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Quantifying barotrauma risk to juvenile fish during hydro-turbine passage

Marshall C. Richmond[a,*], John A. Serkowski[a], Laurie L. Ebner[b], Mirjam Sick[c], Richard S. Brown[d], Thomas J. Carlson[e]

[a] Hydrology Group, Earth Systems Science Division, Pacific Northwest National Laboratory, Richland, WA, United States
[b] Portland District, US Army Corps of Engineers, Portland, OR, United States
[c] Andritz Hydro, Zurich, Switzerland
[d] Ecology Group, Earth Systems Science Division, Pacific Northwest National Laboratory, Richland, WA, United States
[e] Coastal Sciences Division, Pacific Northwest National Laboratory, Sequim, WA, United States

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ABSTRACT

We introduce a method for hydro turbine biological performance assessment (BioPA) to bridge the gap between field and laboratory studies on fish injury and turbine engineering design. Using this method, a suite of biological performance indicators is computed based on simulated data from a computational fluid dynamics (CFD) model of a proposed hydro turbine design. Each performance indicator is a measure of the probability of exposure to a certain dose of an injury mechanism. If the relationship between the dose of an injury mechanism (stressor) and frequency of injury (dose–response) is known from laboratory or field studies, the likelihood of fish injury for a turbine design can be computed from the performance indicator. By comparing the values of the indicators from various turbine designs, engineers and biologists can identify the more-promising designs and operating conditions to minimize hydraulic conditions hazardous to passing fish. In this paper, the BioPA method is applied to estimate barotrauma induced mortal injury rates for Chinook salmon exposed to rapid pressure changes in Kaplan-type hydro turbines. Following the description of the general method, application of the BioPA to estimate the probability of mortal injury from exposure to rapid decompression is illustrated using a Kaplan hydro turbine at the John Day Dam on the Columbia River in the Pacific Northwest region of the USA. The estimated rates of mortal injury increased from 0.3% to 1.7% as discharge through the turbine increased from 334 to 564 m^3/s for fish assumed to be acclimated to a depth of 5 m. The majority of pressure nadirs occurred immediately below the runner blades, with the lowest values in the gap at the blade tips and just below the leading edge of the blades. Such information can help engineers focus on problem areas when designing new turbine runners to be more fish-friendly than existing units.

1. Introduction

Anadromous fish often must pass through hydroelectric facilities during their migration to the ocean. Fish may pass a facility over the spillway, through the turbines, or using an engineered by-pass route (Schilt, 2007). Even at facilities where by-pass routes are present, a significant number of fish pass through the turbines (Hockersmith et al., 2005; Ploskey et al., 2006; Hansel et al., 2008). Field studies generally indicate that turbine passage is hazardous, with mortality rates ranging between 2% and 19% (Whitney et al., 1997). This incremental mortality is magnified when fish have to pass through multiple hydropower facilities during their downstream migration, as occurs on the Columbia and Snake River systems in the Pacific Northwest region of the USA (Ham et al., 2005).

Over the past decade, many studies have described injury mechanisms associated with turbine passage, the response of various fish species to these mechanisms, and the probability of survival through specific dams under certain conditions. But transforming and integrating these data into tools to design turbines that improve survival by minimizing impacts to fish during passage has been difficult and slow. Although identifying the locations and hydraulic conditions where injuries occur is challenging, a more robust quantification of the turbine environment has emerged through integration of balloon tag and sensor fish

* Corresponding author at: PO Box 999, Richland, WA 99352, United States. Tel.: +1 509 372 6241.
E-mail address: marshall.richmond@pnnl.gov (M.C. Richmond).

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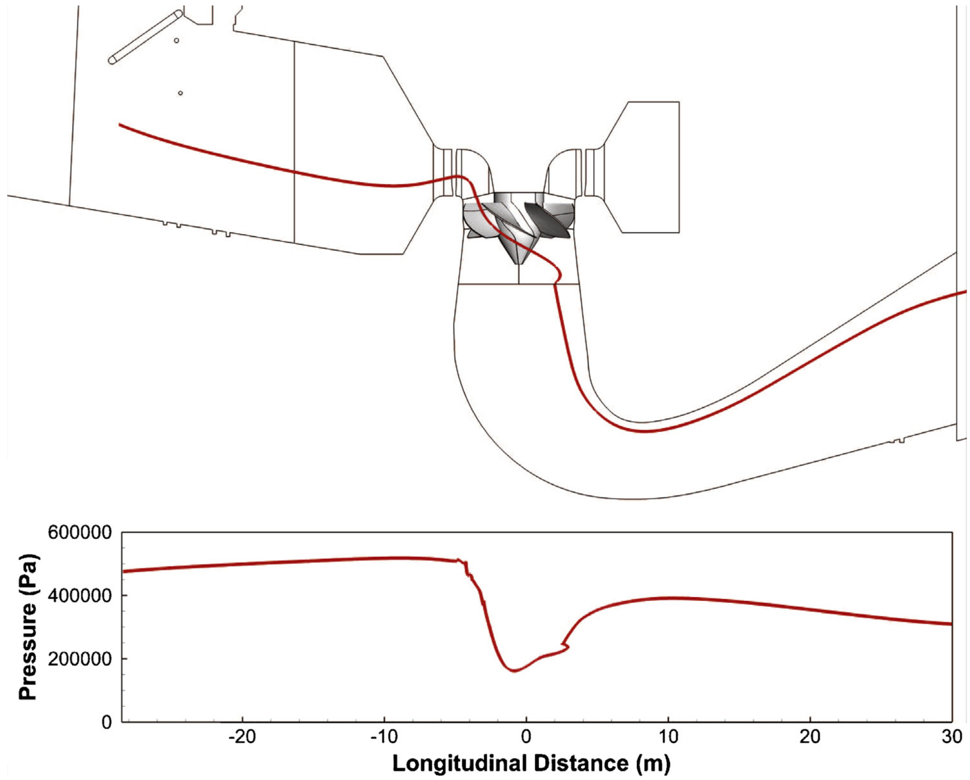

Fig. 1. Typical Kaplan turbine passage pressure profile along a streamline.

data with computational fluid dynamics (CFD) modeling (Dauble et al., 2007). Field-testing new hydro turbines is very expensive, so engineering design tools that improve the linkage between fish injury data and turbine characteristics are needed to identify the most promising designs before full-scale construction begins.

Past attempts to predict the risk to fish passing through the turbine environment have focused on identifying the locations and sizes of potentially hazardous regions (Garrison et al., 2002; Keller et al., 2006; Čada et al., 2006). Improving passage survival was a matter of reducing the volume and number of these regions. However, the presence of dangerous zones within the turbine may be biologically inconsequential if few fish experience them. For example, the undersides and tip regions of runner blades generally have very low pressures, which can be harmful to fish, but only a small fraction of the population may pass through these locations.

More recent work has described the use of minimum pressure threshold criteria to guide turbine design (Brown et al., 2012a). An advantage of using minimum pressure criteria is that it is straightforward to implement because it need not consider the non-uniform distribution of pressure within the turbine environment. However, minimum pressure criteria may have a limitation of assuming, when calculating an estimate of mortal injury rates, that all fish passing the turbine are exposed to the same minimum pressure value. In some cases it is possible that minimum pressure design criteria could be overly conservative and lead to the selection of more costly (e.g., lowering the centerline elevation of the unit through civil structure modifications) and less hydraulically-efficient designs.

The Pacific Northwest National Laboratory (PNNL) has developed a new probabilistic design method, the biological performance assessment (BioPA), for bridging this gap between laboratory studies on fish injury and turbine design. With this method, a suite of biological performance indicators for injury and mortality are computed based on data from a CFD model of a proposed turbine design. Each performance indicator is a measure of the probability of exposure to a certain dose of an injury mechanism. If the relationship between the magnitude of exposure to an injury mechanism and frequency of injury is known from laboratory or field studies, the likelihood of fish injury for a turbine design can be computed from the performance indicator. By comparing the values of the indicators from various turbine designs, the engineer can identify the more-promising designs.

In this work, we introduce the BioPA method with a description of its theory, assumptions, and implementation. To illustrate the concepts, we apply the BioPA to estimate fish mortal injury caused by rapid pressure changes in a Kaplan-type hydro turbine.

2. BioPA method

In order to evaluate the significance of the low pressure regions, the BioPA method estimates the probabilities that fish will encounter specific conditions during passage. This is done with a proportional sampling scheme that uses streamtraces in a numerical flow simulation to model potential pathways through the turbine.

2.1. Response of fish to pressure change

Rapid change in barometric pressure, or barotrauma, is a potential cause of injury and mortality for juvenile salmonids passing through hydro turbines (Brown et al., 2012c). Computational fluid dynamics (CFD) models (Keller et al., 2006) and field studies (Carlson et al., 2008) show that turbine passage exposes all fish to a slow compression in the intake followed by a rapid decompression as they pass either the pressure side or the suction side of the runner blades. This is followed by a return through the draft tube to hydrostatic conditions in the tailrace. A typical profile of pressure along a streamline is shown in Fig. 1.

Research into barotrauma in fish can be traced back to the work of Sutherland (1972) and Tsvetkov et al. (1972) who found a significant potential for injury due to rapid decompression. More detailed studies were performed by Abernethy et al. (2001), who subjected several fish species to a simulated turbine-passage pressure regime after acclimatization at two pressures and three levels of dissolved gas saturation. They observed immediate and delayed mortalities attributed to the development of gas bubbles in vulnerable organs and ruptured swim bladders. Higher levels of dissolved gas in the water appeared to increase injury in some species. In a follow-up experiment (Abernethy et al., 2002), a less severe pressure regime, with a higher nadir pressure and a lower rate of change (3447 kPa/s, rather than 3930 kPa/s), resulted in lower mortalities of the two species tested. The study design could not establish whether the lower mortality was due to the lower rate of pressure change or to the higher nadir pressure.

Recognizing limitations (a lack of true acclimation to depths below surface pressure) in the experimental procedures used by Abernethy et al. (2002), a new series of studies were initiated by Carlson and Abernethy (2005), that progressed to the work of Brown et al. (2012c) where 5767 juvenile Chinook salmon were exposed to a range of conditions that simulated turbine pressure regimes to identify the key factors associated with barotrauma. To quantify the condition of the fish after treatment, they defined a metric called mortal injury. A fish was mortally injured if it suffered any of eight specific injuries that were highly associated with mortality (McKinstry et al., 2007). The fish were first acclimated to constant pressures equivalent to 1.5, 4.6, or 7.6 m of water depth. Then they were exposed to simulated turbine pressure regimes with minimum pressures (nadirs) that ranged from atmospheric pressure (101 kPa) to as low as 4.8 kPa and rates of pressure change ranging from approximately 1400 to 4100 kPa/s. During acclimation, these fish were also exposed to total dissolved gas levels of either 115% or 125%. Statistical analysis indicated that the log of the pressure-change ratio (*LRP*), total dissolved gas (TDG), rate of pressure change, and condition factor of fish were all factors in predicting mortal injury. However, *LRP*, defined as

$$LRP = \ln\left(\frac{P_a}{P_n}\right) \tag{1}$$

where P_a is the pressure to which the fish is acclimated (become neutrally buoyant) prior to laboratory-generated turbine pressure change, and P_n is the lowest pressure (pressure nadir), was, by far, the most influential variable in predicting mortal injury, with TDG, rate of change, and condition factor explaining very little of the relationship. For pressure change histories typical of large Kaplan turbines in Columbia River powerhouses, *LRP* was found to be the most significant variable explaining the probability of injury from barotrauma.

The relationship observed by Brown et al. (2012c) (and the corrected version in Brown et al., 2012b) for Chinook salmon is expressed in the empirical formula for mortal injury probability

$$\mathcal{P}_{mort}(LRP \le LRP_i) = \frac{e^{-5.56+3.85\times LRP_i}}{1+e^{-5.56+3.85\times LRP_i}} \tag{2}$$

where the notation $\mathcal{P}_{mort}(LRP \le LRP_i)$ indicates the probability that the LRP is less than or equal to a certain value LRP_i. Note that Eq. (2) is currently the most complete dose–response model that relates injury and mortality to pressure change across a broad range of pressures typical of Kaplan turbines. Eq. (2) is plotted in terms of absolute pressure (rather than LRP) for several discrete acclimation pressures in Fig. 2 to illustrate its effect on mortal injury probabilities where pressure at the water surface is approximately 101 kPa.

Note that the mortal injury relationship (Eq. (2)) does not include any effects related to indirect mortality where fish may be in a weakened condition due to pressure exposure and then be subject to increased rates of mortality from predation by birds or other fish downstream of the powerhouse.

2.2. Exposure estimation

To assess the exposure of fish to pressure change during turbine passage, the pressure conditions must be characterized. Field measurements of the prototype turbine flow environment that fish may encounter are available only for a limited number of potential pathways and relatively small sample sizes (Carlson et al., 2008). However, even these limited data confirm that the turbine environment is extremely heterogeneous, so the level of exposure to low pressure zones is dependent on the path the fish takes. More complete characterization must be done using reduced-scale physical modeling or computer simulations to capture the variability of the turbine environment.

The BioPA relies on three-dimensional steady-state CFD models to estimate the pressure regime in the turbine domain. To address the heterogeneity issue, the model domain is sampled using a dense array of streamtraces that provides a weighted estimate of exposures over paths likely to be taken by fish passing through the turbine.

2.3. Analysis software

BioPA is built around commercial software packages together with custom post-processing scripts. Implementation was driven by the objective to give turbine designers a convenient tool that could be incorporated into their normal work flow with a minimum of disruption, cost, and computational resources. The tool needed to be easy to use, quick to learn, and robust. Results needed to be consistent and reproducible.

To achieve these aims, the BioPA uses inexpensive, off-the-shelf software components, often already employed by hydro turbine manufacturers, running under the widely-used Microsoft Windows 7 environment. Most tasks were automated with scripts for efficiency and consistency. The application consists of three components:

1. CFD solver: simulation software that generates the model result file.
2. Stressor calculator: a Tecplot360 application that samples CFD using streamtraces and computes statistics.
3. Scoring application: A Microsoft Excel 2010 application that computes BioPA scores based on streamtrace statistics.

To allow manufacturers to use their preferred CFD solver, the BioPA does not require the use of a specific package, so long as it meets the minimum requirements listed below. The other two components require the availability of two commercial products: Tecplot360 and Microsoft Excel. Tecplot360 is a commonly-used scientific data plotting package that includes specialized capabilities for the analysis of CFD model results. Microsoft Excel is a popular spreadsheet application that can be used for processing and charting data sets.

A suitable CFD model of the fluid domain in the turbine system is needed to conduct a biological performance assessment using the BioPA tools. While details of general CFD simulation practice are outside the scope of this paper, certain model characteristics are necessary in order to use the current version of BioPA:

1. The model should be constructed at prototype scale. Although it is common for designers to model turbines at the physical-model scale during development, certain properties of reduced-scale simulations cannot be scaled up to estimate full-scale fish exposure.
2. The model must generate a steady-state solution. Although a transient solution may produce a more-accurate representation of the flow, the BioPA is not currently configured to

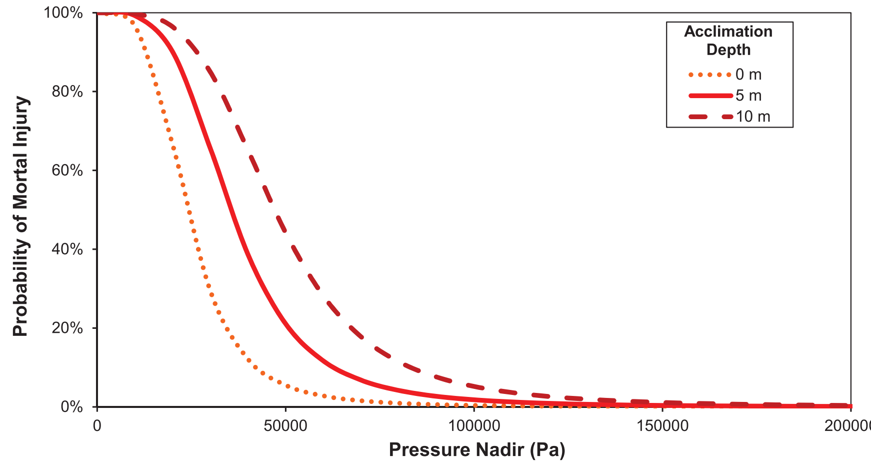

Fig. 2. Dose–response curves for nadir pressures given a typical range of fish acclimation depths (0, 5, and 10 m). Pressure at the water surface (0 m) is approximately 101 kPa.

accommodate this additional level of complexity. Moreover, few designers have the time or resources to produce transient results as part of routine design work.

3. In order to model the moving components of the turbine with a steady-state solution, a multiple reference frame (MRF) scheme is necessary. With the runner in a fixed position, the surrounding fluid is modeled in a rotational reference frame to simulate the appropriate movement.
4. The model must resolve flow features at areas of interest (blades, wicket gates, stay vanes, tip gaps, etc.) at a scale smaller than the length of a fish. Typically, meshes used in these locations are finer than this length scale in order to resolve boundary layers.
5. The model output file must be in a format that can be imported into Tecplot360 and contain, at a minimum, the following variables for each node in the mesh:
   - position coordinates
   - velocity components in the stationary reference frame
   - velocity in the rotational reference frame
   - static pressure

2.3.1. *Streamtrace sampling*

Because of the heterogeneous nature of the flow, all parts of the turbine environment are not equally likely to be visited by fish. Some areas will receive more traffic than others, so these places should be sampled in higher proportion.

Proportional sampling of the simulated turbine domain is accomplished using a streamtrace method. The model inlet is seeded with a large number of points, each representing a possible location of a fish entering the turbine. The seeds are distributed in accordance with available field observations, or a distribution may be assumed based on expected behaviors of the species of interest. If fish are known to be concentrated in the upper part of the water column, seeds are proportionately more dense in these areas. From each seed location, Tecplot360 numerically advects a massless, neutrally-buoyant particle through the flow field to generate a streamtrace trajectory (Fig. 3). The analysis software interpolates CFD model variables at each point along the streamtrace.

Streamtraces must pass completely through the model domain, without interruption, in order to be used in the analysis. However, streamtraces may stop if there are gaps in the model mesh, or if velocity decreases to zero along the route. If these prematurely terminating streamtraces cannot be eliminated through adjustment of the model, they are excluded from the analysis. In general, a prematurely terminating streamtraces rate of less than 5% is desirable.

The number and distribution of the initial streamtrace seeds is an important factor in setting up the BioPA. Ideally, seeds are placed across the entire intake boundary in a pattern that mimics the actual fish distribution. However, fish distribution data are often not available or are uncertain, so a uniform distribution is usually chosen by default.

The number of streamtraces necessary to adequately sample a model domain depends on the resolution of the model and the flow dynamics. A more-finely resolved model grid can produce small flow features that a coarse seeding pattern may not capture. To determine a sufficient number of seeds, a sensitivity analysis should be performed by increasing the seed count until the BioPA score no longer changes significantly. Using fewer seeds will reduce computational resources as increased numbers of seeds requires more computer time and generates larger files. The seed sensitivity analysis determines the optimum number of seeds, which is a balance between an accurate sampling of the model and a tolerable computation time.

2.3.2. *Exposure probability*

After streamtraces have been generated, the nadir pressure along each path is determined. This value is known as a stressor

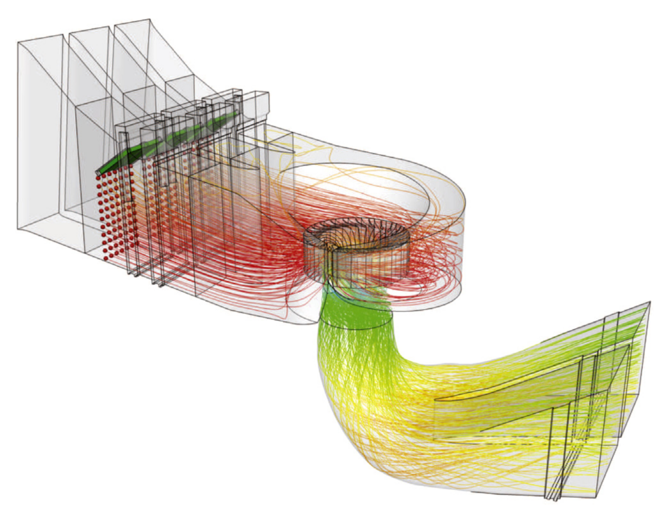

Fig. 3. Example of streamtraces through a CFD model of a Kaplan turbine based on 180 uniformly-spaced seeds starting in the intake. Streamlines are colored by absolute pressure to show the general distribution of higher pressures (reds) and lower pressures (blue-green) in the turbine. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

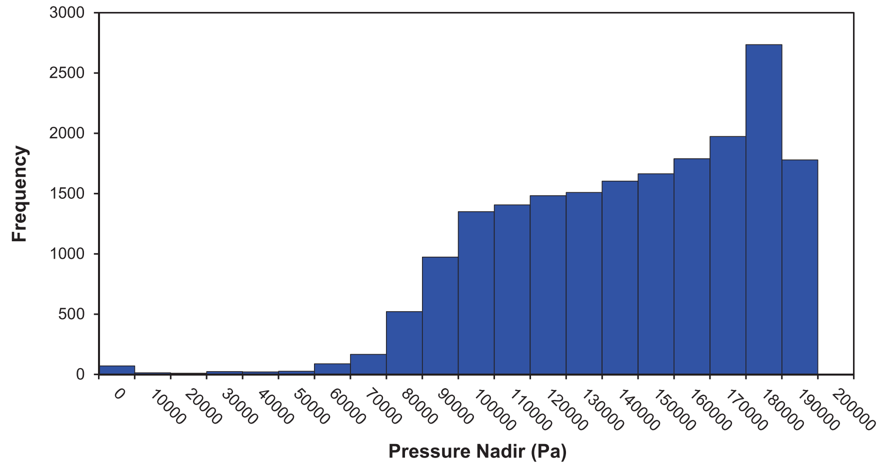

Fig. 4. Histogram of pressure nadirs for 20,352 streamtraces.

variable for pressure. Based on the assumption that each streamtrace represents an equally likely path that a fish might take through the turbine (Section 3), the probability of exposure to a stressor variable S over the interval from s_1 to s_2 is given by

$$\mathcal{P}(s_1 \leq S \leq s_2) = \frac{N_{s_1-s_2}}{N} \tag{3}$$

where $N_{s_1-s_2}$ is the number of streamtraces where the stressor variable S is between s_1 and s_2 and N is the total number of streamtraces. If the range of S is subdivided into a finite number of equal intervals and the probability of each interval is computed, then a probability density histogram for the exposure can be constructed (Fig. 4).

2.3.3. Performance score

The ultimate output of the BioPA process is a score that correlates to the likelihood that a fish can survive passage through a turbine. The score is dependent on:

- **Fish species and size**. Species and individuals of varying size may differ in responses to stressors, locations at turbine entry, and acclimation depth.
- **Turbine design**. The turbine type and geometry dictates the general flow environment.
- **Turbine operating configuration**. Changes in discharge through the turbine together with gate and blade angles affect the flow conditions for a specific turbine design.

The BioPA score is computed by combining the dose–response information obtained from laboratory studies (Section 2.1) with the exposure probability determined through streamtrace sampling (Section 2.3.2). The score is the sum of the products of the probability of mortal injury (the dose–response) and the probability of exposure (the exposure estimate) over all stressor-variable values. If $\mathcal{P}(I|S)$ is the probability of sustaining a mortal injury I for a given stress S and $\mathcal{P}(S)$ is the probability of exposure to stress S then this relationship is expressed as

$$\beta_s = \int \mathcal{P}(I|S) \cdot \mathcal{P}(S)\, dS \tag{4}$$

where β_s is the performance score. This integral is illustrated by the hatched area under the exposure and mortality curves in Fig. 5. Because the probability distributions are discrete functions, this integral is performed as a sum over n equal stressor-variable intervals:

$$\beta_s = \sum \mathcal{P}(I|S_i\, to\, S_{i+1}) \cdot \mathcal{P}(S_i\, to\, S_{i+1}) \tag{5}$$

3. Assumptions

As with any predictive method, the BioPA process relies on confidence in certain data sets and assumptions in how they may be used. This section identifies some of these uncertainties and how they may limit the application of the current BioPA version.

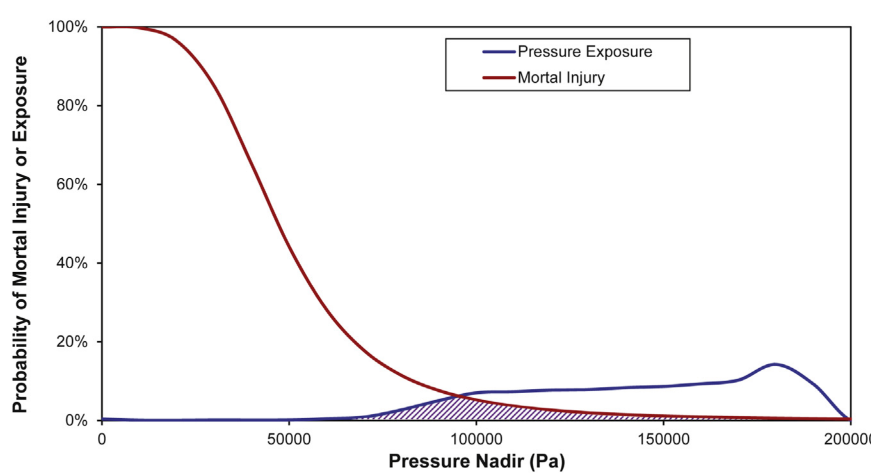

Fig. 5. Hatched area under curves represents expected mortal injury for given pressure distribution as represented by the integral in Eq. (4). The probability of pressure exposure is calculated from the pressure nadir histogram (Fig. 4).

Fig. 6. John Day Dam on the Columbia River in the Pacific Northwest region of the USA.

3.1. Stress response

BioPA depends heavily on the availability of biological test data relating to fish response to stress. Section 2.1 reviews the results of research on dose–response to pressure change. However, for reasons of cost and time, laboratory experiments tend to evaluate very specific situations, which in some cases only approximate the actual conditions within the turbine. Extrapolation of these data to more general situations is a challenge. Moreover, injury studies that yield dose–responses generally do not account for the synergistic effects of multiple doses of a particular stressor or the combined effect of multiple stressors because each injury mechanism is

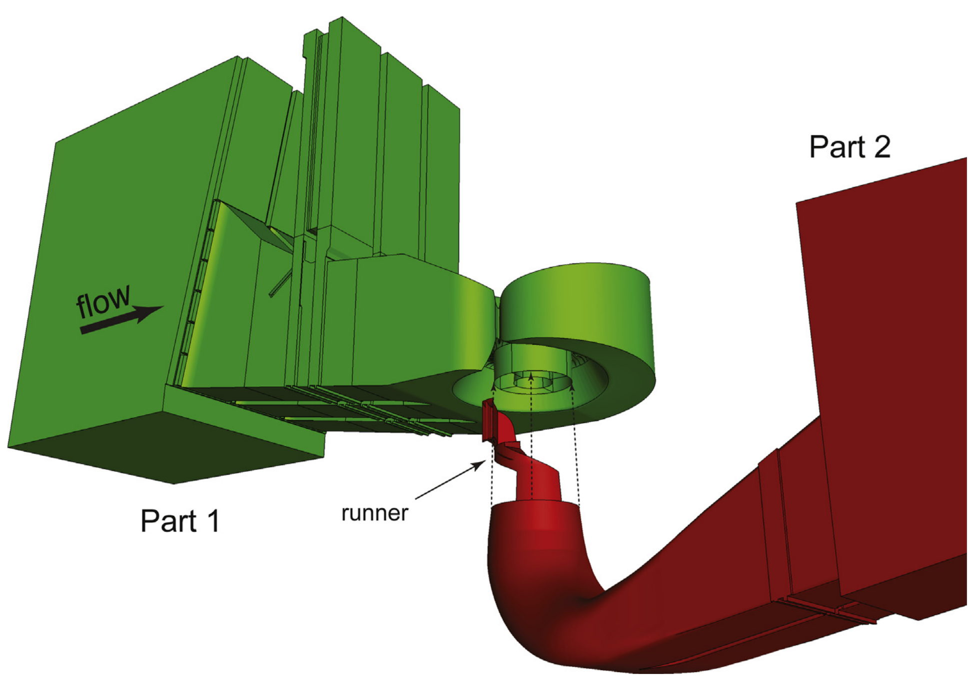

Fig. 7. CFD model domain; Part 1 (left) – intake and spiral case; Part 2 (right) – runner and draft tube.

Table 1
Turbine operating points.

Operating point	Description	Wicket gate angle (°)	Blade angle (°)	Discharge (m^3/s)	Head (m)	Efficiency (%)
BP01	Peak	35	26.2	466	31.4	90.8
BP02	Lower 1%	28.7	19.6	334	31.5	89.5
BP05	Upper 1%	40.8	31.6	564	31.4	90.1

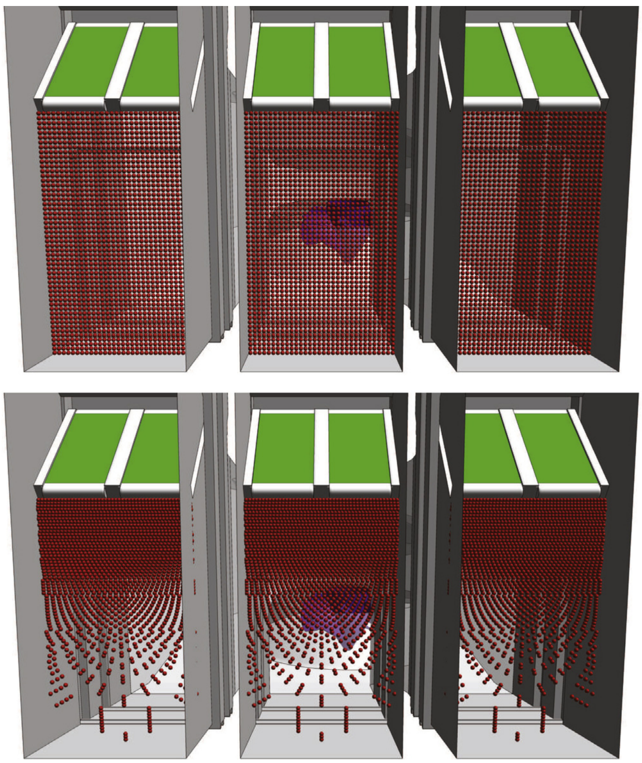

Fig. 8. Streamtrace seed distribution patterns below the fish guidance screens (shown in green) in the intake. Top image shows uniform distribution with 5088 seeds; bottom image shows sigmoidal distribution with 5006 seeds. The view is looking downstream into the turbine intake and the seed locations are shown in red. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

evaluated in isolation. A fish stressed by one mechanism is likely to be more susceptible to injury by another mechanism or repeated instances of the same mechanism, even if the dose of the latter exposure would not ordinarily harm an unstressed individual.

3.2. Fish characteristics

The behavior of fish before and during turbine passage is also the subject of considerable uncertainty among biologists. Of significance to turbine passage is the observation that juvenile salmon tend to exhibit different body orientations as they pass through the intake (Coutant and Whitney, 2000). However, direct observation of fish within the runner region has not been possible (Moursund and Carlson, 2004) so their behavior and their paths past the runner blades has never been measured. This knowledge gap has led many researchers to assume that fish basically follow flow streamlines when encountering the high velocities of the turbine environment. This is also assumed in the BioPA. This is substantiated by the observation that burst speed of juvenile salmon typically do not exceed about nine body-lengths per second (Puckett and Dill, 1984), or about 1 m/s, which is significantly lower than the 5–20 m/s velocities typical of the turbine runner environment.

A second consideration is the depth to which fish are acclimated when entering the turbine, which Brown et al. (2012c) found to be a significant factor in pressure-related injuries. The depth at which fish are observed to travel in the upstream reservoir or their entry depth in the turbine intake does not necessarily represent the depth to which they are acclimated (or the equivalent pressure, P_a in Eq. (1)). There is a need to develop methods to measure depth acclimation of migrating fish in the field. While field data are currently not available, the laboratory studies of Pflugrath et al. (2012) determined that the median maximum depth that a Chinook salmon can become neutrally buoyant is 6.7 m (range 4.6–11.6 m).

3.3. Computational fluid dynamics (CFD)

The BioPA relies on data generated through numerical modeling of the turbine environment. While CFD modeling has a long history of successful application in a variety of fluid-flow problems, including hydro turbine applications, the lack of comprehensive prototype-scale validation data must be noted. Direct measurement of many flow variables in an operating turbine is exceedingly difficult (Čada, 2001; Moursund and Carlson, 2004),

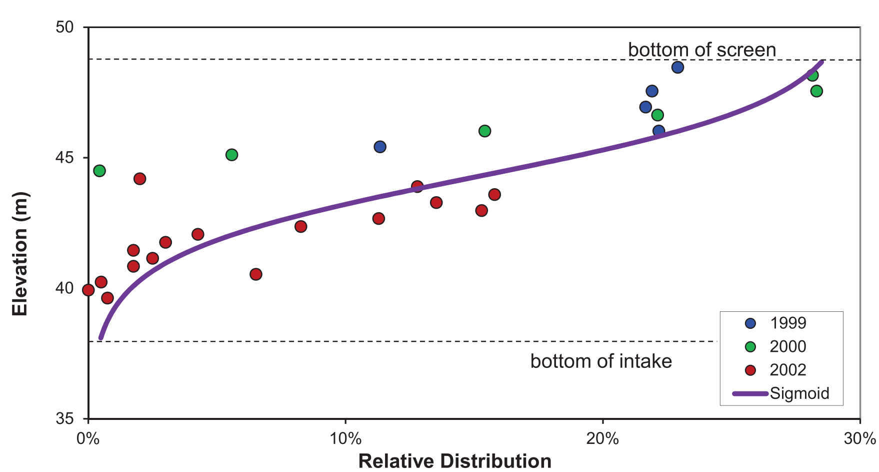

Fig. 9. Sigmoidal distribution based on hydro-acoustic observations of fish distribution at John Day Dam (Johnston et al., 2000; Moursund et al., 2001, 2003).

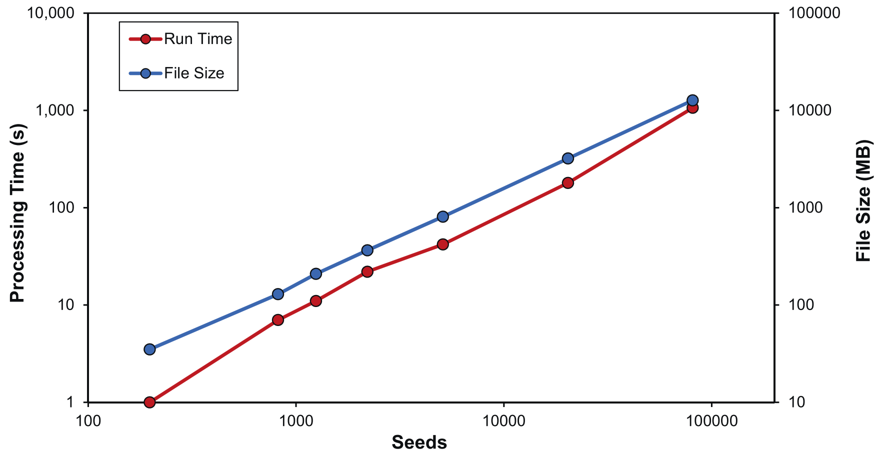

Fig. 10. Rates of increase in processing time and file size with seed number.

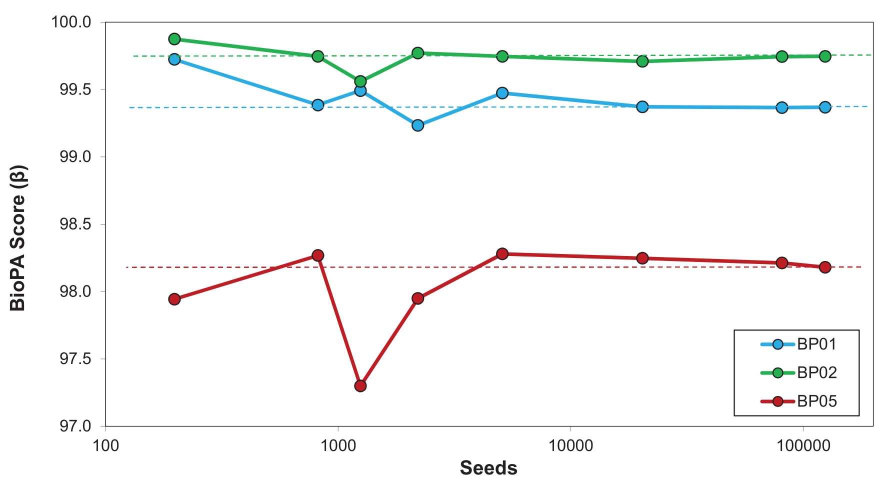

Fig. 11. BioPA scores as a function of number or seeds. All runs use an acclimation depth of 5 m.

so model validation is often limited to confirmation of gross performance measures, such as power and discharge, and data from reduced-scale laboratory physical models. Even in laboratory physical models, comprehensive velocity and pressure measurements are rarely performed. Despite these difficulties, CFD modeling of hydro turbines continues to be routinely used by industry in the development of new turbine designs and the evaluation of installed turbines (Keck and Sick, 2008).

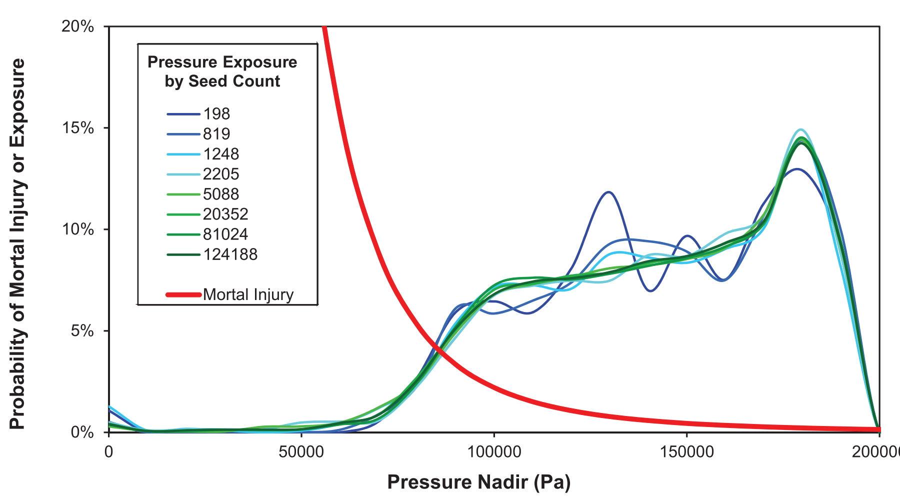

Fig. 12. Exposure probability distributions associated with various numbers of seeds in uniform distributions. Operating condition is BP05 (564 cms) and acclimation depth is 5 m. Note that only a portion of the complete mortal injury curve (Fig. 2) is shown. (For interpretation of the references to color in the text, the reader is referred to the web version of the article.)

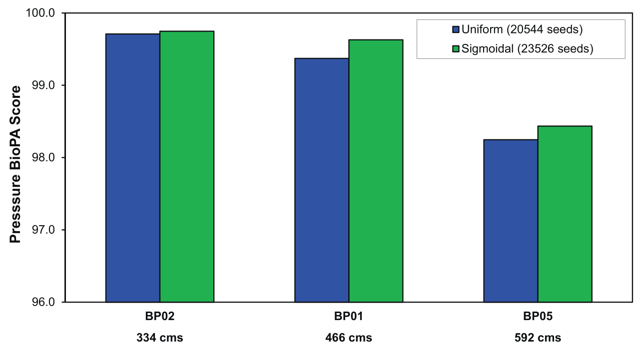

Fig. 13. BioPA scores based on the vertically-weighted sigmoidal distribution are consistently higher than corresponding uniform-distribution scores. Acclimation depth is 5 m.

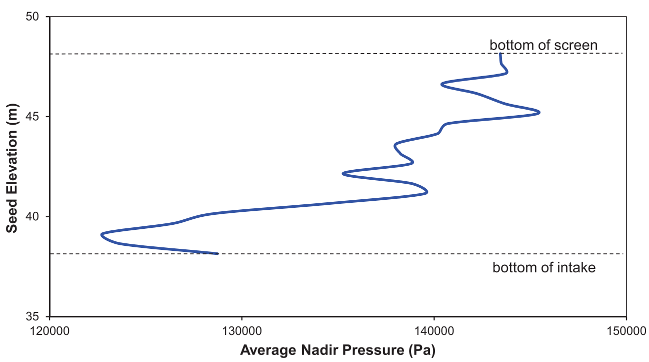

Fig. 14. The average nadir pressure increases with seed elevation. The upstream seed distribution is uniform.

4. Case study – John Day Dam

To illustrate the BioPA method, a sample risk assessment calculation is performed. The analysis uses CFD data from a model of the John Day Dam (JDA) Kaplan turbine to assess juvenile Chinook salmon (*Oncorhynchus tshawytscha*) exposure to rapid pressure change. The John Day Dam is located on the Columbia River about 150 km east of Portland, OR (Fig. 6). The powerhouse has 16 turbine units, each with a maximum generating capacity of 155 MW and a discharge up to 623 m^3/s. The average operating gross head is 30.8 m.

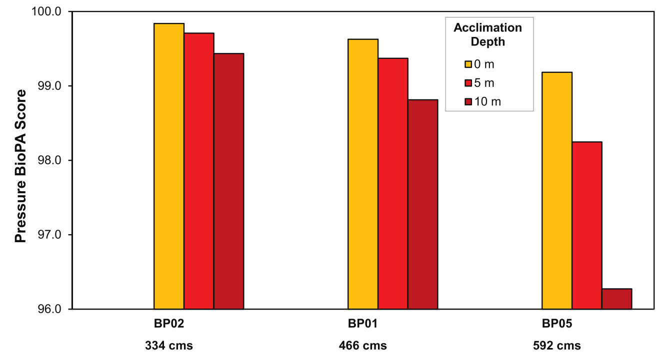

Fig. 15. Effect of acclimation depth on BioPA scores. Analyses performed with uniform distribution of 20,544 seeds.

During the spring and early summer, juvenile Chinook salmon migrate downstream and must pass through JDA on their way to the ocean. Estimates of survival rates for Chinook salmon subyearlings passing through JDA turbines are as low as 84% (Weiland et al., 2011). The 2008 Biological Opinion on operation of the Federal Columbia River Power System (NMFS, 2008), a regulatory document that addresses endangered fish species in the Columbia River basin, mandates that a 96% and 93% survival rate be achieved for spring and summer downstream migrating juvenile salmonids, respectively. Although these rates apply to passage through all routes, powerhouse passage can be significant, especially when spillway operations are not occurring.

BioPA analyses were performed for three turbine operating conditions. Testing included assessments of the method sensitivity to the number and distribution of streamtrace seeds. BioPA scores were also computed for three assumed acclimation pressures to analyze the sensitivity to this factor.

4.1. CFD simulations

The US Army Corps of Engineers, Turbine Survival Program, requested Andritz Hydro to develop a CFD model of a Kaplan turbine unit at the John Day Dam on the Columbia River in order to better understand the flow conditions relevant to fish-passage survival (Andritz Hydro, 2008). This paper uses results from the Andritz model to demonstrate the application of the BioPA method.

The CFD model developed by Andritz consists of a multi-block, primarily hexahedral grid with about 14 million elements. The

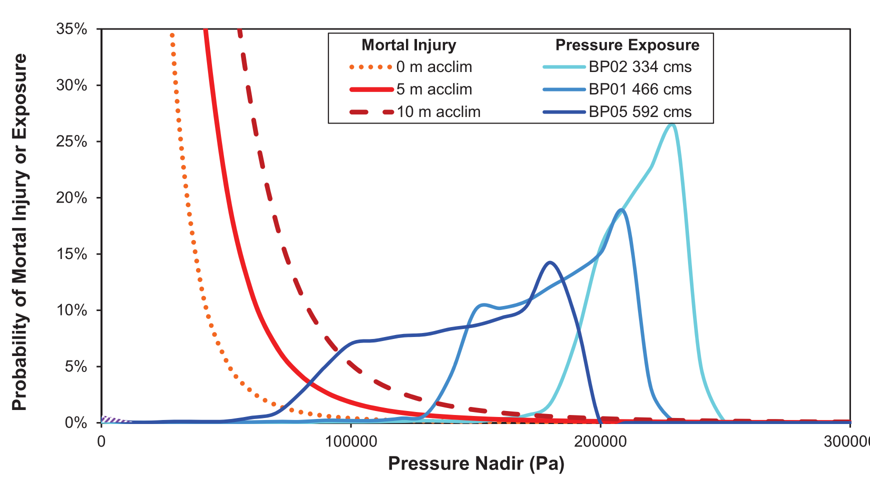

Fig. 16. Effect of acclimation depth is greatest on the BP05 condition because nadir pressure distribution intersects a greater portion of the mortal injury curves. Increases in turbine discharge shift the pressure-nadir exposure distribution to the left, resulting in lower BioPA scores. Analyses performed with uniform distribution of 20,544 seeds. Note that only a portion of the complete mortal injury curves (Fig. 2) are shown.

Table 2
Number of seeds and spacings used for uniform distributions.

Number of seeds	Spacing (m)
198	1
819	0.5
1248	0.4
2205	0.3
5088	0.2
20,352	0.1
81,024	0.05
124,188	0.04

CFX™ solver used the standard $k-\epsilon$ turbulence model and was run in steady-state multiple reference frame (MRF) mode. The model was run in two overlapping parts, Parts 1 and Part 2 (Fig. 7). Part 1, which extended from the turbine intake to the stator outlet, was run first to generate inflow conditions for Part 2. Part 2 included an assembly containing a single stay vane, wicket gate, and runner blade attached to the remainder of the draft tube and outlet box. Isolating a single element of a radially symmetric blade geometry is a common technique used in simulating turbomachinery that substantially reduces the complexity and run-time of the model. Input conditions for Part 2 were obtained by circumferentially averaging velocities from the stator inlet of the Part 1 result. To simulate movement of the runner assembly, the block containing the blade was modeled in a rotating frame of reference. The velocity at the outlet of the runner block was, once again, circumferentially averaged to provide the inflow to the draft tube.

After constructing and validating the CFD model, several scenarios corresponding to different operating conditions were simulated. In a Kaplan turbine, an operating point is defined by a specific combination of wicket gate angle, runner blade angle, head, and discharge. For this paper, three operations representing a wide range of discharges were selected (Table 1). Operating point BP01 is the most efficient power-to-discharge configuration. Points BP02 and BP05 are approximately 1% below the peak of the efficiency curve on the low and high discharge sides, respectively.

4.2. Seed distributions

For this study, two seed distributions, uniform and non-uniform (Fig. 8), were analyzed in order to quantify the significance of this variable. The uniform distribution consists of seeds that are spaced equally in the horizontal and vertical direction on a plane immediately below the fish screens. The non-uniform distribution represents a vertical fish distribution based on hydro-acoustic studies of fish approaching the intake at John Day Dam (Johnston et al., 2000; Moursund et al., 2001, 2003). This distribution is modeled as a sigmoid function with a higher density of seeds near the top of the water column than near the bottom (Fig. 9). The non-uniform seed pattern was created using an algorithm that begins with a uniform pattern and adjusts the spacing of seeds in each horizontal row to match the sigmoidal distribution. With this method, the vertical seed spacing is maintained, but the total seed count differs from the original.

The uniform seed distributions shown in Table 2 were used in this study to determine the optimum number of seeds for general analysis. Computation time for BioPA analyses with each of these seed distributions was measured for a Dell Precision T7600 with a dual six-core Intel Xeon 2.40 GHz (E5645) processor and 96 GB of RAM.

4.3. Test fish

The present analysis focuses on the passage of yearling and subyearling Chinook salmon, which are one of the most common migratory species present at JDA. Moreover, extensive data on barotrauma is available for this fish species (see Section 2.1). A fork length of 100 mm, typical for this age, was assumed.

As noted in Section 3.2, the acclimation depth of fish before passing through a turbine is not known. Incidence of barotrauma during turbine passage is correlated to the ratio of acclimation pressure to nadir pressure (Eq. (2)). For a given nadir pressure, passage mortal injury increases with acclimation depth (Fig. 2). Pflugrath et al. (2012) estimated that the maximum acclimation depth for juvenile Chinook ranged between 4.6 and 11.6 m. Presuming that not all fish are acclimated at maximum depth prior to entering the turbine and to test the significance of this factor, BioPA calculations

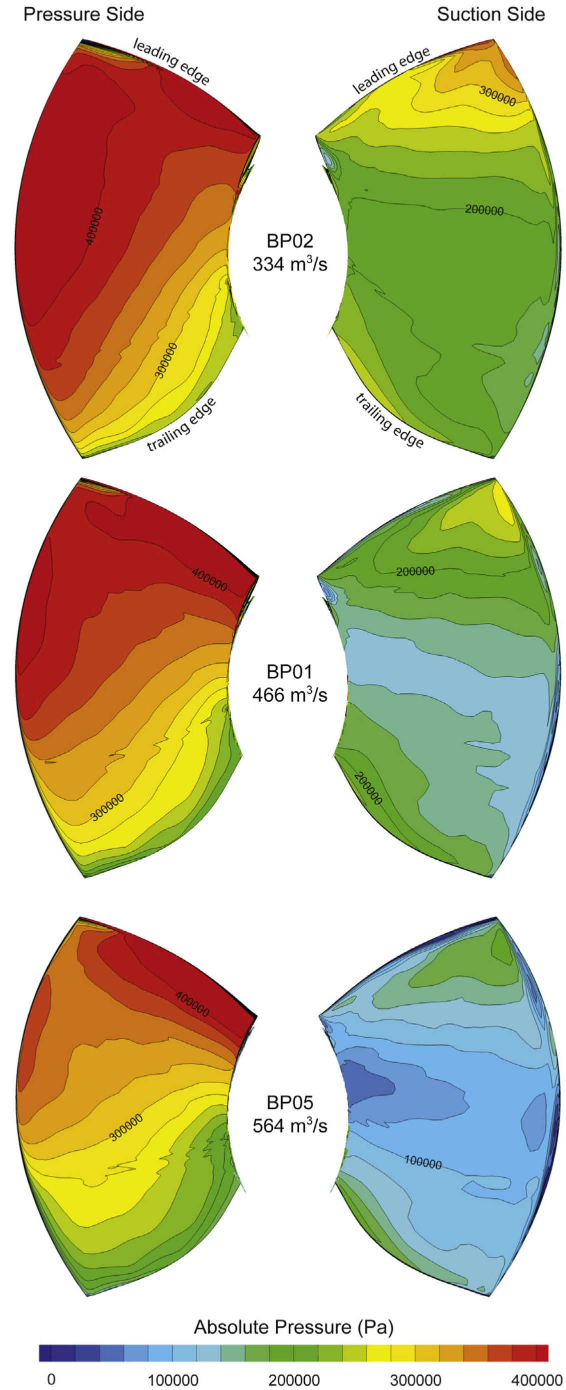

Fig. 17. Pressure distribution on pressure (left) and suction (right) sides of the runner blade.

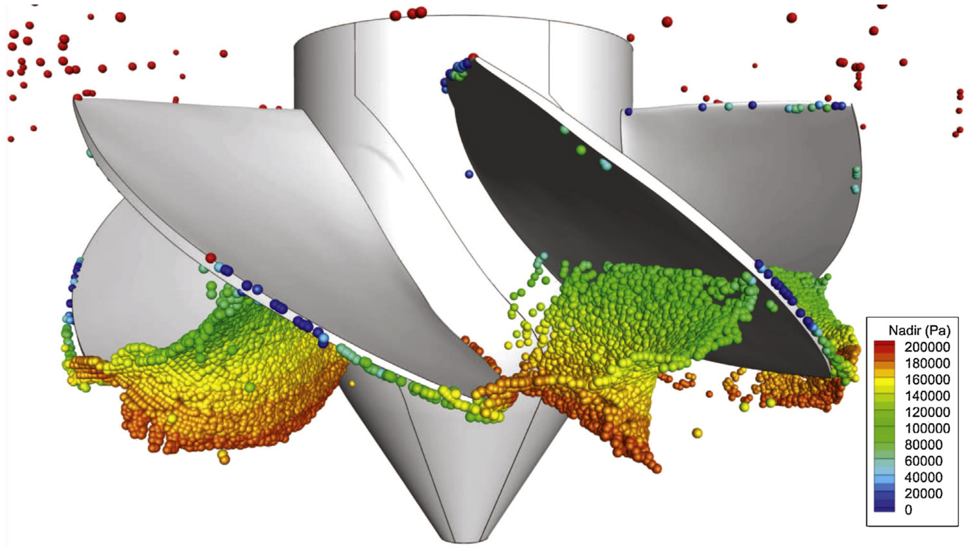

Fig. 18. Locations of absolute pressure nadirs for operating condition BP05 with 20,352 uniformly distributed seeds. Points are colored by nadir value. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of the article.)

were performed for three assumed acclimation depths: 0, 5, and 10 m.

5. Results and discussion

Results of the BioPA runs were analyzed for the influence of several variables, including prematurely terminating streamtraces, number and distribution of seeds, assumed pre-passage fish acclimation depth, and turbine operating condition.

5.1. *Prematurely terminating streamtraces*

Initial tests of the simulation results indicated a prematurely terminating streamtraces rate greater than 10%. Further investigation revealed two causes. The first was the presence of small (less than 1 mm) gaps between CFD model blocks. These were corrected by making slight adjustments to the positions and sizes of the blocks to force small overlaps. After this correction, premature terminations fell to 5.6% of total paths when about 20,000 total seeds were used. The remaining terminations were caused when streamtraces overshoot and collide with a no-slip model wall boundary, where the velocity is zero, and thus terminate the path. This effect could not be corrected, even after reducing the streamtrace advection integration time step. With the increased availability of high performance computing resources, the solution to reduce prematurely terminating streamtraces in future studies is CFD model mesh refinement which was not an available option for this application.

5.2. *BioPA scores*

Here we summarize the results of all BioPA runs performed on the models for the three operating conditions. These results are analyzed in the following sections.

5.2.1. *Seed number sensitivity*

Processing time and file sizes for a BioPA run increase linearly with the number of streamtraces used (Fig. 10). For the JDA model, processing times were acceptable (under an hour) even for the largest number of seeds tested.

A BioPA run was performed for each modeled operating condition using the uniform seed distributions shown in Table 2. Fig. 11 shows that as the number of seeds increases, the volatility of the BioPA score decreases. The score stabilizes to within 0.1% of the value obtained with the maximum number of seeds tested (dashed line), presumed to be the most accurate result, when the seed count exceeded about 5000. Moreover, the shape of the pressure exposure distribution (Fig. 12) changes very little above this number of seeds (green lines). A conservative value of about 20,000 seeds was selected to assure a representative sample for all further BioPA analyses.

5.2.2. *Seed distribution sensitivity*

The elevation at which a fish enters the turbine intake may affect the hydraulic conditions to which it is subjected. To test this hypothesis, BioPA scores for two vertical seed distributions were analyzed. The default uniform seed pattern was compared to a sigmoidal distribution based on field observations, which indicated that juvenile salmon at John Day tend to be concentrated nearer the top of the water column (Fig. 9).

BioPA scores based on the surface-weighted sigmoidal distribution are consistently higher than corresponding uniform-distribution scores (Fig. 13). This result suggests that fish entering the turbine nearer to the top of the intake are subject to a lower pressure differential, and therefore a higher survival rate, than those entering at a lower level. In fact, when streamtraces from a uniform distribution are binned by seed elevation and average nadir pressure computed for each bin, a clear relationship between entry elevation and nadir pressure is observed for the John Day turbine (Fig. 14).

5.2.3. *Accilmation depth sensitivity*

As expected, deeper acclimation depths resulted in lower BioPA scores (Fig. 15). However, the impact on the scores for the BP05 condition is much greater than for the other conditions. This occurs because the left edge of the BP05 nadir-pressure distribution intersects the steep part of the mortality curves (Fig. 16).

5.2.4. *Turbine operating point*

The three tested operating conditions represent not only different discharges, but different power generation points (Table 1). For both the uniform and sigmoidal seed distributions, the BioPA score decreases with increasing turbine discharge (Fig. 13) as the absolute pressure decreases on the suction side of the blade (Fig. 17).

Fig. 16 shows how the pressure-nadir exposure frequency distributions for the three operating points shift to the left (indicating lower nadir pressures) as turbine discharge increases. The estimated rates of mortal injury increased from 0.3% to 1.7% as discharge through the turbine increased from 334 to 564 m^3/sec for fish assumed to be acclimated to a depth of 5 m. Such a trend is expected because in order to increase power generation, the pressure differential across the runner blades must also increase.

5.2.5. Nadir locations

A byproduct of the BioPA method allows the turbine designer to determine the locations where potentially hazardous pressure conditions occur. Based on streamtrace statistics, the vast majority of nadirs occur immediately below the runner blades. Fig. 18 shows the locations of pressure nadirs that occur near the runner for the BP05 operating condition. The lowest nadirs (dark blue points) occur in the gap at the blade tips and just below the leading edge of the blades. Such information can help engineers focus on problem areas when designing new runners to be more fish friendly than existing models.

6. Summary and conclusions

The BioPA tool combines laboratory fish-response data with fluid simulation models to assess the hydro turbine passage environment encountered by migratory fish. It differs from other CFD-based methods in that it uses streamtraces to sample the fluid domain and thereby assigns probabilities of exposure to certain levels of harmful conditions. This method can help turbine engineers improve the fish friendliness of their designs by identifying locations where hazardous conditions are occurring and ranking proposed alternatives. By using software and methods already routinely employed in the turbine manufacturing industry, such as CFD modeling, streamtrace generation, and data visualization, the BioPA application is relatively easy to incorporate into the existing turbine design workflow.

This paper demonstrated the application of the BioPA method to the effect of rapid pressure change on juvenile Chinook salmon passing through a Kaplan turbine at an existing hydroelectric facility. BioPA results for the John Day Dam turbine show several interesting features:

- Higher discharges tend to increase mortal injury rates from exposure to low pressures.
- A sigmoidal seed distribution, with a higher density of seeds closer to the roof of the intake, has slightly lower pressure mortal injury values than uniformly distributed seeds. Fish distribution at turbine entry could be a more significant factor at projects where intake screens are not used.
- Depth of fish acclimation is a significant factor in the prediction of passage mortal injury due to rapid pressure change.

The next step toward extending the applicability of the BioPA tool is to include other key hydraulic stressors for blade strike (Amaral et al., 2007; Amaral and Hecker, 2008), hydraulic shear and turbulence (Neitzel et al., 2000, 2004; Guensch et al., 2005), resulting in a more comprehensive assessment of the passage environment. Currently, laboratory dose–response data for these stressors are more limited and not as extensive as those for pressure-related injury for juvenile Chinook salmon. Performing laboratory dose–response tests for additional fish species (Brown et al., 2012a; Colotelo et al., 2012) would extend BioPA to be directly applicable to a greater variety of rivers in the world. However, such tests can be expensive and it would be beneficial to extend the framework for unstudied fish species by other means, such as those described in (Čada and Richmond, 2011; Čada and Schweizer, 2012). As more studies are conducted, biological criteria and dose–response relationships will be updated accordingly.

The BioPA method should also be applied to a wider range of turbine types that are operating under different site conditions. These additional application tests should include, for example, Kaplan and Francis turbines of different diameters, numbers of blades, rotation rates, and operating heads. Predictions made by the BioPA model also need to be compared to live-fish survival data from prototype field tests (e.g., Dauble et al. (2007)). In addition, the model can be applied to different fish passage routes such as spillways.

The power of computational resources is increasing rapidly and access to parallel computing clusters is becoming widely available. This will allow for more realistic CFD simulations of the hydraulic environment that can include, for example, unsteady turbulence, motion of the runner blade, and cavitation. The BioPA model itself can be enhanced to include the effects of fish mass to the calculations by using Lagrangian particle tracking to simulate the potential pathways taken through the turbine.

Uncertainty analysis for the simulated hydraulic variables such as pressure could be included. The sensitivity to uncertainties in the biological dose–response relationships such as fish acclimation depth could be further tested using depth distribution data in the upstream reservoir and forebay from fish-tracking technologies such as hydroacoustics (Ham et al., 2007) and/or acoustic tags (McMichael et al., 2010). Research to develop direct methods of measuring fish acclimation depth in the field are also needed.

Ultimately, economic analyses must be included to determine costs and benefits associated with incremental BioPA score shifts that are computed for specific turbine operational and design alternatives. For example, what are the cost tradeoffs between a 99 score as compared to a score of 97?

Implementing these improvements in the BioPA model will allow it to be used on a wider basis as a design tool for fish-friendly turbines that are a critical part in the development of sustainable hydropower.

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