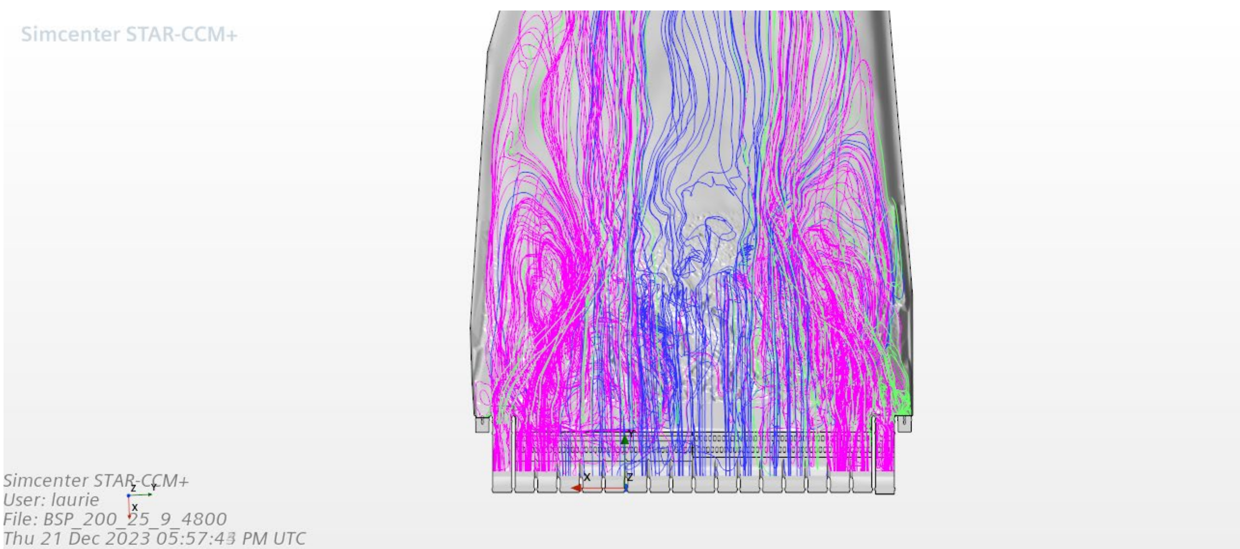

Figure 26 – Streamlines 200 Kcfs Spill and 25.9 foot Tailwater