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Validation of Francis–Kaplan Turbine Blade Strike Models for Adult and Juvenile Atlantic Salmon (*Salmo Salar, L.*) and Anadromous Brown Trout (*Salmo Trutta, L.*) Passing High Head Turbines

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Received: 30 June 2020; Accepted: 5 August 2020; Published: 7 August 2020

Abstract: The negative effects of hydroelectric power (HEP) on salmonid populations has long been recognized and studied. Downstream passage through turbines may potentially constitute a significant source of mortality for both juvenile and adult fish in regulated rivers. Numerical models have been developed to calculate turbine passage mortality based on the probability of collision with the turbine blades, but although widely used in management and conservation, their performance is rarely validated in terms of the accuracy and bias of the mortality estimates. In this study, we evaluated commonly used blade strike models for Kaplan and Francis turbines by comparing model predictions with observed passage mortalities for juvenile 13–27 cm and adult 52–94 cm Atlantic salmon (*Salmo salar*, L.) and anadromous brown trout (*Salmo trutta*, L.) acquired by acoustic telemetry. Predictions made for juveniles aligned closer with observed mortality for both Kaplan and Francis turbines (within 1–3% percentage points). However, the model severely underestimated the mortality of adult fish passing through Francis turbines, with up to 50% percentage points difference between predicted and observed mortalities. Furthermore, the model did not capture a clear negative correlation between mortality and discharge observed for salmon between 50–60 cm (grilse). We concluded that blade strike models are a useful tool for quantifying passage mortality for salmonid smolts passing large, high-head turbines, but that the same models should be used with care when trying to estimate the passage mortality of kelts in iteroparous populations. We also concluded that the major cause of passage mortality for juveniles is injury by collision with the turbine blade, but that other factors seem to contribute substantially to the passage mortality of kelts. Our study reports low mortality for smolts up to 27 cm passing through Kaplan and Francis turbines (0–12%), but high mortality for salmon over 50 cm passing though Francis turbines (56–81%).

Keywords: modeling; validation; blade strike; kelt; turbine passage; animal movement and migrations; animal conservation; hydropower sustainability; ecohydraulics; Francis turbines

1. Introduction

Hydroelectric power (HEP) complexes often lack functional solutions for downstream migration, forcing downstream migrating fish to pass through turbines or spill. Because of this, one of the primary negative impacts of HEP on migratory fish is injury or mortality connected to turbine passage [1]. During the last decades, more attention has been directed towards finding solutions to reduce the risk of injury and the mortality of fish when passing hydropower stations and dams, and yet there are still pieces missing in fishway science, engineering, and practice [2]. Reliable estimates of turbine–mortality is key when prioritizing mitigation efforts for downstream migration in regulated rivers [3]. However, there is still an incomplete understanding of both the magnitude and the underlying processes contributing to turbine mortality in fish.

Empirical studies on live fish have traditionally been used to study mortality from passage through turbines and other routes at hydropower stations (some examples are [4–6]). Although these methods can provide accurate and reliable estimates of mortality, they require that tagged fish are either re-captured or monitored after passage to determine their fate, resulting in logistically challenging and often expensive field studies that are bound by the operating configuration of the hydropower station [7]. A more cost-effective and generic approach to estimating fish mortality through turbines is the use of numerical models. Most numerical models provide quantitative estimates of mortality by modeling the risk of mortality as a function of turbine and fish characteristics [8,9].

Turbine mortality depends on the characteristics of both the hydropower station (turbine type and operating conditions) and the fish (species, size, behavior, and physiological conditions) [10–16]. A fish may experience several dangerous conditions during turbine passage, including rapid pressure changes, shear stress, cavitation, high turbulence, and strikes by the rotating blades of the turbine [13,17]. Blade strike models aim specifically to predict the probability that a fish passing through a turbine is hit by the blades and dies. The basic relationships and components of this process were identified and formulated into a model by von Raben in 1957 [9], whose core equations still form the basis for the majority of blade strike models in use today (e.g., [8,18–24]). Blade strike models take into account the length and velocity of the fish, as well as the physical and operational characteristics of the turbine. They also focus solely on the risk of lethal blade strikes, ignoring all other potential factors affecting mortality during passage. Several slightly modified versions of von Raben's model have been developed to better calibrate it to empirical mortality data, fish type, and turbine designs, including the commonly used Kaplan and Francis turbines [8,25].

Although numerical models, such as blade strike models, are important tools in estimating turbine passage mortality in fish, their accuracies are rarely validated. Validations should focus on comparing the calculated estimates from the models with empirical observations of turbine passage mortality [24]. Given the multiple factors effecting passage mortality, such validations need to be context-specific to be relevant: i.e., models should be specifically validated for particular turbine designs, operation conditions, range of fish sizes, species, and even for different life stages within a species. An important group of fish species that has been negatively affected by HEP is anadromous salmonids. Blade strike models have been used extensively to quantify the mortality of anadromous salmonids passing though turbines [14,20], although model validation has so far focused mainly on juvenile fish (i.e., smolt) passing Kaplan turbines [21,23]. Adult, post-spawning fish have largely been ignored (but see [24]), even though they provide an important component for the population viability of many iteroparous species [26]. Similarly, no validation of blade strike model estimates is readily available for the commonly used Francis turbine, although this turbine design is generally considered to cause considerably higher mortality than other turbine types [27].

In this paper, we validate the accuracy of mortality estimates produced by a commonly used blade strike model developed for Kaplan turbines [9] and a blade strike model developed for Francis turbines [24]. This was done by comparing the model output with the observed mortality estimates from telemetry tracking studies of Atlantic salmon (*Salmo salar*, L.) and anadromous brown trout (*Salmo trutta*, L.) smolts passing hydropower stations with Francis and Kaplan turbines, and adults passing a hydropower station equipped with Francis turbines.

2. Materials and Methods

Fish survival studies were carried out in the field to validate predictions from the blade strike models. In this paper, we used the Bell [18,24] formulation of von Raben's model to estimate mortality in Kaplan turbines, and an extended version of Montén's [8] model formulation, where the probability and lethality of strikes has been related to water velocity and turbine load in a non-linear way [28] to model mortality in Francis turbines.

2.1. The Turbines

The study involved two hydropower stations in Northern Sweden: one in the river Umeälven, and one in the river Dalälven. Both rivers enter the Baltic Sea. Stornorrfors Station (63°51′11.5″ N 20°02′59.7″ E) is located in the river Umeälven, 30 km from the river mouth. Stornorrfors has four Francis turbines, which operate at 75 m of head, generating 600 MW of power with a discharge capacity of 950–1000 m^3 s^{-1}. The turbine outlet is under ground, and the discharge water is led through a tunnel of 4 km until joining the old riverbed 26 km upstream from the river mouth. The last 1.5 km of the tunnel is deeper underground than the first part of the tunnel and lacks a water surface. There is speculation, and some evidence, that surface-oriented fish passing through this part of the tunnel may risk inflicting mortal damage to skin and tissue against the tunnel wall as they seek to remain high in the water column [8].

Lanforsen Station (60°31′50.4″ N 17°24′56.8″ E) is located in the river Dalälven, 23 km from the river mouth. The Lanforsen hydropower station generates 39 MW of power from four Kaplan turbines, operating at 10 m of head with a discharge capacity of 620 m^3 s^{-1}. See Table 1 for the turbine specifications relevant to the parameterization of the blade strike models.

Table 1. Turbine geometry data input parameters in the blade strike model.

Parameter	Stornorrfors Francis Turbine	Lanforsen Kaplan Turbine
No. of turbine blades	Unit I: 15 Unit II–IV: 16	Unit I–IV: 4
Blade rotational speed (r·min^{-1})	Unit I–III: 125 Unit IV: 155	Unit I–IV: 93.8
Overall turbine blades and hub (runner) diameter (m)	Unit I–III: 4.33 Unit IV: 4.75	Unit I–IV: 4.98
Hub diameter (m)	NA	Unit I–IV: 4.5
Height of the wicket gates (m)	Unit I–III: 1.56 Unit IV: 1.73	NA
Turbine discharge (m^3 s^{-1})	Unit I–III: 250 Unit: IV: 275	Unit I–IV: 155

2.2. Telemetry Fish Tracking Studies

Field studies were carried out during 2017–2019 and the mortalities of salmon and trout passing through the turbines during downstream migration were determined using acoustic telemetry. Adult Atlantic salmon (n = 97) and brown trout (n = 10) and juvenile salmon (n = 170) and brown trout (n 17) were tagged with acoustic transmitters (Table 2). As the main focus of this study was to investigate the validity of blade strike models for different size-based life-stages of anadromous salmonids, and because the sample size of the trout was fairly small, the salmon and trout were pooled for the main part of the subsequent validation analysis and data were structured according to the fish's total length rather than species. The validity for such structuring was supported by Saylor et al. [29], who could not find any difference in the blade strike mortality between closely related salmonid species of the same size. Adult individuals were hence divided into two groups: 50–60 cm (i.e., grilse) and >70 cm (i.e., multi seawinter adults; MSW). Adult fish refers to both spawning and post-spawning (i.e., kelts) individuals, whereas juveniles refer to downstream migrating fish <28cm (i.e., smolt).

Table 2. Total number of tagged fish with acoustic telemetry in different locations 2017–2019, mean total fish length (cm) ± standard error (SE) (range). With surg. and gast. means that individuals were tagged surgically or gastrically.

Period	Location	Parameter	Mean TL (cm)	Capture Method	Tagging Method	No. Tagged	No. Passed
6–7 June 2017	Umeälven	Adult Atlantic salmon	70.9 ± 8.7 (54.0–92.0)	net/rod	surg. + PIT	10	3
		Brown trout	59.6 ± 2.6 (52.0–68.0)	net/rod	surg. + PIT	10	4
8–15 June 2017	Umeälven	Juvenile Atlantic salmon	16.0 ± 0.3 (13.6–18.6)	smolt trap	surg. + PIT	50	43
19 July 2018–12 September 2018	Umeälven	Adult Atlantic salmon	62.0 ± 1.3 (54.0–69.0)	net/fish ladder	surg./gast.	31	5
13 June 2018–21 June 2018	Umeälven	Juvenile Atlantic salmon	15.9 ± 0.4 (12.3–18.5)	smolt trap	surg. + PIT	40	16
20 June2019–10 September 2019	Umeälven	Adult Atlantic salmon	61.2 ± 1.6 (52.0–94.0)	net/fish ladder	surg./gast. + PIT	56	13
2 May 2019–20 May 2019	Dalälven	Juvenile Atlantic salmon	16.3 ± 0.4 (13.0–20.0)	electrofishing	surg. + PIT	80	61
		Brown trout	24.6 ± 0.7 (21.0–27.0)	electrofishing	surgically + PIT	17	7

Wild adult fish ascending the river Umeälven in Stornorrfors were captured in the fish ladder, either by a net or by a special built-in fish capturing device (made for hatchery purposes). Descending post-spawning individuals were caught with a net or rod in connection to the power station during their seaward migration. Wild smolts were captured by a smolt trap in the river Umeälven and by electrofishing in Älvkarleby, river Dalälven. In addition, hatchery-reared sea run brown trout aged 2 from the Swedish University of Agricultural Science (SLU) Älvkarleby hatchery were used in the river Dalälven. The acoustic receivers, tags, tagging methods, and release locations differed slightly based on the river system and year of tagging (for more details, see Table 3). The live fish trials were carried out according to national guidelines and laws in Sweden regarding animal ethics and permit approvals from the animal ethics board in Sweden were stated (Dnr 5.2.18-3060/17). To ensure that the fish used in this experiment were in good health, a visual health check was conducted before any tagging procedure took place. Only fish in seemingly good condition (individuals being alert, responding to external stimuli, showing a fright response, and good swimming ability together with no physical injuries or ulcerations) were used within the experiment. The fish were placed in a container with fresh water and anesthetized with MS222. Internal acoustic transmitters were either gastrically or surgically inserted into the fish, and the incision was closed with two sutures. Kelt together with some of the ascending adult individuals in Stornorrfors received a passive integrated transponder (PIT) tag (via a pit tag pistol) in the muscle beneath the pectoral fin, while juveniles had PIT tags internally inserted into the abdominal cavity. While anesthetized, the length, sex, and origin were determined together with a collection of scales and DNA. Tagged juveniles in the river Dalälven recuperated at least 48 h after tagging before release, while kelt and juveniles in the river Umeälven recuperated in between 2 and 6 h. Ascending adults in the river Umeälven were released shortly after tagging. Different release locations were used depending on local environments at each site. Fish movements were tracked using stationary acoustic receivers (model VR2W and VR2AR (69 kHz) together with HR2 and VR2W (180 kHz)) located in close connection to the turbine intake and outlet of the stations to be able to determine the time that the fish entered the turbines, as well as the migration from the trail-race to the river mouth. The probability that a tagged fish was detected at all receiver gates close to turbine inlets and outlets was 100%.

Table 3. Number and specification of tags and receivers used within studies in the river Umeälven 2017–2019 and the river Dalälven 2019.

Tag and Receiver	Specification	Umeälven 2017	Umeälven 2018	Umeälven 2019	Dalälven 2019
PIT	BIOMARK HPT12, 12.5 MM, 134.2 kHz ISO FDXB	70	40	44	97
V16 Acoustic transmitter	V16-4L-069k-1, 69 kHz	20	31		
V9 Acoustic transmitter	V9-2L, 180 kHz	20		57	
V5 Acoustic transmitter	V5-1H, 180 kHz	50	20		97
V7TP Acoustic transmitter	V7TP-180 kHz		20		
VR2W Acoustic receiver	Frequency 69 kHz and 180 kHz	27	48	34	24
VR2AR Acoustic receiver	Acoustic release. Receive transmissions at 69 kHz	15			
HR Acoustic receiver	High Residence. Receive transmissions at 180 kHz	24	23	19	

Individuals were assumed dead after turbine passage if they had their last signal detected on one of the first receivers below the dam, or if a signal continued to be detected for more than 30 days close to a single receiver. In the river Umeälven, thirty-three adult individuals (11 in 2018 and 22 in 2019) had their last detection at the turbine intake, with no additional registrations being detected further downstream. We deemed that these individuals likely entered the turbines and died, but that their body or transmitter remained inside the underground tunnel, where no receivers could be deployed. However, to account for the ambiguous fate of these individuals, subsequent analyses were conducted using observed mortalities that both included and excluded this group of fish. Of the tagged adult salmon, 87 were fallbacks (i.e., pre-spawning individuals that turned downstream after passing the fish ladder instead of continuing upstream to spawn). Serious concern has recently been raised regarding spawning individuals of Baltic salmon showing signs of disease, leading to large die-offs within the Baltic Rivers [30,31]. The situation has been critical in the river Umeälven/Vindelälven since 2014. The health situation within the river is most likely the reason behind these fallbacks, where seemingly healthy spawners turned downstream and ended up aggregated in front of the turbine intake after ascending the fish ladder instead of continuing to their spawning grounds up river.

Based on the subsequent analysis, the fish were divided into four groups: Group 1 = adults with known fate passing Francis turbines, Group 2 = same as Group 1, but including adults that disappeared after entering the turbines, Group 3 = smolt passing Francis turbines, and Group 4 = smolt passing Kaplan turbines.

2.3. Validation Approach

The blade strike models were parameterized based on the turbine specifications provided by the companies operating the hydropower stations (Table 1) and the fish length data from the telemetry study (Table 4). A key parameter influencing the mortality estimates from the blade strike models was the discharge through the turbines. Although the model was based on the maximum load of the turbine (i.e., maximum discharge capacity), mortality estimates could be adjusted based on a correction factor related to the actual discharge at the time of fish passage. In this study, the two hydropower stations had multiple turbines per station, with each turbine operating independently regarding load. Although the telemetry had complete detection probability both upstream and downstream from the turbines, the spatial resolution of the detection data did not allow for determining exactly which turbine the tagged fish passed through. To account for this uncertainty, a fish was assigned to a turbine using weighted bootstrap sampling that assumed a higher probability for a fish to enter a turbine with higher discharge compared to a turbine with lower discharge at the time of fish passage (with zero probability if the turbine was not operating). The discharge of the assigned turbine was then used to derive the corrected mortality estimates from the blade strike models for a particular individual.

The mortality estimates from the model were interpreted as the individual's median "risk of dying" in percent and were accompanied with the 2.5th to the 97.5th percentile. To allow for proper error propagation, the "risk of dying" was then randomly sampled with this range, assuming a triangle distribution with the median as the mode of the distribution. To be able to evaluate how well this estimate reflected the observed mortalities, the value had to be transformed from an individual's "risk of dying" in percent to binary data (i.e., dead/alive), converted to the same format as the observed data. This was achieved by randomly generating a number between 1 and 100 from a uniform distribution and converting this number to percent. This value was then compared to the sampled value from the triangle distribution (the mortality estimate from the model). If the value was smaller than the model estimate, the fish was deemed dead: i.e., the risk of dying predicted by the model was larger than random. The entire process—i.e., from assigning a turbine to deriving a binary fate (i.e., dead or alive)—was conducted for every individual in each experimental group, resulting in a dataset of binary fate outcomes for each group. To derive information about mode and spread of these fate outcomes, 10,000 such datasets were generated for each group of fish, from which mean mortality and associated errors were calculated. This was then compared to the observed mortality from telemetry data to evaluate the accuracy and bias of the estimates.

Table 4. Biological data input parameters in the blade strike model.

Group	Location	Turbine Type	Parameter	Mean TL (cm)	No.
1	Umeälven	Francis	Adult		
			Atlantic salmon	62.1 ± 2.8 (55.0–83.0)	21
			Brown trout	58.0 ± 4.5 (52.0–63.0)	4
2	Umeälven	Francis	Adult		
			Atlantic salmon	61.9 ± 1.8 (52.0–94.0)	54
			Brown trout	58.0 ± 4.5 (52.0–63.0)	4
3	Umeälven	Francis	Juvenile		
			Atlantic salmon	15.9 ± 0.3 (13.5–18.6)	59
			Brown trout	-	0
4	Dalälven	Kaplan	Juvenile		
			Atlantic salmon	16.4 ± 0.4 (13.0–19.5)	61
			Brown trout	25.1 ± 1.0 (23.0–27.0)	7

To investigate how the predictions from the blade strike model potentially deviated from observed data over a range of discharges in relation to the fish's total length (TL), predicted values for five discharges (62, 118, 174, 230, and 286 m^3 s^{-1}) chosen to evenly represent the entire discharge range experienced during the study were compared against the output from a two-way logistic regression based on the telemetry data from the Francis turbine. The average discharge experienced during passage was 192 m^3 s^{-1} for smolt (min = 84, max = 255), 182 m^3 s^{-1} for grilse (116, 221), and 151 m^3 s^{-1} for MSW (117, 176). The probability of dying was modeled as a function of discharge and total length for all fish that passed through the Stornorrfors turbine. Fish fate was treated as the response variable (binary data 1 or 0), the average flow of all running turbines at the time of fish passage as a continuous explanatory variable, and total length as a categorical explanatory variable with three levels: 1) fish <28 cm (i.e., smolt, n = 59), 50–60 cm (i.e., grilse, n = 19), and >70 cm (i.e., multi seawinter adults; MSW, n = 7). The significance of explanatory variables was determined by a log-likelihood ratio test comparing models with and without the terms, assuming a chi-squared distribution of the ratio statistic. The difference between factor levels of significant main effects was tested using a post-hoc Tukey honestly significant difference (HSD) test.

3. Results

3.1. Telemetry Turbine Passage Mortality

In total, 56% (n = 14) of the tagged adults in Stornorrfors (Group 1, n = 25) that passed through Francis turbines died after turbine passage. In 2018 and 2019, thirty-three tagged adults in the river Umeälven had their last recording on one of the last receivers in connection to the intake and no further registrations either up or downstream of the dam. When including these individuals (as passage fate dead), 81% (n = 47) died from turbine passage (Group 2, n = 58). Not a single fish over 70 cm (i.e., MSW) survived during the passage for fish with known fate (n = 10). For juveniles passing through Francis turbines in Stornorrfors (Group 3, n = 59), mortality was 11.9% (n = 7) and for juveniles passing through Kaplan turbines in Lanforsen (Group 4, n = 68), mortality was 0% (n = 0).

3.2. Validation of the Model

Predicted blade strike probabilities were in close alignment with that of observed mortalities for smolt, overestimated mortalities for Kaplan turbines with 1 percentage units, and underestimated mortalities for Francis turbines with 3 percentage units (Table 5). Model predictions substantially underestimated mortalities for adult fish in Francis turbines. When only using adults whose fates could be fully known (i.e., Group 1), the predictions were off by 23% percentage units. When also including adults who disappeared after entering the turbines (i.e., Group 2), predictions were off by 48 percentage units (Table 5).

Table 5. Results of 10,000 trials (Monte Carlo method) assuming binomial distribution of modeled blade strike probabilities for fish passing through four Francis (F × 4) and four Kaplan (K × 4) turbines to be compared with the results from live fish trials.

Group	Turbine Type	Mean Total Length (cm)	Mortality (%) obs.	Mortality (%) Model	Abs. Bias
1 Adult Francis	F × 4	61 ± 2.5 (52–83)	56 ± 20.5 (36–76)	33.2 (4–76)	−0.23
2 Adult Francis	F × 4	61.7 ± 1.8 (52–94)	81 ± 10.3 (71–91)	33.2 (12–59)	−0.48
3 Juvenile Francis	F × 4	15.9 ± 3.1 (13.5–18.6)	11.9 ± 8.4 (3–20)	8.5 (0–25)	−0.03
4 Juvenile Kaplan	K × 4	17.3 ± 7.4 (13–27)	0 ± 0 (0–0)	1.3 (0–7)	0.01

Values presented as the arithmetic mean (median mortality in percent), standard deviation (±), 95% confidence interval (in parentheses). *Abs. bias* is the absolute difference in percentage points between model estimates and observed mortality.

The logistic regression revealed that the fish's total length had a significant effect on the probability of dying (generalized linear model (GLM), $\chi_{\mathrm{df} = 2, \mathrm{de\text{-}err} = 80} = 24.7$, $p < 0.01$), with smolt having a lower probability than grilse and MSW (Tukey $p > 0.05$). There was no significant effect of discharge ($p > 0.05$), although there was a trend for lower mortality with higher discharge for grilse (Figure 1). The interaction between discharge and total length was also not significant ($p > 0.05$). For smolts, the predictions from the blade strike model were in line with the regression estimates over the range of discharges investigated in this study (84–255 $m^3 s^{-1}$) (Figure 1). However, the predictions deviated substantially for grilse and MSW, underestimating both groups of fish over the entire range of discharges, and did not capture the decrease in mortality with higher discharge shown by the grilse (Figure 1).

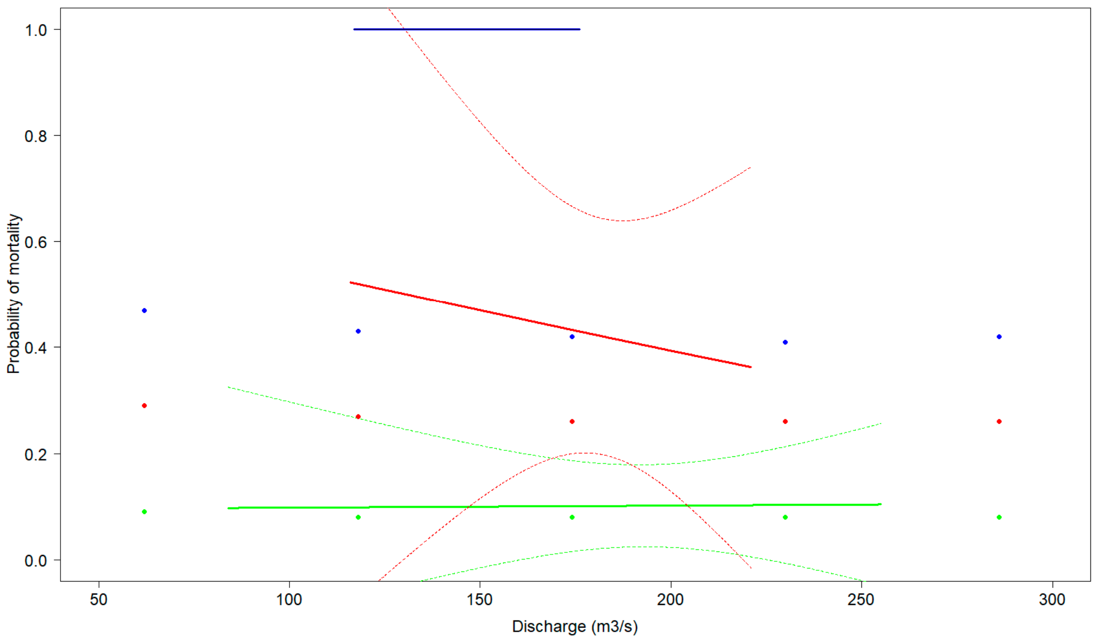

Figure 1. Probability of mortality in relation to the discharge (m^3 s^{-1}) through the turbine for smolts (green line), grilse (red line), and multi seawinter salmon (blue lines) passing through Francis turbines. The lines represent estimates ± 95% confidence bands from logistic regression using observed data from telemetry studies. Points represent predicted mortalities from the blade strike model based on fish's total length (15, 50, and 80 cm) and discharges (62, 118, 174, 230, and 286 m^3 s^{-1}).

4. Discussion

In this study, we showed that commonly used deterministic blade strike models developed for Kaplan and Francis turbines provide reliable estimates of mortality for juvenile salmon and trout, as evaluated using telemetry. Although the variation in the estimates were large, the model values were in accordance with the observed values within 1% for Kaplan and 3% for Francis. No distinct bias in either over or underestimating mortality could be detected. The results are in line with that of Deng et al. [22], who found that predictions from both deterministic and stochastic blade strike models were comparable within a few percent with empirical data of blade strike probabilities from a prototype-scale study of juvenile salmonids passing through a large Kaplan turbine in a dam in Colombia River, US. Interestingly, Fergusson et al. [24] found estimates from the same deterministic blade strike model used in this study to substantially underestimate the mortality of juvenile salmon passing through a large Kaplan turbine in a dam in the river Piteälven, Sweden, compared to the mortality observed from telemetry (8.6% modeled vs. 19.2% observed). They ascribed this bias to confounding factors attributing to non-strike causes of mortality (e.g., shear), outlet tunnel passage, and mortality occurring below the power station due to predation, for example. Fergusson et al. [24] did, however, find high agreement (<2% bias) with the model predictions and empirical observation of mortality for juvenile Atlantic salmon passing through Francis turbines in the river Umeälven, Sweden. The fact that the blade strike models in our study succeeded in predicting the mortality of smolt suggests that injury by rotating turbine blades is the main cause of mortality for juvenile salmonids passing through Kaplan and Francis turbines at our study sites. This conclusion is particularly noteworthy for the Francis turbines at the Stornorrfors hydropower station, given the high head of the turbine, which increases the risk of barotrauma, as well as the 4 km underground tunnel that the smolt needs to navigate after passing the dam.

There was a large discrepancy between model estimates of mortality and the mortality observed from the telemetry data for adult salmon and trout passing through the Francis turbine. The model underestimated the mortality by 22.8%, and when including the fish that were not detected downstream from the dam, the model failed to predict mortality by almost 50%. Given their larger size, adults were more likely to be hit by the turbine blades compared to smolts [17,32], something that is supported by comparing reported turbine mortalities for salmonid kelts with that of smolts [24,33]. Despite the higher mortality, there are very few studies evaluating the performance of blade strike models for adult salmonids. Such validation studies are needed, as they provide information about the usefulness and reliability of blade strike models as a management tool for iteroparous salmonid populations, as well as shedding light on the relative importance of blade collisions as a mortality factor for adult fish during turbine passage. In concurrence with our results, Fergusson et al. [24] found the deterministic blade strike model to substantially underestimate the mortality of adult salmon and trout passing the Francis turbine in Stornorrfors, river Umeälven (32.5% modeled vs. 69% observed). The results from our study and from Fergusson et al. [24] hence suggest that there are additional factors contributing to mortality that are not accounted for by the current blade strike models. Fish orientation relative to the leading edge of the runner blades will influence the probability of a collision and has been highlighted as a factor generating uncertainties in blade strike modeling [22,23]. As information on fish orientations is seldom readily available, the variable is difficult to parameterize in deterministic models, and, hence, is assumed to be perpendicular to the runner blades [9]. This maximizes the risk of collision, and hence generates maximized mortality estimates [34]. As the models in this study substantially underestimated the observed mortality, this suggests that fish orientation did not play a major part in creating the bias.

Although blade strikes have consistently been found as an important factor for injury and death [9,10,34,35], other factors, such as barotrauma resulting from rapid decreases in pressure when a fish passes through the head and turbines and shear stress, also contribute to mortality [35–37]. The high head of the Francis turbines at Stornorrfors expose the fish to a potential rapid pressure change as they drop 75 m into the turbines. In an experimental setup, Brown et al. [38] modeled the probability of mortal injury for juvenile Chinook salmon (*Oncorhynchus tshawytscha*) as a function of rapid pressure change along a range of ratios of acclimation (initial pressure) to the nadir pressure (lowest pressure observed during one "run" through the turbine given all the operational characteristics at that time of passage). Applying this function to the fish passing through Stornorrfors in our study will predict >90% mortality for fish entering the turbine intake close to the surface (which both smolt and adults tend to do [39]). Although this clearly overestimates the mortality based on our observed telemetry data, it still suggests barotrauma to be a potentially important factor contributing to the bias between the model and observed data seen in this study. It does not, however, explain the large discrepancy in model performance between smolt and adults.

A potential explanation for the difference in model accuracy between smolt and adults could be that the adult fish were in poor health compared to the smolt, and, hence, were less able to handle the physical stress during the turbine passage. Since 2014, many salmon populations in the Baltic Sea have had an increasing number of sick and weak adult pre-spawning fish ascending the rivers that show signs of secondary infections and ulcerations in the skin. The population in this study (river Umeälven/Vindelälven) is one of the hardest hit among the Baltic salmon rivers (Vikström et al. in prep or Axén et al. [31]). This likely explains the high proportion of fallbacks of tagged adult fish seen in this study. The cause for the symptoms is yet unknown, but it is clear that salmon smolts, as well as adult and juvenile sea run brown trout, do not show signs of this syndrome or disease [30]. Although this is an urgent and potentially catastrophic issue for the conservation of Atlantic salmon in the Baltic Sea, it does not convincingly explain the poor performance of the model, as brown trout adults in this study still experienced higher mortality than predicted by the model. Furthermore, a decade before the first signs of the disease appeared in the river Umeälven, Fergusson et al. [24] reported a similar substantial underestimation of adult mortality in Stornorrfors, as seen in this study (described above). Still, as primary symptoms appear to be skin infections, the syndrome may affect the proportion of fish receiving mortal injury during passage—e.g., by being more susceptible to shear stress and collisions.

The high mortality seen for adults in this study is in line with a study by Östergren and Rivinoja [40], who found 69% passage mortality for radio tagged sea trout through Francis turbines, and with Nyqvist et al. [39], who reported 62% mortality for radio tagged kelts passing through Kaplan turbines. The fact that not a single MSW fish over 70 cm (from Group 2) survived the passage in our study is concerning and suggests that high-head Francis turbines are not compatible with repeated spawners of multi seawinter fish. This fact may have implications in the long run for the selection of life histories in these systems, favoring grilse to large MSW [41]. The low mortality seen for smolts in this study were lower than reported by other similar studies. In a comparable study, Calles and Greenberg [42] found 11% mortality for Brown trout smolt passing through Kaplan turbines, and 35% for smolts through Francis turbines. These discrepancies could be due to the higher load capacity (i.e., large turbines) used in our study. That 100% of the smolt survived the passage through the Kaplan turbines in our study is noteworthy and should play into the discussion about the need for downstream mitigation efforts around similar HEP facilities.

5. Conclusions

This study is one of very few applying high-resolution telemetry to ground truth mortality estimates from blade strike models, taking into account the ambient water flow at the time of passage. We have shown that a commonly used deterministic blade strike model is a useful management tool for estimating turbine mortality for juvenile salmon and trout passing both Kaplan and Francis turbines, even for complex station designs with high heads, such as the Stornorrfors station. We have also shown that the same model performs poorly when predicting the mortality of adult fish passing through Francis turbines, and, hence, conclude that other tools, such as computational fluid dynamics (CFD) modelling or an autonomous sensor device (Sensor Fish) [35,43], are likely more suitable when making inferences on turbine loss for large salmonids. Furthermore, we conclude that blade collision is a major cause of mortality for smolts during turbine passage, but that other factors substantially contribute to the mortality for adults.

The study also provides much needed management data on the mortality of smolts and adults of Atlantic salmon related to passing through large turbines in big rivers. It is worth noting that up to 80% of the adult salmon and trout in this study were lost prematurely as a direct consequence of having to navigate past the power station. Given the potential importance of repeated spawners in iteroparous salmonid populations, especially in the face of the high post-smolt mortality seen in Baltic salmons [44], it is important that we fully understand the magnitude and underlying causes of this mortality. Another important aspect to consider is delayed mortality associated with turbine passage. In contrast to Fergusson et al. [45], we found no effect of delayed mortality on survival during the time of our experiment, although we cannot exclude the possibility that individuals died from turbine related injuries after entering the sea. Future work should focus on disentangling and quantifying the various mortality components involved in the turbine loss of adult salmonid, as well as potential sub-lethal effects derived from turbine passage, and use this knowledge to expand existing blade strike models for improved accuracy. Furthermore, although the study provides valuable input into our understanding of the accuracy and usefulness of blade strike models, more studies are needed to confirm the general validity of these management tools, especially as passage mortality may be highly context-dependent between different HEP complexes.

Author Contributions: Conceptualization, L.V., K.L., G.H. and O.C.; methodology, K.L., L.V. and G.H.; software, L.V., K.L. and G.H.; validation, L.V., G.H. and K.L.; formal analysis, K.L., L.V. and G.H.; investigation, L.V., J.L., S.S.; data curation, L.V., J.L.; writing—original draft preparation, L.V.; writing—review and editing, L.V., K.L., G.H., J.L., S.S. and O.C.; supervision, K.L. and G.H.; funding acquisition, G.H. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the Swedish Energy Agency program HÅVA (2019-005544).

Acknowledgments: A special thanks to the hydropower companies and especially Åke Forssen, head of the Vattenfall AB hatchery in Norrfors, and Marco Blixt, Fisheries Manager at Fortum Sverige AB, for providing data for analysis. We are grateful for the help provided by the technical personnel at the Department of fish, wildlife and environmental studies, the Swedish University of Agricultural Science in Umeå; Annika Holmgren, Bo-Sören Wiklund, and Mikael Marberg.

Conflicts of Interest: This paper contains no conflict of interest. The funders took no part in the design of the study, data collection, and analysis, interpretation of data, or writing or submitting of the manuscript.

References

1. Bevelhimer, M.; Pracheil, B.M.; Fortner, A.M.; Saylor, R.; Deck, K.L. Mortality and injury assessment for three species of fish exposed to simulated turbine blade strike. *Can. J. Fish. Aquat. Sci.* **2019**, *76*, 2350–2363. [CrossRef]
2. Silva, A.T.; Lucas, M.C.; Castro-Santos, T.; Katopodis, C.; Baumgartner, L.J.; Thiem, J.D.; Aarestrup, K.; Pompeu, P.S.; O'Brien, G.C.; Braun, D.C.; et al. The future of fish passage science, engineering, and practice. *Fish Fish.* **2017**, *19*, 340–362. [CrossRef]
3. Pracheil, B.M.; DeRolph, C.R.; Schramm, M.P.; Bevelhimer, M.S. A fish-eye view of riverine hydropower systems: The current understanding of the biological response to turbine passage. *Rev. Fish Boil. Fish.* **2016**, *26*, 153–167. [CrossRef]
4. Calles, O.; Olsson, I.C.; Comoglio, C.; Kemp, P.S.; Blunden, L.; Schmitz, M.; Greenberg, L.A. APPLIED ISSUES: Size-dependent mortality of migratory silver eels at a hydropower plant, and implications for escapement to the sea. *Freshw. Boil.* **2010**, *55*, 2167–2180. [CrossRef]
5. Heisey, P.G.; Mathur, D.; Phipps, J.L.; Avalos, J.C.; Hoffman, C.E.; Adams, S.W.; De-Oliveira, E. Passage survival of European and American eels at Francis and propeller turbines. *J. Fish Boil.* **2019**, *95*, 1172–1183. [CrossRef]
6. Deng, Z.; Carlson, T.J.; Duncan, J.P.; Richmond, M.C.; Dauble, D.D. Use of an autonomous sensor to evaluate the biological performance of the advanced turbine at Wanapum Dam. *J. Renew. Sustain. Energy* **2010**, *2*, 053104. [CrossRef]
7. Colotelo, A.H.; Goldman, A.E.; Wagner, K.A.; Brown, R.S.; Deng, Z.; Richmond, M.C. A comparison of metrics to evaluate the effects of hydro-facility passage stressors on fish. *Environ. Rev.* **2017**, *25*, 1–11. [CrossRef]
8. Montén, E. *Fish and Turbines: Fish Injuries During Passage Through Power Station Turbines*; Norstedts Tryckeri: Stockholm, Sweden, 1985; pp. 1–111.
9. Von Raben, K. Regarding the Problem of Mutilations of Fishes by Hydraulic Turbines. *Wasserwirtschaft* **1957**, *4*, 97–100.
10. Turnpenny, A.W. Mechanisms of fish damage in low head turbines: An experimental appraisal. In *Fish Migration and Fish Bypasses*; Fishing News Books: Farnham, UK, 1998.
11. Van Esch, B.P.M.; Spierts, I. Validation of a model to predict fish passage mortality in pumping stations. *Can. J. Fish. Aquat. Sci.* **2014**, *71*, 1910–1923. [CrossRef]
12. Skalski, J.R.; Mathur, D.; Heisey, P.G. Effects of Turbine Operating Efficiency on Smolt Passage Survival. *N. Am. J. Fish. Manag.* **2002**, *22*, 1193–1200. [CrossRef]
13. Cada, G.F. The Development of Advanced Hydroelectric Turbines to Improve Fish Passage Survival. *Fish* **2001**, *26*, 14–23. [CrossRef]
14. Ruggles, C.; Palmeter, T. *Fish Passage Mortality in a Tube Turbine*; Fisheries and Oceans: Ottawa, ON, Canada, 1989.
15. Larinier, M.; Travade, F. Downstream Migration: Problems and Facilities. *Bull. Français Pêche Piscicult.* **2002**, *364*, 181–207. [CrossRef]
16. Larinier, M. Fish passage experience at small-scale hydro-electric power plants in France. *Hydrobiologia* **2008**, *609*, 97–108. [CrossRef]
17. Coutant, C.C.; Whitney, R.R. Fish Behavior in Relation to Passage through Hydropower Turbines: A Review. *Trans. Am. Fish. Soc.* **2000**, *129*, 351–380. [CrossRef]
18. Bell, M.C. *Revised Compendium on the Success of Passage of Small Fish Through Turbines*; Report to the U.S. Army Corps of Engineers, North Pacific Division: Portland, OR, USA, 1991.

19. Turnpenny, A.W.; Clough, S.; Hanson, K.P.; Ramsey, R.; McEwan, D. *Risk Assessment for Fish Passage Through Small Low-Head Turbines*; Atomic Energy Research Establishment: Harwell, UK, 2000.
20. Pavlov, D.S.; Lupandin, A.I.; Kostin, V. *Downstream Migration of Fish Through Dams of Hydroelectric Power Plants. Oak Ridge National Laboratory Oak Ridge*; Nauka: Moscow, Russia, 1999.
21. Ploskey, G.R.; Carlson, T.J. *Comparison of Blade-Strike Modeling Results with Empirical Data*; EERE Publication and Product Library: Washington, DC, USA, 2004.
22. Deng, Z.D.; Carlson, T.J.; Ploskey, G.R.; Richmond, M.C.; Dauble, D.D. Evaluation of blade-strike models for estimating the biological performance of Kaplan turbines. *Ecol. Model.* **2007**, *208*, 165–176. [CrossRef]
23. Deng, Z.; Carlson, T.J.; Dauble, D.D.; Ploskey, G.R. Fish passage assessment of an advanced hydropower turbine and conventional turbine using blade-strike modeling. *Energies* **2011**, *4*, 57–67. [CrossRef]
24. Ferguson, J.W.; Ploskey, G.R.; Leonardsson, K.; Zabel, R.W.; Lundqvist, H. Combining turbine blade-strike and life cycle models to assess mitigation strategies for fish passing dams. *Can. J. Fish. Aquat. Sci.* **2008**, *65*, 1568–1585. [CrossRef]
25. Solomon, D.J. *Fish Passage through Tidal Energy Barrages*; Energy Technology Support Unit: Edinburgh, UK, 1988.
26. Halttunen, E. Staying Alive: The Survival and Importance of Atlantic Salmon Post-Spawners. Ph.D. Thesis, University of Tromsø, Tromsø, Norway, 19 August 2011.
27. Fu, T.; Deng, Z.D.; Duncan, J.P.; Zhou, D.; Carlson, T.J.; Johnson, G.E.; Hou, H. Assessing hydraulic conditions through Francis turbines using an autonomous sensor device. *Renew. Energy* **2016**, *99*, 1244–1252. [CrossRef]
28. Leonardsson, K. *Modellverktyg för Beräkning av Ålförluster vid Vattenkraftverk*; ELFORSK-Rapport; Finns att hämta på ELFORSK: Stockholm, Sweden, 2012.
29. Saylor, R.; Sterling, D.; Bevelhimer, M.; Pracheil, B.M. Within and Among Fish Species Differences in Simulated Turbine Blade Strike Mortality: Limits on the Use of Surrogacy for Untested Species. *Water* **2020**, *12*, 701. [CrossRef]
30. Axén, C.; Koski, P. *Laxdöden i Torneälven Lohikuolemat Tornionjoella Salmon Deaths in Torne river 2014—2016*; Report of a Swedish-Finnish Survey; Havs-och Vattenmyndigheten: Göteborg, Sweden, 2017; p. 92.
31. Axén, C.; Sturve, J.; Weichert, F. *Fortsatta Undersökningar av Laxsjuklighet under 2018*; Report of Continued Surveys 2018; Havs-och Vattenmyndigheten: Göteborg, Sweden, 2019; p. 43.
32. Bevelhimer, M.S.; Pracheil, B.M.; Fortner, A.M.; Deck, K.L. *An Overview of Experimental Efforts to Understand the Mechanisms of Fish Injury and Mortality Caused by Hydropower Turbine Blade Strike*; Oak Ridge National Lab: Oak Ridge, TN, USA, 2017.
33. Östergren, J. Migration and Genetic Structure of Salmo Salar and Salmo Trutta in Northern Swedish Rivers. Ph.D. Thesis, Faculty of Forest Sciences, Uppsala, Sweden, December 2006.
34. Deng, Z.; Carlson, T.J.; Ploskey, G.R.; Richmond, M.C. *Evaluation of Blade-Strike Models for Estimating the Biological Performance of Large Kaplan Hydro Turbines*; Pacific Northwest National Lab: Richland, WA, USA, 2006.
35. Klopries, E.-M.; Schüttrumpf, H. Mortality assessment for adult European eels (Anguilla Anguilla) during turbine passage using CFD modelling. *Renew. Energy* **2020**, *147*, 1481–1490. [CrossRef]
36. Brown, R.S.; Colotelo, A.H.; Pflugrath, B.D.; Boys, C.; Baumgartner, L.J.; Deng, Z.; Silva, L.G.; Brauner, C.J.; Mallen-Cooper, M.; Phonekhampeng, O.; et al. Understanding Barotrauma in Fish Passing Hydro Structures: A Global Strategy for Sustainable Development of Water Resources. *Fish* **2014**, *39*, 108–122. [CrossRef]
37. Čada, G.; Loar, J.; Garrison, L.; Fisher, R.; Neitzel, D. Efforts to Reduce Mortality to Hydroelectric Turbine-Passed Fish: Locating and Quantifying Damaging Shear Stresses. *Environ. Manag.* **2006**, *37*, 898–906. [CrossRef] [PubMed]
38. Brown, R.S.; Carlson, T.J.; Gingerich, A.J.; Stephenson, J.R.; Pflugrath, B.D.; Welch, A.E.; Langeslay, M.J.; Ahmann, M.L.; Johnson, R.L.; Skalski, J.R.; et al. Quantifying Mortal Injury of Juvenile Chinook Salmon Exposed to Simulated Hydro-Turbine Passage. *Trans. Am. Fish. Soc.* **2012**, *141*, 147–157. [CrossRef]
39. Nyqvist, D.; Bergman, E.; Calles, O.; Greenberg, L. Intake Approach and Dam Passage by Downstream-migrating Atlantic Salmon Kelts. *River Res. Appl.* **2017**, *33*, 697–706. [CrossRef]
40. Östergren, J.; Rivinoja, P. Overwintering and downstream migration of sea trout (*Salmo trutta* L.) kelts under regulated flows—Northern Sweden. *River Res. Appl.* **2008**, *24*, 551–563. [CrossRef]

41. De Leaniz, C.G.; Fleming, I.A.; Einum, S.; Verspoor, E.; Jordan, W.C.; Consuegra, S.; Aubin-Horth, N.; Lajus, D.L.; Letcher, B.H.; Youngson, A.F.; et al. A critical review of adaptive genetic variation in Atlantic salmon: implications for conservation. *Boil. Rev.* **2007**, *82*, 173–211. [CrossRef]
42. Calles, O.; Greenberg, L. Connectivity is a two-way street-the need for a holistic approach to fish passage problems in regulated rivers. *River Res. Appl.* **2009**, *25*, 1268–1286. [CrossRef]
43. Martinez, J.; Deng, Z.D.; Titzler, P.; Duncan, J.; Lu, J.; Mueller, R.; Tian, C.; Trumbo, B.; Ahmann, M.; Renholds, J. Hydraulic and biological characterization of a large Kaplan turbine. *Renew. Energy* **2019**, *131*, 240–249. [CrossRef]
44. Ices Baltic Salmon and Trout Assessment Working Group. Available online: https://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/Fisheries%20Resources%20Steering%20Group/2019/WGBAST/wgbast_2019.pdf (accessed on 30 June 2020).
45. Ferguson, J.W.; Absolon, R.F.; Carlson, T.J.; Sandford, B.P. Evidence of Delayed Mortality on Juvenile Pacific Salmon Passing through Turbines at Columbia River Dams. *Trans. Am. Fish. Soc.* **2006**, *135*, 139–150. [CrossRef]