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Computational Fluid Dynamics Modeling of the Bonneville Project: Tailrace Spill Patterns for Low Flows and Corner Collector Smolt Egress

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2010

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Computational Fluid Dynamics Modeling of the Bonneville Project: Tailrace Spill Patterns for Low Flows and Corner Collector Smolt Egress

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Prepared for
the U.S. Army Corps of Engineers, Portland District
Portland, OR

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Richland, Washington 99352

Summary

In 2003, an extension of the existing ice and trash sluiceway was added at Bonneville Powerhouse 2 (B2). This extension started at the existing B2 Corner Collector (B2CC) for the ice and trash sluiceway adjacent to Bonneville Powerhouse 2 and the new sluiceway was extended to the downstream end of Cascade Island. The sluiceway was designed to improve juvenile salmon survival by bypassing turbine passage at B2, and placing these smolt in downstream flowing water minimizing their exposure to fish and avian predators. The original model work assumed there would be flows through the spillway; these flows improve juvenile egress. Concerns with low spill flows have raised the question of how much spill is required to have good egress through the B2CC.

In this study, a previously developed computational fluid dynamics model was modified and used to characterize tailrace hydraulics and sluiceway egress conditions for low total river flow and low levels of spillway flow. STAR-CD v4.10 (CD-adapco, Computational Dynamics Limited 2009) was used for seven scenarios of low total river flow and low spill discharges.

The simulation results were specifically examined to look at tailrace hydraulics at 5 ft below the tailwater elevation, and streamlines used to compare streamline pathways for streamlines originating in the corner collector outfall and adjacent to the outfall. These streamlines indicated that for all higher spill percentage cases (25% and greater) that streamlines from the corner collector did not approach the shoreline at the downstream end of Bradford Island. For the cases with much larger spill percentages, the streamlines from the corner collector were mid-channel or closer to the Washington shore as they moved downstream. Although at 25% spill at 75 kcfs total river, the total spill volume was sufficient to “cushion” the flow from the corner collector from the Bradford Island shore, areas of recirculation were modeled in the spillway tailrace. However, at the lowest flows and spill percentages, the streamlines from the B2 corner collector pass very close to the Bradford Island shore. In addition, the very low velocity areas and large areas of recirculation greatly increase potential predator exposure of the spillway passed smolt to predation. For low spill volumes, spill patterns should be modified to maximize egress conditions for the B2CC.

Acknowledgments

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Abbreviations and Acronyms

ABBREV	DEFINITION
2D	two dimensional
3D	three dimensional
ADCP	acoustic Doppler current profiler
B2	Bonneville Powerhouse 2
B1	Bonneville Powerhouse 1
B2CC	Bonneville Powerhouse 2 Corner Collector
CENWP	U.S. Army Corps of Engineers, Portland District
CFD	computational fluid dynamics
ft	feet
kcfs	Thousand cubic feet per second
MARS	monotone advection and reconstruction scheme
PNNL	Pacific Northwest National Laboratory
RANS	Reynolds-averaged Navier Stokes
USACE	U.S. Army Corps of Engineers
UD	Upwind difference
VOF	volume of fluid

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1.0 Introduction

In 2003, an extension of the existing ice and trash sluiceway was added at Bonneville Powerhouse 2 (B2). The sluiceway entrance is adjacent to B2 near Cascade Island, and is better know as the "corner collector" (B2CC). Flow enters the B2CC from the project forebay and the new sluiceway extends from the existing ice and trash sluiceway corner collector to an outfall at the downstream end of Cascade Island (see Figure 1.1). The hydraulics at the outfall location are influenced by B2 operations and the spillway flows. The sluiceway was designed to improve juvenile salmon survival by bypassing turbine passage at B2, and placing these smolt in downstream flowing water minimizing their exposure to fish and avian predators. The original model work assumed there would be flows through the spillway; these flows improve juvenile egress. Concerns with low spill flows have raised the question of how much spill is required to have good egress through the B2CC.

Previous work by Pacific Northwest National Laboratory (PNNL) for the US Army Corps of Engineers (USACE) Portland District (CENWP) used computational fluid dynamics (CFD) modeling to characterize tailrace hydraulics for a variety of flows and several proposed high-flow outfall locations (Rakowski et al. 2001). The models created were rigid-lid models with the various outfall locations included in the mesh. The numerical model was validated to existing field-measured velocities. Based on the results found in the physical and numerical models, one of the sluiceway construction alternatives was chosen and built.

Over the last eight years, there have been many improvements to software capabilities and increases in available computational resources (speed, memory, and data storage). A numerical model that was computationally expensive in 2003 is, for computational resources available today, a model that runs quickly. Now it becomes possible to take the model which ran as a rigid-lid model and make it a free-surface model capable of modeling a full range of water surface elevations without remeshing and to have the free water surface to include the spillway jets, the sluiceway inflows, and a water surface that varies through the reach.

With the B2 corner collector (B2CC) and its sluiceway operating, there have been questions of the optimal project operations for smolt survival especially for low flow scenarios. The corner collector outfall was sited with the intention that there be flow from both B2 and the spillway to move the smolt downstream and away from predators in the near-shore areas. However, in low flow periods, there is not much water available for spill so the spillway operations need to be adjusted to get the most egress improvement with the least amount of spillway flow.

The objective of this study was to characterize tailrace hydraulics and sluiceway egress conditions for low total river discharge and low levels of spillway flow.

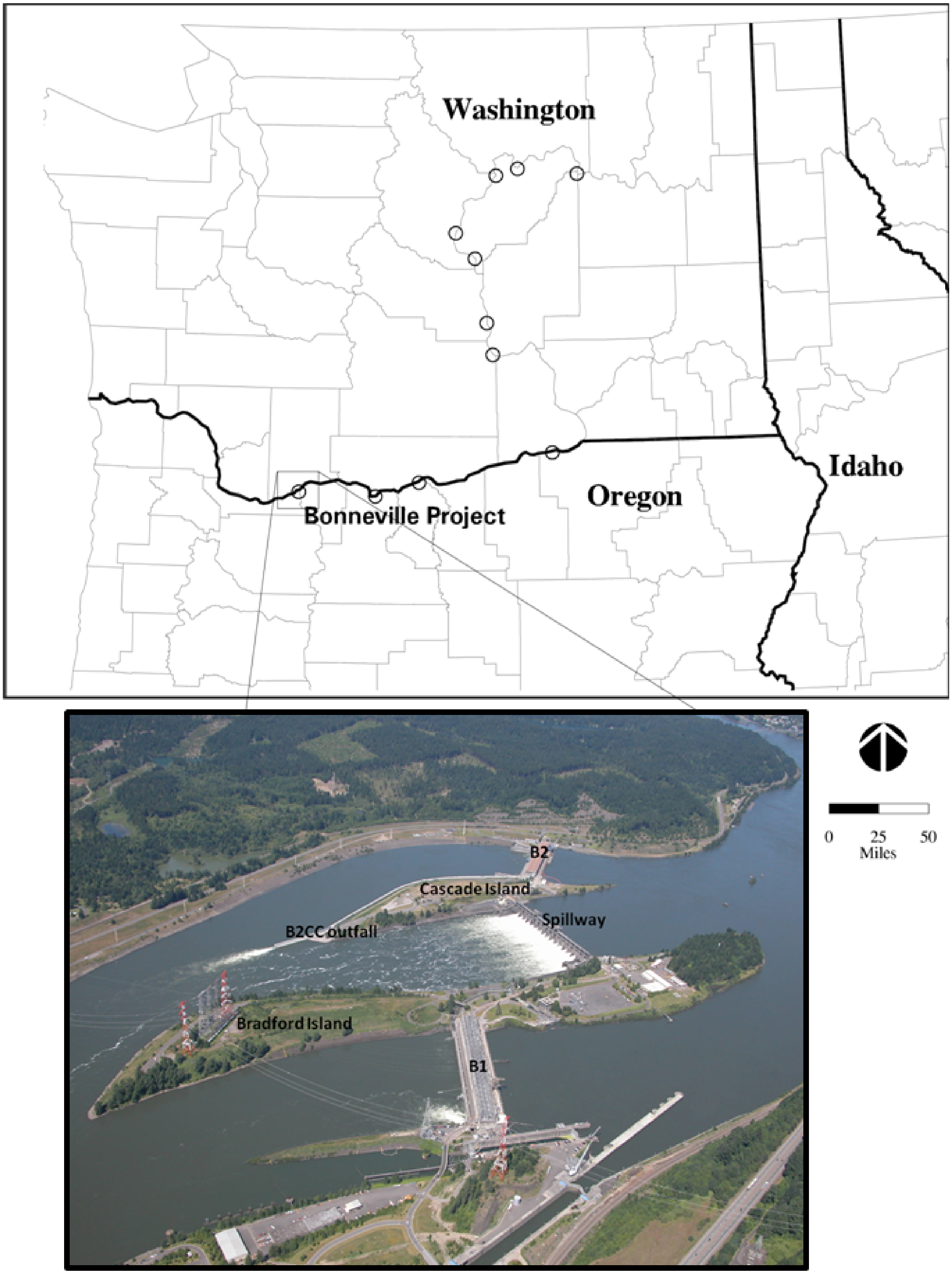

Figure 1.1. Location of the Bonneville Project and its features. Flow is from right to left; the Washington shore is in the upper portion of the photo. The B2CC outfall is at the downstream end of Cascade Island.

2.0 Methods

This work used a commercial CFD code, STAR-CD v4.10 (CD-adapco, Computational Dynamics Limited 2009), to solve the Reynolds-averaged Navier Stokes (RANS) equations for fluid flow. This work followed the modeling approach used in Rakowski et al. (2008) and Rakowski et al. (2010) although an existing computational mesh intially designed for steady-state, rigid-lid flow, was used. The computational mesh used for wall-loading calculations at flood flows for the chosen high-flow outfall alternative (see Rakowski et al. 2001) was modified for this study. The flood-flow model was chosen as the computational mesh included higher elevation area of the shore that were not included in the other models with lower tailwater elevation. This mesh made it possible to have a free surface which could be run for a large range of water surface elevations in the tailrace.

The existing model was modified and improved in several ways.

- A sluiceway inflow was added that was sufficiently far inside the sluiceway channnel to allow a water surface elevation to evolve.
- The computational mesh near the shorelines was refined in plan view to reduce their aspect ratio.
- The cells near the range of expected water surface elevations were refined in the vertical to provide better resolution of the air / water interface.
- The spillway was modified to add a section of hexahedral cells with increased resolution in all dimensions.
- Spillway boundaries were located in such a way as to include the elevation of the deflectors and as part of the inflow boundary conditions.
- Downstream boundary was modified to be hydrostatic with a specified water surface elevation.

2.1 Numerical Model Configuration

As in the Rakowski et al. (2008) work, STAR-CD version 4.10 (CD-adapco, Computational Dynamics Limited 2009) was used as the flow solver.

The models were run with steady boundary conditions but the solver was run in the transient mode. The free surface in the model was simulated with the volume of fluid (VOF) method. A k-ε high-Reynolds-number turblence closure and a standard wall function. Algebraic Multigrid for pressure was not used; the conjugate gradient (CG) algorithm is more robust. Upwind differencing (UD) was used for momentum and turbulence, and relaxation coefficients of 0.7, 0.3, 0.7 for momentum, pressure, and turbulence quanitities, respectively and the cell quality remediation was used. Although using a second order differencing scheme is theoretically the preferred approach, PNNL's experience with this version of the STAR-CD code is that the more dissipative UD gives more reasonable solutions for these VOF runs.

The inflows were specified as velocities orthogonal to the boundaries; flow velocities were calculated from flow discharge and boundary area. The downstream boundary was specified in user coding as a hydrostatic boundary with a specified water surface elevation. For these two-phase VOF simulations, it is necessary to add a large volume of air over the river; this is required for model stability. The convergence of the model was assessed by overall momentum and mass residuals as well as the outflow volume at the downstream boundary.

2.2 Scenarios

A total of seven scenarios were run: a baseline case with higher flows and larger spill percentages (116.5 kcfs, 64% spill), but the most of the cases focused on a single flow volume (75 kcfs total river) for a variety of spill percentages and flow distributions. Table 2.1 details the operations for each scenario.

2.3 Analysis of Simulation Data

Simulation results graphics were used to show overall tailrace hydraulics and particle streamlines. Particle streamlines represent the trajectories of massless, neutrally-buoyant particles. These streamlines characterize hydrodynamics, not fish movement. Each scenario had an overall graphic with vectors and contoured velocity magnitude at an elevation 5 ft below the specified downstream tailwater elevation. Also shown in these graphics were streamlines of particles released in the B2CC outfall and in the spillway tailrace.

For the baseline and cases 1 through 5, a second graphic was developed that shows vectors at an elevation 5 ft below the tailwater elevation, gray-shaded bathymetry, and streamlines for particles seeded in the corner collector outfall and at seven locations adjacent and just downstream of the corner collector outfall; the seven seed locations extended from just downstream of the outfall to about half way across the spillway tailrace. The seven seeded locations had streamlines run both upstream and downstream for consistency. These streamlines were used to determine if the flows from the corner collector passed near or impinged upon the downstream Bradford Island shore.

Table 2.1. Bonneville Scenarios

Case:	Baseline	Case 2	Case 3	Case4	Case5	Case 6	Case 7
Tailwater	11 ft	9 ft	7 ft	7 ft	7 ft	7 ft	7 ft
Unit			**Flow in kcfs**				
Unit 11	17.5	17.5	16	16	16	16	16
Unit 12	0	0	0	0	0	0	0
Unit 13	0	0	0	0	0	0	0
Unit 14	0	0	0	0	0	16	15.5
Unit 15	0	0	0	0	0	17	15.5
Unit 16	0	0	0	0	0	0	0
Unit 17	0	0	17	17	17	0	0
Unit 18	17.5	17.5	17	17	17	17	16
PH2 Total	35	35	50	50	50	66	63
B2CC	5	5	5	5	5	5	5
B2 Total	40	40	55	55	55	71	68
B1, All Units	0	0	0	0	0	0	0
ICE	1.5	1.5	1	1	1	1	1
S1	4.5	4.5	4.5	4.5	4.5	1.5	4.5
S2	5.5	4.5	0	0	5.5	0	0
S3	4.5	4.5	0	0	4.5	0	0
S4	4.5	0	0	0	0	0	0
S5	4.5	4.5	0	0	0	0	0
S6	4.5	0	0	0	0	0	0
S7	4.5	0	0	0	0	0	0
S8	4.5	4.5	0	5	0	0	0
S9	0	0	0	5	0	0	0
S10	4.5	4.5	0	0	0	0	0
S11	4.5	0	0	0	0	0	0
S12	0	0	0	0	0	0	0
S13	4.5	4.5	0	0	0	0	0
S14	4.5	4.5	0	0	0	0	0
S15	4.5	0	0	0	0	0	0
S16	5.5	4.5	4.5	0	0	0	0
S17	5.5	5.5	5.5	0	0	0	0
S18	4.5	4.5	4.5	4.5	4.5	1.5	1.5
Spill Total	75	50.5	19	19	19	3	6
TOTAL FLOW	116.5	92	75	75	75	75	75

3.0 Results and Discussion

This study focused on characterizing the interaction between flow from Bonneville Powerhouse 2, the spillway, and the B2 corner collector. The numerical model was used to simulate seven scenarios (Table 2.1) from a total river of 116.5 kcfs (64% spill) baseline, to low river flow (75 kcfs) and spill percentages between 4% and 25%. The objective of this study was to assess if there were spillway flows and spill patterns for which streamlines seeded in the corner collector passed near the shore of Bradford Island. The close proximity to shore could indicate a possible greater exposure to predators during tailrace egress.

For each scenario, graphics were produced. Contours of velocity magnitude and vectors are plotted for the overall modeled flow 5 ft below the water surface (upper plots, Figures 3.1 to 3.5. Streamlines seeded in the B2CC outfall (fuschia) and between the B2CC outfall and Bradford Island shore (red) are also shown. The latter seed locations were traced upstream and downstream from the seed location to show general spillway tailrace hydraulics. A second graphic was produced (lower plots, Figures 3.1 to 3.7) that included the B2CC-seeded streamlines and streamlines seeded closer to the B2CC over gray-shaded bathymetry.

In the baseline scenario (Figure 3.1), there is a large percentage of the flow in spill. The streamlines from the corner collector are closer to the Washington shore but are in the higher velocity downstream flow (as desired) rather than in the low velocities near the shorelines.

Case 2 also had a large spill percentage of the flow as spill (55%). Again, the spill flow is sufficient to move streamlines from the corner collector to midchannel and away from the Bradford Island shore, although the streamlines are closer than in the baseline case. (Figure 3.2).

Cases 3, 4, and 5 have the same total river and spill percentage (75 kcfs with 25% spill) but use different spillway distributions. Case 3 (Figure 3.3, top) concentrated spill at the southern bays along the Bradford Island shore, Case 4 (Figure 3.4, top) used the end bays and two bays in the middle, and Case 5 (Figure 3.5, top) concentrated flow at the northern bays near Cascade Island (see Table 2.1 for details).

In general, for the 75 kcfs total river flow with 25% spill (Cases 3, 4, and 5), there was not sufficient flow for the spillway tailrace to be without large areas of recirculation. When the flow was concentrated on the Bradford Island shore (Case 3), streamlines from those bays crossed the spillway tailrace and there were large areas of recirculation along both the Cascade and Bradford Island shorelines (Figure 3.3, bottom). When half the spillway flow was through the center bays (Case 4), there were again large areas of recirculation within the spillway tailrace, however the streamlines not entrained in recirculation zone had a shorter streamline path length (Figure 3.4, bottom). Concentrating flow on the Cascade shore (Case 5) had very large areas of recirculation and circuitous streamlines (Figure 3.5, bottom). However, if one compares the lower figures for Cases 3 to 5, the corner collector streamlines are virtually unchanged for these cases.

Case 6 and Case 7 had very low flow spill percentages (4% and 6%, respectively). For both of these cases (see Figures 3.6 and 3.7), there is not adequate flow through the spillway to counter the the recirculation across the downstream end of the spillway tailrace (between the downstream ends of Bradford and Cascade Island.   With the downstream flow from Powerhouse 2 and the Corner Collector outfall, the spillway tailrace is like a driven cavity with a large area of recirculation.   The extent of recirculation into the spillway tailrace appears to be controlled by bathymetry and the planform aspect ratio..

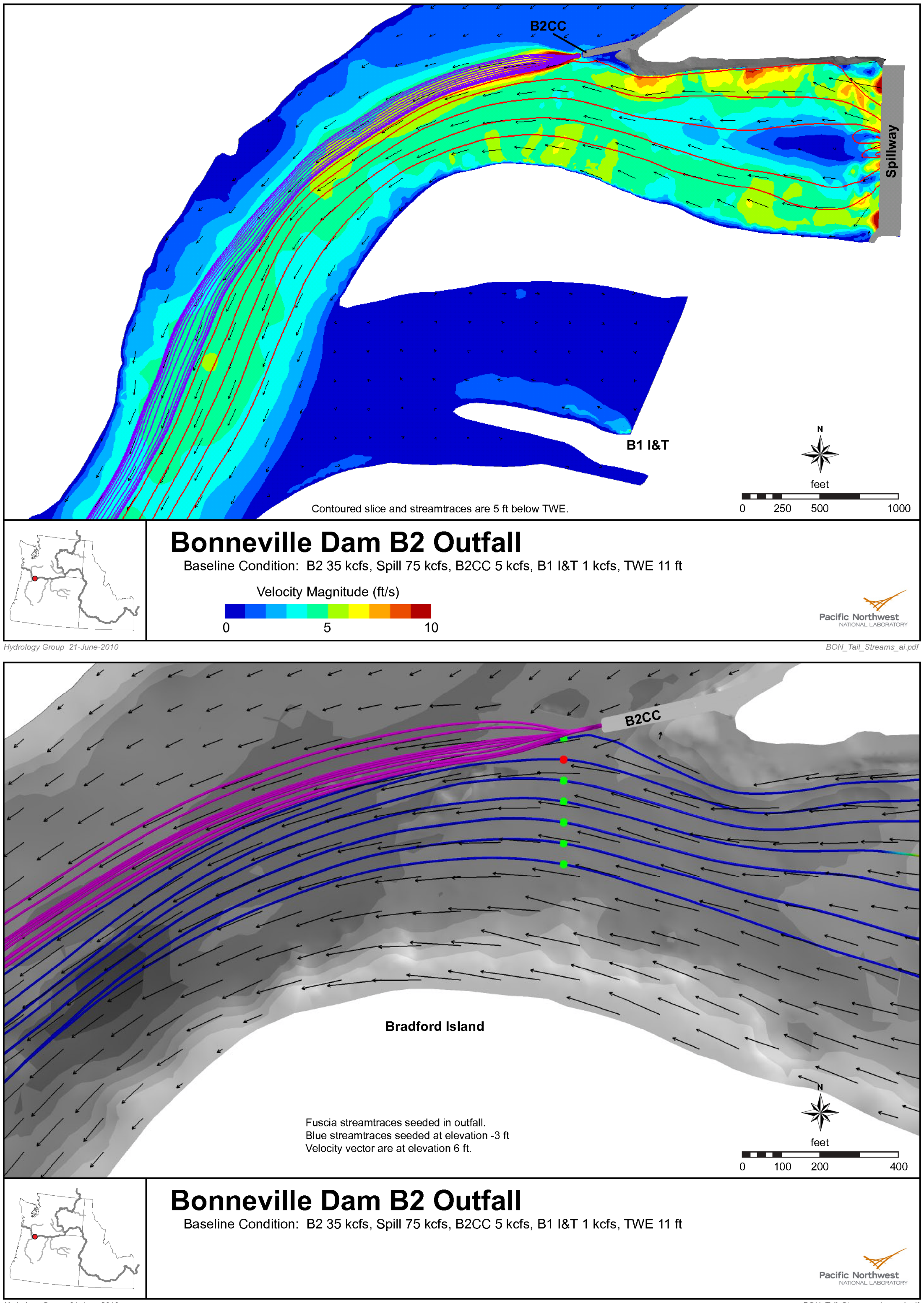

Figure 3.1. Baseline simulation results showing contours of velocity magnitude 5 ft below the water surface (upper) and streamlines seeded in the spillway tailrace(red, top), the B2CC outfall (fuschia, upper and lower) and those seeded in the spillway tailrace adjacent to the B2CC outfall (blue, lower) on gray-shaded bathymetry.

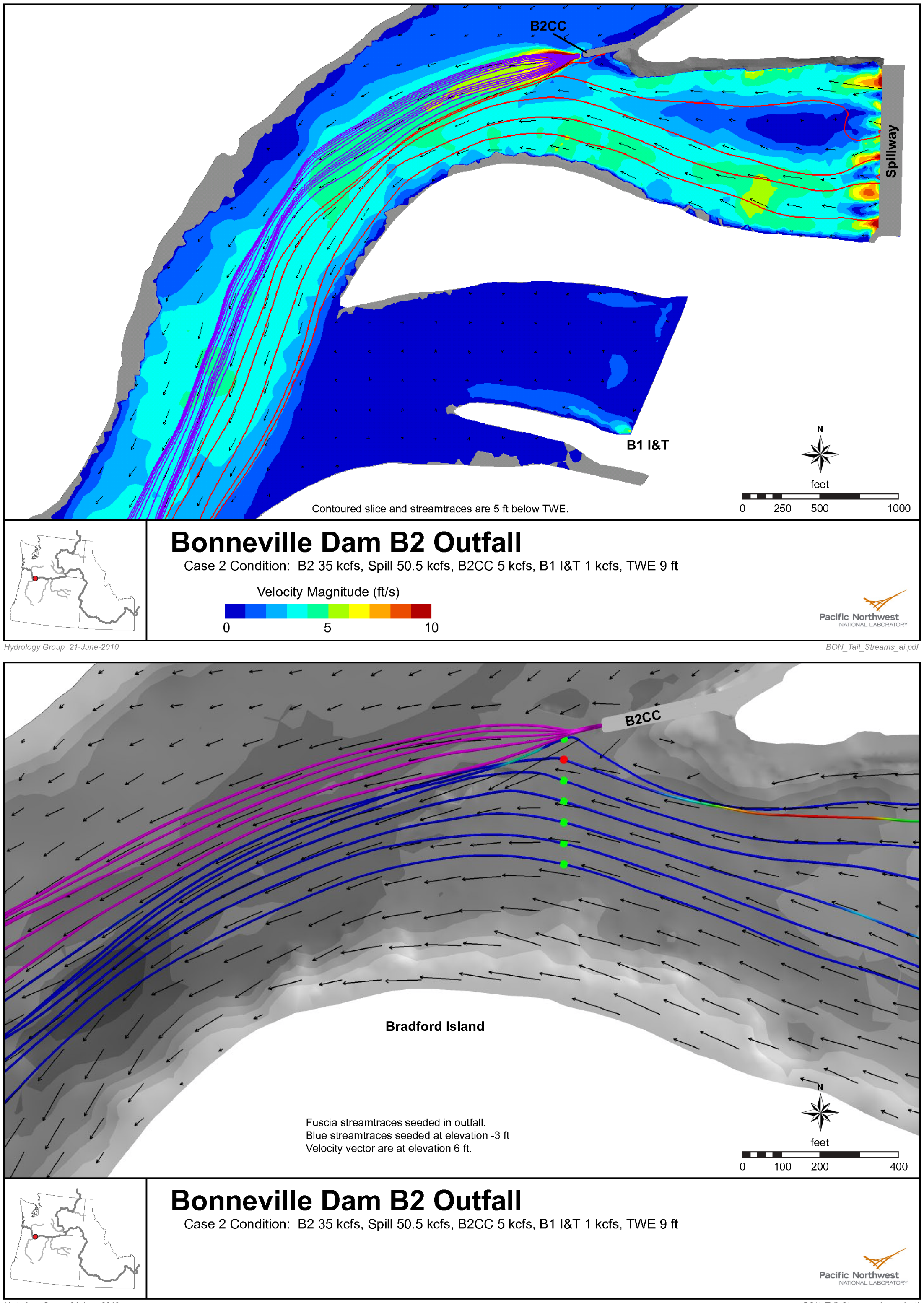

Figure 3.2. Case 2 simulation results showing contours of velocity magnitude 5 ft below the water surface (upper) and streamlines seeded in the spillway tailrace(red, top), the B2CC outfall (fuschia, upper and lower) and those seeded in the spillway tailrace adjacent to the B2CC outfall (blue, lower) on gray-shaded bathymetry.

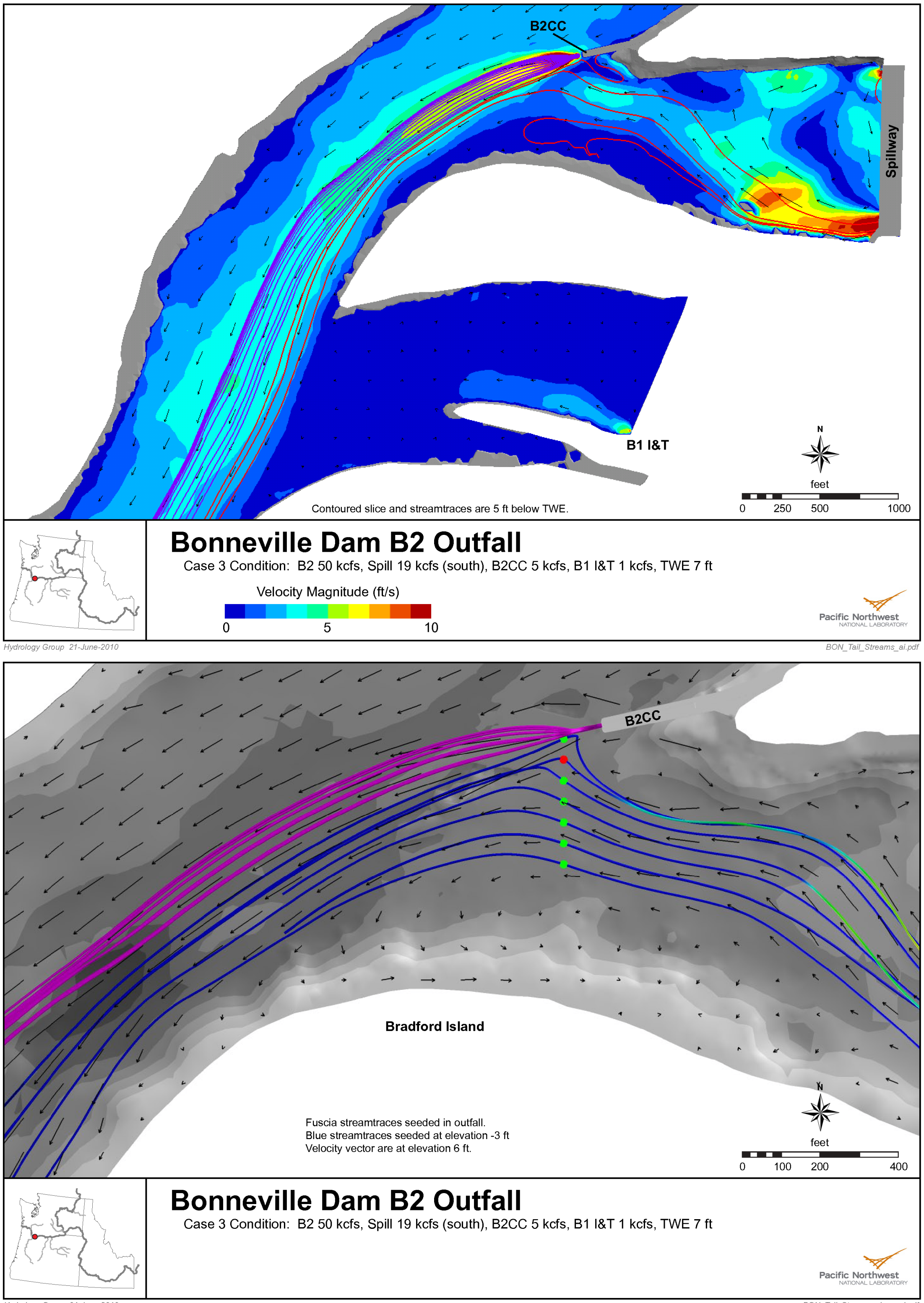

Figure 3.3. Case 3 simulation results showing contours of velocity magnitude 5 ft below the water surface (upper) and streamlines seeded in the spillway tailrace(red, top), the B2CC outfall (fuschia, upper and lower) and those seeded in the spillway tailrace adjacent to the B2CC outfall (blue, lower) on gray-shaded bathymetry.

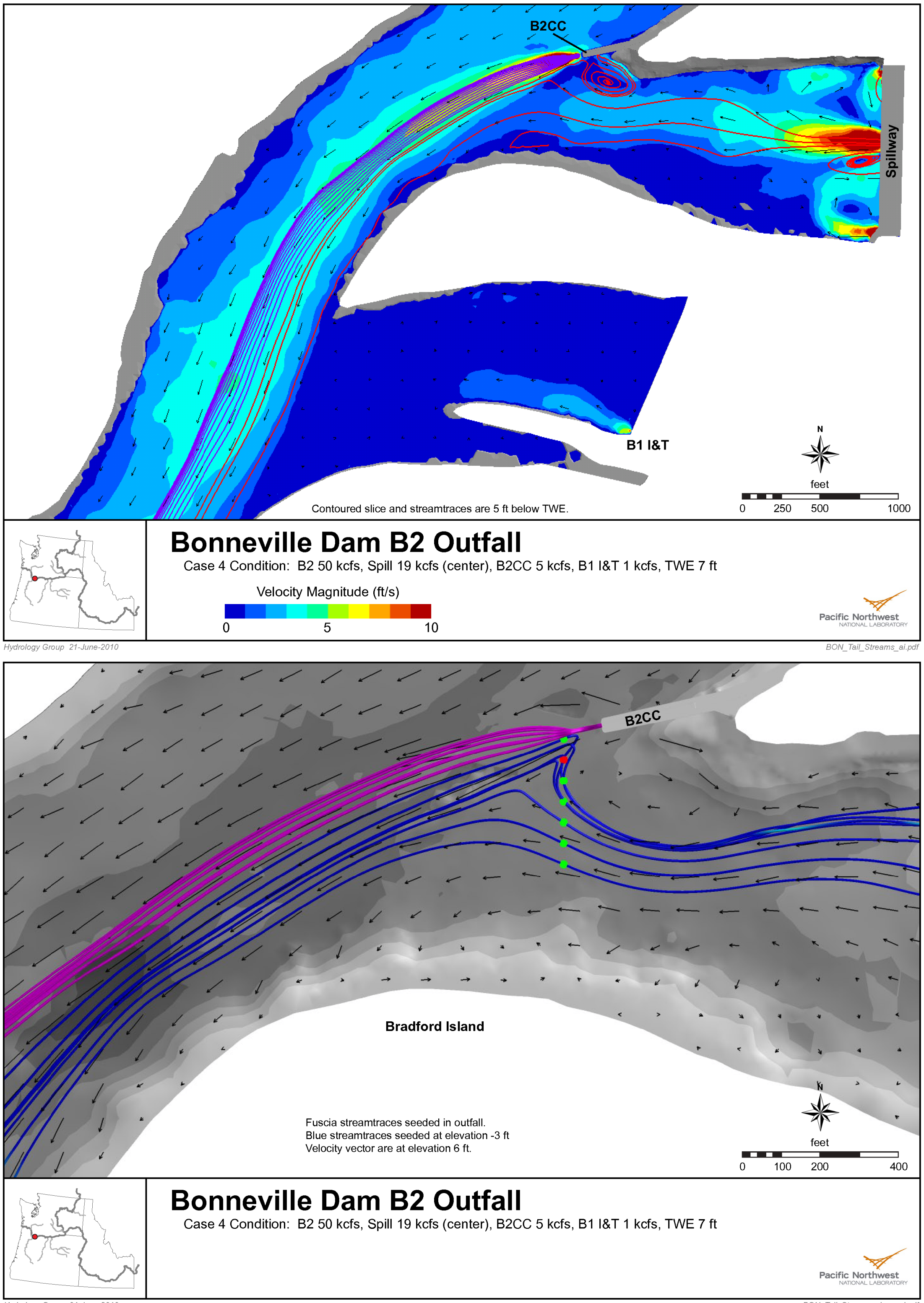

Figure 3.4. Case 4 simulation results showing contours of velocity magnitude 5 ft below the water surface (upper) and streamlines seeded in the spillway tailrace(red, top), the B2CC outfall (fuschia, upper and lower) and those seeded in the spillway tailrace adjacent to the B2CC outfall (blue, lower) on gray-shaded bathymetry.

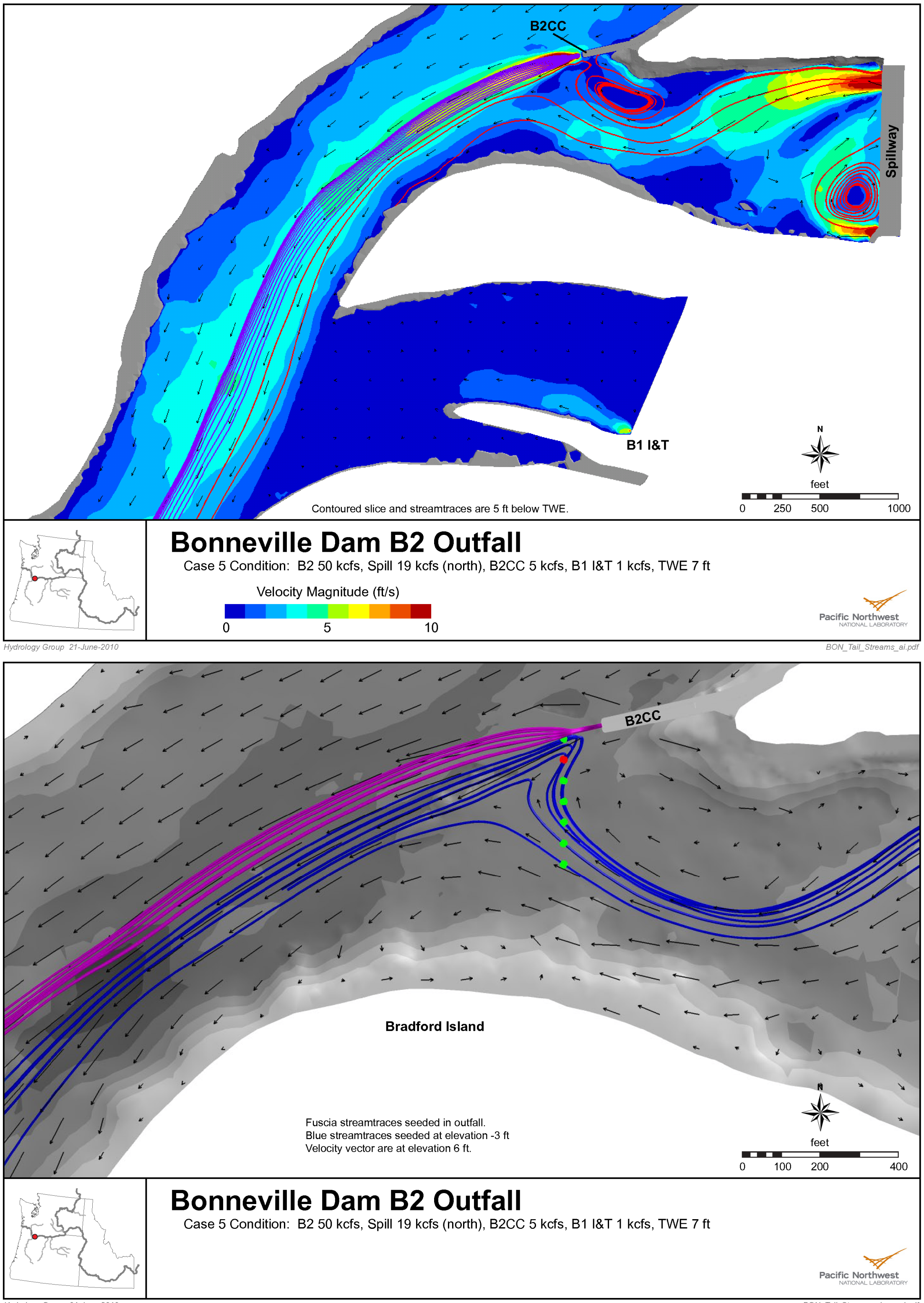

Figure 3.5. Case 5 simulation results showing contours of velocity magnitude 5 ft below the water surface (upper) and streamlines seeded in the spillway tailrace(red, top), the B2CC outfall (fuschia, upper and lower) and those seeded in the spillway tailrace adjacent to the B2CC outfall (blue, lower) on gray-shaded bathymetry.

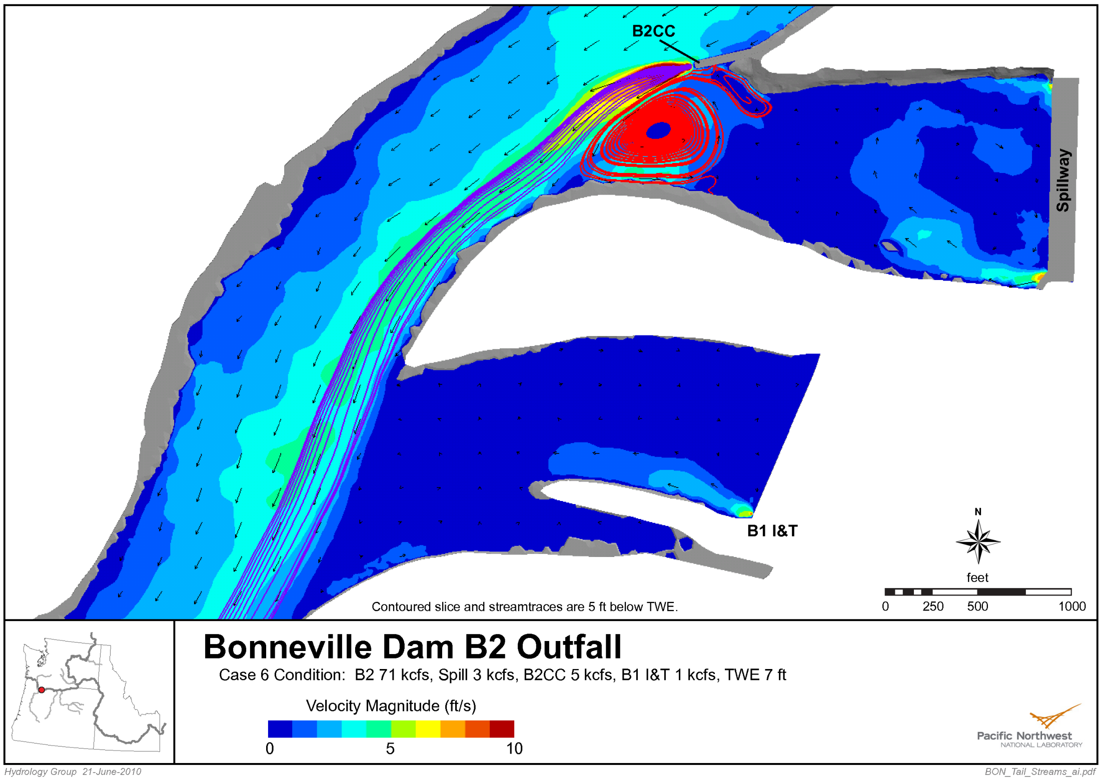

Figure 3.6. Case 6 simulation results showing contours of velocity magnitude 5 ft below the water surface and streamlines seeded in the spillway tailrace (red) and the B2CC outfall (fuschia).

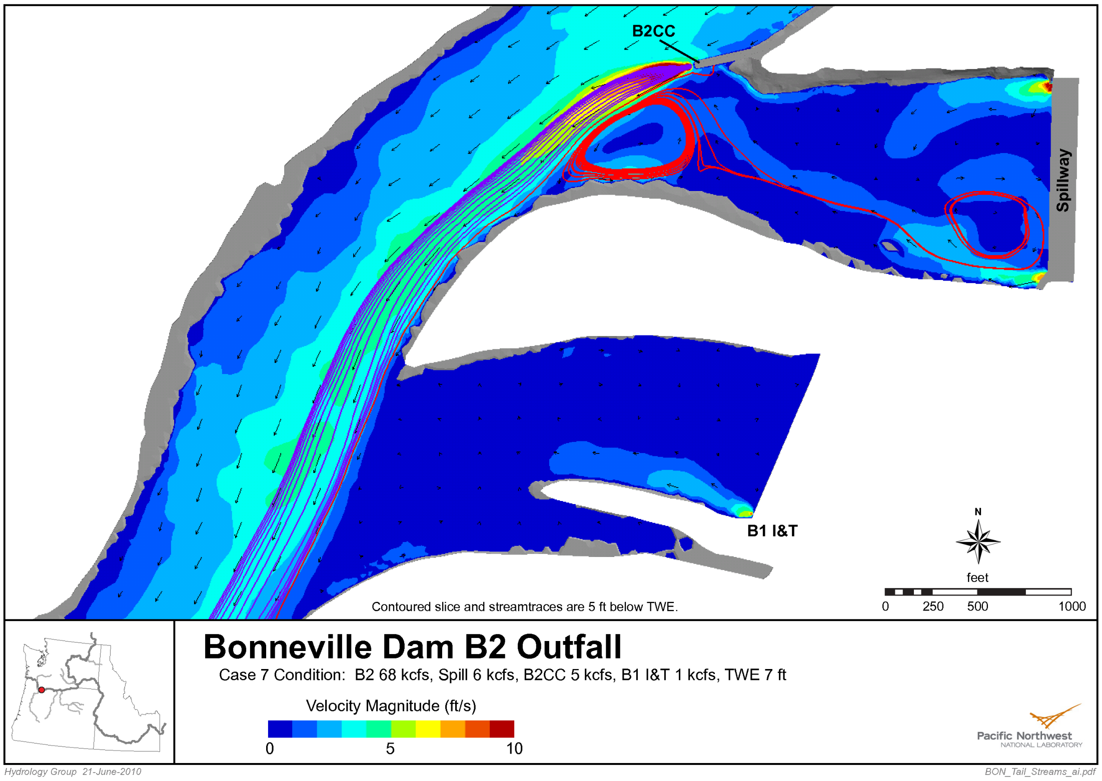

Figure 3.7. Case 7 simulation results showing contours of velocity magnitude 5 ft below the water surface and streamlines seeded in the spillway tailrace (red) and the B2CC outfall (fuschia).

4.0 Conclusions

This study characterized the effect of spill percentage and spillway flow distribution on the Bonneville spillway tailrace. Simulation scenarios included a baseline with a total river flow of 116.5 kcfs and using the numerical model to explore alternative distributions at lower flow (75 kcfs).

The simulation results were specifically examined to look at tailrace hydraulics at 5 ft below the tailwater elevation, and streamlines used to compare streamline pathways for streamlines originating in the corner collector outfall and adjacent to the outfall. These streamlines indicated that for all higher spill percentage cases (25% and greater) that streamlines from the corner collector did not approach the shoreline at the downstream end of Bradford Island. For the cases with much larger spill percentages, the streamlines from the corner collector were mid-channel or closer to the Washington shore as they moved downstream. Although at 25% spill at 75 kcfs total river, the total spill volume was sufficient to “cushion” the flow from the corner collector from the Bradford Island shore, areas of recirculation were modeled in the spillway tailrace. However, at the lowest flows and spill percentages, the streamlines from the B2 corner collector pass very close to the Bradford Island shore. In addition, the very low velocity areas and large areas of recirculation greatly increase potential predator exposure of the spillway passed smolt to predation. If there is concern for smolt egress in the spillway tailrace, the spill pattern and volume need to be revisited.

Some model and analysis improvements should be included in future work. First, future studies should include more a accurate represenations of the spillway tailrace bathymetry in the computational mesh. The re-used mesh was coarse as can be seen in the faceting of the bathmetry in the spillway tailrace. Second, additional validation studies of field-measured velocities which include low flow data and data collected near the corner collector outfall would be useful and enhance our understanding of the hydraulics near the outall. Last, in addition to streamlines, particle tracking with turbulent dispersion and particles with mass could be used to more accurately represent the wider envelope of particle pathways that result from including the effects of turbulence.

5.0 References

CD-adapco, Computational Dynamics Limited. 2009. *CCM User Guide, STAR-CD Version 4.10*. CD-adapco, http://www.cd-adapco.com.

Rakowski C, W Perkins, M Richmond, and J Serkowski. 2008. *Simulation of The Dalles Dam Proposed Full Length Spillwall*. PNNL-17322, Pacific Northwest National Laboratory. Memorandum for Record to the U.S. Army Corps of Engineers Portland, Oregon.

Rakowski C, W Perkins, M Richmond, and J Serkowski. 2010. *Computational Fluid Dynamics Modeling of the John Day Dam Tailrace*. PNNL-19349, Pacific Northwest National Laboratory, Richland, Washington. Prepared for the U.S. Army Corps of Engineers, Portland District.

Rakowski C, J Serkowski, M Richmond, and G Guensch. 2001. *Development and Application of a 3D CFD Model for the Bonneville Project Tailrace for Proposed High Flow Outfall Structures*. Memorandum for Record, Pacific Northwest National Laboratory. Prepared for the U.S. Army Corps of Engineers, Portland Distric.

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