Updated mortality estimation formulae for salmonids passings through Francis turbines at hydropower plants

Sylvie Tomanova, Dominique Courret, Blaise Tymen, Sylvain Richard, Lionel Dumond, Pierre Sagnes

Knowl. Manag. Aquat. Ecosyst. 2023, 424, 6
© S. Tomanova *et al.*, Published by EDP Sciences 2023
https://doi.org/10.1051/kmae/2023001

www.kmae-journal.org

Knowledge & Management of Aquatic Ecosystems

Journal fully supported by Office français de la biodiversité

SHORT COMMUNICATION

OPEN ACCESS

Updated mortality estimation formulae for salmonids passing through Francis turbines at hydropower plants

Sylvie Tomanova[1,2,*], Dominique Courret[1,2], Blaise Tymen[2,3], Sylvain Richard[2,4], Lionel Dumond[3] and Pierre Sagnes[1,2]

[1] Office français de la biodiversité, Direction de la recherche et de l'appui scientifique, Toulouse, France
[2] Pôle R&D écohydraulique, OFB-IMFT-PPRIME, Toulouse, France
[3] EDF CIH, Pôle Énergies Renouvelables, Toulouse, France
[4] Office français de la biodiversité, Direction de la police et du permis de chasser, Service prévention appui prospective, Toulouse, France

Received: 8 November 2022 / Accepted: 10 January 2023

Abstract – Downstream migrating fish can be strongly affected by hydroelectric facilities. To set up adapted mitigation measures, it is important to identify these impacts (*e.g.* induced mortality rates). For Francis turbines, two mortality prediction formulas, developed in 1989 and updated in 2000, are currently used in France for salmonids according to turbine characteristics and fish size (Larinier and Dartiguelongue, 1989, updated by Bosc and Larinier, 2000). However, their use is limited when some parameters are unknown, such as turbine speed. Moreover, the updated version of can be criticized because of its unpublished development procedure and its unknown predictive power. The main purpose of this study is to update the existing formulae to meet the following objectives: (1) a transparent development procedure, (2) formulae simplification, (3) the use of simple (usually the best-known) turbine parameters, and (4) a maximization of the predictive power and an assessment of prediction errors. Based on data from 73 *in situ* mortality tests available in peer-reviewed and 'grey' literature, we developed two new formulae to estimate salmonid mortality rate in Francis turbines. The first one uses turbine peripheral speed, diameter and fish size (correlation between predicted and observed mortality rates $r = 0.89$, and root mean square error RMSE = 0.11). The second one is based on usually known parameters: turbine discharge, water head and fish size, to allow a broader applicability ($r = 0.89$, RMSE = 0.10). This study comforts the validity of previous formulae and provides two new ones allowing a satisfactory precision in the estimations.

Keywords: Renewable energy / fish / downstream migration / impact prediction

1 Hydropower and mortality predicting formulae for Francis turbines

One of the main environmental impacts of hydropower development is related to fish upstream and downstream passage (Larinier, 1998; Therrien and Bourgeois, 2000). If unprotected by diversion systems, fish (and especially individuals of diadromous species like salmon or eel) can suffer injury or death by passing through turbines at hydroelectric plants during their migration to the sea (EPRI, 1987). An accurate quantification of fish mortality rates is necessary to set up efficient protection measures. However, establishing such relationships generally requires costly, time- and fish-consuming studies implying fish injection into the turbines and their recapture (alive and dead individuals) downstream (see list of studies in Suppl. Material). In comparison, the use of predictive formulae to roughly estimate fish mortality is much less expensive and doesn't require animal sacrifices. In France, two fish mortality predicting formulae are used for the estimation of salmonids mortality in Francis turbines (Larinier and Dartiguelongue, 1989; Bosc and Larinier, 2000), which are the most widely installed hydro turbines in the world (IRENA, 2012) and among the most installed on the migration routes of amphidromous species in France (Briand *et al.*, 2015). These formulae are based on findings from field trials conducted at several hydroelectric facilities around the world but both have been criticized for reasons pointed here below.

The historically first one, from Larinier and Dartiguelongue (1989), hereafter called LD1989, is:

$$M = [\sin(6.54 + 0.218 * H + 118 * L_m - 3.88 * D + 0.0078 * N)]^2$$

*Corresponding author: sylvie.tomanova@ofb.gouv.fr

with M – fish mortality ranging between 0 (no mortality) and 1 (100% of mortality), H – water head (m), L_m – fish length (m), D –turbine diameter (m), N – turbine rotation speed (rotations per minute, rpm). The main difficulty for using this formula is that the turbine rotation speed is frequently unknown.

The second formula (hereafter called BL2000) was determined by Bosc and Larinier (2000):

$$M = [\sin(-17.98 + 45.62 * H^{0.181} * D^{-0.207} * L_m{}^{0.224})]^2.$$

However, the authors did not present the methodology used for the formula development nor its predictive power, and did not determine whether it resulted in improvements, with respect to LD1989 formula.

From a practical point of view, the application of any of these formulae in impact studies resulted in frequent errors in mortality estimations, for example if the sinus transformation was incorrectly computed (*e.g.* in degrees instead of radians). For these reasons, we decided to update the existing formulae to meet the following objectives: (1) a transparent development procedure, (2) formulae simplification, (3) the use of simple (usually the best-known) turbine parameters, and (4) a maximization of the predictive power and an assessment of prediction errors.

2 Review of existing field mortality studies

We conducted an extensive literature review on fish mortality studies in Francis turbines, performed on various hydroelectric facilities, mainly in the United States and Europe. Only the studies using an injection/recapture method were selected. This method was the most widely used and was considered precise enough to asses fish mortality in turbines (as recommended in Baran and Courret, 2013). Basic data allowing mortality estimation for salmonids were compiled into a database (available in Suppl. Material), where each row contains empirical data from a mortality test on a Francis turbine (of different diameter, head, discharge) and under a given running operation type (rotation speed). The collected fish experimental data were: tested species, fish length, number of fish injected and recaptured in test and control groups, number of recaptured fish dying immediately after the test, and 24 or 48 h after. Replicated tests on the same site under similar conditions (same species, fish length, same turbine and operation type) were pooled together. All studies were checked for their credibility in terms of study execution, completeness of work and data quality (coherence of reported turbine dimensions and coherence of test mortality results related to control mortality). Doubtful data were eliminated as we preferred to increase the data quality rather than their quantity. The final database included the data from 73 field studies.

3 Standardization of mortality rate computation

Using these basic data, fish mortality was recomputed to homogenize the mortality estimates among the selected studies. We used Bell's formula (1981) employing control survival rate (S_{control}, measuring the mortality related to fish handling) to adjust observed test survival (S_{test}), and then obtained the mortality only due to turbine passage, as follows:

$$\text{Mortality} = 1 - \frac{S\_\text{test}}{S\_\text{control}}.$$

Two mortality computations were applied depending on the data available in the published study. In the first case (type 1), if the numbers of released fish in test and control groups were available, the mortality was computed as follows:

$$\text{Mortality 1} = 1 - \frac{(R_t - d_t) \times R_c}{R_t \times (R_c - d_c)}$$

with d_t and d_c: number of dead fish recaptured in test and control groups, respectively, either 48 h after experimentation, or if not available, 24 h or immediately after experimentation; R_t and R_c: number of released fish in test and control groups, respectively.

This mortality computation assumes that after their passage through the turbine, all uncaptured fish are still alive and all dead fish are recaptured. Even if this assumption is likely to be too optimistic, this approach was adopted for the development of LD1989 and BL2000 formulae as there were no reliable means to determine the probability of dead fish recapture among studies.

In a second case (type 2), if the numbers of fish released in test and control groups were not available, the mortality rate computation was only possible from the number of recaptured fish, assuming a same proportion of dead and alive individuals between captured and uncaptured fish, as follows:

$$\text{Mortality 2} = 1 - \frac{s_t \times (s_c + d_c)}{s_c \times (s_t + d_t)}$$

with s_t and s_c number of live fish recaptured in test and control group, respectively, either 48 h after experimentation, or if not available, 24 h or immediately after experimentation.

Mortality rates range from 0 (no fish damage) to 1 (all fish dead). The data available from the 73 studies of our database allowed for the calculation of 47 Mortality rates of type 1 and 14 Mortality rates of type 2. For the remaining 12 tests, only the original published mortality rates (with frequently unknown mortality computation method) could be included in the database.

4 Candidate explanatory variables

All the turbine parameters considered were correlated to observed fish mortality (Fig. 1). Their strong inter-correlation excluded their simultaneous use as explanatory variables in predictive mortality formulae. Previous studies (EPRI, 1987; Larinier and Dartiguelongue, 1989; Bosc and Larinier, 2000) demonstrated the importance of different turbine parameters on fish mortality. Therefore, we first combined turbine peripheral speed U (m/s, usually computed as: $U = \pi * D * N/60$) and turbine diameter D (m) (two variables with low inter-correlation) with fish length L (mm, a parameter reflecting different ontogenetic stages), to build a first model, hereafter called the "UDL" type model. According to our objective 2

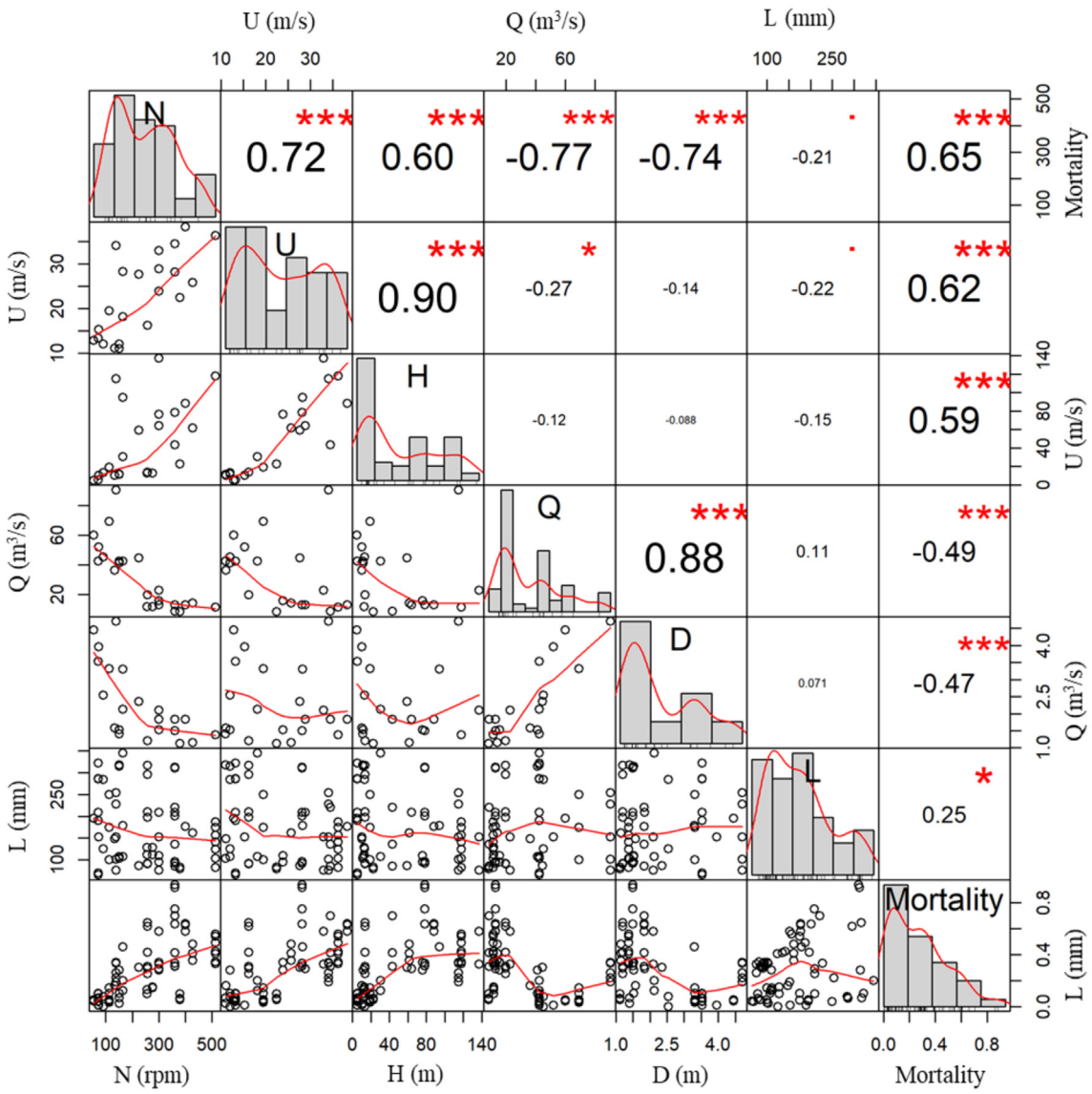

Fig. 1. Candidate explanatory variables, their inter-correlations and relations to salmonids mortality resulting from collected data (N – rotation speed (rpm), U – peripheral speed (m/s), H – water head (m), Q – nominal discharge (m^3/s), D – diameter (m), L – fish length (mm) and mortality (unitless, range = 0–1)). Distribution histograms of each variable (on the diagonal), bivariate scatterplots with a fitted line (below the diagonal) and Pearson coefficients of correlation (above the diagonal) with the following significance levels: *** < 0.001; ** < 0.01, * < 0.05, ° < 0.1.

(the use of simple and usually known turbine parameters), we combined a second set of variables: turbine discharge Q (m^3/s), water head H (m) and fish length L (in mm) (variables with also low inter-correlation), to build a second model, hereafter called the "QHL" type model. This approach led to the development of two different formulae (see a description of the available dataset in Table 1). Turbine rotation speed N was not selected as a candidate explanatory variable because of its strong correlation with all other variables (Fig. 1).

5 Development and validation of new formulae

Three simple expression forms were tested for predicting models: an additive form ($M = a\text{Var1 } 6 + b\text{Var2} + cL$), a form where L is multiplied by two other variables ($M = aL$ (bVar1+cVar2)), and a multiplicative form ($M = \text{Var1}^{a}\text{Var2}^{b}L^{c}$). We used the Pearson coefficient of correlation (r) between predicted and observed mortality rates and the root mean square error (RMSE) to compare different predictive formulae. *ln* and square root transformations of explanatory variables were tested to maximize the model fit.

All tested expressions resulted in valid predicting formulae (all models with $p < 0.001$). The best expressions for both UDL and QHL formulae (with the highest r and the lowest RMSE values) were of the second form: $M = aL(b\text{Var1} + c\text{Var2})$.

The resulting formula using UDL was:

$$\text{M} = L\left(-4.714 * 10^{-4} * D + 1.035 * 10^{-4} * \text{U}\right) + 7.841 * 10^{-2}$$

($r = 0.89$, RMSE = 0.11, $p < 0.05$ for intercept and all coefficients).

Table 1. Description of the dataset used for UDL and QHL formulae development: U – peripheral speed (m/s), D – diameter (m), Q – nominal discharge (m^3/s), H – water head (m), L – fish length (mm).

	U (m/s)	D (m)	Q (m^3/s)	H (m)	L (mm)
Min.	11.0	1.1	8.2	5.0	65.5
1st quartile	16.2	1.4	12.7	12.8	101.0
Median	22.5	1.8	19.7	22.6	157.0
Mean	23.8	2.3	32.9	49.7	168.0
3rd quartile	34.1	3.3	43.1	78.6	209.5
Max.	38.3	4.7	90.6	137.0	345.0

The expression using QHL was:

$$M = L\left(-2.522 * 10^{-4} * \sqrt{Q} + 7.762 * 10^{-4} * \ln(H)\right) + 8.382 * 10^{-2}$$

($r = 0.89$, RMSE = 0.10, $p < 0.01$ for intercept and all coefficients).

Both new UDL and QHL formulae showed a high prediction power and a strong relationship between observed and predicted values along with low RMSE values (Fig. 2). The previous predicting formulae (LD1989 and BL2000) had also good fits to the collected data (albeit with slightly lower r and higher RMSE values), indicating the possible use of a similar dataset for their development. In the new UDL and QHL formulae, some remaining unexplained variability (RMSE between 0.10 and 0.11) is not really surprising because (1) different methods were used for mortality computation (type 1 or 2 or values from original publication without details on computational methods) and (2) unexplained variability often occurs even using closely controlled experiments (Bell, 1981; EPRI, 1987).

The new formulae without sinus-transformation (a transformation applied in LD1989 and BL2000, resulting in frequent errors during application), could produce negative mortality rates (see Fig. 2) or values higher than 1. In these cases, the mortality estimates must be rounded to 0 and 1 respectively.

In order to quantify the strength of the relationship between the four predicting formulae (LD1989, BL2000, UDL and QHL), we used simple linear regressions. We considered that two formulae produced similar results if the coefficient of correlation (r) and the regression slope (a) approached 1, and the intercept (b) approached 0. All predicted mortalities, resulting from the application of different formulae, were highly correlated to each other (all coefficients of correlation with $p < 0.001$). The best correlation was detected between the new UDL and QHL formulae ($r = 0.98$, $a = 0.97$ and $b = 0$) indicating that both expressions produce quite similar mortality estimation rates. The lowest correlation (but still with a significant relationship) was between LD1989 and both new formulae (with UDL: $r = 0.84$, $a = 0.79$, $b = 0.06$; with QHL: $r = 0.85$, $a = 0.79$, $b = 0.06$). BL2000 was highly correlated with LD1989 ($r = 0.93$, $a = 1.03$ and $b = 0$) and less correlated with both new formulae (with UDL: $r = 0.94$, $a = 0.79$, $b = 0.06$; with QHL $r = 0.95$, $a = 0.80$, $b = 0.06$). It appeared that, in comparison with new formulae, LD1989 and BL2000 slightly overestimated low mortalities and underestimated high mortalities (Fig. 3).

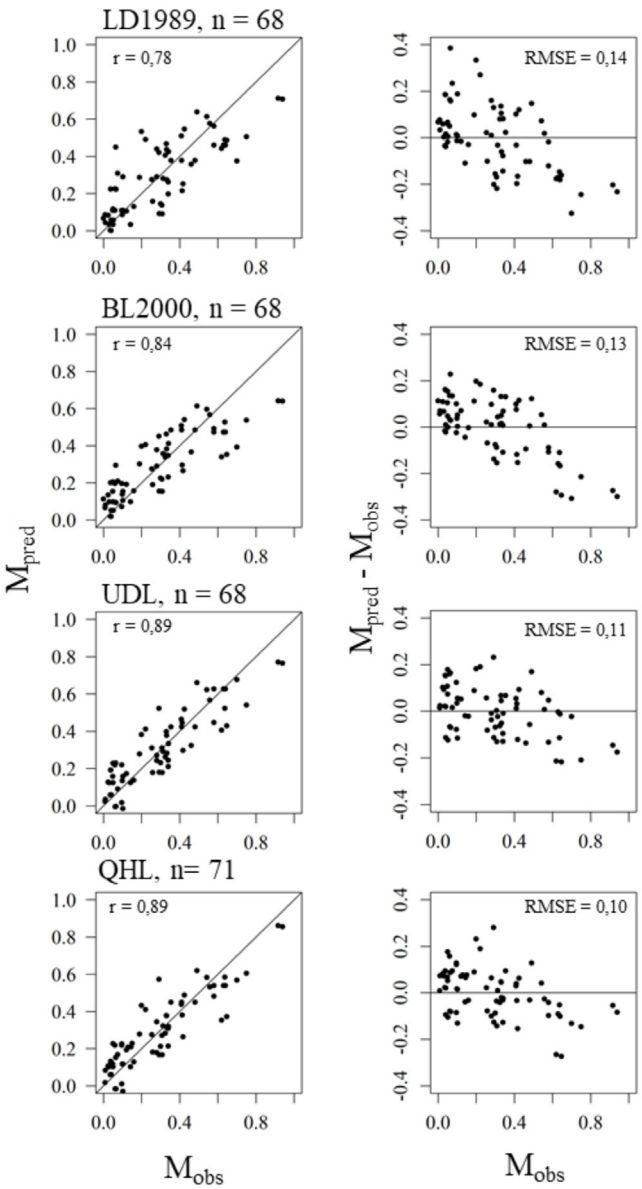

Fig. 2. Relationship between observed (M_{obs}) and predicted mortalities (M_{pred}) resulting from formulae LD1989 (Larinier and Dartiguelongue, 1989), BL2000 (Bosc and Larinier, 2000), UDL and QHL (see text), and variability of errors (difference between M_{pred} and M_{obs}) in relation to M_{obs}. r = Pearson coefficient of correlation between M_{pred} and M_{obs}, RMSE = root mean square error, straight lines on graphics represent $M_{pred} = M_{obs}$ n = number of available data.

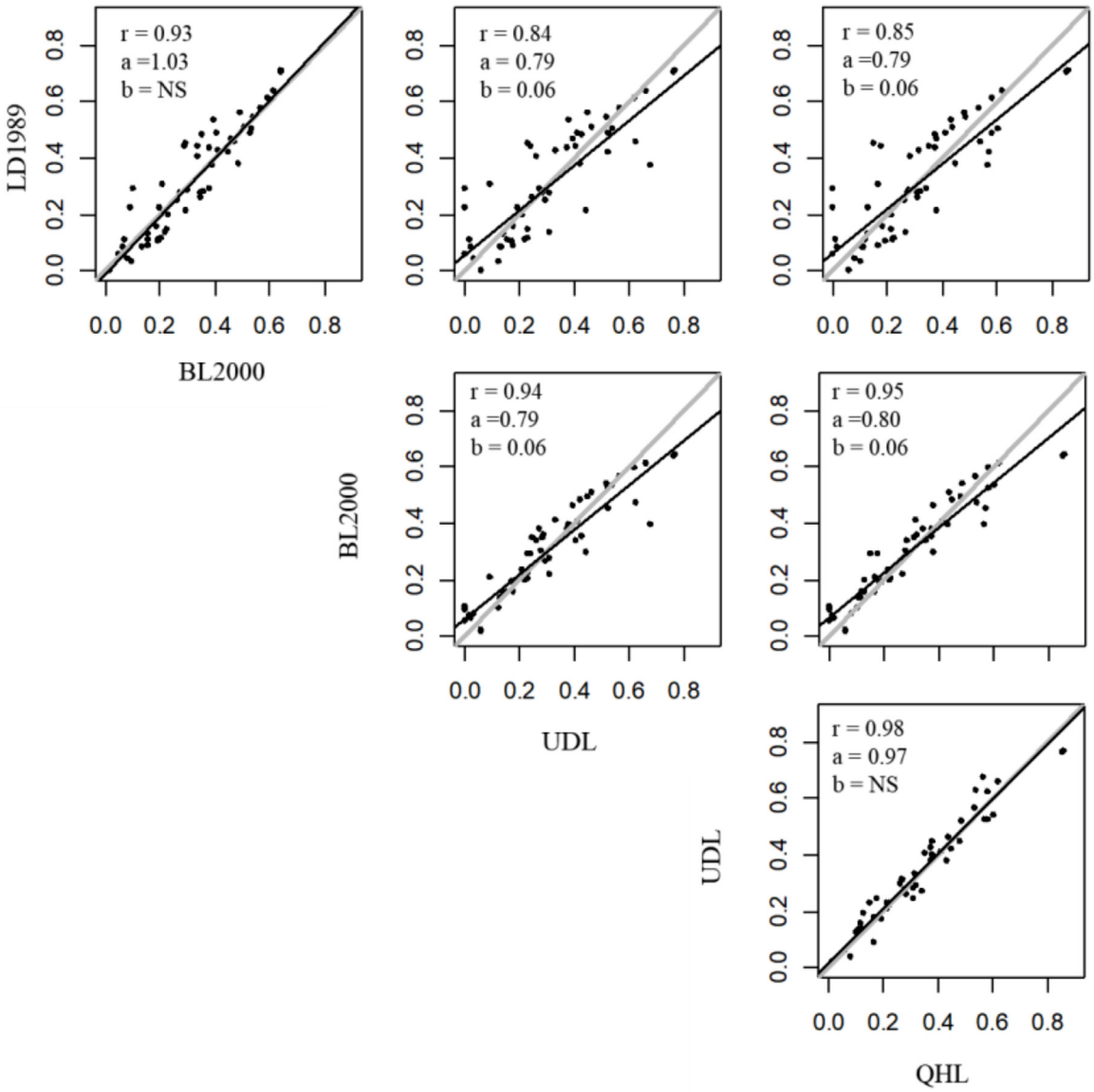

Fig. 3. Relationships between different mortality estimates resulting from different formulae LD1989 (Larinier and Dartiguelongue, 1989), BL2000 (Bosc and Larinier, 2000), UDL and QHL (see text). r = Pearson coefficient of correlation, grey lines on graphics represent $y = x$, black lines $y = a*x+b$, all p values of r, a and b were < 0.05, NS – not significant.

6 Conclusion and formulae applicability

All four initial objectives: (1) a transparent development procedure, (2) the simplification of formulae, (3) the use of simple and usually known turbine parameters, and (4) a maximization of the predictive power with assessment of prediction errors, were achieved. This study also confirms the validity of both formulae previously used (LD1989, BL2000) to estimate salmonids mortality in Francis turbines. However, the newly proposed formulae, based on UDL and QHL, better fit to the calibration dataset and are easier to apply. QHL formula uses simple and usually known turbine parameters, opening a broader scope of application. Indeed, from the available database of 355 installed Francis turbines in France, mortality rates can be estimated for only 67–68% of cases with LD1989, BL2000 and the new UDL formula (turbine parameters lack for the remaining 33–32% of cases). Using the QHL formula, the evaluation can be done for 89% of cases, bringing hence, until now, missing information about the potential ecological impacts of many installed Francis turbines.

It's important to consider that new UDL and QHL predicting formulae, so as the previous ones, probably underestimate total fish mortality. Firstly, the Mortality 1, mostly used during formulae development, is certainly a too optimistic way to compute fish mortality, as all uncaptured fish are considered alive. Secondly, available field studies usually report fish mortality between 0 and 48h after fish passage through the turbine and delayed mortality, occurring afterward (Ferguson *et al.*, 2006; Algera *et al.*, 2020; Ben Ammar *et al.*, 2020), remains unknown.

New formulae were developed using mortality tests performed on a quite wide panel of Francis turbines (Tab. 1) from many different locations in North America and Europe, and with a salmonid mean length up to 345 mm. We consider that the applicability and robustness of the formulae are good within these limits. Mortality estimations using turbine parameters or fish lengths outside of the ranges used for the formulae development is possible, but with caution because of the unknown precision of the subsequent mortality predictions. In such cases, the new UDL and QHL formulae can still be useful to roughly indicate potential ecological impacts (*e.g.* low, moderate or high). If the mortality estimation needs to be more accurate, direct mortality tests must be performed, while making sure to respect animal welfare as much as possible. Lastly, note that mortality tests also remain necessary for modified Francis turbines (*e.g.* with a modification of blades' shape), developed to minimize fish mortality or injuring.

Acknowledgements. The authors would like to thank Leah Beche for the English corrections clarifying the text, and two anonymous reviewers for their valuable comments which improved the manuscript.

Supplementary Material

Dataset used for UDL and QHL formulae development.

The Supplementary Material is available at https://www.kmae.org/10.1051/kmae/2023001/olm.

References

Algera DA, Rytwinski T, Taylor JJ, Bennett JR, Smokorowski KE, Harrison PM, Clarke KD, Enders EC, Power M, Bevelhimer MS, Cooke SJ. 2020. What are the relative risks of mortality and injury for fish during downstream passage at hydroelectric dams in temperate regions? A systematic review. *Environ Evid* 9: 3.

Baran P, Courret D. 2013. Ichtyocompatibilité de turbines hydroélectriques : définition des attentes et des protocoles de tests nécessaires. Rapport ONEMA-IRSTEA-IMFT, 15 p.

Bell MC. 1981. Updated compendium on the success of passage of small fish through turbines. Washington, D.C.: US Army Corps of Engineers, North Pacific Div.

Ben Ammar I, Baeklandt S, Cornet V, Antipine S, Sonny D, Mandiki SNM, Kestemont P. 2020. Passage through a hydropower plant affects the physiological and health status of Atlanstic salmon smolts. *Comp Biochem Physiol A Mol Integr Physiol* 247: 110745.

Briand C, Legrand M, Chapon P-M, Beaulaton L, Germis G, Arago M-A, Besse T, De Canet L, Steinbach P. 2015. Mortalité cumulée des saumons et des anguilles dans les turbines du bassin Loire-Bretagne. 260 p., Available on: https://www.migrateurs-loire.fr/download/mortalite-cumulee-des-saumons-et-des-anguilles-dans-les-turbines-du-bassin-loire-bretagne/

EPRI. 1987. Turbine Related Fish Mortality : Review and Evaluation of Studies. Final report AP-5480. Eicher Associates, Inc., 200 p.

Ferguson JW, Absolon RF, Carlson TJ, Sandford BP. 2006. Evidence of delayed mortality on juvenile pacific salmon passing through turbines at Columbia River Dams. *Trans Am Fish Soc* 135: 139–150.

IRENA. 2012. Renewable energy technologies: cost analysis series—Hydropower. Volume 1: Power Sector, Issue 3/5. International Renewable Energy Agency, 44 p.

Larinier M. 1998. Upstream and downstream fish passage experience in France. In: Jungwirth M, Schmutz S, Weiss S, eds. Fish Migration and Fish Bypasses. England: Oxford, pp. 127–145.

Therrien J, Bourgeois G. 2000. Fish Passage at Small Hydro Sites. Report by Genivar Consulting Group for CANMET Energy Technology Centre, Ottawa, 114 p.

Cite this article as: Tomanova S, Courret D, Tymen B, Richard S, Dumond L, Sagnes P. 2023. Updated mortality estimation formulae for salmonids passing through Francis turbines at hydropower plants. *Knowl. Manag. Aquat. Ecosyst.*, 424, 6.