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Bonneville Powerhouse 2 3D CFD for the Behavioral Guidance System

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

2010

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Summary

In 2008 and 2009, a 700-ft long, 10-ft deep floating forebay guidance wall called a behavioral guidance system (BGS) was deployed in the Bonneville Powerhouse 2 forebay. The US Army Corps of Engineers, Portland District (CENWP) contracted with the Pacific Northwest National Laboratory (PNNL) to develop tools to assess the impact of the BGS on forebay hydraulics (this study). The tools developed provide a physical characterization of forebay hydraulics to be integrated with acoustic telemetry studies designed to measure the impact on juvenile salmon guidance and survival through Bonneville Powerhouse 2.

In previous work, PNNL performed computational fluid dynamics studies for the Bonneville forebay for CENWP. In this study, the existing model was modified to include the BGS. The model included a bay-by-bay spillway, a truncated Powerhouse 1 forebay, Powerhouse 2 turbine intakes and corner collector, and the forebay bathymetry extending approximately 1.5 km upstream from the tip of Cascade Island.

Model validation outcomes were similar to those of past studies. Additional checks were included on the impact of the differencing scheme to flow solution. It was found that using upwind differencing performed well. It was also possible to use a truncated computational mesh of this model that included a BGS upstream of Powerhouse 2 and increased spatial resolution in the vicinity of the BGS. This model has been validated, run, and provided to CENWP to use for additional analysis of the Powerhouse 2 forebay hydraulics.

The PNNL particle tracking software was used to assess the impacts of mass and relative buoyancy on particle fate. The particle tracker was run for the Half Load case for the clean forebay and for the forebay with the BGS in place and the Corner Collector on. All tracker cases showed that the BGS moved the particles across the forebay increasing the number of particles exiting the model through the Corner Collector and (for streamlines and neutrally-buoyant particles) the lower numbered turbine units.

Acknowledgments

Financial support for this study was provided by the U.S. Army Corps of Engineers under MIPR W66QKZ91562575. The authors would like to thank Laurie Ebner, US Army Corps of Engineers, Portland District, for the discussions, support, and insight that improved this study. In addition, we would like to thank Adam Maxwell for his technical review and Denice Carrothers for her editorial review of this document. Their roles in the preparation of this document were appreciated.

Abbreviations and Acronyms

ADCP	acoustic Doppler current profiler
B2	Bonneville Powerhouse 2
BGS	Behavior Guidance System
CENWP	U.S. Army Corps of Engineers, Portland District
CFD	computational fluid dynamics
kcfs	Thousand cubic feet per second
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NGVD29	National Geodetic Vertical Datum of 1929
ORN	Oregon North State plane feet
MARS	monotone advection and reconstruction scheme
PNNL	Pacific Northwest National Laboratory
VMag	Velocity magnitude
UD	Upwind difference

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1.0 Introduction

The Bonneville Dam (Powerhouse 1 and the spillway) was constructed during 1934-1937 at River Mile 146.1 (Figure 1.1) on the Columbia River. Bonneville Powerhouse 2 (B2) was subsequently constructed in 1974 - 1982. In previous work (Rakowski et al. (2001), Rakowski et al. (2005)), Pacific Northwest National Laboratory (PNNL) performed computational fluid dynamics (CFD) studies for the Bonneville forebay for the U.S. Army Corps of Engineers, Portland District (CENWP) Hydraulic Design. The Bonneville 3D CFD model used for fish guidance efficiency (FGE) work in the B2 forebay (Rakowski et al. 2005) was modified to include a floating forebay guidance wall called a behavioral guidance system (BGS). The original model included a bay-by-bay spillway, a truncated Powerhouse 1 forebay, B2 turbine intakes and Corner Collector, and forebay bathymetry extending approximately 1.5 km upstream from the tip of Cascade Island. This model was run to assess the forebay hydraulic impacts resulting from flow operations and the use of the B2 Corner Collector for smolt passage.

The objective of this current study was to provide a characterization of the physical environment encountered by juvenile salmon as they approached and passed the shallow-draft BGS deployed in 2008. This required that the following take place:

- Modify the existing model to include a BGS with increased resolution in the vicinity of the BGS,
- Validate the modified model,
- Run the flow model for some base scenarios,
- Run particle tracking and create visualizations, and
- Prepare the model for transfer to CENWP.

CENWP ran the numerical model for scenarios corresponding to periods for which fish data were collected. Numerically modeled hydraulic data were provided to fisheries biologists for integration with their fish sampling data.

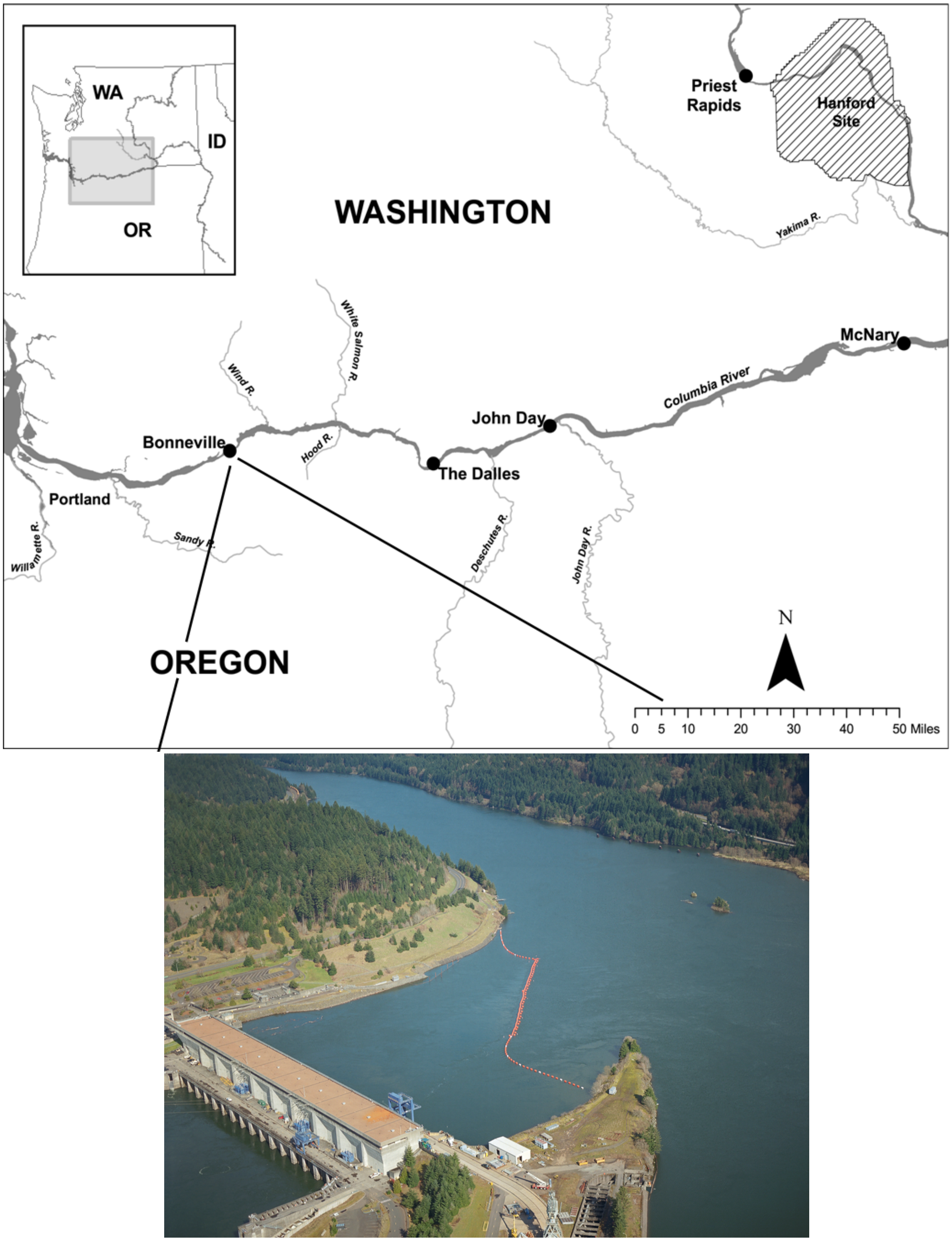


Figure 1.1. Location of Bonneville Project and other dams of the Columbia River. Powerhouse 2 is on the left of the photo, and the BGS is the straight portion of the orange line across the Powerhouse 2 forebay in the center of the photo. The photo was taken looking upstream.

2.0 Methods

The CFD solver, STAR-CD version 4 (ADAPCO, Computational Dynamics Limited 2006), was used to solve the three-dimensional unsteady Reynolds-averaged Navier-Stokes equations together with the k-epsilon turbulence closure. The computational mesh used in Rakowski et al. (2005) was updated to work with the newer version of the STAR-CD CFD software (from v3.24 to v4.08). However, the BGS location needed to be included in the computational mesh with increased resolution in its vicinity. To accomplish this, a section of the existing structured computational mesh was removed and replaced with a hybrid mesh, which included a structured (hexahedral) mesh near the BGS location and prisms elsewhere. The inclusion of prism cells allowed a resolution transition from the finer spatial resolution hexahedral cells required near the BGS to the coarser resolution of the existing model in the rest of the forebay. The modified mesh was then validated to existing field measurements of velocity (ENSR 2000). The simulation results from the validated model were then used to numerically simulate Bonneville forebay particle paths for streamlines, neutrally buoyant, and buoyant particles.

2.1 Existing Model and Model Configuration

The 2005 FGE study model included a well-resolved Bonneville Powerhouse 2 (B2), including representations of the trash racks, screens and vertical barrier screen (VBS), and the turbine intake extensions. (Figure 2.1 shows the configuration of the Bonneville Project.) However, this model was built in STAR-CD version 3.24 and model configuration requirements have changed since that time (STAR-CD v4.08 is the current version). Consequently, it was necessary to modify some existing parts of the computational mesh so that it would function properly in the current code version.

The Powerhouse 1 portion of the forebay was truncated just downstream of the head of Bradford Island. This sensitivity of the flows near B2 to this truncation of the model was tested in in the FGE study (Rakowski et al. 2005) and found to be negligible. The B2 turbine intakes are represented bay by bay, with flow splits of 37.8, 34.2, and 28 percent for Bays A, B, and C, respectively, as specified by CENWP and used for the 1:12 reduced-scale physical model work (ENSR 2001).

2.1.1 Model Modification

For consistency and simplicity, the coordinate system used in the original work was not changed. During the original study, the Oregon North State plane feet (ORN) coordinate system in the NAD27 datum was used. All elevation data were in NGVD29 vertical datum. The preferred datum is ORN, NAD83 for new models.

The modified section included the BGS, which was represented as a straight section with end points (provided by CENWP, Table 2.1). CorpsCon was used to convert these BGS end point coordinates to Oregon North State plane feet, NAD83, then Arc/Info used to project into NAD27.

A translation (-1630000, -720000) was applied to the model coordinate system to reduce the number of significant digits for the spatial coordinates and making it consistent with the existing

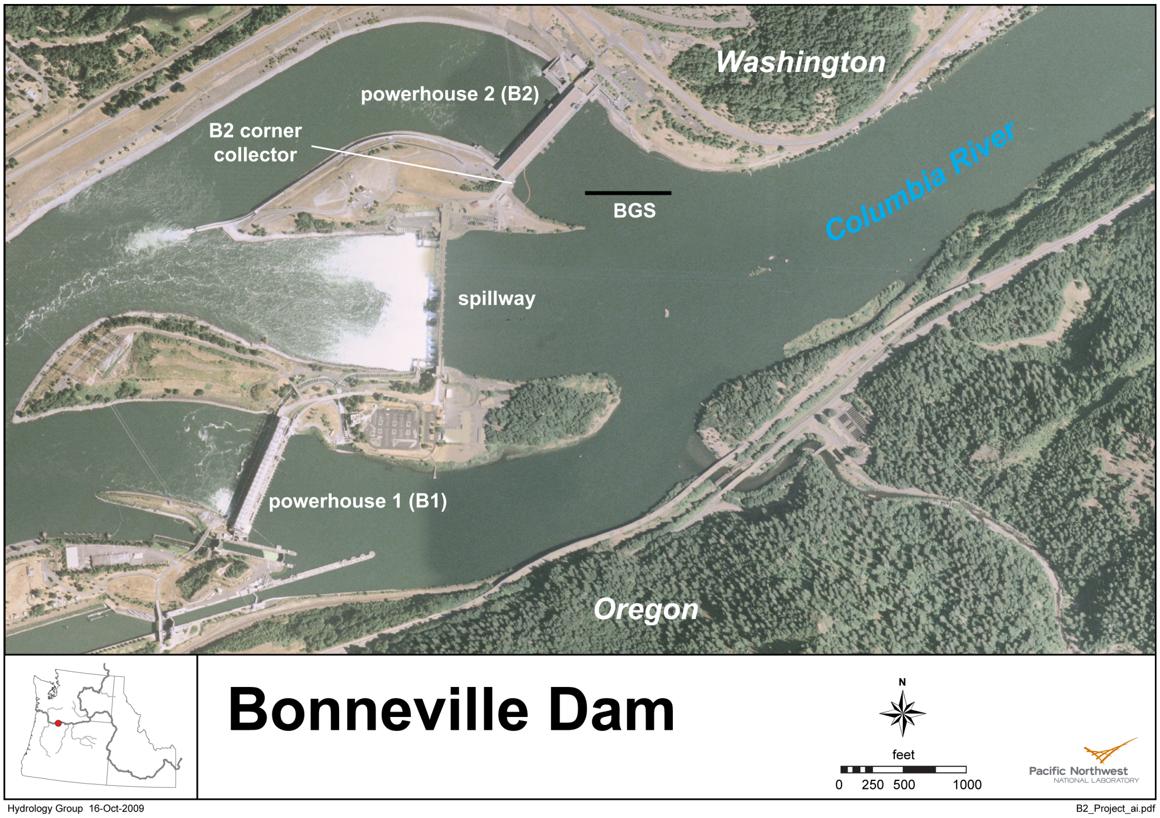


Figure 2.1. Configuration of the Bonneville Project

Table 2.1. BGS end point locations in geographic coordinates and ORN

Latitude	*Longitude*
45.64693N	121.93604W
45.64697N	121.93321W
ORN Easting	*ORN Northing*
1633064.12	725269.0
1633788.1	725270.6

model.

The original model was created by extruding a two-dimensional mesh from a shell on the bathymetry up to the water surface to create a volume mesh. That two-dimensional mesh created in Gridgen (Pointwise, Inc. 2003) was reblocked and modified so that the BGS and the surrounding area could be meshed with hexahedrals with approximately (in plan view) 1ft resolution moving perpendicularly off the BGS, 2 ft along the BGS, and 0.31 ft in the vertical near the water surface and about 0.6ft below the floats. The cylindrical floats were represented as continuous rectangular solid 3 ft in width and 1.5 ft in depth. The BGS curtain was represented as an impermeable baffle.

2.1.2 Model Configuration

Model configuration options have changed since the FGE and Bonneville forebay models were initially created. Rather than specifying outflow volumes, velocities were calculated for each boundary based on flow and boundary area. Local coordinate systems were used to specify vectors orthogonal to the boundary. Flow splits for the B2 turbines were 37.8, 34.2, and 28 percent for Bays A, B, and C, respectively. These splits were based on field measurements and also used in past CFD studies.

In running the model, the maximum global residual tolerance was reduced to 1e-4 and the residual tolerances were 0.001, 0.0005, and 0.001 for momentum, pressure, and turbulence respectively. With larger residual values, flow features that were artifacts of the mesh were observed. It was necessary to reduce the relaxation coefficients for the models to converge (0.2, 0.1, 0.2 for momentum, pressure, and turbulence, respectively). The model was run with a k-epsilon high-Reynolds number turbulence closure and standard wall functions. These steady-state models were run with SIMPLE and algebraic multigrid. Both upwind (UD, a first-order scheme) and monotone advection and reconstruction scheme (MARS, a second-order scheme) differencing were tested.

2.2 Model Scenarios

Several scenarios were run, and most were a variation of the flow conditions during the acoustic Doppler current profiler (ADCP) measurements (ENSR 2000). These measurements were on-station 10-minute duration measurements of velocity in many locations in the forebay. Table 2.2 details the operational scenarios for the specified runs. These runs were for two total river flows (233 and 177 kcfs), with and without the BGS, and with the B2 Corner Collector on (5kcfs) or off (see Figure 2.1). The spillway had only attraction flows for the fish ladders from the two end bays. The BGS runs had a baffle representing the BGS, and the cells representing the floats were turned into solids.

2.3 Particle Tracking and Break Through Plots

The Bonneville forebay CFD results were used with a Lagrangian particle tracking code developed at PNNL. The tracker can simulate paths for particles without mass (streamlines) and with mass subject to forces such as drag and buoyancy.

Table 2.2. Specified scenarios for the validation and the addition of the BGS and Corner Collector. Feb. 4, 2000, had the distributed across the full powerhouse, Feb. 6, 2000, had the load split between the two units on each end of the powerhouse. The Corner Collector was run at 5kcfs, and water surface elevation was 74.5 ft for all simulations.

Case	B1 (kcfs)	Spillway (kcfs)	B2 (kcfs)	Total River	BGS	Corner Collector
ENSR Feb. 4, 2000 (Full Load)	85.3	2.6	145.0	233	off	off
ENSR Feb. 6, 2000 (Half Load)	102.7	2.6	71.7	177	off	off
Full Load, CC	85.3	2.6	145.0	233	off	on
Half Load, CC	102.7	2.6	71.7	177	off	on
Full Load, BGS	85.3	2.6	145.0	233	yes	off
Half Load, BGS	102.7	2.6	71.7	177	yes	off
Full Load, BGS, CC	85.3	2.6	145.0	233	yes	on
Half Load, BGS, CC	102.7	2.6	71.7	177	yes	on

Particles were tracked in two of the models: the Half Load case and the Half Load case with the BGS deployed and the Corner Collector running. These particles paths were run to show the general flow pathways and the impacts of the BGS and Corner Collector; they also showed the influence of turbulence and buoyancy on particle fate. The STAR-CD simulation results and geometry files were used as inputs to the tracker code along with seed data files. Particles were seeded along a plan view line, upstream of the BGS near the water surface (about 73.8 ft; the water surface elevation was 74.5 ft). For the streamlines, 22 seed locations were used. For the neutrally buoyant and buoyant cases, 10 particles were started at each of the 22 locations used as seeds for the streamline data. Turbulence quantities from the numerical model were used to estimate dispersion (see Rakowski et al. (2008) for a detailed discussion) for the particles with mass. The buoyant particles had a density of 947 and 972 kg/m^3. Two densities were used to assess the impact of the relative buoyancy on particle path.

The tracking software created ASCII data files that included, for each time step, the particle location and the simulation results associated with that location. Tecplot was used to plot the particle paths through the computational domain and the path lines were overlaid on an orthophoto to provide a greater context for the tracks.

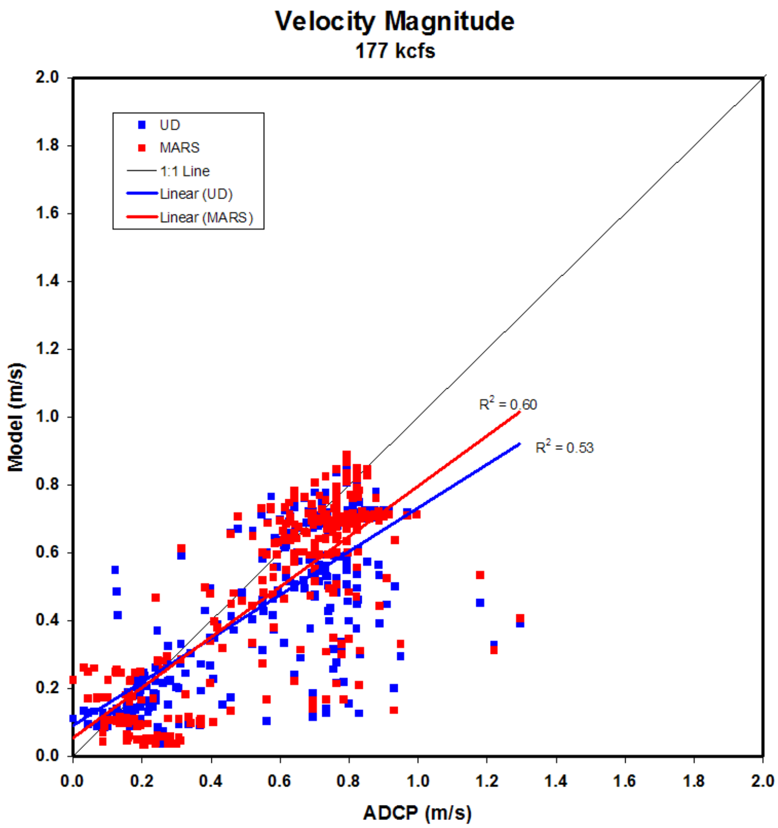
3.0 Results

Model validation and information on final model configuration are presented in this section. Visualizations of streamlines and particle tracking information are included to provide a sample of ways to look at the modeling and tracking data.

3.1 Model Validation

Vector plots and 1 to 1 plots of the field and simulation data were created. Figure 3.1 (top) shows the points on the 1:1 plots for the Half Load case run with MARS and UD and the regression line. The same MARS data are shown in Figure 3.1 (bottom) with the standard deviation for each measurement. Figure 3.2 shows the MARS data again, but grouped by measurement line locations (top) and the physical locations of those lines (bottom). The MARS differencing scheme gave a slightly better R^2 than UD (0.60 and 0.53 for MARS and UD, respectively). When the field-measured and model vectors are overlaid (Figure 3.3), the largest differences are near the powerhouse. The sampling lines near the powerhouse are more problematic to measure. Also, this location has some of the larger differences between the UD and MARS differencing schemes. Using the MARS differencing scheme, the backroller that develops in front of the powerhouse in both models (Figure 3.4) has larger velocities in the recirculation. The backroller is most pronounced in the Half Load case where the load is split between the end units. While MARS underestimates the measured velocities near the powerhouse, it is better, as shown in Figure 3.1, than the UD solution for this case.

While sampling during the Full Load, there was a large area of recirculation (with abundant floating debris) between the powerhouse and Cascade Island where it was not possible to sample. Figure 3.5 shows the modeled area of recirculation and the location of the ADCP points. Figure 3.6 (top) shows that the MARS differencing has a better match to the field data, although it still underestimates the velocities very close to the powerhouse and overestimates the velocities upstream of the spillway (Figure 3.7). As before, the standard deviation of the field-measured data was very large – on the order of the measured velocities (Figure 3.6, bottom). This indicates turbulent river flows at these locations. Measured flow vectors are overlaid on simulation results in Figure 3.8.



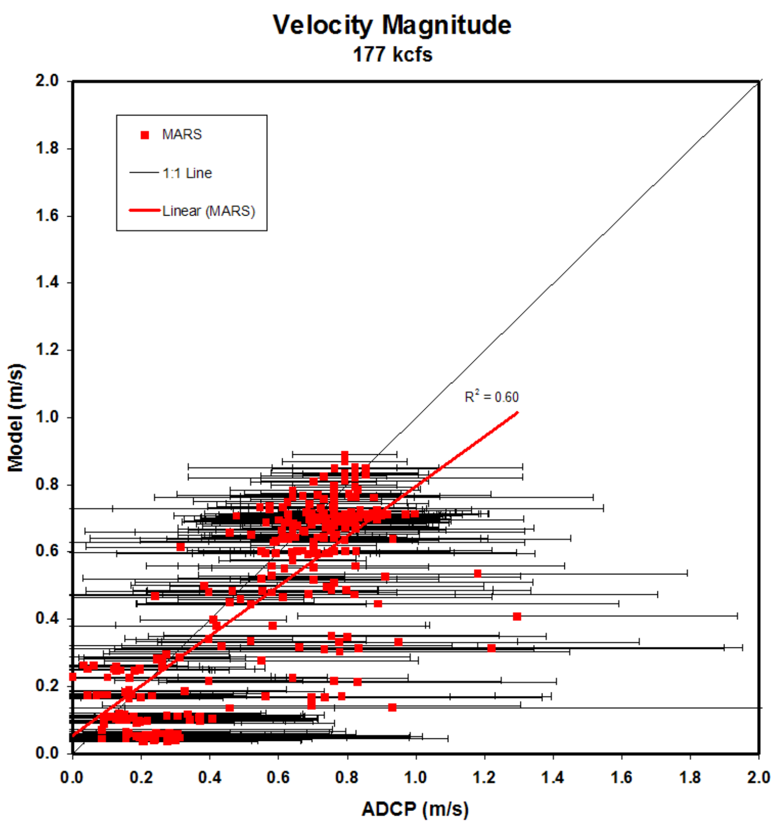


Figure 3.1. Half Load comparison for MARS and UD simulation results and ADCP measurements with regression lines (top) and with measurement standard deviation (bottom)

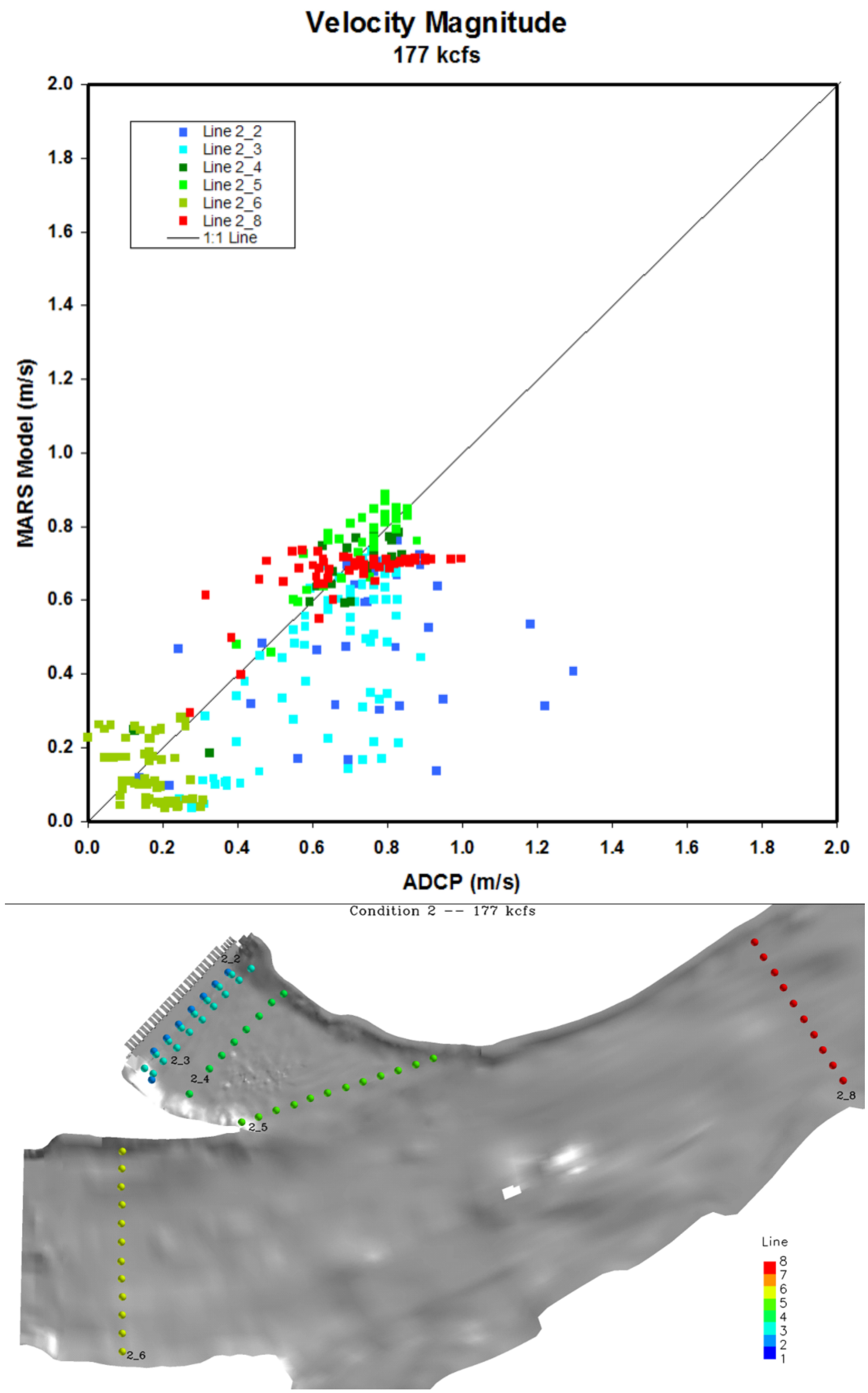


Figure 3.2. Half Load comparison for MARS simulation results and ADCP measurements by transect location

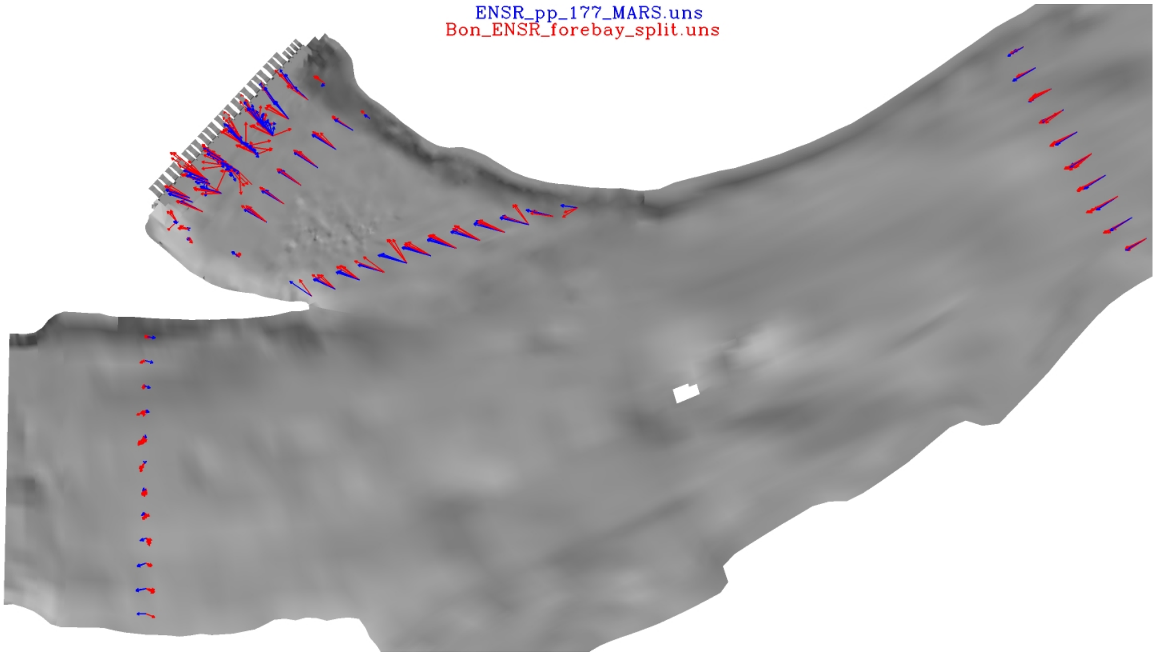


Figure 3.3. Half Load vectors for ADCP (red) and STAR (MARS scheme, blue) model

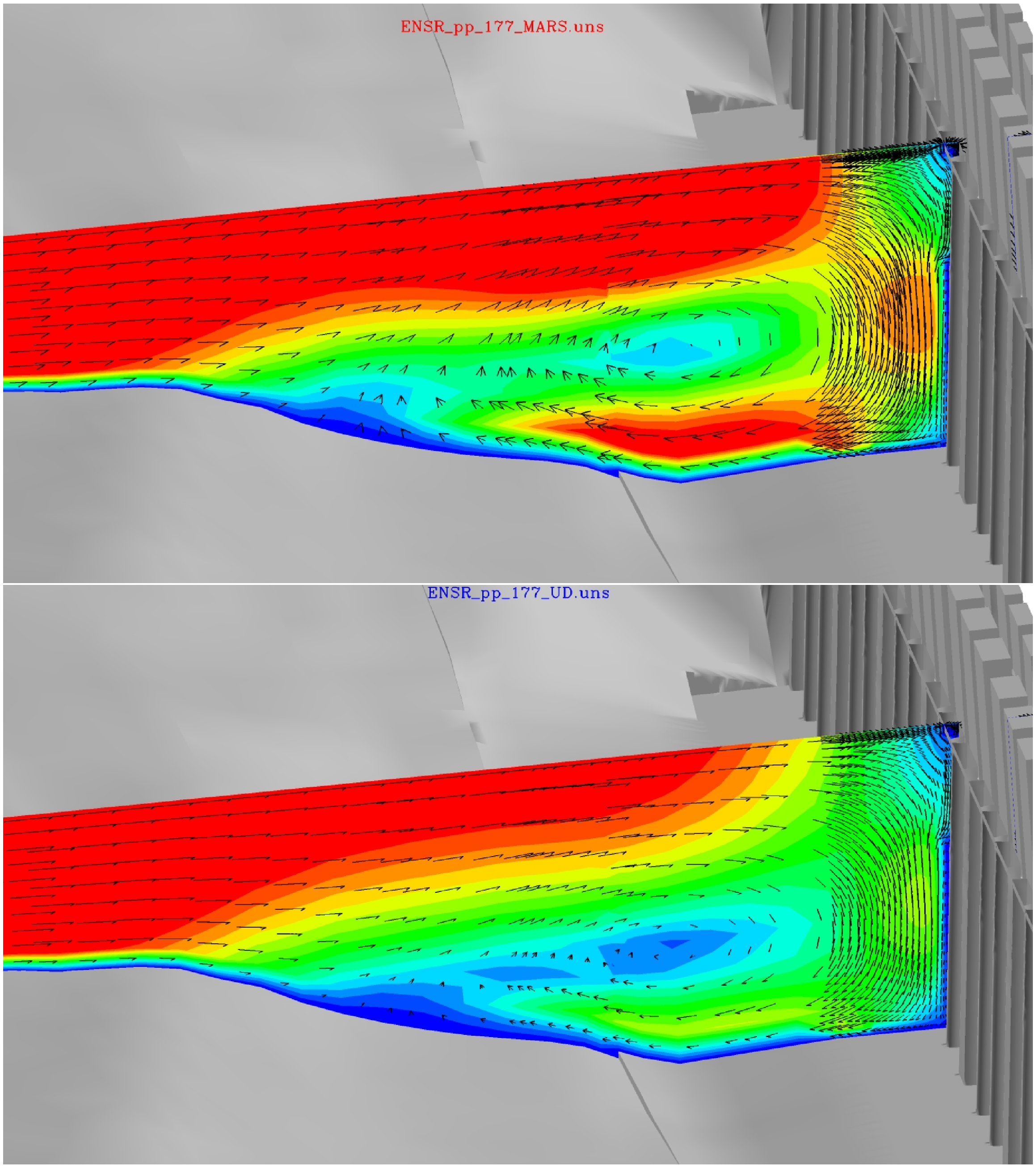


Figure 3.4. Vertical slice in the center of B2 forebay with velocities and contours of velocity magnitude. In this Half Load case, MARS differencing (top) has a stronger recirculation than results from using upwind differencing (bottom).

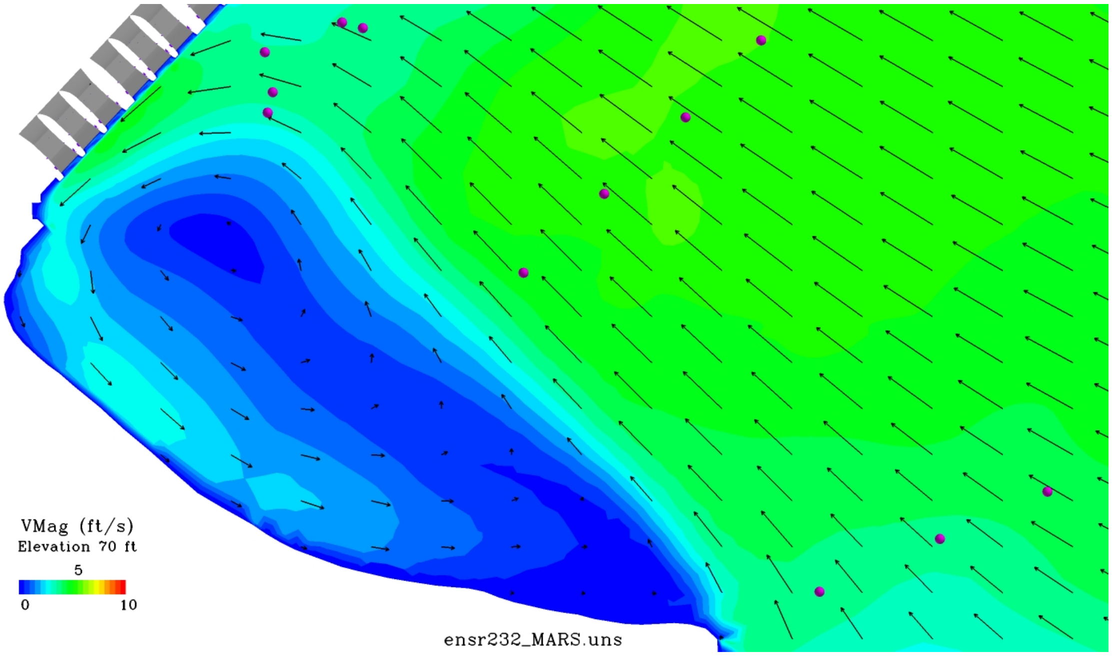


Figure 3.5. Area of recirculation between B2and Cascade Island and the ADCP measured points for the Full Load case. It was noted that the field measurements were made outside the area of recirculating debris. The location of point measurements relative to the modeled recirculation area gives added confidence that the model results correctly model the extent of recirculation.

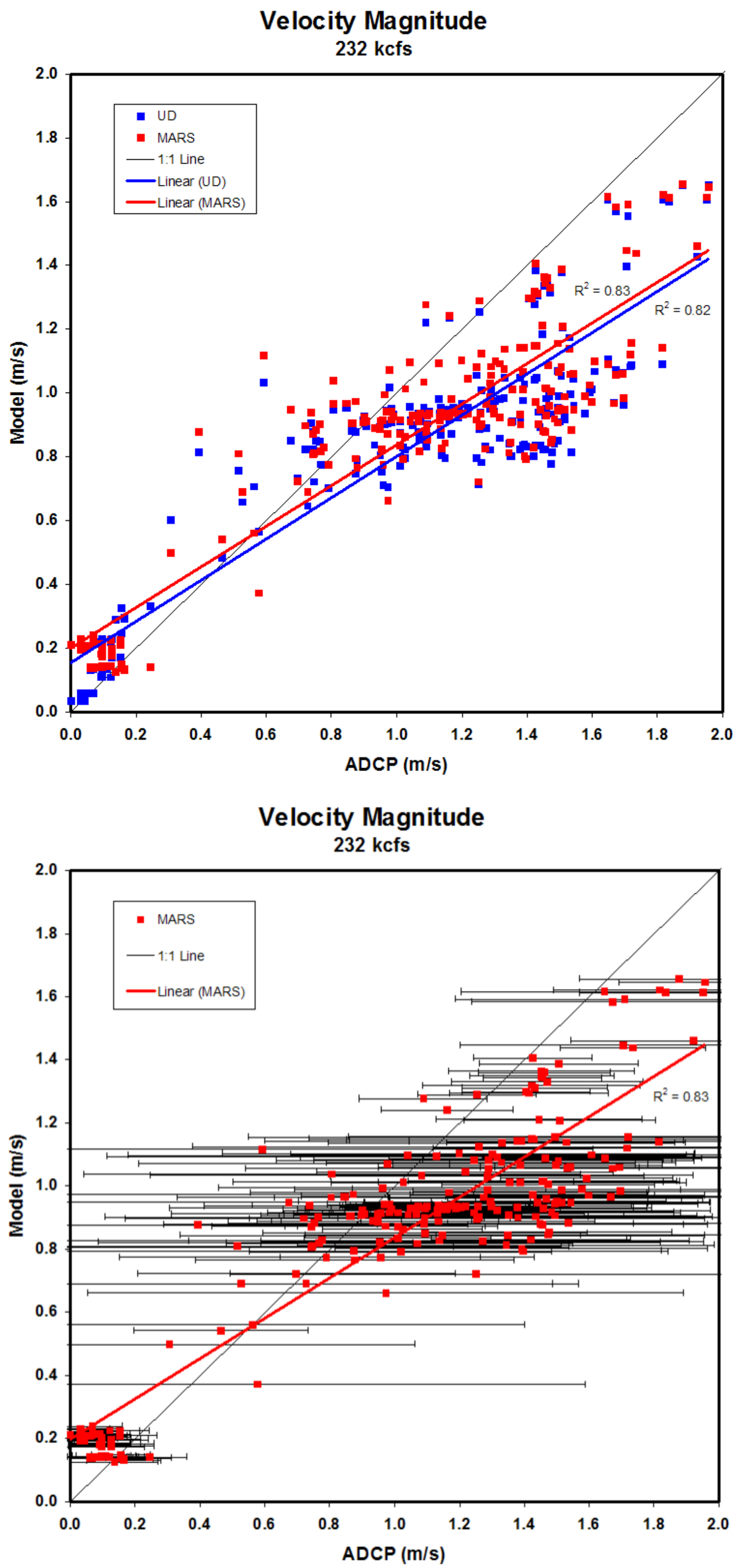


Figure 3.6. Full Load comparison for MARS simulation results and ADCP measurements with regression lines (top) and with measurement standard deviation (bottom)

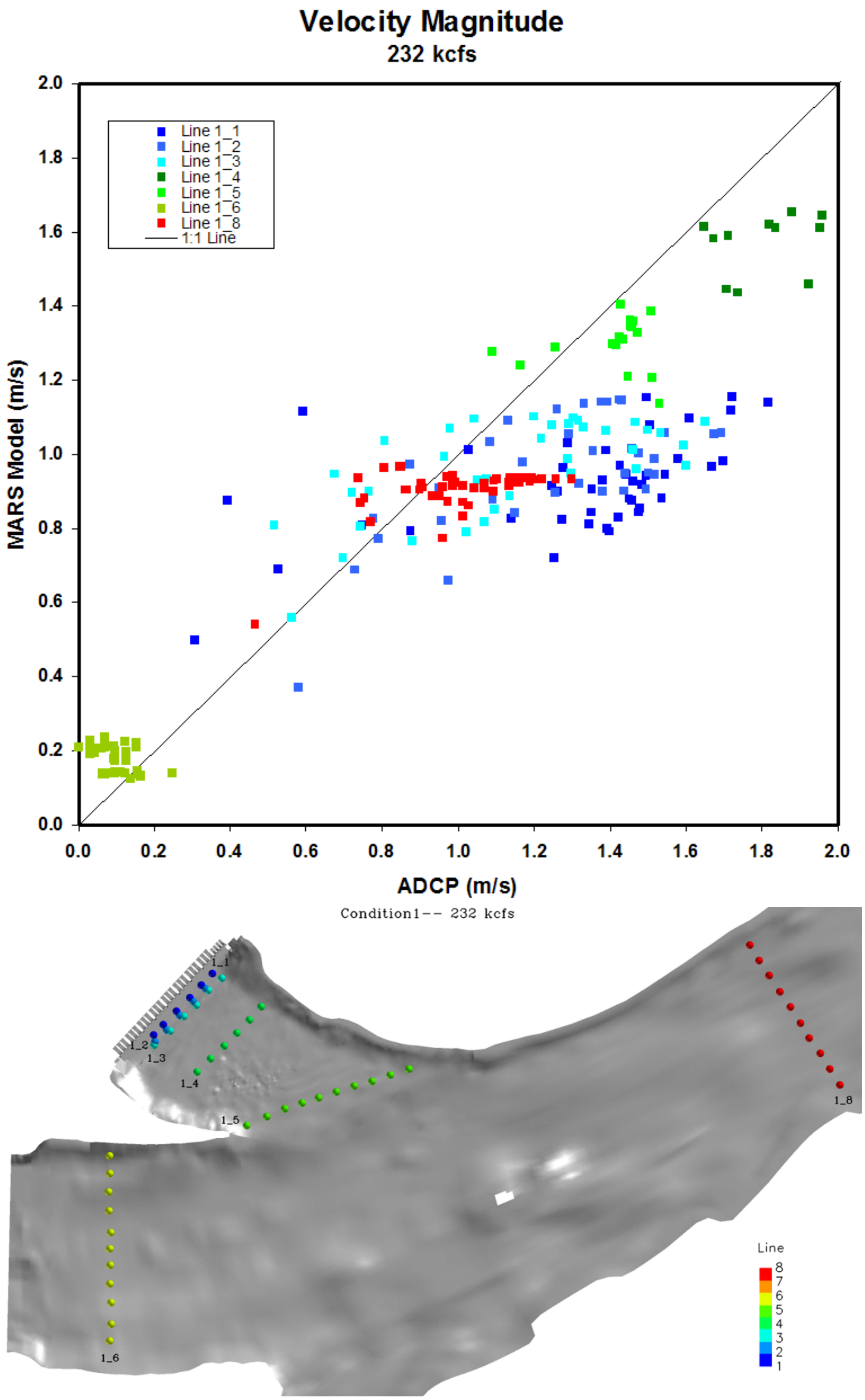


Figure 3.7. Full Load comparison for MARS simulation results and ADCP measurements by transect location

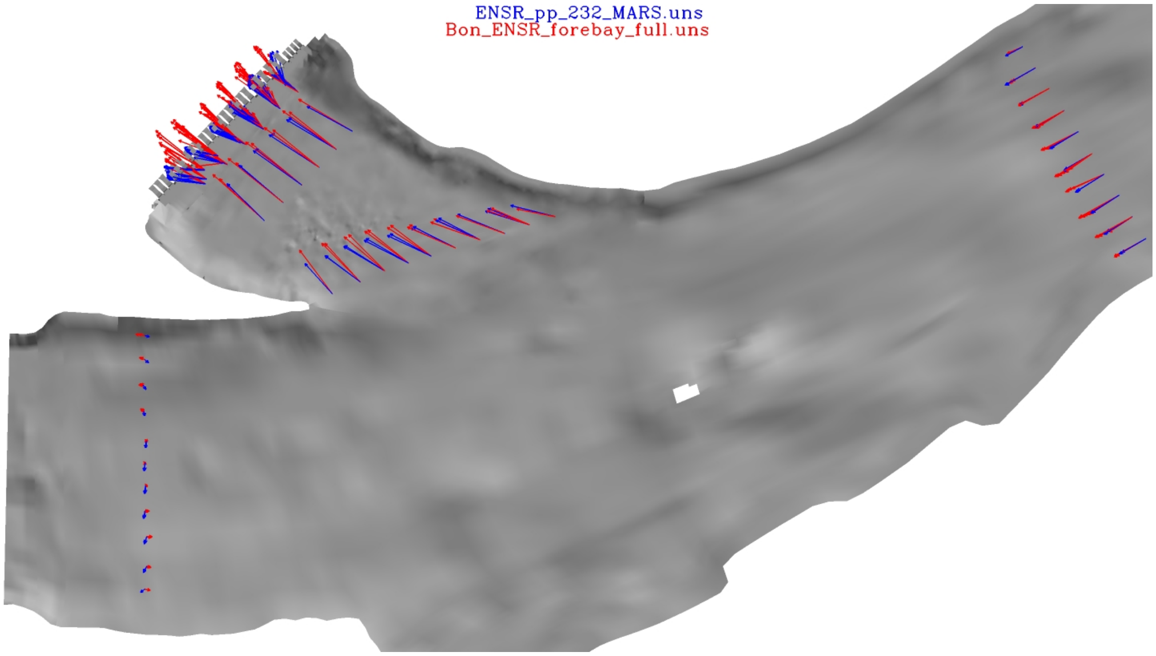


Figure 3.8. Full Load vectors for ADCP (red) and STAR model (MARS scheme, blue)

3.2 Streamlines

Streamline plots were used to see the three-dimensional differences in flow paths for the Full Load case with and without a BGS in the forebay (Figures 3.9 and 3.10). These streamlines show that the addition of the BGS moves many of the streamlines more towards the Corner Collector location. Many of the particles are entrained in the helical flow along the back side of the BGS.

To show the vertical displacement of the streamlines, an oblique view was created for the Full Load case (Figure 3.11). The helical flow pattern behind the BGS is expected and is what was observed in the numerical and physical models of a BGS in The Dalles forebay (Rakowski et al. 2006).

3.3 Particle Tracking

Two cases were used for particle tracking. The Half Load case was run with a clean forebay, and the Half load case was run with the BGS in place and the Corner Collector on. Downstream migrant juvenile salmon tend to be surface oriented, so adding buoyancy to the particles might provide a better representation of fish movement. To understand the differences, particle tracks were simulated for massless particle streamlines, neutrally-buoyant, and buoyant particles with mass. The latter runs were used to present possible ways to assess the differences in forebay hydraulics and potential impacts to fish. Streamlines (Figure 3.12), are very similar to the streamlines shown in Figure 3.10. When mass was added for neutrally-buoyant particles, there was little difference in the paths until they encountered a turbulence generating structure such as the BGS (Figure 3.13). With the BGS in place and buoyancy added, the particle paths changed. The streamlines and neutrally-buoyant particles passed underneath the BGS and were entrained in the helical flow along the back side. The buoyant particles did not move under the BGS but moved along the front of the BGS (Figure 3.14), exiting, for the most part, the model through the Corner Collector.

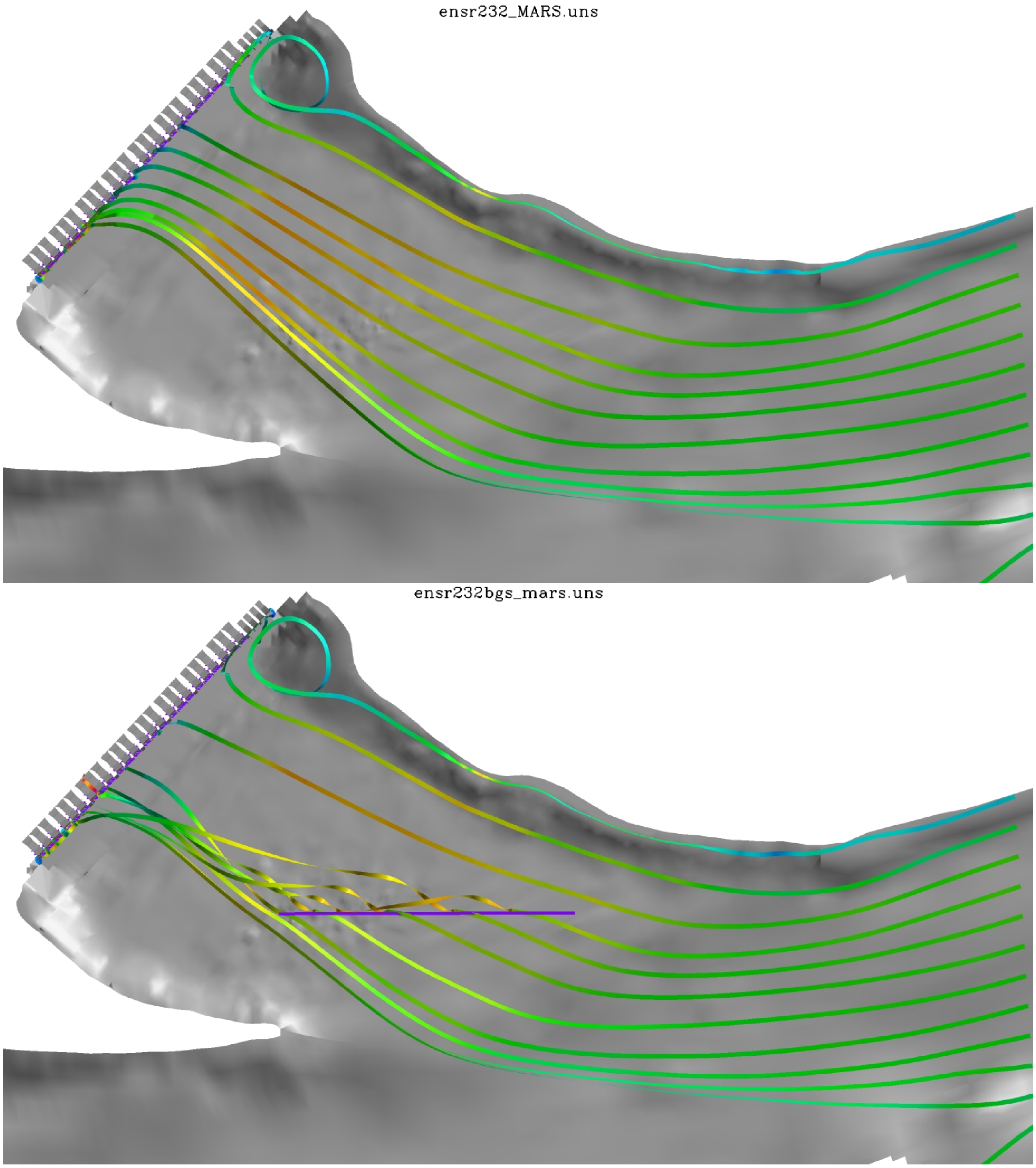


Figure 3.9. Full Load comparison for MARS simulation results without (top) and with (bottom) the BGS. Streamlines are colored by velocity magnitude; the BGS location is in purple.

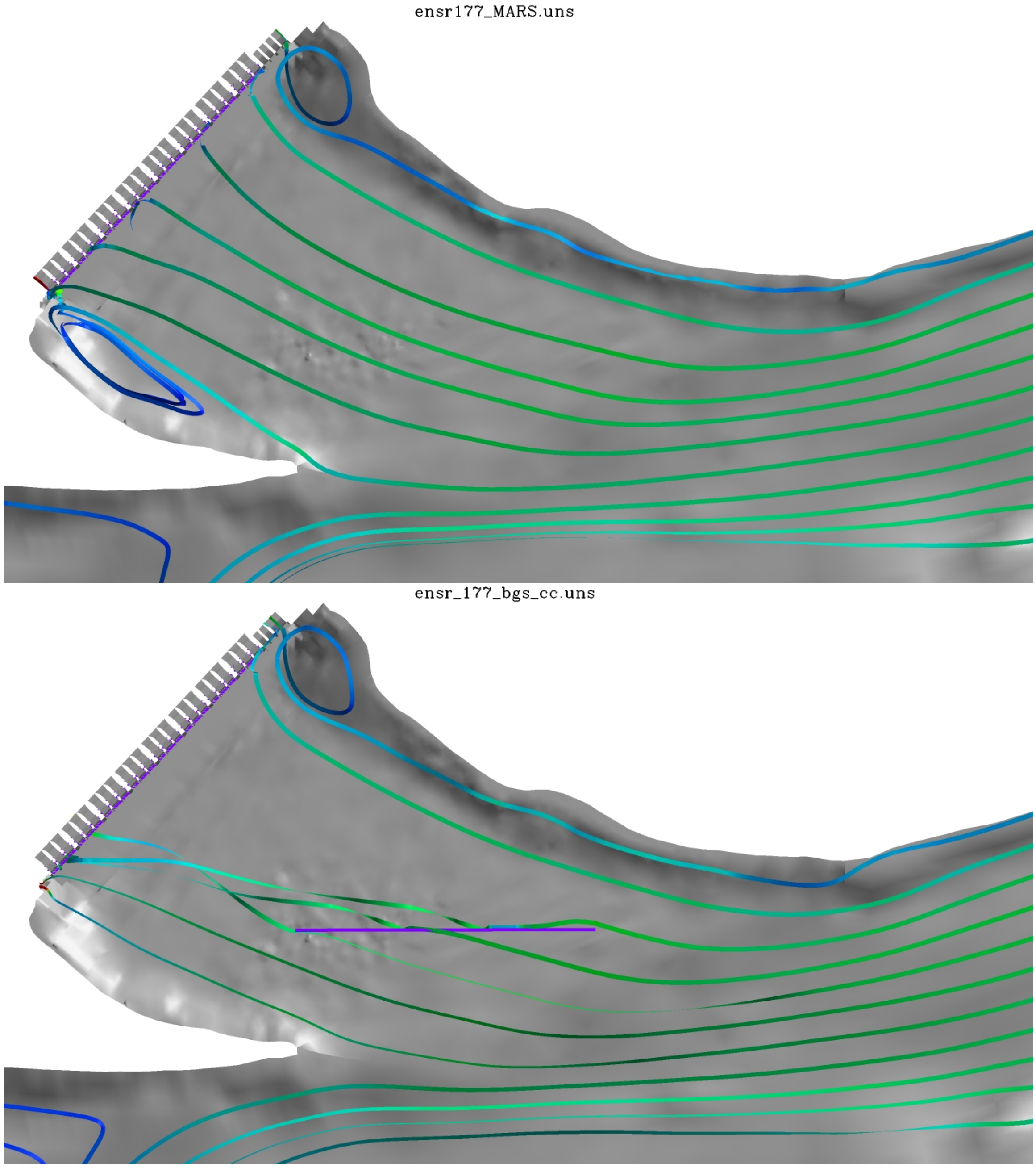


Figure 3.10. Half Load comparison for MARS simulation results without (top) and with (bottom) the BGS. Streamlines are colored by velocity magnitude; the BGS location is in purple.

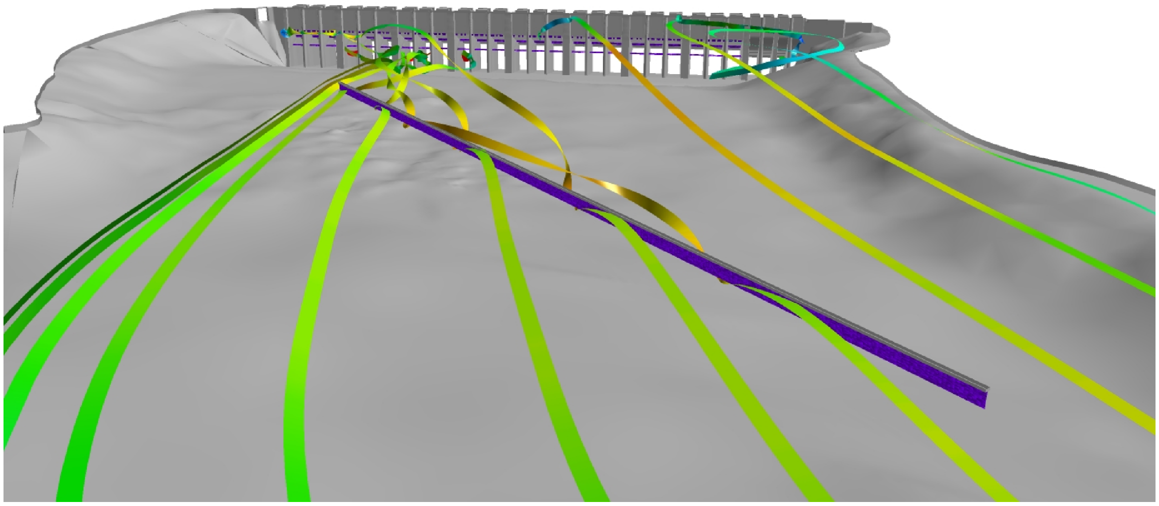


Figure 3.11. Oblique view of the streamlines looking downstream into B2. Streamlines are colored by velocity magnitude.

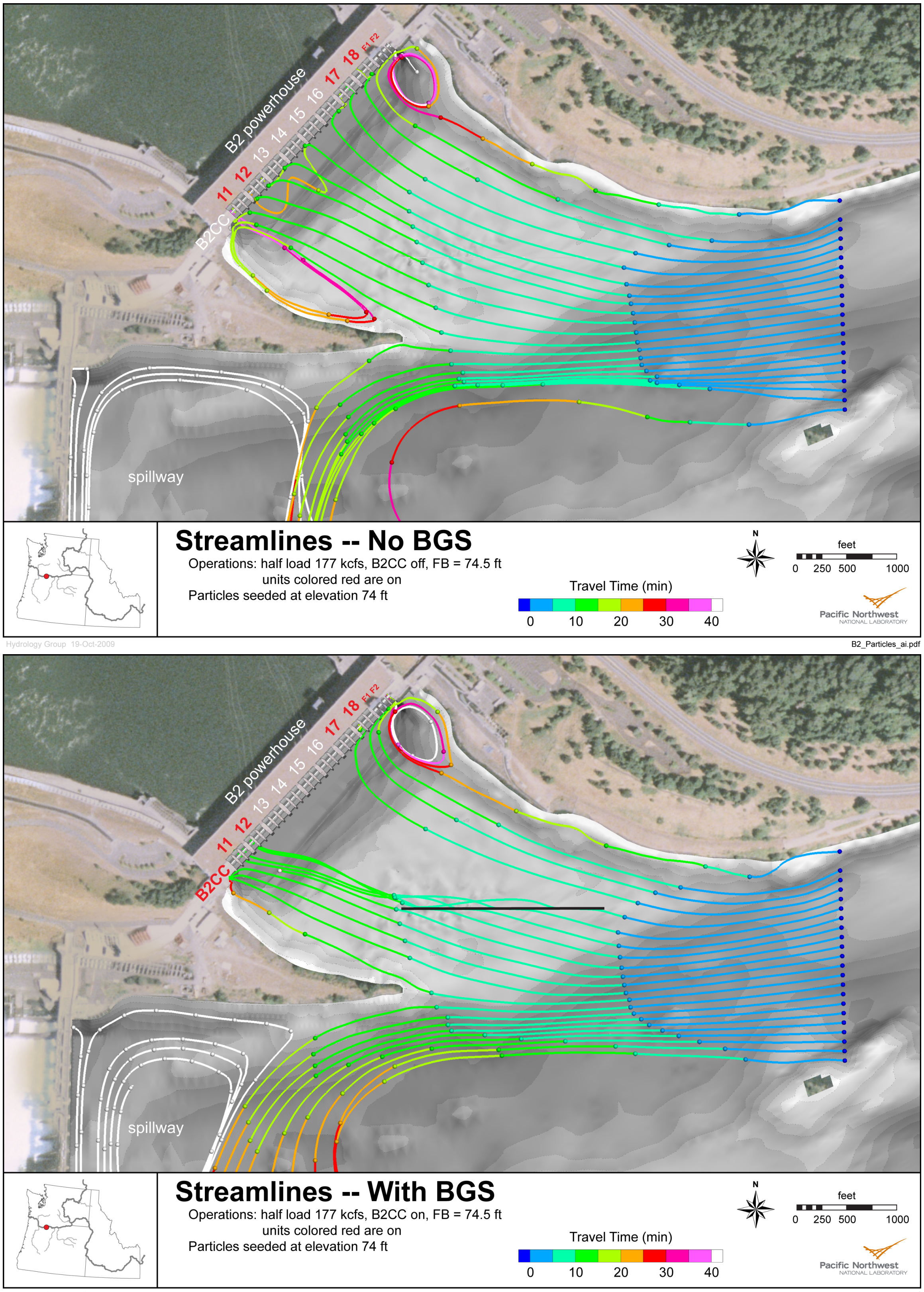


Figure 3.12. Streamlines for B2 for the Half Load case without (top) and with (bottom) a BGS. The BGS case had the Corner Collector on.

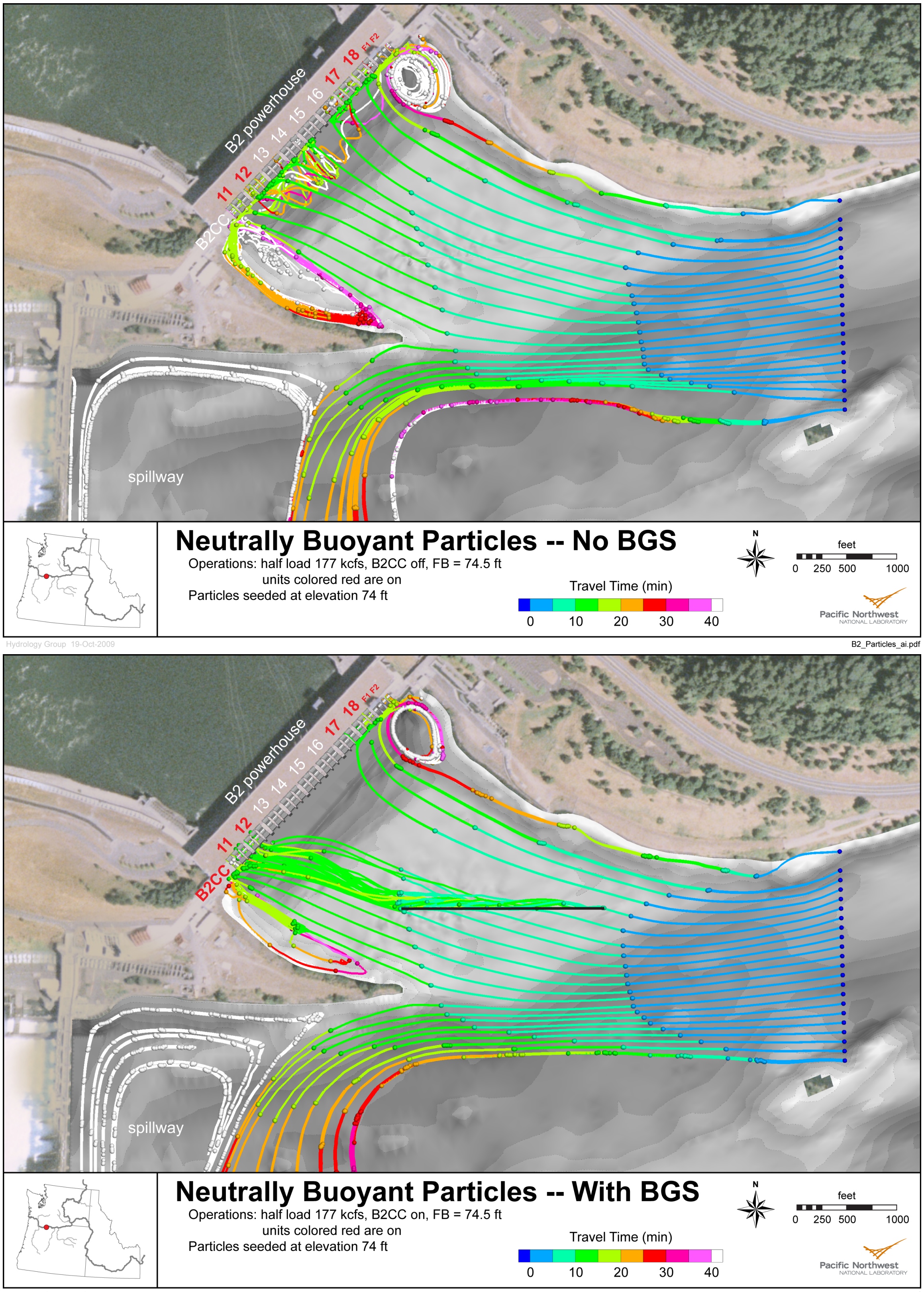


Figure 3.13. Neutrally-buoyant particles tracks for B2 for the Half Load case without (top) and with (bottom) a BGS. The BGS case had the Corner Collector on.

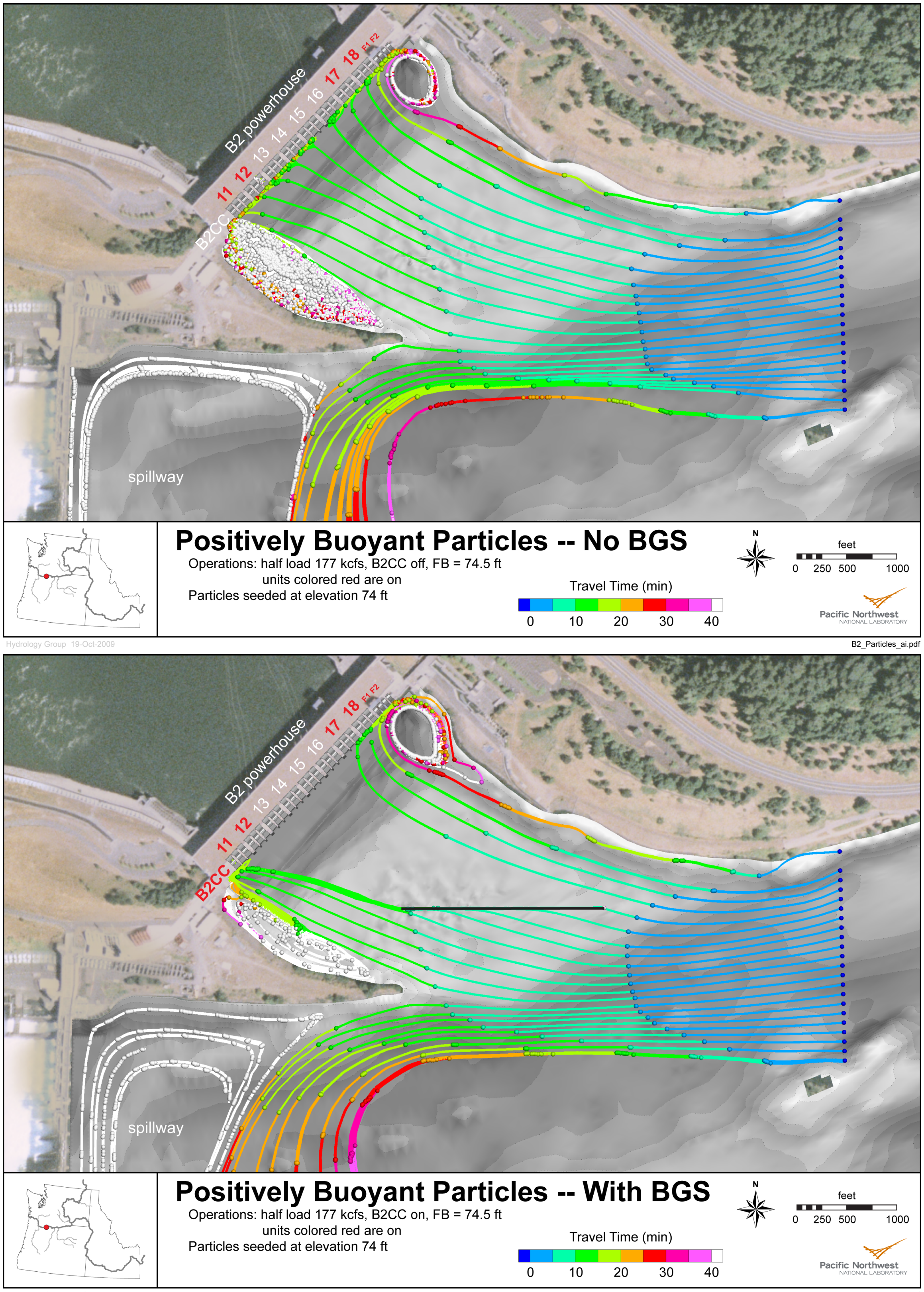


Figure 3.14. Buoyant particles tracks for B2 for the Half Load case without (top) and with (bottom) a BGS. The BGS case had the Corner Collector on.

4.0 Conclusions

A numerical model was developed and validated for the B2 forebay. Model validation outcomes were similar to those of past studies. Additional checks were included on the impact of the differencing scheme to flow solution. It was found that using upwind differencing performed well, and it was possible to use a truncated computational mesh of this model that included a BGS upstream of B2 and increased spatial resolution in the vicinity of the BGS. The new model is ready for use by CENWP.

The forebay hydraulics were modeled with the addition of the BGS and operation of the Corner Collector for the Full Load and Half Load cases. The particle tracker was run for the Half Load case for the clean forebay and for the forebay with the BGS in place and the Corner Collector on. All tracker cases showed that the BGS moved the particles across the forebay, increasing the number of particles exiting the model through the Corner Collector and (for streamlines and neutrally-buoyant particles) the lower numbered turbine units.

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