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Evaluation of Blade-Strike Models for Estimating the Biological Performance of Large Kaplan Hydro Turbines

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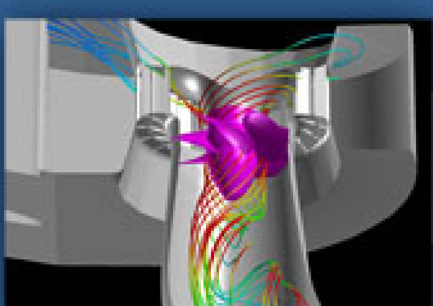

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Executive Summary

Bio-indexing of hydro turbines has been identified as an important means to optimize passage conditions for fish by identifying operations for existing and new design turbines that minimize the probability of injury. Cost-effective implementation of bio-indexing requires the use of tools such as numerical and physical turbine models to generate hypotheses for turbine operations that can be tested at prototype scales using live fish. Blade strike has been proposed as an index variable for the biological performance of turbines. Here we report on an evaluation of the use of numerical blade-strike models as a means with which to predict the probability of blade strike and injury of juvenile salmon smolt passing through large Kaplan turbines on the mainstem Columbia River.

Numerical blade-strike models were developed for a 1:25-scale physical turbine model built by the U.S. Army Corps of Engineers for the original design turbine at McNary Dam and for prototype-scale original design and replacement minimum gap runner (MGR) design turbines at Bonneville Dam's first powerhouse. The numerical blade-strike models were run in both deterministic and stochastic modes. Predictions of blade strike and injury probability made with the models were then compared to data available for the McNary 1:25-scale physical turbine model and the Bonneville Dam prototype-scale original and MGR turbine runner units.

Based on the comparisons of numerical blade-strike model predictions with 1) observations from both physical turbine models using beads and 2) prototype-scale live fish tests of turbine biological performance, we recommend the stochastic blade-strike models as the preferred method for prediction of blade-strike probability. This recommendation follows from much better agreement between numerical model and physical model predictions of blade-strike probability and prototype-scale observations of live fish mortality and injury assigned to blade strike. Our analysis clearly shows that consideration of the aspect that smaller fish present to the leading edges of turbine runner blades is a significant factor in assessment of blade strike.

Blade-strike probability predicted by the numerical blade-strike stochastic model agreed with the overall trends in blade-strike probability observed in both physical model predictions and prototype-scale live fish observations. However, the numerical model did not show the variability between operating conditions present in physical model bead strike data or in the trend in differences in fish injury and mortality estimates between Bonneville Dam original and MGR design runners. We conclude that blade-strike models, as implemented for juvenile salmon smolts, provide a good overview of the general blade-strike probabilities for prototype-scale turbines but lack the capability to contribute significantly to development of testable bio-indexing hypotheses. The requirements for numerical models that will prove useful for turbine bio-indexing are more rigorous than those provided by the simple blade-strike modeling done to date. The reason is that small differences in turbine biological performance, on the order of 1% or so in strike probability, are significant improvements or degradations in turbine biological performance because they may represent improvements or degradations of 25% to 50% due to the relative small percentage in strike probability or other turbine-blade-related injury. Numerical modeling, if it is to contribute to development of testable bio-indexing hypotheses, will likely need to move toward computational fluid dynamics models of moving machinery that may have a better chance of detecting and quantifying the differences critical to improved biological performance of operating hydro turbines.

Acknowledgments

The authors thank the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy (DOE EERE) Wind and Hydropower Technologies Program for supporting this work. We are grateful also for the contributions and input of many people on this project. Bob Davidson and Martin Ahmann of the U.S. Army Corps of Engineer provided many design drawings, hard-to-obtain dimensions, and experimental data generated from a 1:25-scale physical model of a McNary Dam turbine. Within Pacific Northwest National Laboratory, we greatly appreciate Dennis Dauble's involvement and oversight. Bill Perkins provided many constructive and insightful comments. John Serkowski and Tao Fu provided technical help preparing the manuscript. Andrea Currie was the technical editor for this document.

Contents

Figures

Tables

1.0 Introduction

Bio-index testing of hydro turbines is sought as an analog to the hydraulic index testing conducted on hydro turbines to optimize their power production efficiency. In bio-index testing, the goal is to identify those operations within the range identified by hydraulic index testing where the survival of fish passing through the turbine is maximized. The scope of bio-index testing includes the immediate tailrace region as well as the turbine environment between turbine intake trash racks and the exit of its draft tube. The U.S. Department of Energy, the U.S. Army Corps of Engineers (USACE), and turbine industries have been evaluating a variety of means, such as numerical and physical turbine models, to investigate the quality of flow through a hydro turbine and other aspects of the turbine environment that determine its safety for fish. The overall goal of this study is to use these tools to develop hypotheses that identify turbine design alternatives and operations that optimize their biological performance and can be tested at prototype scales. We evaluated the performance of numerical blade-strike models by comparing predictions of fish mortality resulting from strike by turbine runner blades with 1) observations of fish injury made using live test fish at mainstem Columbia River dams and 2) predictions of blade strike made observing beads passing through a 1:25-scale physical turbine model.

Injuries and mortality of fish that pass through hydroelectric turbines can result from several mechanisms, such as rapid and extreme pressure changes, shear stress, turbulence, strike, cavitation, and grinding (Figure 1.1). (For overviews, see Coutant and Whitney [2000]; Odeh and Sommers [2000]; Čada [2001]). Strike by turbine runner blades was identified almost immediately as a significant source of injury and mortality to fish when study of fish passage through turbines began. One of the early study methods was numerical modeling of the probability of strike with validation using live fish in laboratory experiments or prototype-scale turbine tests. Over the years, these models have become more accurate and useful. We built on the basic concepts of these models and have added elements that incorporate stochastic variables, such as the probability of fish having specific orientation aspects relative to runner blade edges as they enter a turbine runner.

1.1 Background

Recent investigations of turbine passage survival suggest that fish are most vulnerable to injury during turbine passage in the immediate vicinity of the turbine runner. Here they can be injured by direct contact with turbine runner blades or exposure to the hydraulic environment where hazardous conditions may exist. Improvement in the survival and the injury rates for fish passing through turbines is being sought by hydropower owners and operators through changes in hydro turbine design and operation.

Blade strike has traditionally been thought of as the direct contact between a fish and the leading edge of a turbine blade. Von Raben (1957) first identified the variables that could affect the probability of strike and developed one of the first models for predicting probability of strike. Monten (1985) and Solomon (1988) expanded the model and included empirical field experimental results to better understand the dynamics of fish passage through turbine runners and associated injuries. Other studies and reviews that investigated the dynamics and probabilities of blade strike included those of Bell (1981, 1991), Eicher et al. (1987), Stone and Webster Environmental Services (1992), Čada et al. (1997), Turnpenny et al. (1992, 2000), Coutant and Whitney (2000), and Pavlov et al. (2002).

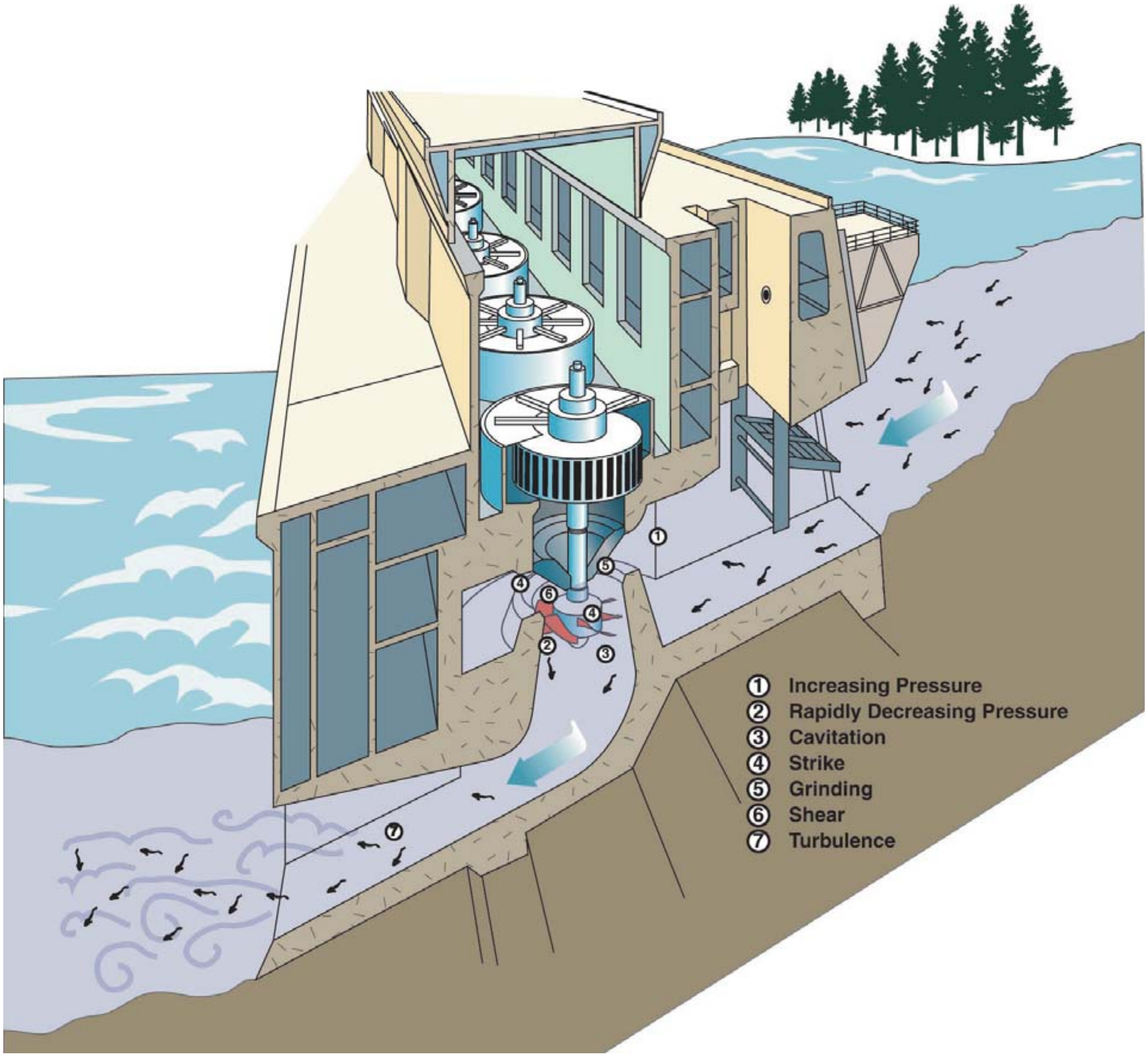

Figure 1.1. Mechanisms of Injury and Mortality of Fish Passing Through Hydroelectric Turbines

In the past few years, the use of observational physical turbine models[(a)] has identified other types of probable contact between fish and turbine runner blades. The most common is *slap* by turbine blades. Slap occurs when a fish has passed by the leading edge of a blade without contact but is then hit by the blade surface behind the leading edge. Contact between the trailing edge of turbine blades and fish also is suspected, given observations of beads coming into contact with the trailing edges of turbine blades. In addition to strike by the blade, fish may be exposed to shear in the blade wake (Odeh 1999; USACE 1995, 2000, 2004).

(a) They are referred to as observational models because of the plexiglass construction. Their prototype-model relationship is Froude similitude.

Physical variables identified by researchers as important in estimating the rate of runner blade strike were the number and length of blades in a turbine runner, the rotational speed of the runner, discharge through the runner, and the velocity of impact, which is related to the velocity of the turbine runner blade relative to that of a fish. Important biological variables identified include fish length, mass, stiffness, and the probability of tissue trauma from a strike of a given force, which is specific to fish species and age. Also identified as important were the vertical distribution of fish as they pass through the turbine wicket gates and behavior that might influence the aspect a fish presents to an approaching runner blade.

For Kaplan turbines, fish that pass higher through the wicket gate openings will pass nearer the runner hub, while those passing lower through the wicket gate openings will pass nearer to the tips of the runner blades (assuming fish follow the flow streamlines). Field studies conducted by Normandeau Associates et al. (2000) have shown that the risk of injury and death is significantly higher for fish that are released to have passed through the turbine runner near blade tips than those that passed mid-blade or nearer the runner hub.

In all cases, researchers have found that estimates of blade-strike probability obtained using numerical models exceed observed injury and mortality rates (from all causes) from prototype-scale tests with live fish. These differences appear to be a function of biological factors (the mechanics of injury for fish struck by runner blades) and the physical dynamics of the blade-fish impact process. Turnpenny et al. (2000) found that fish geometrically aligned so that strike would occur if other factors did not intercede, would have a variable probability of collision with a blade, depending upon their absolute mass, the location of the center of mass relative to the leading edge of the turbine blade, and the fluid dynamics at the leading edge of the turbine blade.

During a previous study (Ploskey and Carlson 2004), we reviewed four papers describing deterministic blade-strike models (Von Raben 1957; Bell 1991; Turnpenny 1998; and Pavlov et al. 2002) and found that they all were essentially the same except for the semantics of naming variables and describing equations. We evaluated the performance of deterministic and stochastic implementations of blade-strike models of new minimum gap and original Kaplan runner turbines at the Bonneville Dam first powerhouse using biological test results for these turbines. We concluded that the stochastic implementation of the blade-strike model, which considered the aspect that fish present to the leading edge of a turbine runner blade as an additional variable, provided blade-strike estimates (and mortality rate estimates derived from the blade-strike estimate) that compared favorably with the live fish biological test results.

In the study described in this report, we continued to evaluate the validity of using strike and proximity as a reliable estimate of the biological performance of turbines. We have made several improvements to our strike model regarding wicket gate geometry and water velocity estimates. We applied the strike model with the improved geometry and velocity calculations to the Units 5 and 6 turbines of Powerhouse 1 of Bonneville Dam and obtained better predictive performance than we did using our original model. We also applied our strike model to the 1:25-scale physical model of a McNary Dam turbine with original runner blades and compared our prediction of blade-strike probability with those obtained by observing the interactions between turbine runner blades and beads in the McNary physical turbine model. In all cases, we evaluated the predictive performance of both stochastic and deterministic versions of our new model.

1.2 Report Contents

In this report, we document our evaluation of the use of estimates of blade strike obtained with numerical models to predict the biological performance of turbines. Chapter 2 of this report describes the blade-strike model, the general information about the implementation, and evaluation of our deterministic and stochastic versions of the model. Chapter 3 provides modeling results for the McNary Dam turbine physical model and comparison with estimates of blade strike obtained from observations of neutrally buoyant beads. Chapter 4 provides modeling results for Unit 5 (existing Kaplan) and Unit 6 (minimum gap runner [MGR] Kaplan) at Bonneville Dam and comparison with field evaluations of the biological performance of these turbines using live fish. Chapter 5 is a discussion of our findings and their applicability to bio-index testing.

2.0 Methods

2.1 Blade-Strike Model

Von Raben (1957) first proposed the general form of a blade-strike model that was subsequently used by other researchers in various equivalent forms. The theory behind the model is that the fish must pass through the plane of the leading edges of the blades in a turbine runner after the sweep of one blade and before the sweep of the next to avoid strike by a runner blade. Turnpenny et al. (2000) defined the "water length" between two successive blades as

$$Water\ Length = \frac{V_{axial}}{cos\theta \bullet n \bullet \frac{N}{60}} \tag{2.1}$$

where V_{axial} is axial velocity, θ is the angle between V_{axial} vector and the absolute water velocity vector, n is the number of blades, and N is the runner speed in revolutions per minute (RPM). They stated that any fish longer than the water length would be struck by a blade, and the probability of strike was then given by

$$P = \frac{Fish\ Length}{Water\ Length} = \frac{l \bullet cos\theta \bullet n \bullet \frac{N}{60}}{V_{axial}} \tag{2.2}$$

where *l* is the fish length.

In our model, we use another construct as a factor affecting the probability that a fish will be struck during runner passage. We define "critical passage time" t_{cr} as the time between sweeps of two successive blades as

$$t_{cr} = \frac{1}{n \bullet \frac{N}{60}} \tag{2.3}$$

and the time a fish needs to pass safely through the plane of the leading edges of the runner blades is

$$t = \frac{l \bullet cos\theta}{V_{axial}} \tag{2.4}$$

A fish will experience a blade strike if it does not pass through this plane within t_{cr}, and the probability of strike is then expressed as

$$P = \frac{t}{t_{cr}} = \frac{l \bullet cos\theta \bullet n \bullet \frac{N}{60}}{V_{axial}} \tag{2.5}$$

which is the same as Equation (2.2).

Von Raben (1957) observed that his blade-strike model always produced an estimate of blade strike that was higher than the proportion of live fish he observed to be injured during passage through the turbine he was modeling. To account for the obvious fact that not all fish struck by a turbine blade were injured, Von Raben introduced the idea of a *mutilation ratio* (MR). The mutilation ratio was simply the ratio between the proportion of fish he estimated to be struck by a turbine blade and the proportion he observed to be injured. To deal with the same issue in his experiments, Turnpenny et al. (2000) empirically developed a regression equation of MR for different fish lengths:

$$MR = 0.15533\mathrm{Ln}(l) + 0.0125 \tag{2.6}$$

where MR is mutilation ratio, Ln is natural logarithm, and l is fish length (in centimeters).

2.2 Estimated Velocity and Geometry Relationship

Of the five variables in the model, n, N, and l are usually known, and V_{axial} is estimated by dividing the turbine discharge Q by the turbine blade-swept area A_{tip}:

$$V_{axial} = \frac{Q}{A_{tip}} = \frac{Q}{\pi(R_{tip}^2 - R_{hub}^2)} \tag{2.7}$$

where R_{tip} and R_{hub} are the radii of circles formed by the runner blade tip and runner hub, respectively. An estimate of the fifth variable θ in the model requires several steps to calculate, beginning at the turbine wicket gates and ending at entry to the turbine runner.

Picture an imaginary vertical cylinder, where the cylinder side touches the downstream tips of all wicket gates (Figure 2.1). The radius of this cylinder R_{wgc} is a function of the wicket gate opening angle in degrees (WGA, degrees) or wicket gate opening in inches (WGO, inches). Sometimes WGA and WGO are measured in terms of servomotor stroke (inches) or percentage servomotor stroke (%). A servomotor is a hydraulic ram that controls the opening and closing of a turbine wicket gates. Details of the calculations are included in the next chapters when they are applied to turbines at McNary and Bonneville Dams. Here we assert that R_{wgc} can be obtained from the wicket gate operation parameters. Then the axial velocity of water at the wicket gate is

$$V_{axial\_wg} = \frac{Q}{A_{wgc}} \tag{2.8}$$

where A_{wgc} is the surface area of the imaginary cylinder and is calculated by

$$A_{wgc} = 2\pi \bullet R_{wgc} \bullet h_{wg} \tag{2.9}$$

where h_{wg} is the height of wicket gate.

The tangential velocity at the wicket gate is given by

$$V_{t\_wg} = \frac{V_{axial\_wg}}{\mathrm{Tan}\,(\theta_{\mathrm{wgt}})} \tag{2.10}$$

where θ_{wgt} is the angle between the absolute velocity and tangential velocity at the downstream tip of wicket gate. θ_{wgt} can be obtained from the WGA or WGO. Details of these calculations are included in the next chapters.

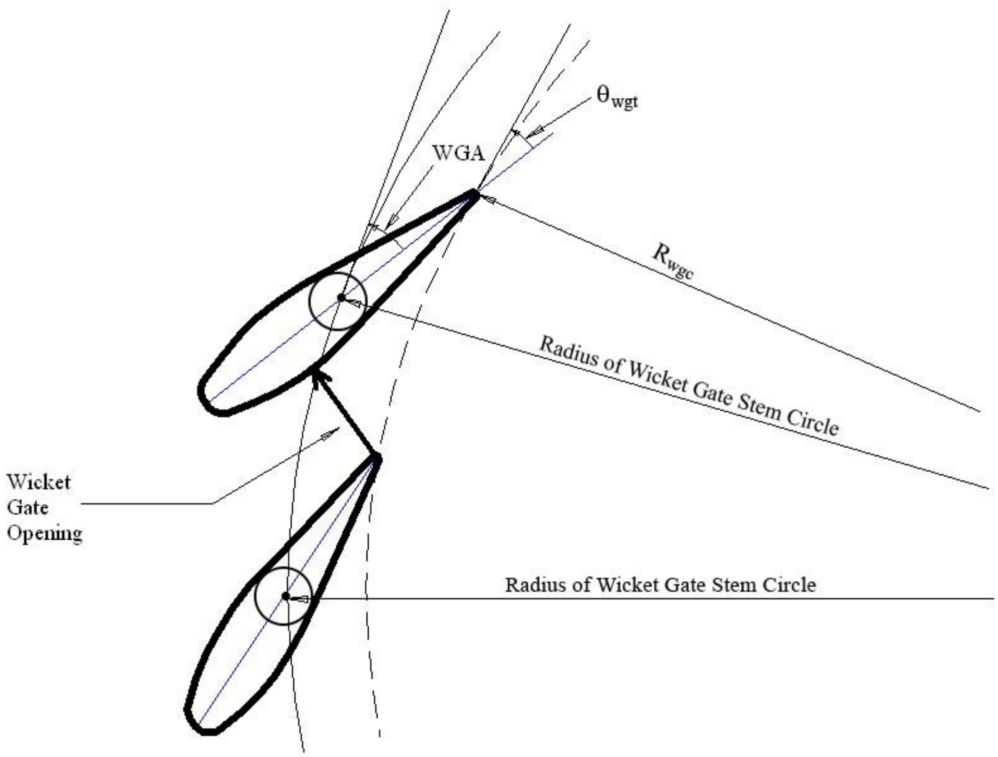

Figure 2.1. Wicket Gate Angle, Wicket Gate Opening R_{wgc},, and θ_{wgt}, the Angle Between the Absolute Velocity and Tangential Velocity at the Downstream Tip of Wicket Gate

According to the principle of conservation of angular momentum, the tangential velocity at the runner entrance (V_t) is equal to the tangential velocity at the wicket gate (V_{t_wg}) multiplied by the ratio of radial distances out from the center of the runner at the two respective elevations:

$$V_t = \frac{V_{t\_wg} \bullet R_{wgc}}{R_1} \tag{2.11}$$

where R_1 is the fish-passage radius, that is, the radius of a circle extending out along the blade from the runner hub to where fish enter the runner. For the Bonneville and McNary fish survival studies considered here, three release mechanisms at different wicket gate elevations (high, middle, and low) were used. From neutrally buoyant bead experiments in physical models, the USACE (2004) reported that beads released near the top of wicket gate openings pass near the runner hub, those released mid-gate pass mid-blade, and those released near the bottom of the wicket gate openings pass near the tips of the runner blades. Here, we divided the area swept by runner blades (A_{tip}) into three equal doughnut-shaped (concentric) areas and calculated the average radius for hub, mid, and tip releases ($R_1 = \overline{R}_{hub}$, $\overline{R}_{mid}$, or $\overline{R}_{tip}$) from the radii bounding each successive area:

$$R_1 = \begin{cases} \overline{R}_{hub} = \sqrt{\dfrac{A_{tip}}{6\pi} + R_{hub}^2} \\ \overline{R}_{mid} = \sqrt{R_{hub}^2 + \dfrac{A_{tip}}{2\pi}} \\ \overline{R}_{tip} = \sqrt{R_{tip}^2 - \dfrac{A_{tip}}{6\pi}} \end{cases} \tag{2.12}$$

For a given fish passage location, the absolute velocity is estimated by

$$|V_1| = \sqrt{V_{axial}^2 + V_t^2} \tag{2.13}$$

and the angle between axial and absolute velocity vectors (θ) is given by

$$\theta = 90 - \alpha = 90 - \sin^{-1}\left(\frac{V_{axial}}{V_1}\right) \tag{2.14}$$

where α is the angle between tangential and absolute velocity vectors.

These relationships are diagrammed in Figure 2.2.

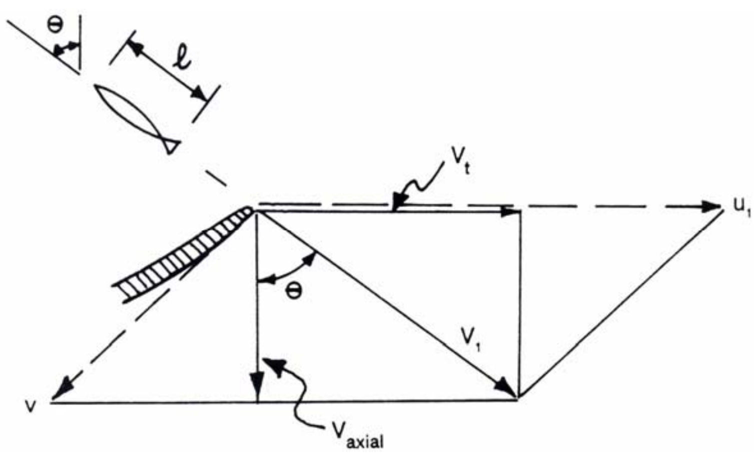

Figure 2.2. Water Velocity Vectors at the Runner Blade (Bell 1991). The diagram shows a fish of length *l* in flow approaching the leading edge of a runner blade in a Kaplan turbine, velocity vectors, and associated angles. Velocity vectors include V_t = tangential velocity; V_1 = absolute velocity; V_{axial} = axial velocity; u_1 = blade peripheral velocity, and v = velocity relative to the blade. Angles are as follows: α = the angle between tangential and absolute velocity vectors; θ = the angle between axial (parallel to the runner axis) and absolute velocity vectors (θ = 90º – α); and β = the angle between the horizontal plane and the velocity relative to the blade (v) and is called the “angle of attack.”

2.3 Deterministic Model Implementation and Evaluation

In this study, we applied the deterministic model (Section 2.1) to two Kaplan turbines at the Bonneville Dam first powerhouse and to the 1:25-scale McNary observational physical turbine model. The predicted probabilities of blade strike and injury obtained from our model were compared with results of live fish test data obtained by Normandeau Associates et al. (2000) at Bonneville Dam and with bead experimental data obtained by the USACE Engineering Research and Development Center using the McNary physical turbine model.

A deterministic model lacks probability, that is, it predicts a single unique estimate for each combination of input values. In this deterministic model, blade-strike predictions are a function of fish length and radial injection location, runner geometry, runner rotation rate, and axial flow. The model assumes that fish are rigid bodies oriented perpendicular to the leading edge of the blade, with the result that predictions of blade-strike probability are worst case. Some models (Von Raben 1957; Bell 1991; Pavlov et al. 2002) do not account for fish that are struck but not injured. We chose the Turnpenny model (Section 2.1) for the deterministic analysis because it also incorporated an empirically derived regression equation for estimating the probability of injury from blade strike that considered fish size. This approach combines the probability of blade-strike and injury into the regression coefficients into the unadjusted blade-strike probabilities (Turnpenny et al. 2000). Other multiple-regression models like those of Bell (1991) and Headrick (2001) that predict the survival of turbine-passed fish were considered, but those models were derived from data from many turbines and were not applicable for predicting survival with varying treatments at single turbines. Many of the input variables in those models would be constants when applied to the two Kaplan turbines studied at Bonneville Dam or the McNary turbine physical model.

2.4 Stochastic Model Implementation

The stochastic version of the model was implemented in Microsoft® Excel using @Risk, statistical analysis software developed by the Palisade Corporation. The software allows users to define distributions for any or all independent variables so that the variation in variable values is propagated through calculations and is reflected in model predictions. The Monte Carlo simulation method and 10,000 realizations were used for all analyses. Sensitivity and scenario analyses were also performed using @RISK to identify the most important input parameters to the predicted results.

3.0 Comparison of Modeling Results with Bead Data of McNary Original Runner Physical Model

Reduced-scale physical models have been used by turbine designers to evaluate the hydraulic and power performance characteristics of turbine design and operational alternatives for many years. The McNary physical model of the original runner blade design is located at the USACE Engineering Research and Development Center at Vicksburg, Mississippi. The model materials are mainly Plexiglas with some metal (Figure 3.1), which allow visualization of essentially all of the turbine water passage for bead tracking experiments and various measurements including the use of laser Doppler velocimetry to measure water velocities. More details about the model can be found in USACE (2004).

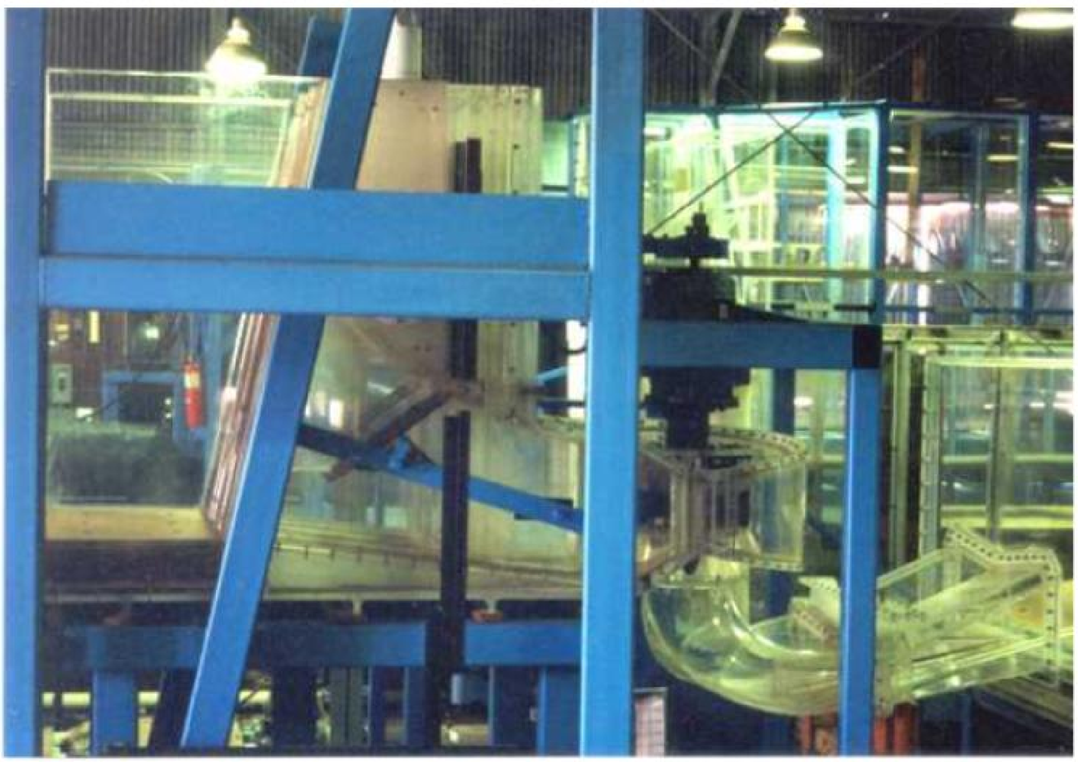

Figure 3.1. McNary Dam Observational Physical Model. The model is oriented with the immediate powerhouse forebay and turbine intake to the left and the turbine draft tube exiting into the tailrace to the right.

3.1 Model Preparations and Input Variable Calculations

For McNary Dam, both wicket gate opening (WGO, in inches) and wicket gate angle (WGA, in degrees) were used to define wicket gate position. From Drawing No. 3828-RW-1 Gate Detail (Figure 3.2), we derived equations for wicket gate geometry over their operating range. We computed the minimum distance between two gates using a linear search algorithm for any given wicket gate angle. By this method, we described the relationships given below between WGA, WGO, R_{wgc}, and θ_{wgt} (plotted in Figure 3.3):

$$\begin{aligned}
R_{wgc} &= 3.3854\times10^{-4}\,\mathrm{WGO}^2 - 0.6779\mathrm{WGO} + 168.25\\
\theta_{\mathrm{wgt}} &= 3.5498\times10^{-4}\,\mathrm{WGO}^3 - 4.7016\times10^{-3}\,\mathrm{WGO}^2 + 1.3808\mathrm{WGO} - 5.1548\\
R_{wgc} &= 2.7246\times10^{-5}\,\mathrm{WGA}^3 - 8.1433\times10^{-4}\,\mathrm{WGA}^2 - 0.4806\mathrm{WGA} + 170.31\\
\theta_{\mathrm{wgt}} &= -1.0977\times10^{-6}\,\mathrm{WGA}^3 + 1.7090\times10^{-3}\,\mathrm{WGA}^2 + 0.9657\mathrm{WGA} - 9.4225
\end{aligned} \tag{3.1}$$

As shown in Figure 3.3a, R_{wgc} and wicket gate opening have a linear relationship, which were used to estimate R_{wgc} for given wicket gate openings.

3.2 Bead Experiments at McNary Scaled Physical Turbine Model

The USACE (2004) used a 1:25-scale observational physical model of McNary turbines to identify the locations for the terminuses of the piping used to inject test fish into the turbine environment. This model was also used to estimate the distribution of test fish from the various in-turbine release locations at entry into the turbine runner and to assess the frequency of occurrence and severity of exposure to strike, collision, and shear during entry, passage, and exit from the turbine runner and other locations. Beads and live test fish were released from the same four locations in intake bay A—blade hub, mid-blade, blade tip at the turbine stay vanes, and worst stay vane release just off the divider wall between the A and B intake slots in the physical model and the prototype, respectively. The test beads used in the physical model, which are essentially cylindrical, have a specific gravity of 1.02 g and are about 4 mm long and 2.2 mm wide, giving them a prototype equivalent length of 100 mm and thickness of 55 mm. At each of the four release locations, numerous beads were released, and 350 beads were tracked with high-speed video camera to observe and quantify bead collisions with stay vanes and wicket gates, strike by turbine blades, collisions with other turbine structures, and exposure to shear and extreme turbulence. To classify the response of beads to the various interactions with turbine structure and hydraulic events during turbine passage, the following subjective grading system was established:

1 = Very Severe (direct, hard contact causing a severe change in direction)

2 = Severe (direct contact with change in direction)

3 = Moderate Strike (light contact with change in direction)

4 = Glancing Strike (makes contact with surface with little change in direction)

5 = Touching (bead travels with slight bump of surface or sliding along surface)

6 = No Contact with Any Surface.

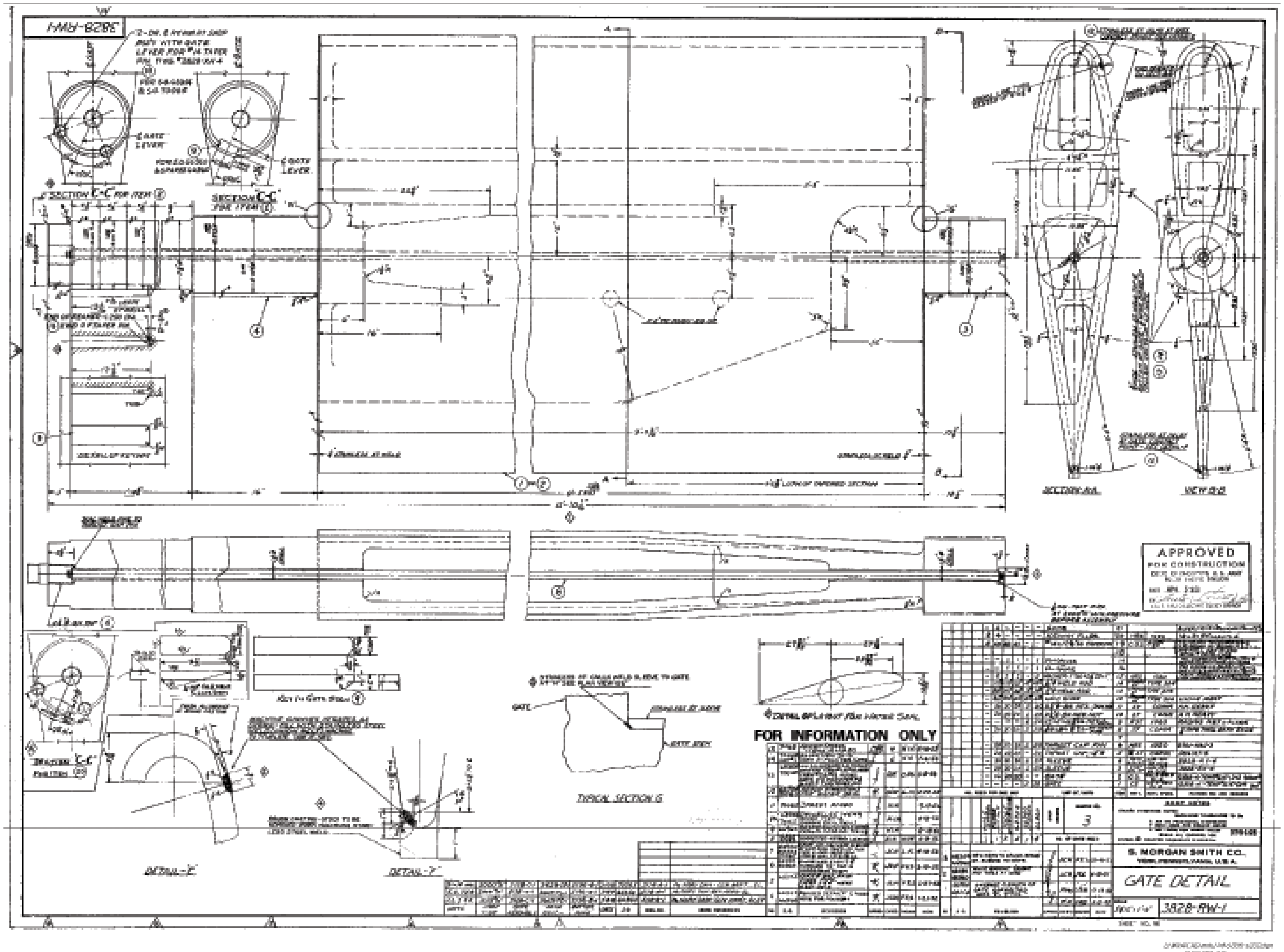

Figure 3.2. Wicket Gate Details for McNary Dam, Original Runner (Drawing No. 3828-RW-1)

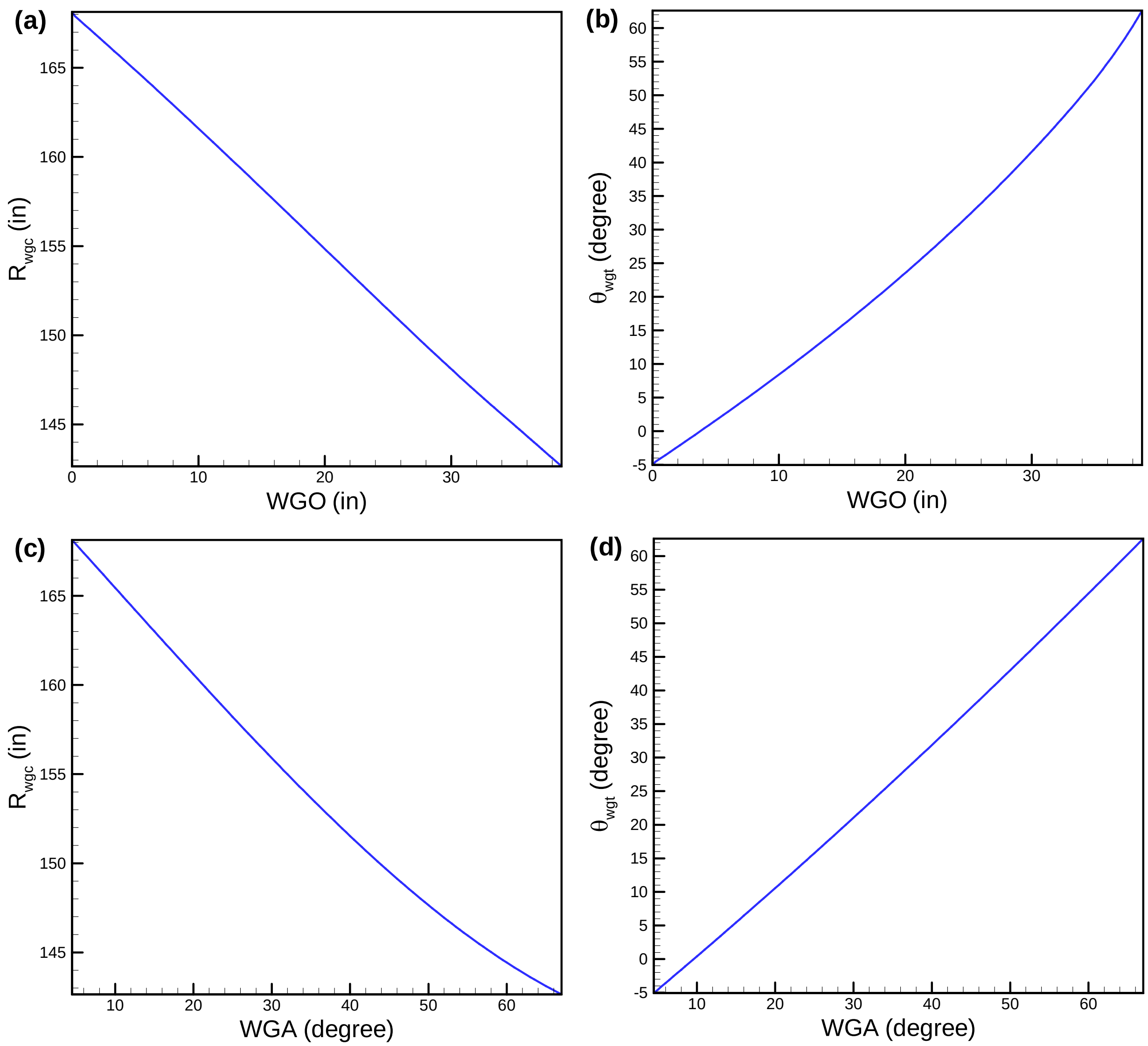

Figure 3.3. Relationship Between WGA, WGO, R_{wgc} and θ_{wgt}, McNary Dam Original Runner. (a) R_{wgc} vs. WGO; (b) θ_{wgt}, vs. WGO; (c) R_{wgc} vs. WGA; (d) θ_{wgt}, vs. WGA

The USACE found that beads released near the top of wicket gate openings passed through the runner close to the runner hub, while beads released near the middle of wicket gate openings passed near the middle of runner blades, and beads released near the bottom of wicket gate openings tended to pass close to tips of the runner blades. The results of the three releases for the severe and very severe classifications of bead-blade interaction are shown in Table 3.1.

Table 3.1. Percentage of Severe and Very Severe Bead Contact by Release Location and Discharge for Bead Passage Through McNary Dam 1:25-Scale Physical Turbine Model

Prototype discharge (cfs)	Top (Hub) Release (%)	Mid-Blade Release (%)	Bottom (tip) Release (%)	All Releases (%)
10220	4.85	3.45	4.94	4.38
12190	3.64	0.66	9.72	4.98
13417	7.14	0.46	3.62	3.84
16450	4.53	1.99	7.49	4.88
17770	4.29	1.00	2.80	2.71

As previously discussed, an important factor in the blade-strike model is the distribution of fish (or beads) as they pass through the runner region. We derived a relationship between the distribution of fish at a turbine's wicket gate and the location of entry into the turbine runner by using a computational fluid dynamics (CFD) numerical model for a Kaplan turbine at Lower Granite Dam developed for another DOE Hydropower research project at Pacific Northwest National Laboratory. We assumed that fish would be distributed uniformly in elevation at passage through the turbine wicket gates (Figure 3.4). Then using transient solutions with a time step of 0.01 second and a particle-tracking algorithm, we obtained the distribution of particle passage radius shown in Figure 3.5. We used this distribution to model the radius of fish passage for any wicket gate elevation. As expected, the CFD results confirmed the general relationship between the elevation of passage through wicket gates and the location of entry into the turbine runner observed for beads in the physical turbine model. Particles released close to the top of the wicket gates passed through the runner region close to the runner hub; those released close to middle point at the wicket gate passed mid-blade, and particles released close to the bottom of the wicket gate passed close to the tips of the runner blades.

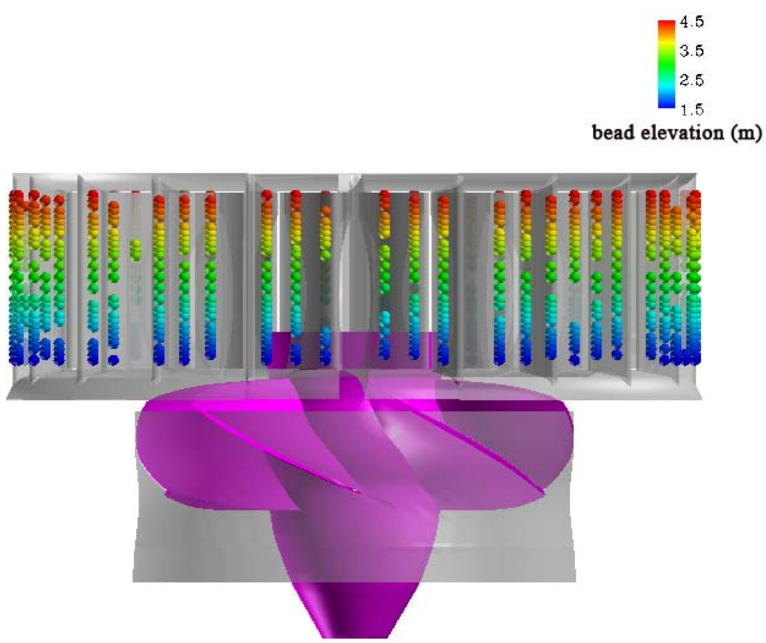

Figure 3.4. Uniform Distribution of Beads at Wicket Gate

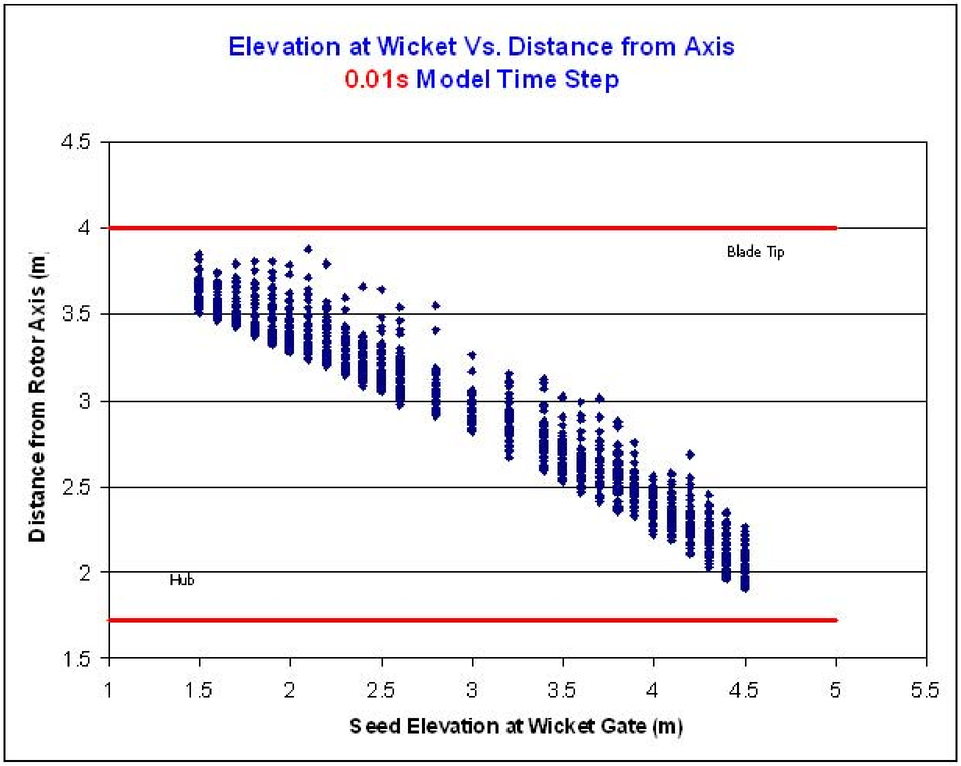

Figure 3.5. Relationship Between Particle Release Elevation at the Turbine Wicket Gates and Particle Passage Radius Distribution Obtained Using a CFD Model of a Lower Granite Dam Kaplan Turbine

3.3 Deterministic Model Predictions

The deterministic blade-strike model was run with top, mid-blade, and bottom wicket gate releases for each of the five discharges: 10,220, 12,190, 13,417, 16,450, and 17,700 cfs. The results of the blade-strike model runs were compared to the bead data acquired by the USACE using the McNary Dam physical turbine model. Bead data severe contacts (score of 1 and 2) were selected as the bead data most similar to the criteria in the blade-strike model used to estimate the percentage of blade strikes (Table 3.1). Blade-strike model predictions were within the range of bead experimental results for top and bottom releases and significantly higher than those of the bead experiments for mid-blade releases (Figure 3.6). The mean blade-strike model prediction for all three releases combined was higher in all cases than the physical model bead observations (Figure 3.7), significantly so at the lowest and highest discharges examined.

Bead observations in the physical model were more variable than the numerical blade-strike model results. One possible explanation is that the physical model by its nature incorporates sources of variability that factor into blade-strike probabilities that were not considered in the deterministic blade-strike model. The large overprediction by the blade-strike model relative to bead observations may be due to the classification of blade strikes of beads in the physical model. For example, those that occurred in the mid-blade region were, in general, less severe and were assigned to one of the less severe strike categories that were not included in the analysis we performed.

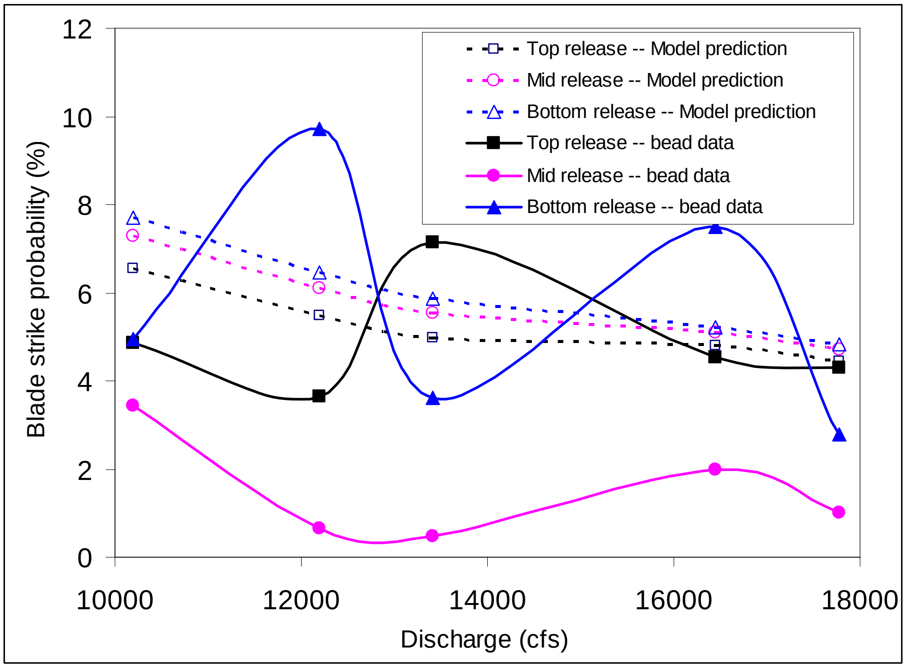

Figure 3.6. Predictions of Blade Strike as a Function of Discharge and Comparison with Bead Experimental Results, McNary Original Runner

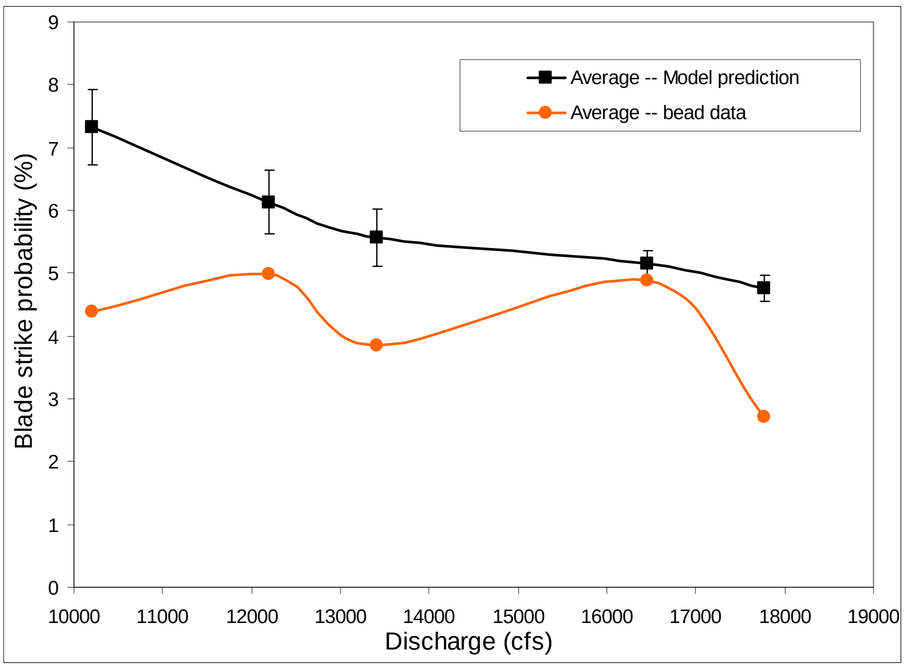

Figure 3.7. Average of the Predictions of Blade Strike as a Function of Discharge and Comparison with Bead Experimental Results, McNary Original Runner

3.4 Stochastic Model Implementation

For each of the five discharges, stochastic model analysis was performed by assuming uniform distribution of bead passage radius (i.e., uniform vertical distribution of beads at the turbine wicket gates) and uniform or normal distribution of bead length relative to the leading edge of the runner blade (Table 3.2). These distributions resulted in modeled beads having a random passage radius and random aspect as they approached the plane of the leading edges of the runner blades; the probability of a specific passage radius and approach aspect was governed by the applied distributions. Bead passage radius was modeled as a uniformly distributed random variable over the radial range of 67.6 to 140 prototype inches. The blade-strike probabilities using the two relative bead length distributions were almost identical (Table 3.2) and much more comparable to the bead experimental observations than to the results from the deterministic model. Note that the deterministic model assumed that all fish were oriented perpendicular to the leading edge of the runner blade, while the stochastic model employed more realistic distributions of fish body orientation. Figure 3.8 shows the stochastic blade-strike model predictions and physical model bead observations of severe bead strike as a function of discharge for all release locations combined. The stochastic model predictions of blade-strike probability were contained within the range of observations of bead severe blade contact from the USACE McNary observational physical turbine model study. Only blade-strike model predictions using the uniform fish orientation distribution were included because of the similarity of blade-strike model results with both uniform and normal distributions.

Table 3.2. Blade-Strike Probabilities for All Three Release Locations Combined, Obtained Using the Stochastic Blade-Strike Model Assuming Uniform or Normal Distribution of Bead Length at Passage Through the Plane of the Runner Blade Leading Edges

Discharge (cfs)	Model Prediction (%) (uniform distribution)	Model Prediction (%) (normal distribution)	Bead Data (%)
10200	5.55	5.54	4.38
12190	4.67	4.66	4.98
13417	4.23	4.23	3.84
16540	3.93	3.91	4.88
17700	3.66	3.66	2.71

The performance of the blade-strike model was investigated further by pooling the physical model bead strike data into two flow categories (high and low), and the blade-strike stochastic model was run using two flow distributions. The discharge of low flow was modeled using a uniform distribution over the discharge range of 10220 to 13417 cfs, while the model distribution of high flow was uniform from 16450 to 17770 cfs. The mean bead length relative to the leading edges of runner blades was assumed uniform or distributed normally. The predictions from the stochastic blade-strike model were very close to the bead experimental results when they were grouped into the same two flow ranges (Figure 3.9).

In addition, sensitivity and scenario analysis reports were generated by @RISK,[a] which identifies the input distributions most critical to the simulation results. The higher the regression coefficient between

(a) Risk analysis software available from the Palisade Corporation, Ithaca, New York.

the input and the output, the more significant the input is in determining the value of the output. Figure 3.10 shows the standardized regression coefficients for different input variables within the two flow regions. For both high and low flows, bead blade-strike probability depended on the mean length most significantly, followed by bead passage radius and discharge, respectively.

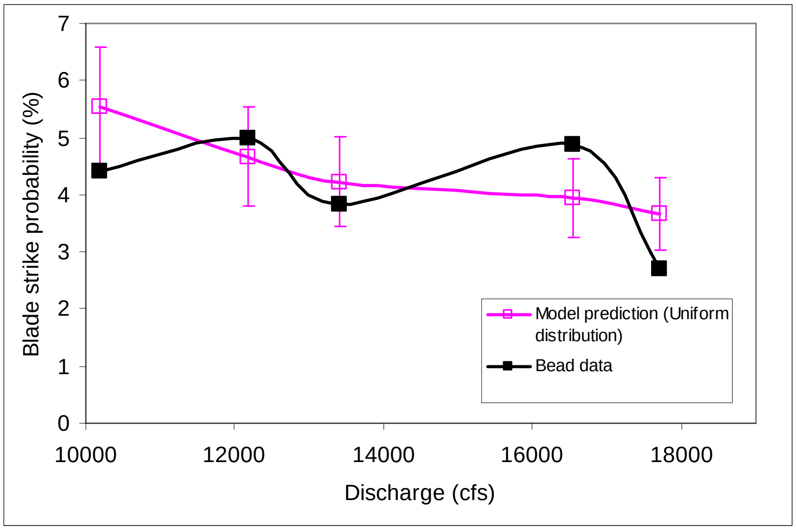

Figure 3.8. Model Prediction of Strikes Compared to Experimental Bead Strikes as a Function of Discharge, McNary Original Runner. The mean bead length relative to the leading edges of runner blades was assumed to be distributed uniformly.

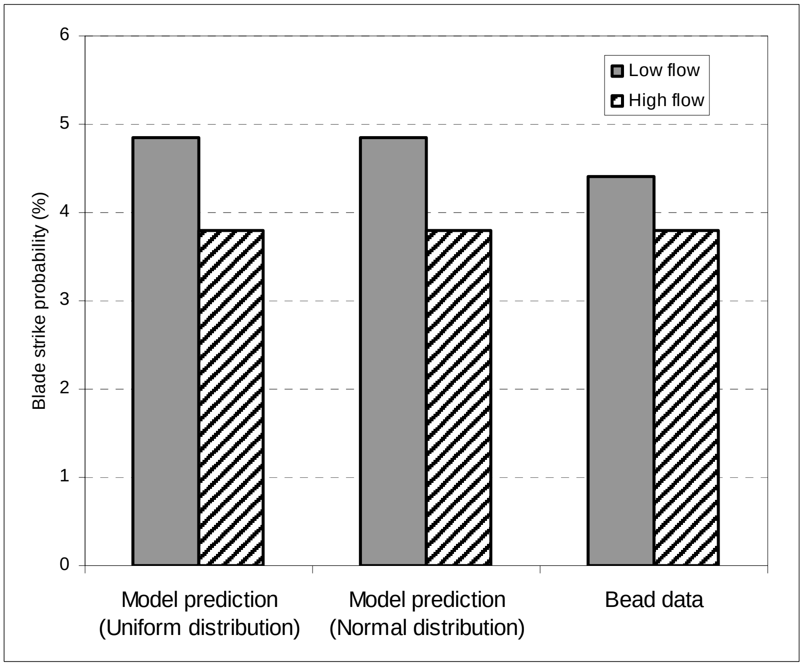

Figure 3.9. Comparing the Predictions of the Stochastic Model with the Bead Experimental Results for McNary Original Runner. The mean bead length relative to the leading edges of runner blades was assumed uniform or distributed normally.

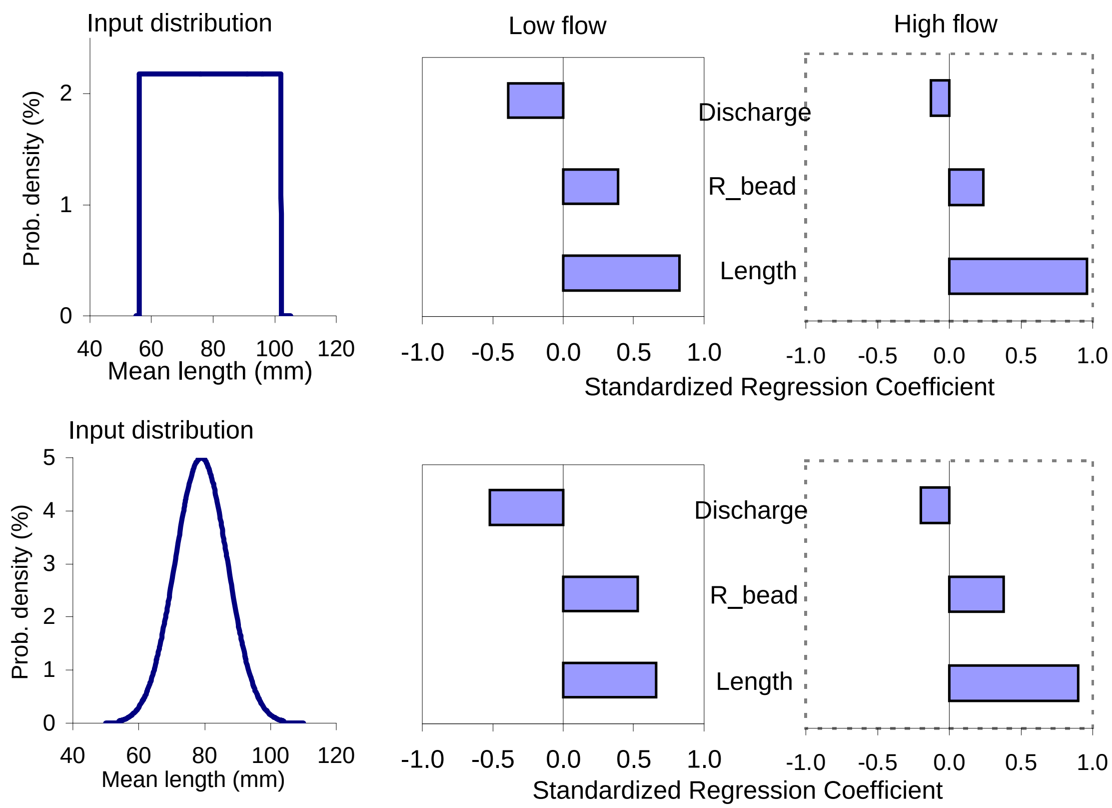

Figure 3.10. Two Different Input Distributions of Relative Bead Length (expressed in units at the prototype scale) and Standardized Regression Coefficients (right) Indicating the Sensitivity of Blade-Strike Predictions to Bead Length, Turbine Discharge, and Bead Runner Passage Radius (R_bead)

4.0 Comparison of Modeling Results with Empirical Data from Bonneville Dam Turbines

4.1 Model Preparations and Input Variable Calculations

During the Bonneville Dam assessment of the biological performance of new MGR and original design runners, observations of servomotor stroke (%) were acquired for each live fish release. Because wicket gate opening (WGO, in inches) is necessary for the linear regression to obtain estimates of R_{wgc}, we needed to establish the relationship between WGO and servomotor stroke. For Unit 6, the calibration shown in Table 4.1 was available from the USACE (USACE 2004, p. A-30). Using polynomial regression, we obtained the following relationship between wicket gate opening and servomotor stroke (%):

$$WGO = -1.3204\times10^{-5} S^3 + 1.4476\times10^{-3} S^2 + 0.3744S - 0.1454 \tag{4.1}$$

where S is the servomotor stroke percentage.

Previously when working with the McNary Dam physical model, we concluded that R_{wgc} could be approximated as a linear function of WGO. For Bonneville Dam, as shown in Drawing 2672-1270 of Voith Siemens HydroPower Generation, R_{wgc} was 166 in. when the wicket gates were closed and 140.4 in. when the wicket gates were fully open. Based on this information, the equation obtained for R_{wgc} given WGO using linear regression was

$$R_{wgc} = -0.6558\times WGO + 166 \tag{4.2}$$

θ_{wgt} was estimated by applying Equation (4.1) to Equation (3.1). (Equation (3.1) was developed for McNary Dam turbines and used for Bonneville Dam turbines due to their geometric similarity.)

Correlations between blade-strike probabilities obtained using the blade-strike model and different operational parameters were computed using Pearson's correlation:

$$R = \frac{\sum_{1}^{N}(X_i - \overline{X})(Y_i - \overline{Y})}{(N-1)S_x S_y} \tag{4.3}$$

where X and Y are two variables, $\overline{X}$ and $\overline{Y}$ are their mean values, S_x and S_y are their respective standard deviations, and N is the number of samples. P-values also were computed to test the hypothesis of no correlation. Each p-value is the probability of getting a correlation as large as the observed value by random chance when the true correlation is zero. If the p-value is small, say less than 0.05, then the correlation R(i,j) is significant. On the other hand, if the p-value is large, then the correlation is not statistically significant.

Table 4.1. Bonneville Unit 6 Index Test Wicket Gate Calibration July 1999 (USACE 2004, p. A-30)

Governor Reading	Gate Ring Reading	Actual Machinist Scale Reading	Machinist Scale Reading inches	Servo Stroke inches	Servo Stroke %	Wicket Gate Opening Top inches	Wicket Gate Opening Middle inches	Wicket Gate Opening Bottom inches	Wicket Gate Opening Average* inches
squeeze	0	53/64"	0.83	0	0.00	-----	-----	-----	0
zero		10/64'	1.00	0.17	0.46	-----	-----	-----	0
10.1	1.05	54/64'	5.06	4.23	11.37	3.997	3.991	3.997	3.994
17.5	1.85	754/64"	7.84	6.84	18.37	7.165	7.135	7.400	7.150
28.0	2.90	1152/64"	11.81	10.81	29.03	11.660	11.672	12.293	11.666
35.5	3.78	1452/64"	14.81	13.81	37.08	15.150	15.121	16.069	15.136
46.6	4.73	1852/64"	18.81	17.81	47.82	19.742	19.688	21.126	19.715
59.5	6.05	2353/64"	23.83	22.83	61.28	25.230	25.134	27.051	25.182
67.5	6.85	2653/64"	26.83	25.83	69.34	28.365	28.252	30.242	28.309
78.0	7.90	3052/64"	30.81	29.81	80.03	32.316	32.247	34.290	32.282
89.0	8.95	3453/64"	34.83	33.83	90.81	35.881	35.890	37.774	35.886
99.8	10.00	3855/64"	38.86	37.86	101.64	39.059	39.010	40.636	39.035

4.2 Deterministic Model Predictions

For Unit 5 (original design Kaplan runner) and Unit 6 (turbine with MGR) at Bonneville Dam's first powerhouse (see Figure 4.1), the deterministic model was implemented for each of the discharge and release location combinations and test blocks for fish releases in the 1999–2000 survival study (Normandeau Associates et al. 2000; Wittinger and Ramirez 2000). For every fish release treatment block, we calculated 48-hr mortality from numbers of control and turbine-passed fish released, recovered alive or dead, or not recovered, as follows:

$$1-\left[\frac{N_{\mathrm{TA}} \div (N_{\mathrm{TR}} - N_{\mathrm{TN}})}{N_{CA} \div (N_{CR} - N_{CN})}\right] \tag{4.4}$$

where N = number of fish. The first subscript indicates whether fish passed through a turbine (T) or were released into the tailrace as a control (C), and the second subscript describes fish classification—alive (A), released (R), or not recovered (N). This control-corrected mortality calculation described by Bell (1981) allowed us to compare predicted and empirical results for each turbine with 59 pairs of estimates. We also averaged predictions by treatment to compare with empirical estimates presented by Normandeau Associates et al. (2000). This approach provided 12 pairs of predicted and empirical estimates for each turbine unit. Survival or injury estimates for each of the 59 releases per turbine were not presented in the Normandeau Associates et al. (2000) report; they presented only estimates pooled by treatment (unit, power level, and release location).

For both units, estimates of blade-strike probability were higher at low discharge than at high discharge (Figure 4.2). The mean predicted blade-strike probabilities were slightly higher for Unit 5 than for Unit 6 at low discharge, but the opposite was true at high discharge.

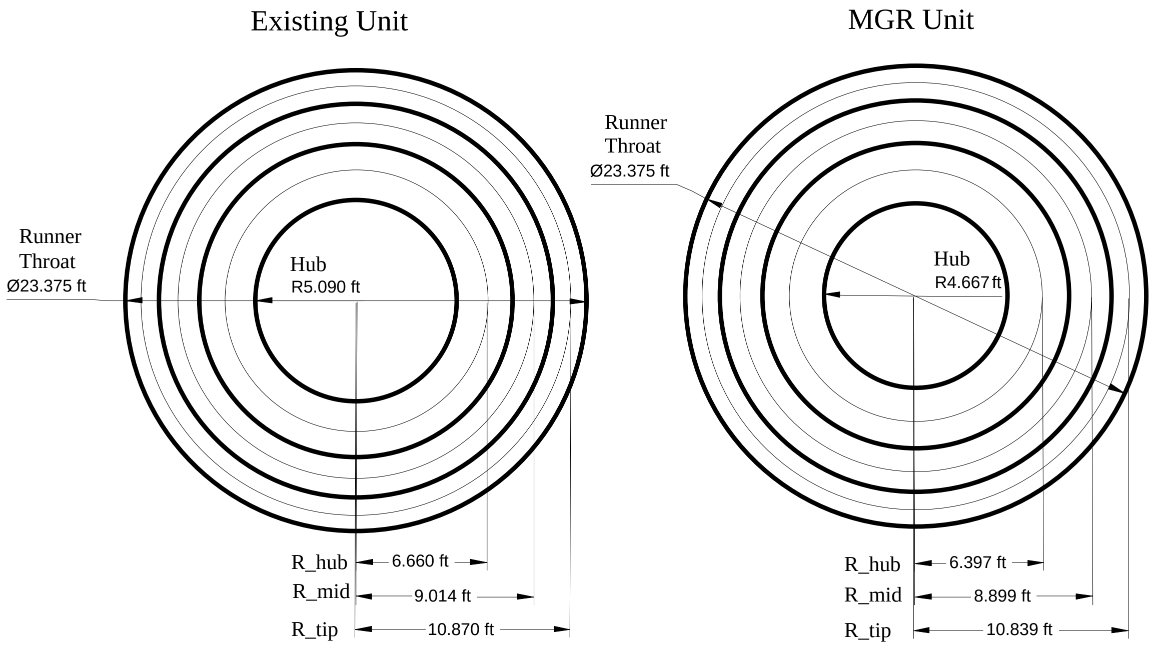

Figure 4.1. Plan View Showing Radial Dimensions of the Hub and Throat of an Existing Kaplan Turbine at Unit 5 and a New Minimum Gap Runner Turbine at Unit 6 at Bonneville Dam. The area between the runner hub and throat was divided into three equal areas and then the average radius of two at the inner and outer bounds of each area (heavy lines) was calculated.

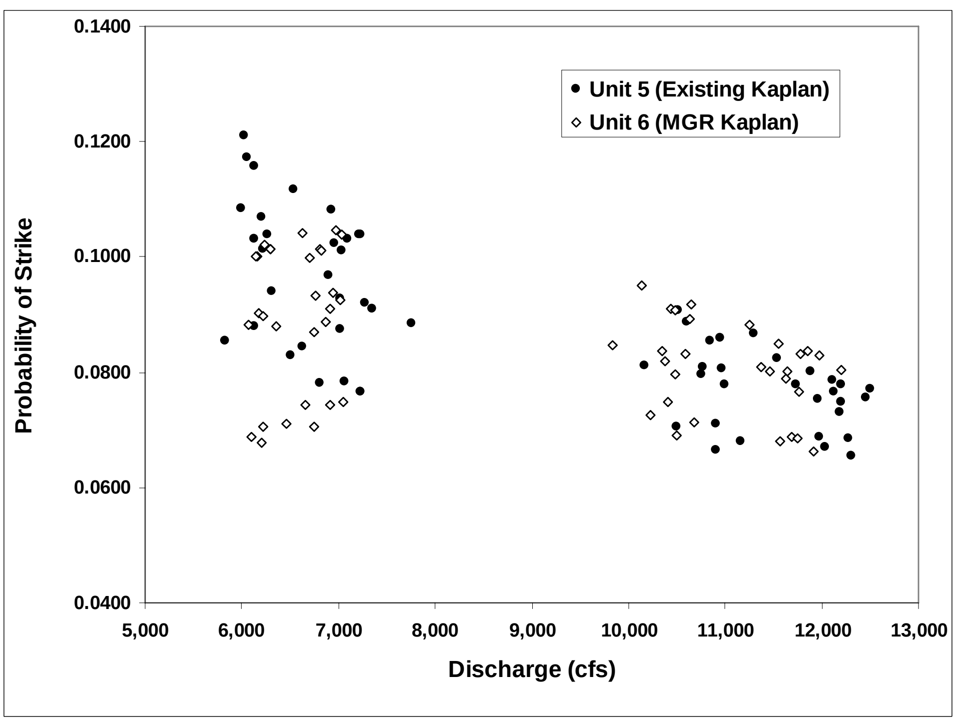

Figure 4.2. Predictions of Blade Strike Obtained with the Deterministic Blade-Strike Model as a Function of Discharge for Units 5 (original design Kaplan runner) and Unit 6 (minimum gap runner)

As shown in Table 4.2, blade-strike probabilities and operating head for both Units 5 and 6 were not correlated (p-values were 0.36 and 0.48, respectively). In addition, there was no statistical evidence to suggest correlation between blade strike and turbine efficiency as the p-values were 0.36 and 0.65 for Units 5 and 6, respectively. For both units, predictions of blade strike were positively correlated with fish passage radius and inversely correlated with wicket gate opening, blade angle, power output, discharge, and fish length. For Unit 5, the turbine operational parameters showed the highest correlation with blade strike (correlation coefficients were around −0.7). However, for Unit 6, fish passage radius and fish length were the variables most highly correlated with blade-strike predictions.

Table 4.2. Correlation Coefficients and p-Values for Blade Strike and Test Turbine Operational Variables from the 1999–2000 Bonneville Dam First Powerhouse Minimum Gap Runner Study (Normandeau Associates et al. 2000; Wittinger and Ramirez 2000)

Prediction	Head (ft)	Wicket Gate Opening (in.)	Blade Angle (°)	Power (kw)	Efficiency (%)	Discharge (cfs)	Fish Passage Radius (in.)	Mean Length (mm)
Unit 5 (N = 59)								
Blade strike (R)	-0.13	-0.73	-0.76	-0.75	-0.12	-0.75	0.59	-0.39
Blade strike (p-value)	0.32	0.00	0.00	0.00	0.38	0.00	0.00	0.002
Unit 6 (N = 58)								
Blade strike (R)	-0.09	-0.40	-0.43	-0.41	-0.06	-0.42	0.85	-0.79
Blade strike (p-value)	0.48	0.002	0.001	0.001	0.65	0.001	0.00	0.00

4.3 Comparison of Model Predictions and Live Fish Experimental Data

Table 4.3 lists the average prediction of blade strike and injury for the three fish release locations in the two units. For a given release location, there was no significant difference in blade-strike or injury probabilities between the two turbines. However, the average predicted probabilities of blade strike and injury were slightly higher for the existing Kaplan at Unit 5 than for the new MGR at Unit 6. For both units, the prediction of blade-strike injury was higher at low discharge than at high discharge (Table 4.4). In addition, average predicted probabilities of blade-strike injury were slightly higher for Unit 5 than for Unit 6 at low discharge, but the opposite was true at high discharge.

Combining results over the full range of discharges, based upon overlap of 95% confidence intervals, neither the model predictions of blade-strike injury nor the empirical (live fish test) estimates of injury and mortality resulted in any significant differences between the two turbine design types (Figure 4.3). However, there were overall trends in the data. For example, probabilities of predicted blade strike were higher, in general, compared to 1-hr mortality, 48-hr mortality, dead or injured, and dead, injured, or loss of equilibrium categories for the blade hub releases, about equal to those for mid-blade, and lower than those for blade tip releases. In addition, while the MGR unit (Unit 6) live fish test biological performance was slightly worse at the hub than the original unit (Unit 5) and slightly better at the runner blade tips, the blade-strike model predictions were essentially the same for both units.

Table 4.3. Average Prediction of Blade Strike and Injury for Different Release Locations at Units 5 and 6

Turbine Unit	Release Location	Average Predicted Blade Strike	Average Predicted Blade-Strike Injury
Unit 5	Tip	0.0957	0.0421
	Mid	0.0875	0.0386
	Hub	0.0748	0.0334
Unit 6	Tip	0.0946	0.0417
	Mid	0.0856	0.0378
	Hub	0.0708	0.0316

Table 4.4. Average Prediction of Blade Strike and Injury for Low and High Discharges at Units 5 and 6

Turbine Unit	Discharge	Average Predicted Blade Strike	Average Predicted Blade-Strike Injury
Unit 5	Low	0.0968	0.0427
	High	0.0770	0.0341
Unit 6	Low	0.0894	0.0394
	High	0.0804	0.0356

4.4 Stochastic Model

For the two units at Bonneville Dam, three variables were assigned distributions of possible values in simulations. Discharge was assigned a uniform distribution ranging from the minimum to the maximum observed for each turbine at each turbine discharge treatment in the survival study. We also applied distributions for two variables with the greatest uncertainty: fish-passage radius and fish length relative to the leading edge of the runner blade. Fish-passage radius is the radius of a circle with its origin at the center of the runner and its circumference at the location where a fish passed the runner blade. The distribution of fish-passage radius was assumed uniform between the runner hub and discharge ring radii so that the model predicted an average injury rate for fish equally distributed along the runner blades.

The mean length of released fish in the 1999–2000 study varied little (6.49 ± 0.03 in. – 95% confidence interval), and the orientation of individuals passing the runner blades was unknown. A fish is much more likely to be struck if it is oriented perpendicular rather than parallel to a runner blade. To account for the uncertainty in test fish orientation during runner passage, we modeled several different normal and uniform distributions of fish mean relative length at the time of turbine runner entry. The 4-in.-diameter hoses for releasing fish were attached to a stay vane and oriented within 15 degrees of horizontal at three elevations just upstream of the turbine wicket gates. The orientation of the terminal ends of the pipes differed slightly. The end of the uppermost pipe was angled downward about 15 degrees below horizontal. The middle pipe end was horizontal, and the end of the bottom pipe was angled upward about 15 degrees above horizontal. If fish oriented into or with the flow immediately after exiting an injection pipe terminus, they could have been oriented mostly perpendicular to the leading edge of the runner blade, and their relative length distribution would have been a narrow normal or uniform distribution with a mean nearly equal to actual fish lengths. However, if fish were oriented parallel to the long axis of the hose and maintained that orientation as they passed the runner, they would have been mostly parallel to the leading edge and would have had a short relative length perpendicular to a runner blade leading edge, something approaching the thickness or width of test fish. With a uniform distribution of relative length ranging from 0.75 to 6.78 in., we assumed that fish were tumbling as they passed the runner blade and could have any orientation or relative length at the instant of passage through the plane of the leading edges of the turbine runner blades.

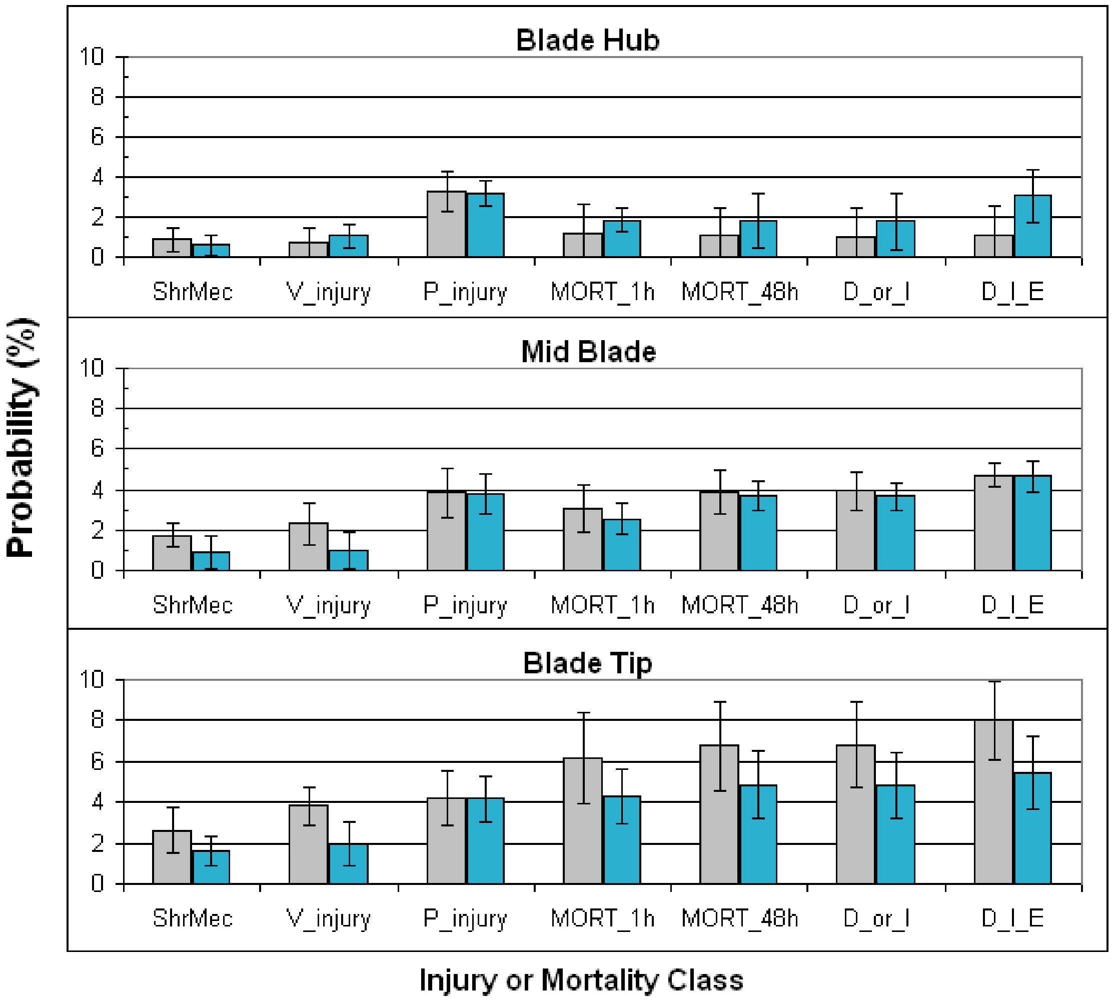

Figure 4.3. Comparing Probabilities of Predicted Blade-Strike Injury (P_injury) with Empirical Estimates of Shear + Mechanical Injury (ShrMec), Visible Injury (V_injury), 1-h Mortality (MORT_1 h), 48-h Mortality (MORT 48 h), Dead or Injured (D_or_I), or Dead, Injured, or Loss of Equilibrium (D_I_E) for Units 5 (gray bars) and 6 (blue bars). Error bars are 95% confidence intervals.

For the first eight runs of the stochastic model implemented, the fish length relative to the runner blade edge was assigned to eight different distributions (Figures 4.4 and 4.5). For all the scenarios, there was no statistical evidence to suggest any major difference between the two units in probability of blade strike or blade-strike injuries. When the relative mean fish length was close to mean fish full-body length (first case in Figures 4.4 and 4.5) and had a very narrow distribution, the model predictions were highly dependent on discharge, which was consistent with the observations from the deterministic model (Table 4.2) because the deterministic model assumed that all fish entered the runner region perpendicular to the leading edge of the runner blade. Conversely, the deterministic model can also be considered as a special case of the stochastic model in which the relative fish length mean is the fish full-body length and the distribution has zero bandwidth. When the fish length distribution increased and became more realistic (assuming random distribution of fish at entry into the runner for all eight scenarios), the dependence of blade-strike injury on discharge decreased significantly while the dependence on fish passage radius and fish body length increased accordingly. Normandeau Associates et al. (2000) also reported that fish mortality and injury rates were not a function of turbine discharge or efficiency.

In two additional model runs (Figures 4.6 and 4.7), fish passage radius was distributed over the entire runner region for one case and limited to the radial range from mid-blade to the tip of runner blades in another case. For each case, fish lengths were assumed to be either uniformly distributed (ranging from 0.75 to 6.78 in.) or normally distributed (μ = 3.75 in., σ = 0.8 in.). As can be seen from Figures 4.6 and 4.7, the predictions from the stochastic model with more realistic consideration of relative fish length distribution were closer to the empirical data of Normandeau Associates et al. (2000) than they were to the predictions from the deterministic model, regardless of whether the fish passage radius distribution included the entire runner region or was limited to a localized region. In addition, as observed earlier, while the blade-strike model predicted essentially the same injury probabilities for both units, the live fish tests showed trends of differences between the two different designed turbine runners not reflected in the blade-strike model results.

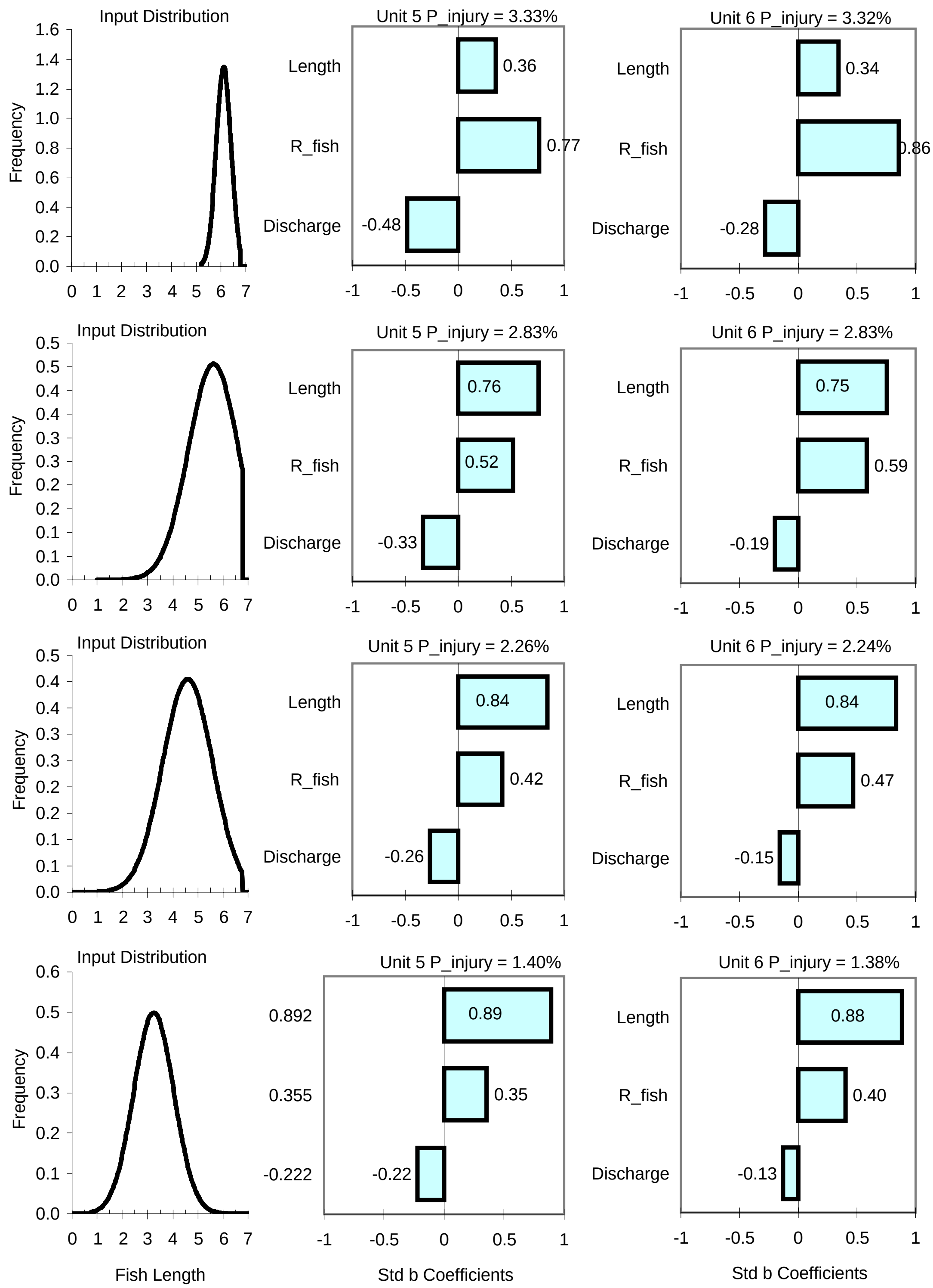

Figure 4.4. Plots of Various Normal Distributions of Relative Fish Length (left) and Standardized Regression Coefficients (right) Indicating the Sensitivity of Injury Predictions (P_injury) to Fish Length, Turbine Discharge, and Fish-Passage Radius (R_fish). Mean predicted percentages of fish injury are presented above each sensitivity plot.

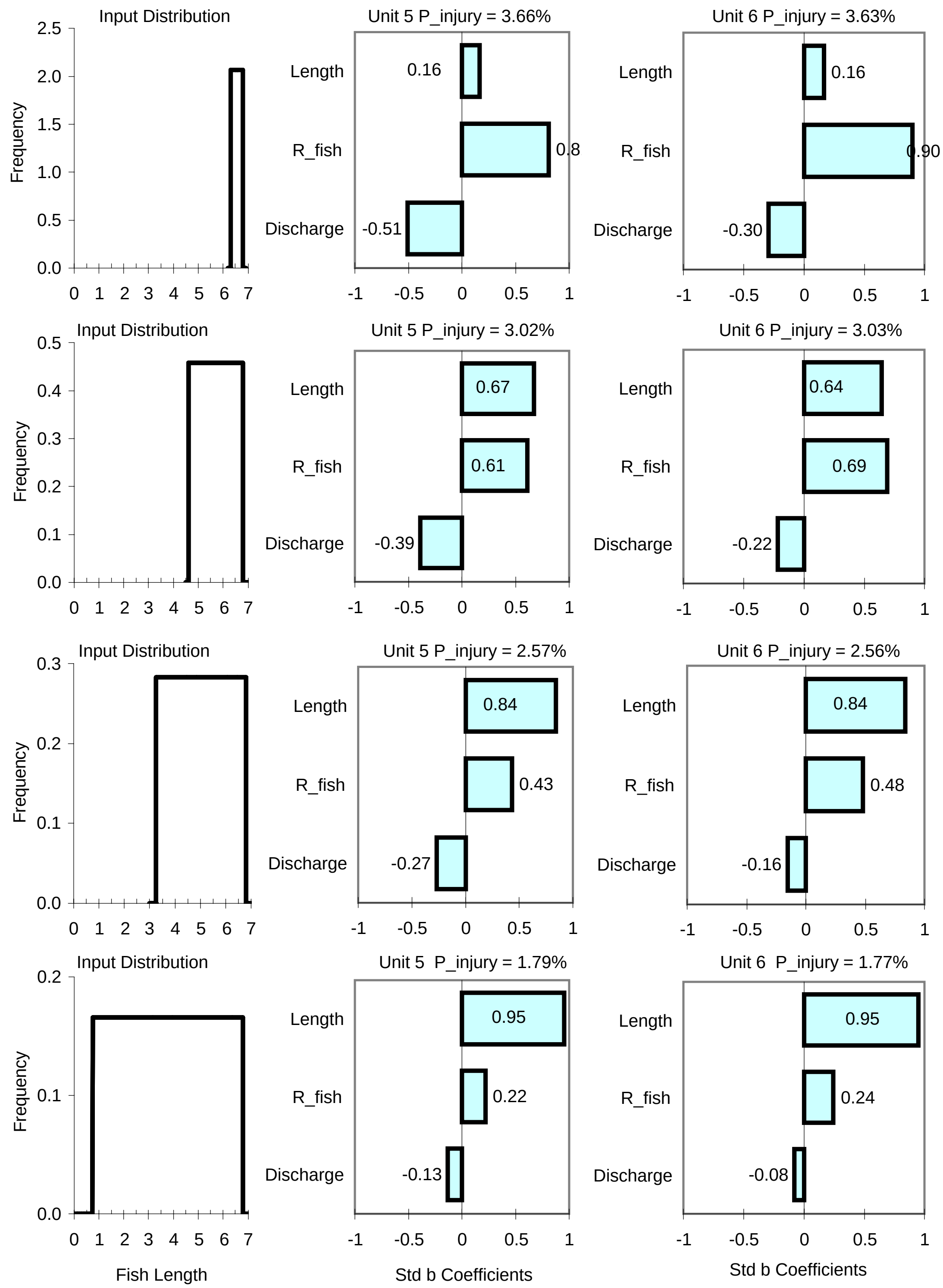

Figure 4.5. Plots of Various Uniform Input Distributions of Relative Fish Length (left) and Standardized Regression Coefficients (right) Indicating the Sensitivity of Injury Predictions (P_injury) to Fish Length, Discharge, and Fish-Passage Radius (R_fish). Mean blade-strike probability predictions are presented above each sensitivity plot.

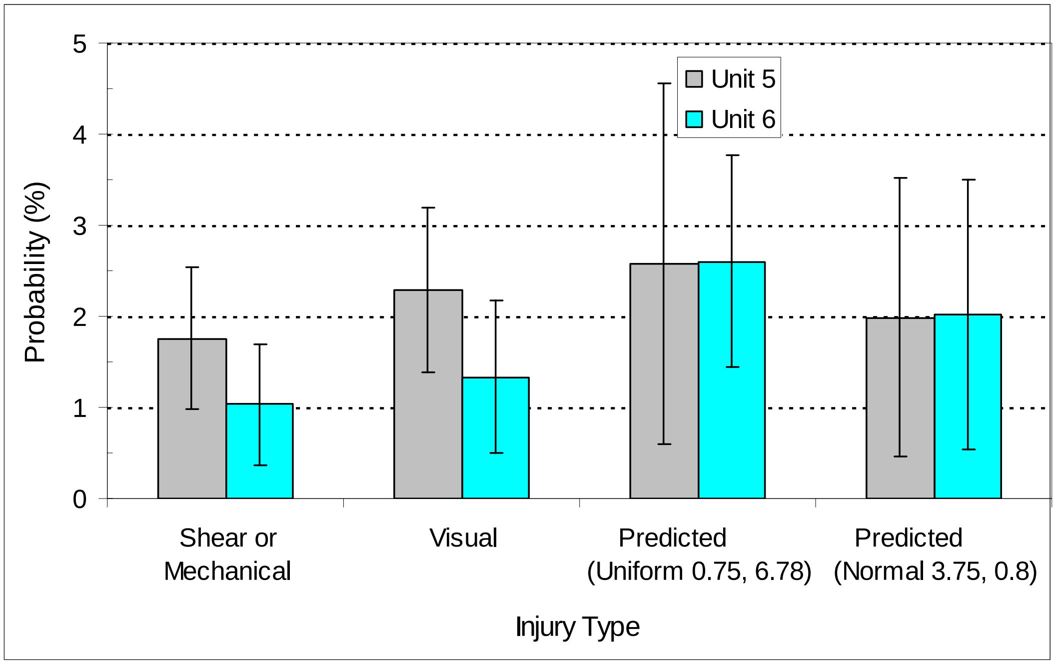

Figure 4.6. Comparison of Empirical and Predicted Injury Probabilities. Fish passage radius was distributed uniformly over the entire runner region. Error bars are 95% confidence intervals about mean values.

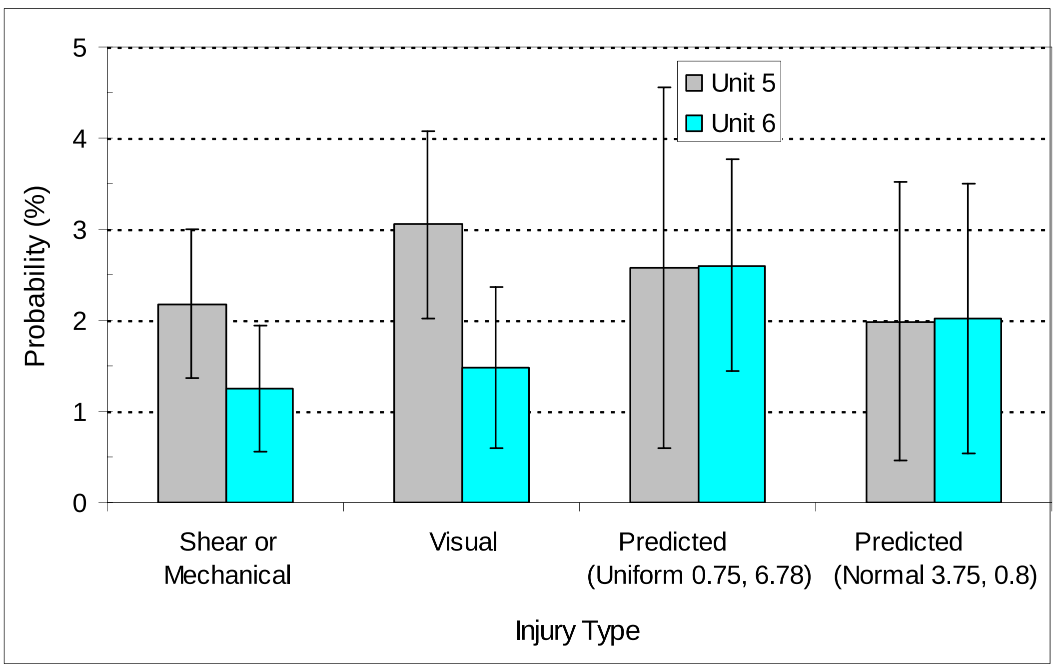

Figure 4.7. Comparison of Empirical and Predicted Injury Probabilities. Fish passage radius distribution was limited to the radial range from mid-blade to the tip of runner blades. Error bars are 95% confidence intervals about mean values.

5.0 Discussion

The blade-strike probability predictions obtained with the deterministic model were within the range of the runner hub and tip release severe bead strikes observed in the 1:25-scale McNary physical turbine model. However, the blade-strike probability estimates from the deterministic model were considerably higher than the severe strike observations from the McNary physical model for beads that passed mid-blade through the turbine runner. The available data were not helpful in explaining the large difference between predictions made using the deterministic model and those made using the physical turbine model. The average of deterministic model predictions over all release locations compared more favorably with the average proportion of severe blade-strike observations made using the physical turbine model.

Stochastic model predictions of blade-strike probability were closer to the probability of severe blade-strikes estimated using the McNary physical turbine model. The stochastic model accounted for the aspect of beads upon entry into the turbine runner better than the deterministic model. Additional improvement in the comparability of numerical model and physical model blade-strike probability estimates was obtained by grouping the data into high and low discharge bands. When the discharge was modeled as a uniform distribution within each band, the results from the blade-strike and physical model compared favorably.

One obvious difference between the blade-strike model results and physical model observations was the higher variability between test conditions seen in physical model observations (USACE 2004). The reasons for this higher variability cannot be explained from available data but may be due, in part at least, to a more accurate simulation of turbine hydraulic conditions in the physical model, notably turbulence. In addition, estimates of blade-strike probability obtained using physical turbine models have not been evaluated against observations of live fish injury and mortality obtained from prototype-scale testing. Therefore, at this time, it is not clear if the variability with discharge shown in the bead blade-strike data obtained using physical turbine models is also a feature of blade-strike probability with discharge for live fish at prototype scales or is an artifact of the methods used to obtain observations of bead contact with model turbine runner blades.

For Unit 5 (original design runner) and Unit 6 (MGR) at Bonneville Dam, deterministic model predictions of blade-strike probability were slightly higher at low discharges for Unit 5 than for Unit 6, and the opposite occurred at high discharges. However, there was no significant difference between the two units over the full range of discharge, based upon overlap of the 95% confidence intervals of mean blade-strike probability estimates. For both Units 5 and 6, blade-strike probability and head or turbine efficiency were not correlated For Unit 5, the turbine operational parameters had the strongest correlation with blade strike, while for Unit 6, fish passage radius and fish length were the most highly correlated with blade-strike predictions.

For all Bonneville turbine simulated scenarios, our numerical model provided no strong statistical evidence to suggest a major difference between the two test units (MGR and original design runner) in terms of blade-strike or injury probabilities. When the mean fish length relative to the leading edges of turbine runner blades was close to the mean full-body length of the fish and had a very narrow distribution (i.e., when the scenario was close to the deterministic model), the model predictions and discharge were strongly correlated. Thus, our finding was consistent with the observations from the deterministic model. When fish distributions were more realistic (i.e., with a wider-range distribution of relative fish length depending on fish orientation as they entered the runner region), the correlation between the stochastic model results and discharge decreased drastically, and the model prediction became more dependent on fish passage radius and fish body length distributions. Overall, our findings were consistent with observations by Normandeau Associates et al. (2000) that at Bonneville there was no effect of discharge on rates of injury or mortality of live test fish.

While not statistically significant, live fish test results for Bonneville Dam's first powerhouse original design and MGR turbine units showed trends in differences between the two units, with the MGR unit providing better biological performance than the original design runner. Similar trends were not observed in the blade-strike deterministic or stochastic model injury predictions. While the observed trends in the live fish data were not statistically significant, the assessment of significance is a consequence of experimental design and should not be used as a reason to ignore the trends in the injury and mortality estimates, which were consistent over the range of test conditions. The stochastic blade-strike model did not show the trend of better biological performance for the MGR unit, although the magnitudes of the blade-strike probability and injury probability predictions compared favorably in general with the live fish test results. This is troublesome, because improvements in turbine design that address the issues such as the radius of the leading edge of turbine runner blades are likely to provide biological benefits in the form of lower strike probability on the order of the non-significant differences, as shown in the trends of lower injury and mortality probabilities for the MGR unit versus the original design runner unit at Bonneville Dam.

In summary, fish orientation at the time of entry into the plane of the leading edges of turbine runner blades appears to be one of the most significant factors and uncertainties in blade-strike modeling. Turbine discharge was not significantly correlated with empirical estimates of injury or mortality, even though it was the most significant factor affecting predicted strike and injury for deterministic models where fixed orientation of fish at runner entry is assumed. When the fish were assumed to be oriented perpendicular to the leading edge of the runner blades (deterministic model assumption), discharge was the most important factor affecting injury predictions, and predictions were 2 to 5 times higher than empirical estimates of shear + mechanical injury or visual injury. However, when fish were assumed to be oriented with their long axis within 30 degrees of the leading edge of the blade instead of perpendicular to it, 1) the relative mean length decreased to one half of the actual length, 2) discharge became much less important than relative length, and 3) predictions of injury became more comparable to empirical data (stochastic model assumptions). Similar results were obtained using the stochastic model by assuming that fish exited the release hoses and tumbled as they passed the runner blades. Overall, whether the test cases were the fish survival studies at Bonneville Dam or bead experiments with the McNary physical model, the predictions from the stochastic analysis were closer to the empirical data than the predictions from the deterministic model because the stochastic model could include more realistic fish (bead) length (fish or bead orientation) relative to the leading edge of the runner blades.

Based on our results, we recommend the use of stochastic blade-strike models that consider the aspect of fish approaching the leading edges of a turbine runner's blades. Randomization of fish aspect appears to provide a more realistic simulation of actual conditions and should be the preferred method for prediction of blade-strike and injury probability for yearling salmon smolt using numerical blade-strike models. The blade-strike modeling method presented in this report is limited to initial screening assessments in that it can not address more detailed design issues such as runner blade shaping and the interaction between the stay vanes and wicket gates. More realistic blade-strike models will need to be developed in order to move beyond these limitations. Future models of blade strike will need to be based on three-dimensional computational fluid dynamics simulations of the turbulent flow environment that are coupled with computing the motion of fish-sized objects interacting with the turbine system components.

6.0 References

Drawing No. 2672-1270. Bonneville Dam First Power House. Voith Siemens HydroPower Generation, York, Pennsylvania.

Drawing No. 3828-RW-1. Wicket Gate Details for McNary Dam Original Runner. U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, Washington.

Bell MC. 1981. *Updated Compendium of the Success of Passage of Small Fish Through Turbines*. Report to the U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Bell MC. 1991. *Revised Compendium of the Success of Passage of Small Fish Through Turbines*. Report to the U.S. Army Corps of Engineers, North Pacific Division, Portland, Oregon.

Čada GF, CC Coutant, and RR Whitney. 1997. *Development of Biological Criteria for the Design of Advanced Hydroturbines*. DOE/ID-10578, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Čada GF. 2001. "The development of advanced hydroelectric turbines to improve fish passage survival." *Fisheries* 26(9):14-23.

Coutant CC and RR Whitney. 2000. "Fish behavior in relation to passage through hydropower turbines: A Review." *Transactions of the American Fisheries Society* 129:351-380.

Eicher GJ, CJ Campbell, RE Craven, and MA West. 1987. *Turbine Related Fish Mortality: Review and Evaluation of Studies*. EPRI AP-5480, Electric Power Research Institute, Palo Alto, California.

Headrick MR. 2001. "Predicting fish survival in axial flow turbines." *Hydro Review* 20(4):114-119.

Monten E. 1985. *Fish and Turbines: Fish Injuries During Passage Through Power Station Turbines*. Vattenfall, Sweden.

Normandeau Associates, Inc., JR Skalski, and Mid-Columbia Consulting, Inc. 2000. *Direct Survival and Condition of Juvenile Chinook Salmon Passed Through an Existing and New Minimum Gap Runner Turbines at Bonneville Dam First Powerhouse, Columbia River*. Report to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Odeh M. 1999. *A Summary of Environmentally Friendly Turbine Design Concepts (Concepts Developed by Alden Research Laboratory, Inc., Voith Hydro, Inc. and their Teams)*. DOE/ID-13741, U.S. Department of Energy, Idaho Operations Office, Idaho Falls, Idaho.

Odeh M and G Sommers. 2000. "New design concepts for fish friendly turbines." *Int. J. Hydropower and Dams* 7(3):64-71.

Ploskey GR and TJ Carlson. 2004. *Comparison of Blade-Strike Modeling Results with Empirical Data*. PNNL-14603, Pacific Northwest National Laboratory, Richland, Washington.

Pavlov DS, AI Lupandin, and VV Kostin. 2002. *Downstream Migration of Fish Through Dams of Hydroelectric Power Plants*. Trans. T. Albert, trans. ed. GF Čada. ORNL/TR-02/02, Oak Ridge National Laboratory, Oak Ridge, Tennessee.

Solomon DJ. 1988. *Fish Passage Through Tidal Energy Barrages*. ETSU TID4056, Energy Technical Support Unit, Harwell, United Kingdom.

Stone and Webster Environmental Services. 1992. *Fish Entrainment and Turbine Mortality Review and Guidelines*. EPRI TR-101231, Electric Power Research Institute, Palo Alto, California.

Turnpenny AWH. 1998. "Mechanisms of Fish Damage in Low-Head Turbines: An Experimental Appraisal." In *Fish Migration and Fish Bypasses*, eds. M Jungwirth, S Schmutz, and S Weiss, pp. 300-314. Fishing News Books, Blackwell Publishing, Oxford, United Kingdom.

Turnpenny AWH, DM Davis, JM Fleming, and JK Davies. 1992. *Experimental Studies Relating to the Passage of Fish and Shrimps Through Tidal Power Turbines*. National Power PLC, Fawley, Hampshire, United Kingdom.

Turnpenny AWH, S Clough, KP Hanson, R Ramsay, and D McEwan. 2000. *Risk Assessment for Fish Passage Through Small, Low-Head Turbines*. ETSU H/06/00054/REP, Energy Technical Support Unit, Harwell, United Kingdom.

U.S. Army Corps of Engineers (USACE). 1995. *Proceedings of the Turbine Fish Passage Survival Workshop*. U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

U.S. Army Corps of Engineers (USACE). 2000. *Proceedings of the Turbine Fish Passage Survival Workshop*. U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

U.S. Army Corps of Engineers (USACE). 2004. *Turbine Survival Program (TSP) Phase I Report, 1997-2002*. U.S. Army Corps of Engineers, Portland District, Portland, Oregon.

Von Raben K. 1957. "Regarding the problem of mutilations of fishes by hydraulic turbines." Originally published in *Die Wasserwirtschaft* (100):4:97. *Fisheries Research Board of Canada Translation Series*, No. 448, 1964.

Wittinger RJ and D Ramirez. 2000. *Bonneville Dam First Powerhouse, Unit 5 & 6 Biological Test, November 1999-January 2000, Turbine Operating Conditions*. Report to the U.S. Army Corps of Engineers, Portland District, Portland, Oregon.