HYDROPASSAGE

TUTORIAL GUIDE: BIOLOGICAL PERFORMANCE ASSESSMENT (BIOPA) TOOLSET FOR HIGH HEAD PASSAGE

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Acronyms and Abbreviations

DEM	discrete element method
BEP	best efficiency point
BioPA	Biological Performance Assessment
CFD	computational fluid dynamics
DOE	Department of Energy
PIC	PNNL institutional cluster
PNNL	Pacific Northwest National Laboratory
PQI	Passage Quality Index
TKE	Turbulent Kinetic Energy

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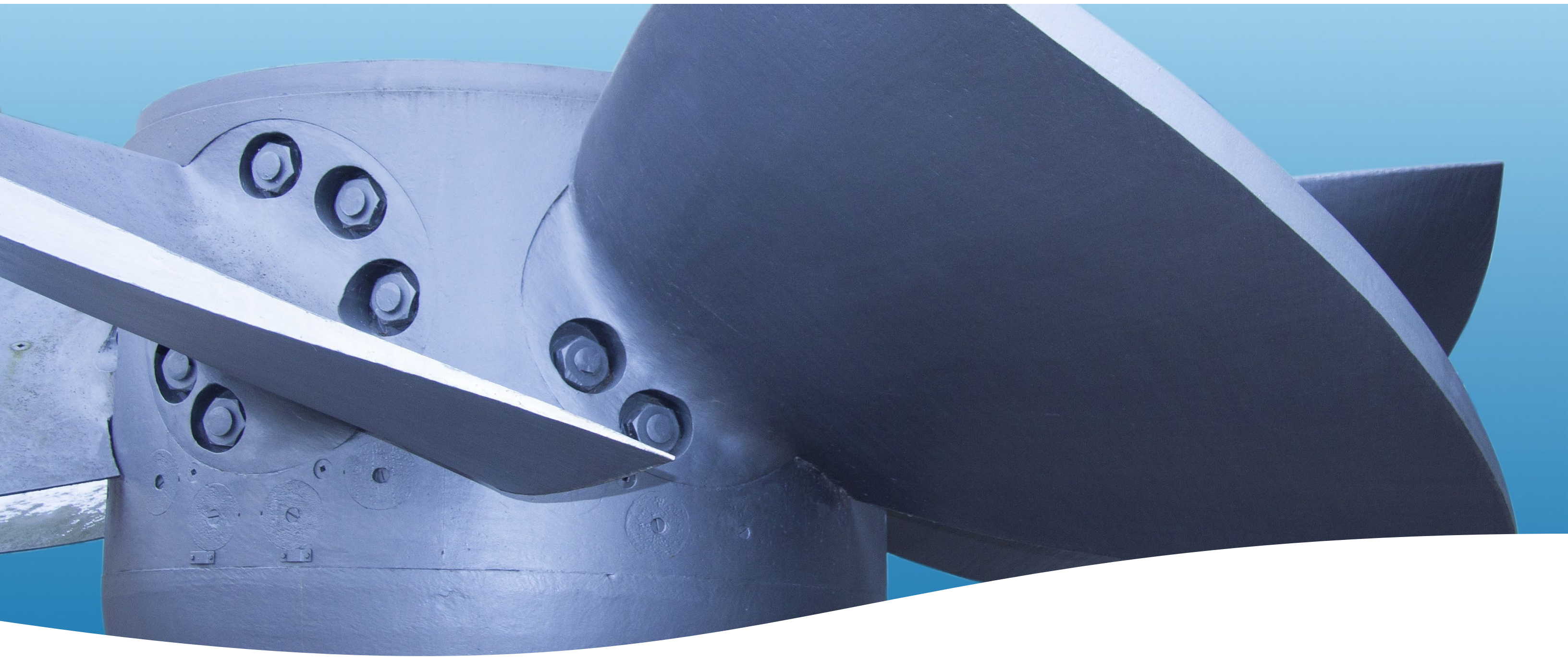
1.0 INTRODUCTION

The BioPA (Biological Performance Assessment) toolset, developed by Pacific Northwest National Laboratory (PNNL), is designed to estimate the relative biological performance of fish passage at a hydroelectric dam. PNNL has developed this high-level overview to serve as a tutorial for applying BioPA to downstream fish passage at high head dams. Contained within the document are descriptions of the high head passage, the basis for BioPA, methods necessary to model fluid flows for high head passage, the application of the toolset to flows, and a final interpretation of results. This document will provide users with an additional use case to those previously performed, which demonstrate fish passage through turbines. With this additional use case, users will understand the application and flexibility of the BioPA toolset for general water conveyance methods.

1.1 TUTORIAL ORGANIZATION

This document is organized at follows:

- **Section 2.0** – Provides a problem statement and high-level overview of the BioPA toolset.
- **Section 3.0** – Describes the Computational Fluid Dynamics (CFD) application methods and outputs files necessary.
- **Section 4.0** – Discusses the fish species applications and interpretation of results.



2.0 PURPOSE AND SCOPE

Hydropower facilities represent physical barriers for fish species in both upstream and downstream migrations. To date most of the improvements and innovations in fish passage have occurred at relatively low heads of 100 feet or less. Innovations in downstream passage include weirs in spillways, improvements in turbine designs, improvements in the slopes in fish ladders, and methods developed for collection and discharge of passage outside of the influence of the facilities. The low head applications are more suitable for fish passage for a few reasons. First, the head and corresponding pressures are lower allowing for methods of rerouting to improve survival. With lower pressure and higher flows, the low head facilities have pressures more suitable to passage. In the case of turbine passage, low heads and high flow rates result in turbine selection of Kaplan, propeller, and bulb turbines, which have large flow areas and slower speeds.

Higher head facilities that impede migratory fish use trap and transport to varying levels of success. There are ongoing efforts to improve the downstream passage. One such effort seeks to attract fish by using large flow, shedding most of the attraction flow, and routing fish downstream using minimal flows. To demonstrate BioPA is suitable for improving downstream high head fish passage, a similar type flow path will be used in this document.

2.1 BIOPA BACKGROUND

The BioPA toolset uses “relative” performance to compare cases of design or operating points because absolute survival cannot be estimated using current technology. Users may change designs and compare cases to determine the probability of increased or decreased survival. The BioPA toolset approach is based on the use of CFD and fish dose-response relationships to accomplish the following:

- Simulate a representative flow field and associated hydraulic stressors throughout the passage route.
- Calculate the expected trajectory of fish from a given seeding (starting) location.

- Use the exposure history along the trajectories to develop a frequency-of-exposure estimate and adverse-effect estimate for each hydraulic stressor.

The hydraulic stressors considered in BioPA 3.0 and the critical stressor doses of each are presented in Table 1. These hydraulic stressors are extracted along each of the simulated fish trajectories. The biological impact of each hydraulic stressor is calculated using the critical stressor dose as an input to the user-selected dose-response relationships.

Table 1. Hydraulic stressor doses considered in BioPA 3.0.

Hydraulic Stressor	Critical Stressor Dose
Rapid Decompression	CFD Nadir Pressure (Pa)
Fluid Shear	CFD Max. Shear (/s)
Turbulence	CFD Max. Turbulent Kinetic Energy (TKE) (J/kg)
Collision	CFD Max. Impact Velocity (m/s)

2.2 BioPA Toolset Components

The BioPA toolset consists of the four components listed here and described in greater detail in the cited sections.

1. Model – The CFD model that describes the hydraulic environment (Section 3.0).
2. Trajectories – The particle trajectories using the Euler-Lagrangian approach (Section 3.0).
3. Probabilities – Calculation of exposure probabilities to pressures and velocities (Section 4.1).
4. Passage Quality Index – Conversion of exposures to a Passage Quality Index (PQI) using biological response data (Section 4.2).

3.0 CFD Modeling Method

This demonstration details the flow and particle flow in the penstock of a high head dam. The available head is 236 feet and the flowrates are described in Table 1. The dam is equipped with Francis turbines, but they have been removed from this tutorial, so only the flow constraints are applied at the discharge. This setup will emulate a high head passage illustrating the velocity and pressure gradients throughout the flow path. Fish, in the form of neutrally buoyant particles, are inserted just downstream of the shown trash rack and allowed to follow the flow path to the discharge. As reported earlier, CFD investigations allow us to model the flow physics according to widely accepted standards in hydropower industry. The CFD simulation methods for the transient turbulent flow in the intake and penstock of the high head Francis turbine have been explained in a previous report (Harding et al. 2019). The CFD setup is briefly presented here. The CFD simulations for the particle-flow simulations were conducted in two steps:

1. **Turbulent flow simulations for water flow:** Flow simulations are conducted until flow achieved pseudo-steady states. The time-averaged velocity fields were further used for the particulate flow.
2. **Particle-flow simulations:** Particle-flow simulations using a Lagrangian/discrete element method (DEM) approach were conducted to compute the fish trajectory in the passage. The trajectory data for fish contain the temporal and spatial history of all stressor variables.

CFD flow simulations for the intake region and penstock of the turbine intake were conducted for four operating conditions of the turbine: minimum flow rate, best efficiency point (BEP), 1% percent lower power than BEP, and maximum flow rates. In each case, reference flow rate was chosen from the independent experimental measurement of discharge through the penstock (Harding et al. 2019). The inlet for the flow domain, the forebay, is shown in red in Figure 1. The exit of the downstream extension of the penstock was specified as outflow, a fully developed flow boundary condition. The remaining surface of the flow domain was specified as no-slip wall with wall roughness. The nominal water surface at the forebay was represented as slip walls. The trash rack model was specified as a porous baffle interface with a porosity of 92% and a resistance coefficient of 0.17 (Serkowski et al. 2019).

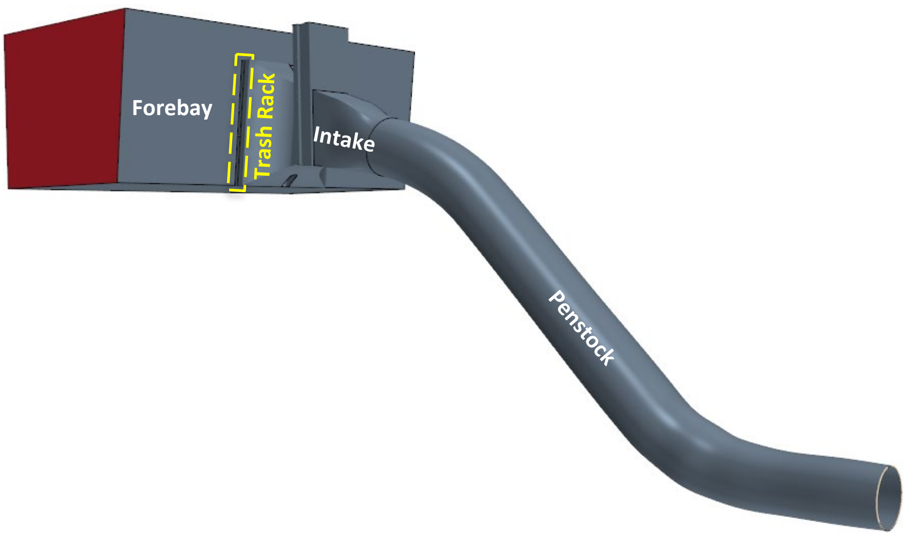


Figure 1. Schematic of the flow domain that includes the forebay, trash rack, intake, and penstock. Water enters the flow domain from the forebay (red colored area) as shown above.

Figure 2 illustrates the flow development in the intake and penstock in the flow domain at the BEP. The flow simulations were conducted at the full physical scale according to the estimated reference discharge value at the BEP (see Table 2). The range of the velocity in the contour plots covers the entire range of the velocity magnitude. The velocity contour plots in the relative size of planes are self-explanatory. At Plane 1, the effect of the downstream wake caused by the pier is clearly seen to cause the lower velocity in the upper mid region. At the bottom, the higher velocity suppresses the wake. Further, the effect of the bends on the flow in the penstock is visible from Planes 2–6. Further, the curvature effect is found to be pronounced in Planes 4–6. The core flow moves away from the center because of the radial pressure gradient. As expected, a pair of dean type contrarotating vortices appear at the bottom of Planes 4–6. Further, convergence in the region between Planes 5–6 results in accelerated flow that engulfs the low velocity regime at the bottom.

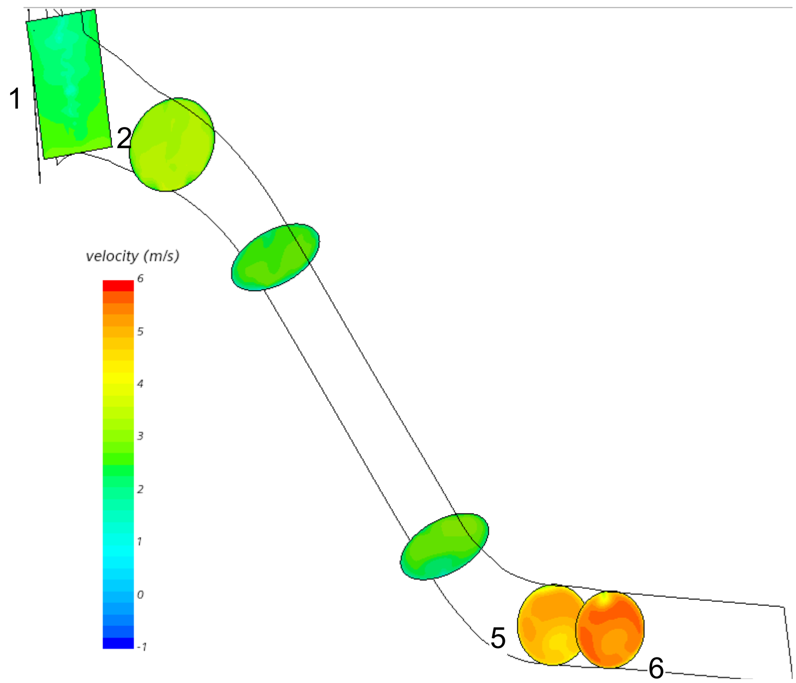


Figure 2. Position and velocity contour showing the flow development by distribution at selected cross sections (planes).

Table 2. Water discharge rate under different operating conditions

Unit Control	Operating Point	Q_R (m^3/s)
Constant Power	Min. Flow	4465
Constant Power	Lower 1%	5332
Constant Power	BEP	5857
Constant Power	Max. Flow	6635

The particle-flow simulations were conducted using the Euler-Lagrangian approach. Details of the flow simulation methodology can be found in the STAR-CCM+ user guide (Siemens PLM 2018). The DEM is a soft particle method that can accurately provide insight into collision phenomena. Therefore, the DEM method was selected in the current flow simulation framework. The particle's trajectory and their collision with the wall of penstock pipes were computed at all operating conditions mentioned earlier as well as in the previous report (Harding et al. 2019). The collisions of particles with the penstock's wall were detected via a java script that was plugged into the simulation. The script enables capture of the desired stressor data associated with particle identity. Neutrally buoyant cylindrical beads having the dimensions (diameter: 24 mm; length: 96 mm) of the Sensor Fish[1] developed at PNNL were chosen for use in the particle-flow simulations. The walls of the flow domain were specified as featuring a no-slip wall boundary condition. For the DEM simulations, 800 particles were randomly injected from Plane 1 (downstream of the trash rack) at given intervals of time (20 sec). Particles were randomly injected into the flow domain analogous to the fish entry into the passage. The larger duration of the injection was chosen to avoid the particle-particle collision in the beginning. However, inter-particle collision also may occur later (see Figure 3). Because DEM simulation resolves the surface-to-surface contact, the flow simulations can iterate thousands of sub-steps for single time step. The DEM-flow simulations were conducted until all particles exited the flow domain. As a result, flow simulations became computationally expensive; it took 2–3 days of wall clock time with 120 cores in the PNNL institutional cluster (PIC) to simulate the flow.

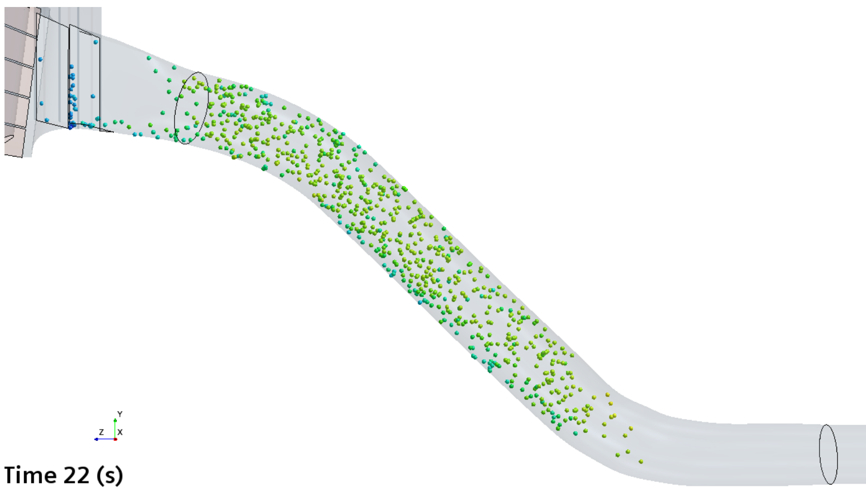


Figure 3. Snapshot showing the particle distribution in the penstock at time 22 sec. The color of the particles indicates their velocity. Neutrally buoyant cylindrical beads (diameter: 24 mm and length: 96 mm) were seeded at Plane 1.

Once the simulation was completed, the trajectory of each particle and the collision data were stored. The trajectory data contain the temporal history of all relevant variables such as position, pressure, velocity, shear, etc. Figure 4 shows the trajectory of all the particles. A single line represents the trajectory of an individual particle, and line colors represent the magnitude of the particle velocity. The trajectory and collision data were further processed to develop the input file for the BioPA toolset. The steps taken to prepare the BioPA input data are described later in this document.

[1] Sensor Fish is a small autonomous device that measure the physical stressors that fish experience when passing through or around dams via multiple sensors.

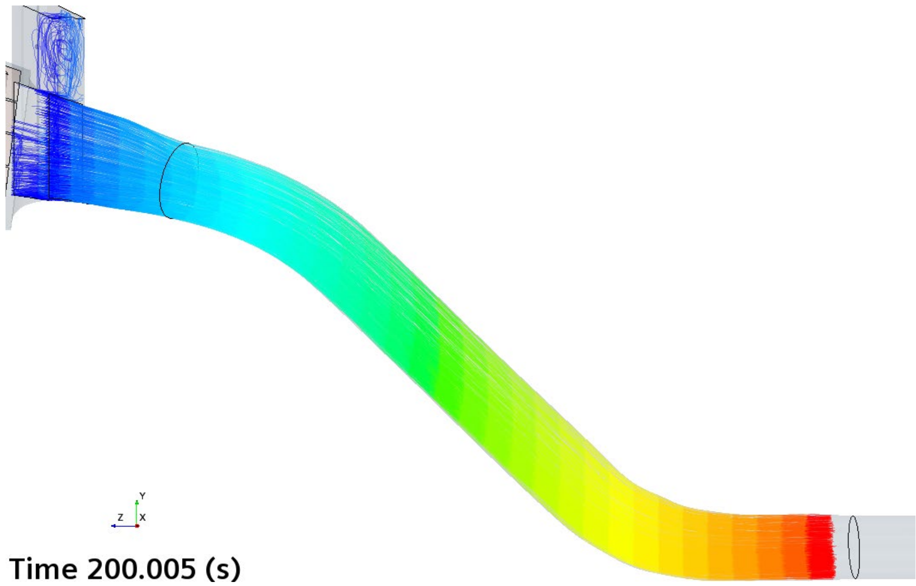


Figure 4. Trajectory of the particles colored by the magnitude of their velocity. Particles accelerate as they pass through the penstock.

3.1 Processing Techniques

3.1.1 Inputs

As mentioned earlier, the trajectory file (*_trj.csv) contains all temporal data such as position, particle velocity, pressure, shear, turbulent kinetic energy, etc. for each particle. In addition to these, the data for the collision event such as collision velocity, time and location of collision, etc. for every collision event are stored via a java script file. The collision data are combined and processed to make a single file (*_Coll.csv) that contains the collision events of all particles. Steps for extraction of the trajectory file are shown in the Figure 5.

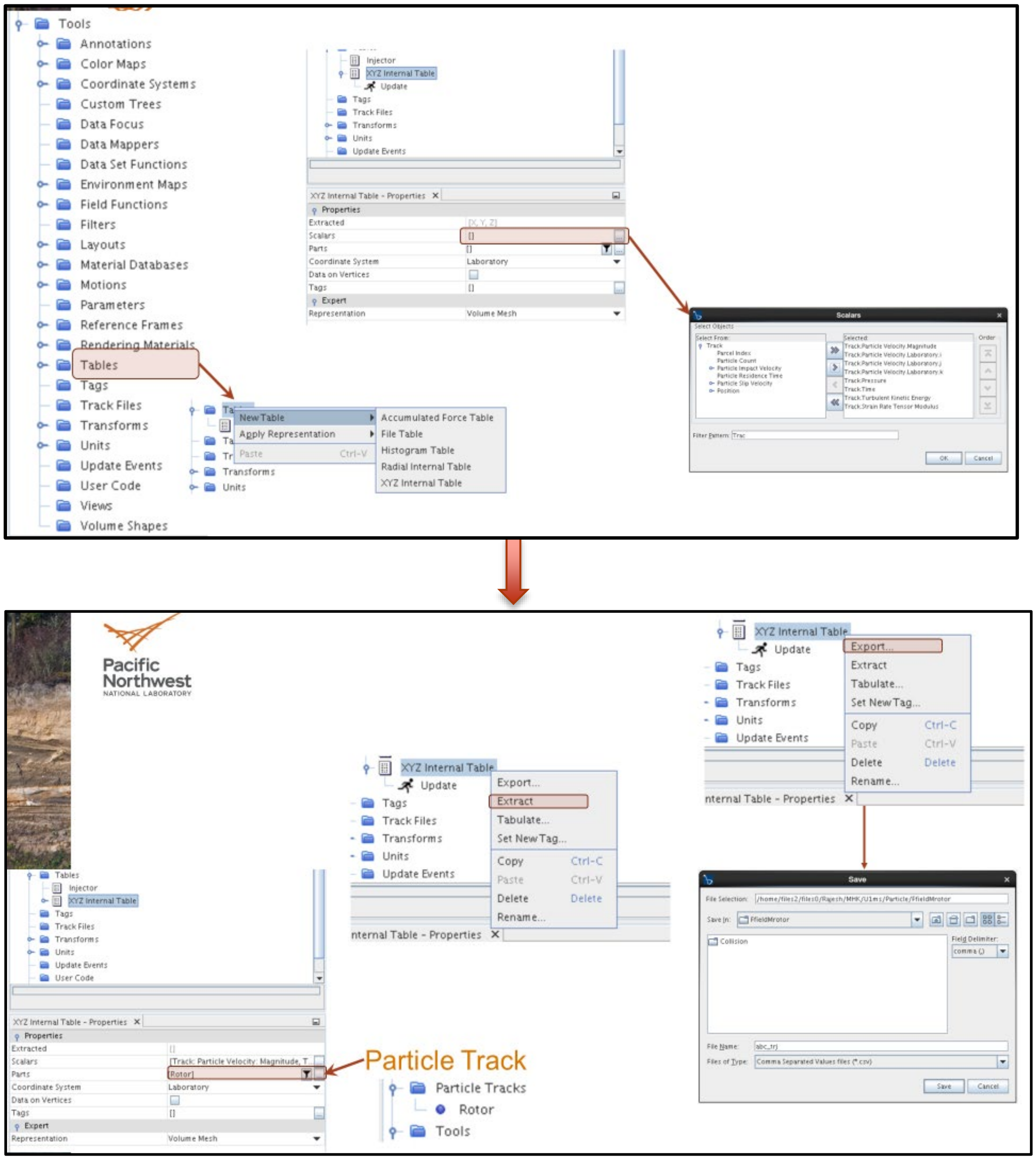


Figure 5. Steps for extracting the trajectory data (*_Trj.csv).

The steps for extracting the trajectory data are as follows:

Tool → Track File → Load Track file

Tool → Tables → New Tables → XYZ internal Table → Select scalar and Vector Variables → Select parts as Particle Track → Extract → Export files.

The scalar stressors are exported in a trajectory file, with the file name suffix of _Trj.dat. This file is saved to the streamtrace directory, so that the file path is

`…\BioPA_Run\data\trajectories\<filename>_Trj.dat`,

where `<filename>` is a useful identifier of the CFD simulation from which the scalar stressors were exported. Figure 7 shows a snapshot of the trajectory files.

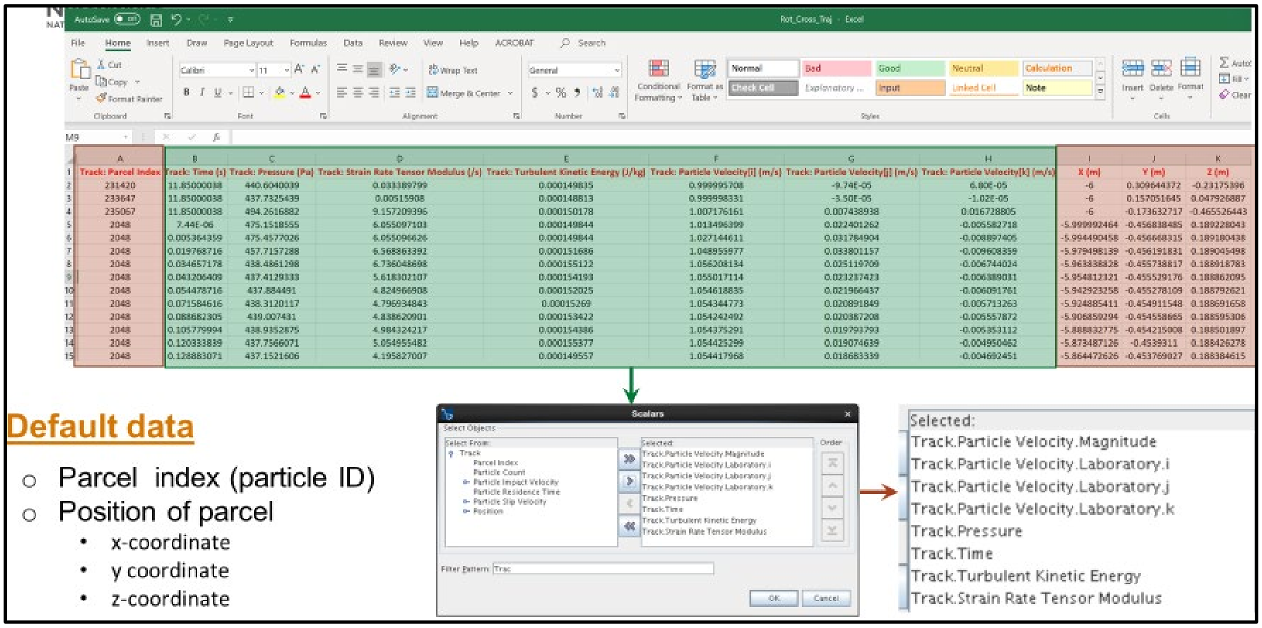


Figure 6. Snapshot showing the trajectory files used to create the statistics files.

Next, the output data of the collision are stored in separate file for each collision event. A typical snapshot of the collision events and the setting for the collision data is shown in Figure 7. The collision data are exported from the CFD in a separate file, with the file name suffix of _Coll.dat (see Figure 8). This file is also saved to the streamtrace directory, so that the file path is …\BioPA_Run\data\streams\<filename>_Coll.dat. Again, the collision file is an intermediate step toward the statistics file.

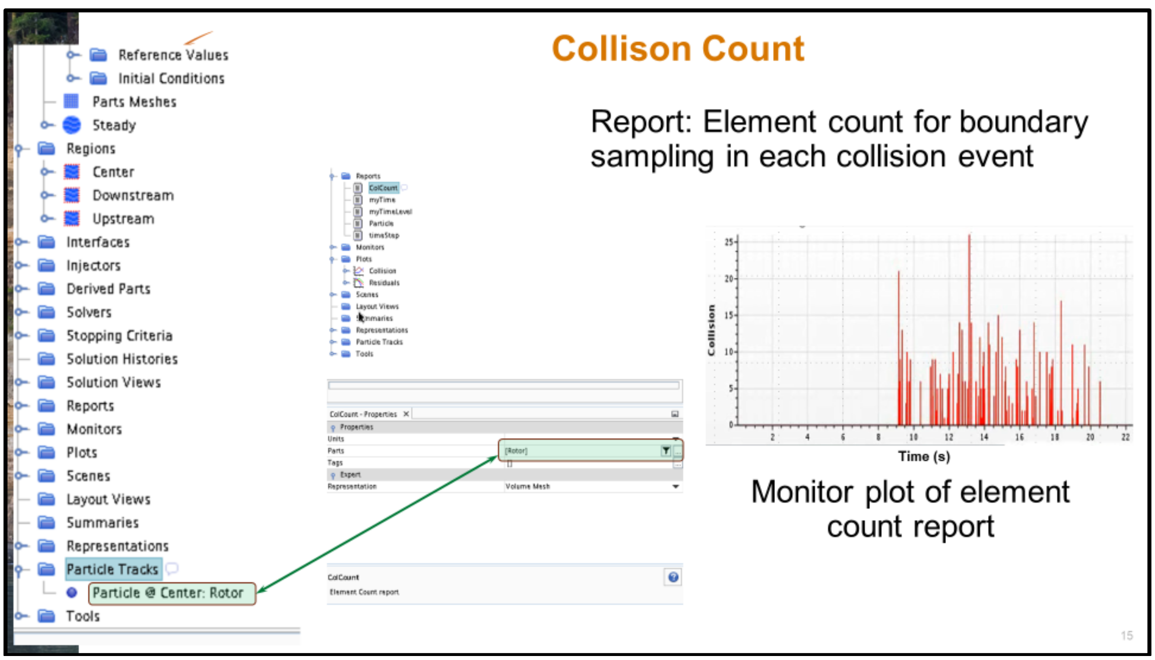


Figure 7. Snapshot show the setting of collision and collision events.

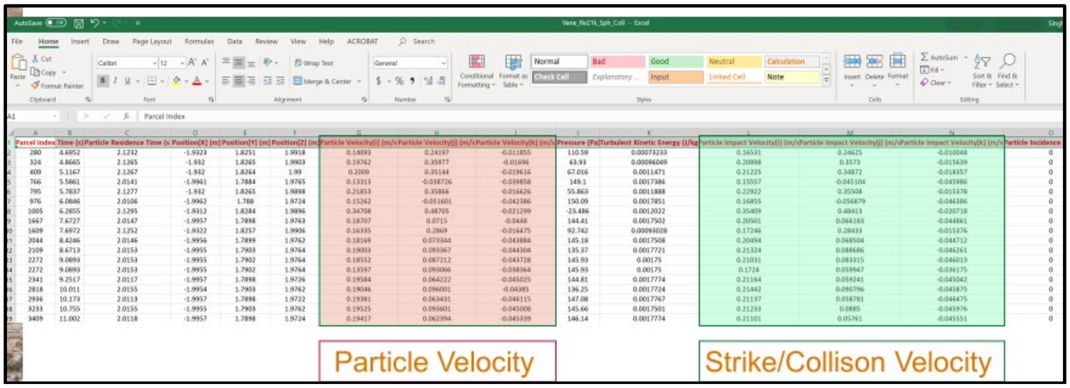


Figure 8. Snapshot showing the collision files used to create the statistics files (BioPA input files).

3.1.2 Outputs of CFD Simulations as Input of BioPA Toolset

BioPA uses the input statistics files as input files that contain all stressor data. Once extracted from the *_Traj.csv and the *_Coll.csv data files, the statistics files are saved to the

…\BioPA_Run\data\stats\ directory as …\BioPA_Run\data\stats\<filename>.dat,

where <filename> is the same useful identifier of the CFD simulation used to name the _Traj.dat and the _Coll.dat data files. The statistics file is shown in the figures, and the title of each column is also shown in the left side. Fields that have no value (for example Collision, Intense, and Thick if a collision analysis was not conducted) are set equal to the placeholder value of -9999.

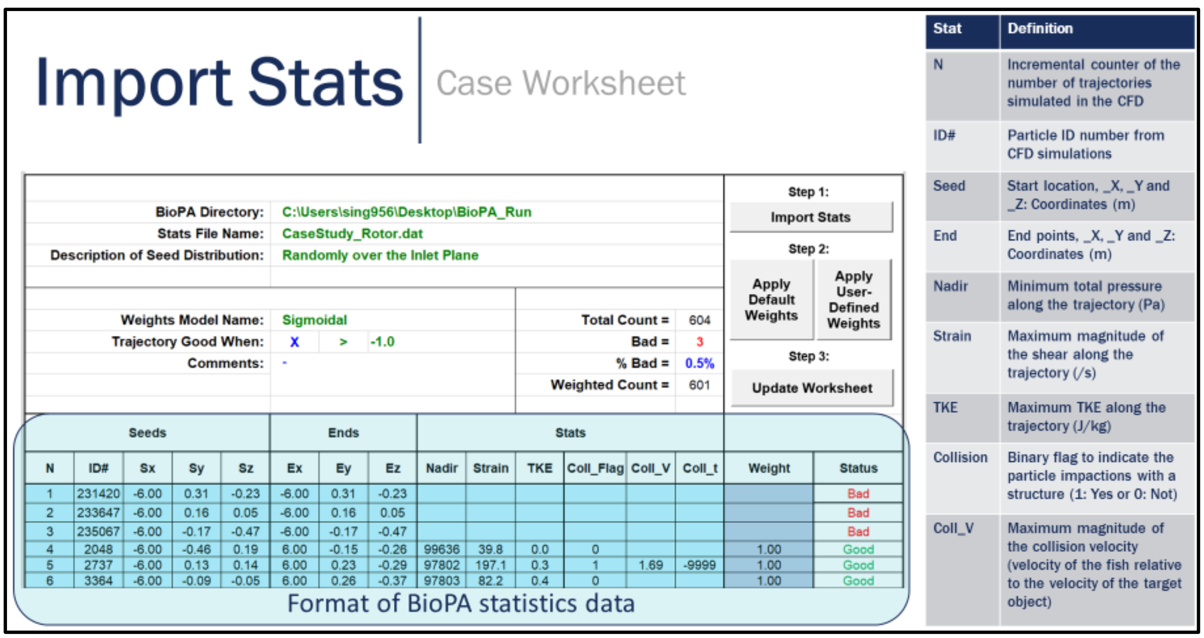


Figure 9. Snapshot showing the collision files used to create the statistics files (BioPA input files).

The BioPA toolset also provides a separate Excel application developed for BioPA 3.0 to convert CFD output (trajectory files and collision files) to BioPA input (statistics files) format. The steps for the file conversion are shown in Figure 10. The user specifies the column numbers required in each of the *_Traj.dat and the *_Coll.dat files in the input table shown on right side of Figure 10.

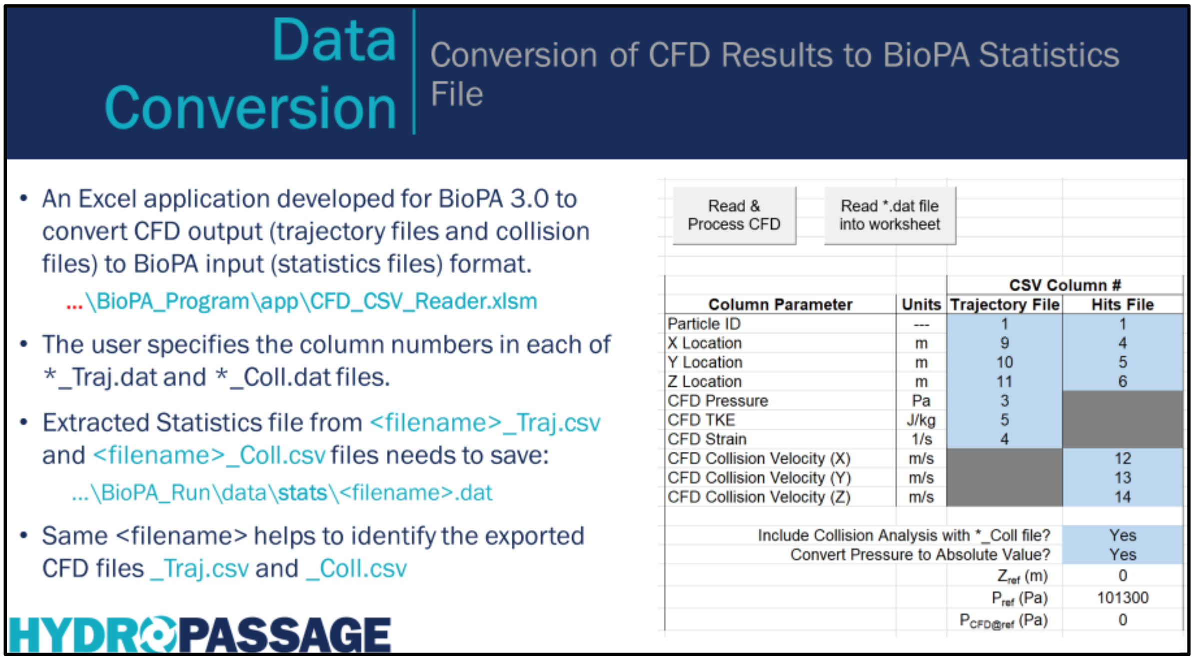


Figure 10. Snapshot showing the steps and conversion application files.

3.1.3 BioPA Analysis

Once the statistics file is created, the BioPA analysis is performed using the worksheet of the toolset. Each Case Worksheet requires several specific inputs to define the given PQI calculation. These inputs are identified in green font in

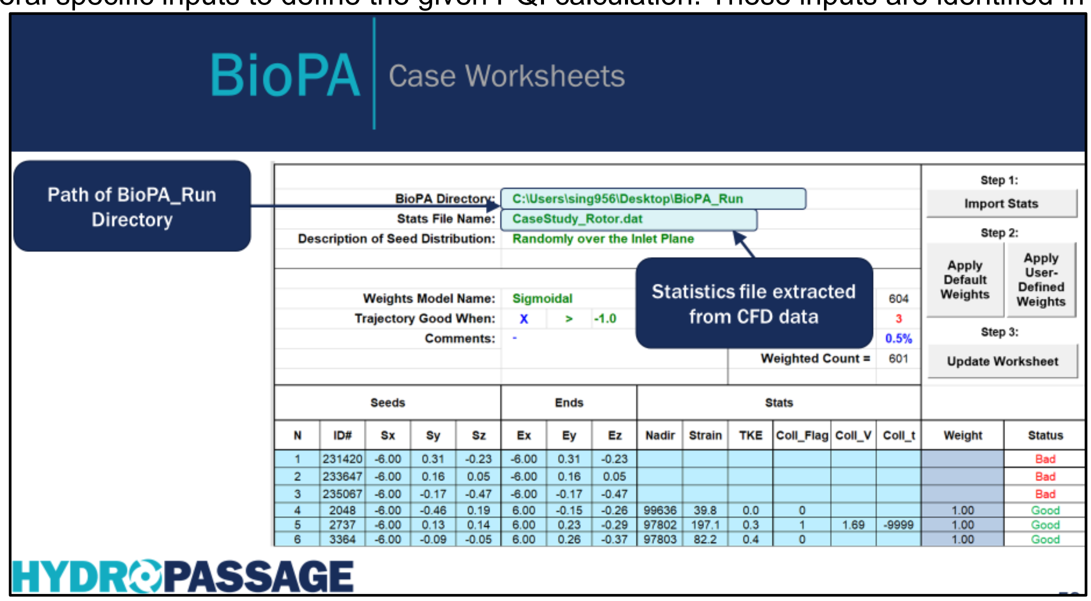


Figure 11. The path and BioPA needs to be accurately defined otherwise the program will not run. Once these inputs are accurately specified, the “Import Stats” button is clicked to load the statistics data.

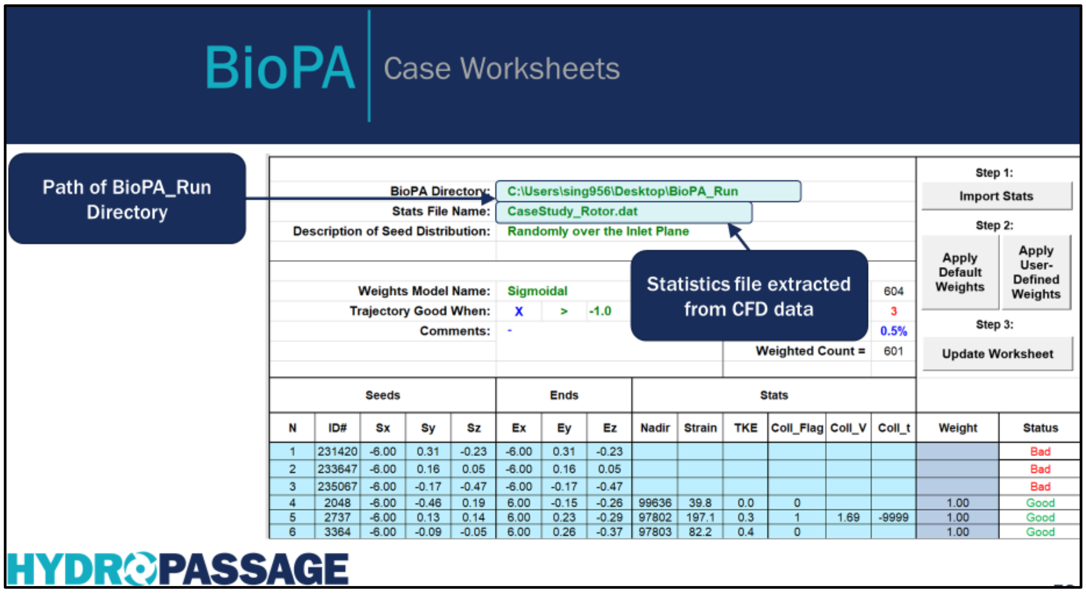


Figure 11. Example of file path inputs and worksheet.

Upon completing the above steps, trajectory and collision data files were created for each operating condition. The final statistics files were saved in the stats directory in the BioPA run folder. The BioPA_Run directory tree is the repository for files used and generated by the BioPA application (see Figure 12).

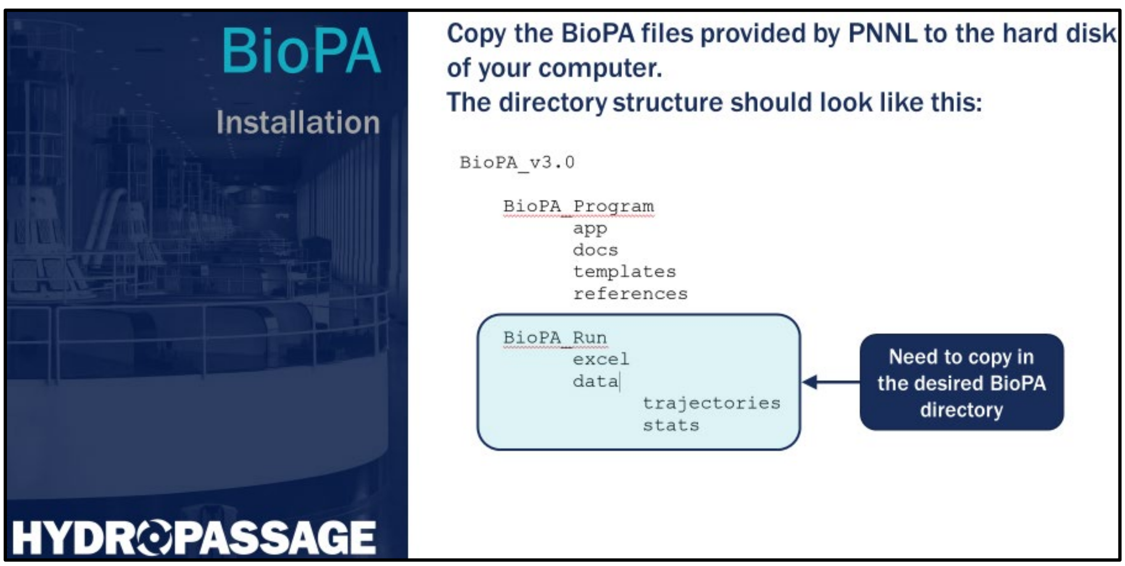
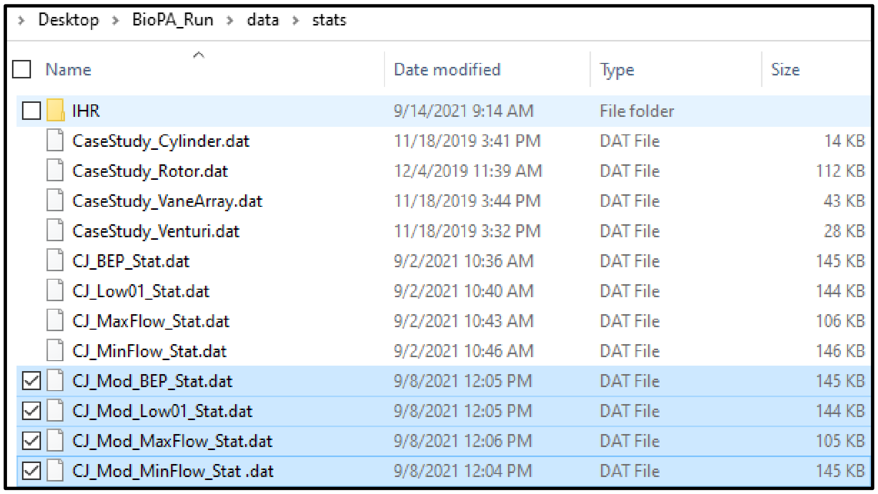


Figure 12. The steps, structure, and location of the stats directory in the BioPA run folder.

The statistics files for these operating conditions are the files highlighted in the Figure 13. These files are loaded in a separate worksheet of the BioPA toolset. BioPA analyses were performed for the computation of each stressor and compared to all operating conditions. The stressor distribution and exposure probability are shown in Figure 14 under four operating conditions.



> Desktop > BioPA_Run > data > stats

Name	Date modified	Type	Size
IHR	9/14/2021 9:14 AM	File folder	
CaseStudy_Cylinder.dat	11/18/2019 3:41 PM	DAT File	14 KB
CaseStudy_Rotor.dat	12/4/2019 11:39 AM	DAT File	112 KB
CaseStudy_VaneArray.dat	11/18/2019 3:44 PM	DAT File	43 KB
CaseStudy_Venturi.dat	11/18/2019 3:32 PM	DAT File	28 KB
CJ_BEP_Stat.dat	9/2/2021 10:36 AM	DAT File	145 KB
CJ_Low01_Stat.dat	9/2/2021 10:40 AM	DAT File	144 KB
CJ_MaxFlow_Stat.dat	9/2/2021 10:43 AM	DAT File	106 KB
CJ_MinFlow_Stat.dat	9/2/2021 10:46 AM	DAT File	146 KB
CJ_Mod_BEP_Stat.dat	9/8/2021 12:05 PM	DAT File	145 KB
CJ_Mod_Low01_Stat.dat	9/8/2021 12:05 PM	DAT File	144 KB
CJ_Mod_MaxFlow_Stat.dat	9/8/2021 12:06 PM	DAT File	105 KB
CJ_Mod_MinFlow_Stat .dat	9/8/2021 12:04 PM	DAT File	145 KB

Figure 13. Statistics files (Highlighted) created and used in BioPA applications.

The outcome of the exposure probability distribution for each stressor quantity is not surprising. The impact velocity and shear increase with increasing load. Similarly, turbulence was also expected to increase with the increased load. Therefore, a wider distribution of all stressors was observed. The exposure probability distribution was further used in conjunction with the biological response model to calculate the PQI for different species as discussed in the Exposure Probabilities section.

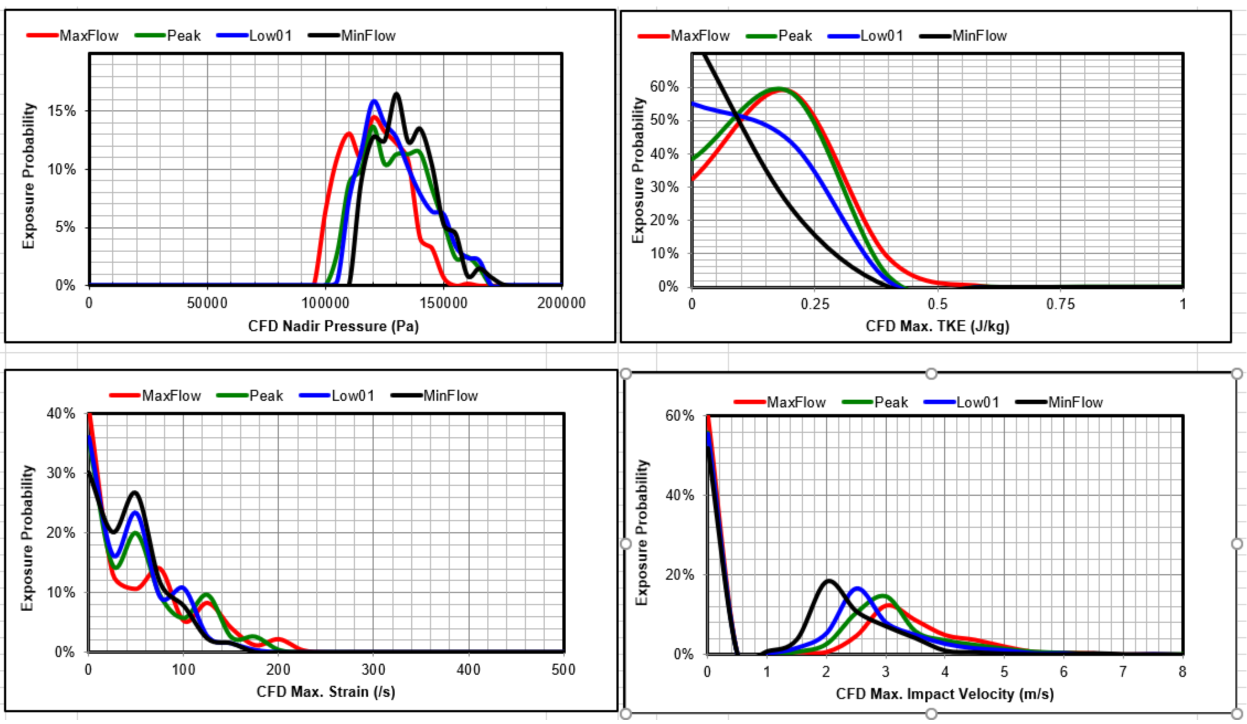


Figure 14. Comparison of the exposure probability of all stressors (nadir pressure, shear, turbulence, and strike) under four turbine operating conditions.

4.0 Interpretation of Results

Four species—Chinook salmon (*Oncorhynchus tshawytscha*), American shad (*Alosa sapidissima),* American eel (*Anguilla rostrata*), and bluegill (*Lepomis macrochirus*)—were selected for analysis based on their conservation importance and contrast in susceptibility to the stressors. Each species was analyzed for each stressor except for turbulence. Turbulence was not examined in this analysis because (1) none of these species currently has a biological response model for turbulence and (2) for the existing models from other species, there is a 0% likelihood of response for the predicted exposures for all operations. There is no collision model for Chinook salmon, therefore rainbow trout (*O. mykiss*) was used as a surrogate. Default weights were applied for the depth weighting for each particle track and an acclimation depth of 7.5 m was input for rapid decompression models.

Several of the models have various responses that can be selected for a species. For example, there are three rapid decompression models for bluegill exposure to rapid decompression—injury, mortal injury, and immediate mortality. Similarly, there are three responses for bluegill exposed to fluid shear—minor injury, major injury, and immediate mortality. For this analysis, mortal injury (injuries highly associated with and likely to predict mortality) was selected for the rapid decompression models and major injury (injuries likely to lead to mortality) was selected for fluid shear models. Collision models all have mortality as the response.

4.1 Exposure Probabilities

The probability of exposure (P_e) is calculated from the statistics file data and is displayed as a histogram (blue lines) for each stressor. The distribution data for each stressor are located below each stressor, as are the calculations for the probability of response (P_m) at the various stressor magnitudes. Once a model is selected, the red line on the chart will display the probability of response and the probability of adverse passage is calculated by multiplying the probability of exposure by the probability of response for the full range of stressor magnitudes. The cumulative sum of adverse passage is located at the bottom of the adverse passage column and is a prediction of the overall likelihood that a fish will exhibit the selected response when exposed to the stressor conditions described by the statistics file. For example, in this demonstration, the juvenile Chinook salmon mortal injury model was selected for rapid decompression and under the MaxFlow condition, it is expected that juvenile Chinook would have 1.2% likelihood of incurring mortal injuries when exposed to these conditions.

The probability of adverse passage was calculated for each stressor for the four selected species and the four modeled operations. Bluegill were the species most susceptible to all three stressors, particularly rapid decompression (Table 3). American eel was the least susceptible species and is not likely to be severely injured by any of the stressors for any of the operations. The stressor of most concern is rapid decompression, which resulted in mortal injury rates ranging from 2.8 to 4.7% for juvenile Chinook salmon and 22.8 to 33.6% for bluegill.

Table 3. Probability of adverse passage for four species exposed to stressors during various operations of a high head fish bypass.

Stressor	Response	Species	Probability of Adverse Passage per Operation			
			BEP	Low01	MaxFlow	MinFlow
Rapid Decompression	Mortal injury	Chinook Salmon	0.90%	0.90%	1.20%	0.80%
		American Shad	3.40%	3.30%	4.70%	2.80%
		American Eel	0.00%	0.00%	0.00%	0.00%
		Bluegill	25.20%	25.00%	33.60%	21.80%
Fluid Shear	Major Injury	Chinook Salmon	0.01%	0.00%	0.01%	0.00%
		American Shad	0.06%	0.04%	0.06%	0.04%
		American Eel	0.00%	0.00%	0.00%	0.00%
		Bluegill	0.06%	0.05%	0.06%	0.05%
Collision	Mortality	Chinook Salmon	0.38%	0.47%	0.58%	0.33%
		American Shad	0.20%	0.32%	0.33%	0.21%
		American Eel	0.00%	0.00%	0.00%	0.00%
		Bluegill	3.05%	2.47%	3.95%	1.48%

Because it is uncertain how exposure to multiple stressors during passage through a hydropower facility will affect a fish's susceptibility, a performance score is given by the BioPA toolset. This PQI (Passage Quality Index) score is a relative comparison of the various operations or "runs." The PQI is based on a scale of 0 to 500 with a higher score representing a better biological performance (i.e., a better quality of fish passage).

For this demonstration, all operations performed similarly, although MaxFlow is expected to be the most detrimental to fish (shown in Table 3). All operations scored relatively high for Chinook salmon, American Shad, and American Eel. Bluegill had the lowest scores—about 10% lower than those for the other three species.

Table 4. Passage Quality Indices for four fish species during various operations of a high head bypass facility.

Species	PQI per Operation				Mean PQI
	BEP	Low01	MaxFlow	MinFlow	
Chinook Salmon	497.0	497.0	497.0	498.0	497.3
American Shad	493.0	493.0	491.0	494.0	492.8
American Eel	500.0	500.0	500.0	500.0	500.0
Bluegill	452.0	454.0	437.0	461.0	451.0

4.2 BIOLOGICAL PERFORMANCE CONCLUSION

Overall, this bypass facility is expected to perform well for most species—survival rates for each interindividual stressor were in the mid to high 90% range. However, if there are species of fish that are more susceptible to rapid decompression, such as bluegill or largemouth bass, survival rates may be significantly lower, potentially as low as 60%. If species such as these are of concern at a location with this bypass design, modification may be necessary to alleviate the low pressures that fish are likely to encounter when passing this facility.

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For information about licensing the BioPA toolset, HBET, and Sensor Fish:

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