

Injury and Mortality of Juvenile Salmon Entrained in a Submerged Jet Entering Still Water

ZHIQUN DENG,* ROBERT P. MUELLER, MARSHALL C. RICHMOND, AND GARY E. JOHNSON

Pacific Northwest National Laboratory, Post Office Box 999, Richland, Washington 99352, USA

Abstract.—Development of more eco-friendly hydroelectric facilities requires better understanding of the biological response of juvenile fish when they migrate through the turbines and other downstream passage facilities. Juvenile fall Chinook salmon *Oncorhynchus tshawytscha* were exposed to turbulent shear flows in a laboratory by using a fast-fish-to-slow-water mechanism in which test fish were carried by the fast-moving water of a submerged turbulent jet into the slow-moving water of a flume. Fish were released at six nozzle velocities: 6.1 (reference control), 12.2, 15.2, 18.3, 21.3, and 22.9 m/s. The onset of minor and major injuries occurred at 15.2 and 21.3 m/s, respectively. The acceleration magnitude threshold (m/s^2) of major injury for the fast-fish-to-slow-water mechanism in this study was found to be significantly higher than that for a slow-fish-to-fast-water mechanism used in a previous study in which test fish were introduced into a turbulent jet from slow-moving water through an introduction tube placed just outside the edge of the jet. Fish responded differently and sustained different injuries when they were subjected to turbulent shear flows under the two exposure mechanisms. This information is applicable to the design and operation of turbines and spillways because these two tested mechanisms simulate the severe hydraulic events fish usually experience during passage at hydropower dams.

Hydropower is a major source of renewable, non-carbon-based electrical energy. Although hydropower has many environmental advantages, hydropower dams alter the natural ecohydrological conditions of the rivers and cause significant ecological impact, especially for fish that live in or migrate through impounded river systems (Čada 2001; Hu et al. 2008). Injury and mortality of fish that pass through hydroelectric turbines and other downstream passage routes can result from several mechanisms, such as rapid and extreme pressure changes, shear stress, turbulence, strike, cavitation, and grinding (Coutant and Whitney 2000; Odeh and Sommers 2000). Understanding the biological responses of fish to hydraulic conditions is critical for the design of advanced fish-friendly hydroelectric facilities because fish—especially downstream-migrating juvenile salmonids—are susceptible to injury and death caused by turbulent shear flows, which are among the least understood mechanisms that injure and kill fish migrating through hydroelectric dams (Čada 2001).

Several laboratory and field studies have been conducted to develop biological criteria for acceptable passage conditions that quantify the hydraulic forces that fish can withstand based on fish injury and mortality rates. Turnpenny et al. (1992) and Turnpenny (1998) conducted experiments that simulated the

collisions between different turbine blades and fish at different approach velocities to investigate how fish size, orientation, and position relative to the blade influence fish injury and mortality. Neitzel et al. (2004) performed a laboratory study of juvenile salmonids (e.g., rainbow trout *Oncorhynchus mykiss* and Chinook salmon *O. tshawytscha*) and juvenile American shad *Alosa sapidissima* to suggest an injury–mortality threshold based on hydraulic strain rate. Johnson et al. (2003), who were specifically interested in the effects on juvenile salmon *Oncorhynchus* spp. from hydraulic conditions at high-flow outfalls ($>28.3 \text{ m}^3/\text{s}$), performed joint field and laboratory studies. Focusing on jet entry velocity as the key independent variable because it can be readily measured in the field and the laboratory, Johnson et al. (2003) determined that outfall jet entry velocities of 15.2 m/s or less into the receiving water provided benign passage conditions for the species and sizes tested. These studies determined relationships between fish injury–mortality and various hydraulic conditions; however, they did not directly address the mechanisms causing injuries and mortalities.

We conducted injury–mortality studies by using two methods of applying turbulent shear to fish: slow-fish-to-fast-water and fast-fish-to-slow-water scenarios. These studies generally characterized the flow field of turbulent shear environments and the fish motion in sufficient detail to facilitate a more fundamental understanding of the mechanics of the injury process and the dynamic variables involved. In the first study,

* Corresponding author: zhiqun.deng@pnl.gov

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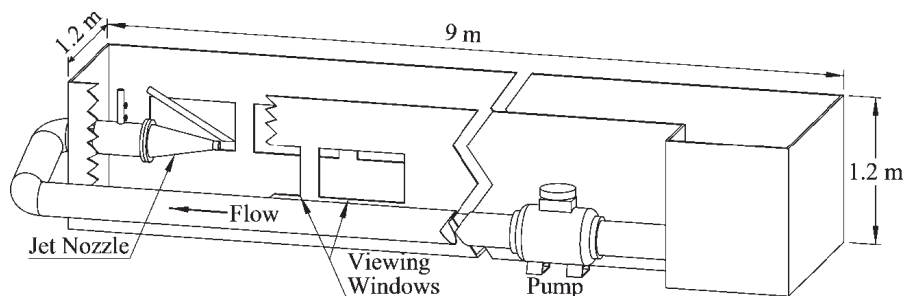


FIGURE 1.—Rectangular fiberglass flume used to expose juvenile Chinook salmon to turbulent shear in a submerged jet.

reported previously by Deng et al. (2005), hatchery-reared fall Chinook salmon (93–128 mm fork length) were actively introduced from standing water into a submerged, 6.35-cm-diameter water jet through an introduction tube. This application, termed the slow-fish-to-fast-water scenario, is typical of conditions within the turbine environment, where fish moving past turbine runners go from relatively slow to fast water. In that study, fish were exposed to seven different water jet velocities: 3.0 (reference control), 12.2, 13.7, 15.2, 16.8, 18.3, and 19.8 m/s. The onset of minor, major, and fatal injuries (10% of test fish) occurred at nozzle velocities of 12.2, 13.7, and 16.8 m/s, respectively. Three-dimensional fish trajectories were generated by using motion tracking analyses of high-speed digital videos. Time series of velocity, acceleration, force, jerk, and bending angle were then computed from the three-dimensional trajectories.

Acceleration was found to be the most predictive parameter for different fish injuries. Binomial logistic regression was used to relate the probability of specific biological responses to fish acceleration.

The objective of the second study, reported herein, was to evaluate the biological response (injury–mortality rate) of juvenile Chinook salmon subjected to turbulent shear flows under another common exposure mechanism, termed the fast-fish-to-slow-water scenario. This scenario is common where high-velocity outfall or spillway jets enter low-velocity tailwaters. For this mechanism, juvenile Chinook salmon were introduced into the flows upstream of the jet, were carried by the fast-moving water of the submerged turbulent jet, and were then exposed to the standing water of a test flume.

Methods

Test fish.—Fish selected for testing were juvenile fall Chinook salmon from stocks originating at the Priest Rapids Hatchery, Washington. The test fish were approximately 7 months old, in good to excellent health condition, and in the presmolt stage. Fork length of test fish ranged from 92 to 128 mm (mean = 114 mm), and mass ranged from 7 to 18 g (mean = 13 g).

Test facility.—A rectangular fiberglass flume (9 m long, 1.2 m wide, and 1.2 m deep) containing a submerged water jet was used to create a quantifiable shear environment consistent with conditions expected within a hydroelectric turbine (Figure 1). Flow was generated by using a centrifugal pump with a programmable electronic speed controller that could produce jet velocities in excess of 20 m/s. Jet velocities were measured with a two-dimensional laser Doppler velocimeter (Figure 2; similar to that used by Deng et al. [2005] except for the fish injection mechanism).

In the fast-fish-to-slow-water mechanism, test fish were introduced into the flows upstream of the nozzle via the vertical deployment tube, were carried through the jet nozzle by the fast-moving water of the submerged turbulent jet, and were exposed to the

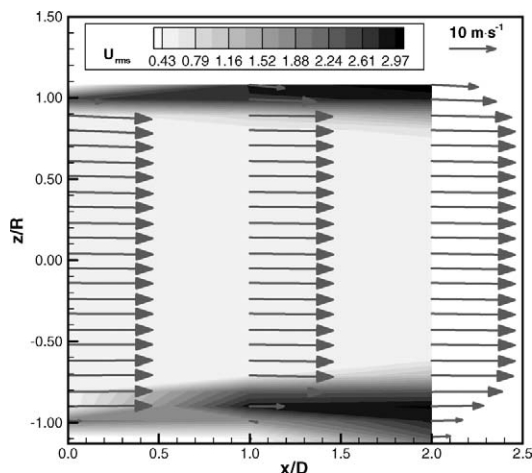


FIGURE 2.—Vector plot of velocity and contours of root-mean-square velocity (U_{rms}) for a submerged jet at a nozzle exit velocity of 18.3 m/s (D = diameter of the nozzle, x = horizontal distance to the nozzle exit, z = vertical distance to the nozzle center, R = radius of the nozzle).

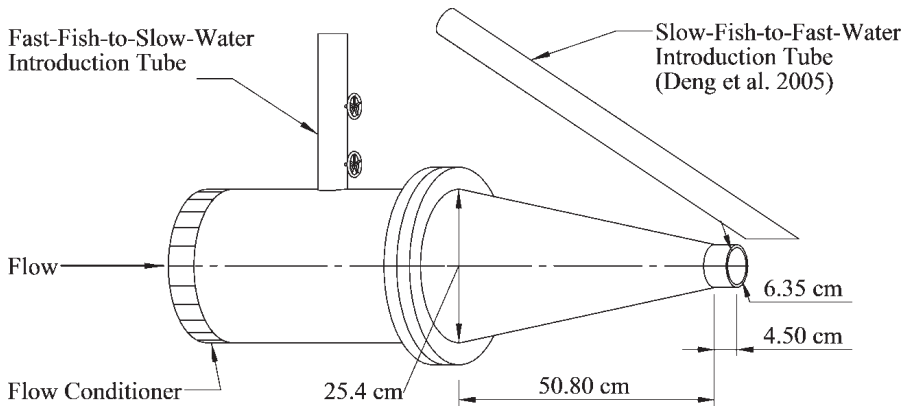


FIGURE 3.—Nozzle dimensions and fish release mechanisms for the fast-fish-to-slow water scenario (present study) and the slow-fish-to-fast-water scenario (Deng et al. 2005).

standing water in the flume (Figure 3). In contrast to the previously studied slow-fish-to-fast-water mechanism (Deng et al. 2005), fish orientation could not be controlled in the fast-fish-to-slow-water mechanism reported here.

Fish handling and injury characterization.—Test fish were held near the test facility in a 1,700-L trough with a complete turnover of water every 30 min at an inflow of approximately 57 L/min. The test flume and holding trough were supplied with 16–17°C well water. Individual fish were exposed to the jet; within about 10 s, the pump was turned off and fish were captured from the flume with dip nets. After recapture, each fish was examined to assess the type and severity of the external injuries. Each test group was held for 96 h to monitor delayed mortality or other effects indicative of stress or injury. Fish were examined at posttest intervals of 24, 36, 48, and 96 h. Injury levels (scale of 0 to 4) similar to those used by Neitzel et al. (2004) were assigned according to the following criteria: (0) no injury (no observable physical injury or brief minor disorientation); (1) single minor injury (visible but non-life-threatening injuries, such as minor bruising, operculum damage, slight gill bleeding, minor isthmus tear, minor descaling, or temporary disorientation); (2) multiple minor injuries (more than one minor injury but not life-threatening); (3) major injury (life-threatening injuries, such as severe bruising, bleeding, tearing, creasing, multiple injuries, or prolonged swimming impairment, disorientation, and loss of equilibrium); and (4) mortality (immediate or delayed mortality).

Data acquisition and analysis.—Through viewing windows located on the side and bottom of the flume, all fish exposures to the water jet were digitally recorded by using two synchronized high-speed digital cameras (Photron PCI FastCAM 1280; Photron USA,

Inc., San Diego, California) at 1,000 frames/s. The volume at which data were collected for motion analysis was $\pm 7.4(z/R)$ from the center (where z = vertical distance to the nozzle center and R = radius of the nozzle) and $7.4(x/D)$ from the exit of the nozzle (where x = horizontal distance to the nozzle exit and D = diameter of the nozzle). Ten fish were released at a nozzle velocity of 6.1 m/s (reference control), and 20 fish were released at each of five other nozzle velocities (12.2, 15.2, 18.3, 21.3, and 22.9 m/s). Approximately 100–200 frames were recorded per fish exposure. Trajectories of the fish positions were obtained by using a motion-tracking software package (Visual Fusion 4.2; Boeing-SVS, Inc., Albuquerque, New Mexico). Velocities of the fish were then computed by numerical differentiation of the measured position trajectories. Accelerations of the fish were computed by numerical differentiation of the velocity time histories. Only the magnitudes of the acceleration were used, regardless of acceleration (slow-fish-to-fast-water mechanism) or deceleration (fast-fish-to-slow-water mechanism). Binomial logistic regression (McCullagh and Nelder 1989; Zar 1999) was used to assess the relationship between the expected biological responses and the acceleration of live fish (see Deng et al. 2005 for additional details). Acceleration was the focus of this analysis because of the findings of Deng et al. (2005). The onset of injury or biological response at or above the 10% level was used to indicate threshold levels of the parameters evaluated.

Results

Biological Responses

Mass and fork length did not differ significantly among test groups, and for each group the mean injury level increased with increasing nozzle velocity (Table

TABLE 1.—Summary of the test characteristics for juvenile Chinook salmon exposed to each nozzle velocity ($N = 20$ for all nozzle velocities except 6.1 m/s, for which $N = 10$). Injury level was scored on a scale of 0 to 4 (see Methods).

Nozzle velocity (m/s)	Mean fish fork length (mm)	Variance of fork length (mm)	Mean fish mass (g)	Variance of fish mass (g)	Mean injury level	Variance of injury level
6.1	111.6	7.2	13.0	1.8	0.00	0.00
12.2	114.0	7.4	13.0	2.2	0.05	0.22
15.2	113.9	4.0	12.8	1.3	0.30	0.92
18.3	115.2	5.9	14.0	1.9	0.55	0.60
21.3	115.3	4.8	13.9	1.9	1.15	1.39
22.9	111.7	5.7	13.2	2.0	1.55	1.23

1). No injury occurred at the lowest nozzle velocity (6.1 m/s), and only one fish sustained minor injury at 12.2 m/s (Figure 4). Major injuries were first documented at the nozzle velocity of 21.3 m/s. There was only one immediate mortality among all the test fish; this occurred at the highest nozzle velocity (22.9 m/s). There were also four delayed mortalities: one at 15.2 m/s, two at 21.3 m/s, and one at 22.9 m/s. Head or body bruises were the most common injuries, occurring in 40–50% of the fish tested at nozzle velocities of 21.3 m/s or greater. The onset of minor, major, and fatal injuries occurred at nozzle velocities of 15.2, 21.3, and 21.3 m/s, respectively.

Motion and Statistical Analysis Results

Motion analysis results computed from fish trajectories showed that fish were moving with velocities similar to or slightly lower than nozzle velocities when they exited from the jet (Figure 5); that is, the fish were either swimming along with the water flow or carried away by the fast-moving water. In contrast to nozzle velocity, the kinematic and dynamic parameters estimated from motion analysis were specific to each

test fish. Acceleration of fish increased with increasing nozzle velocities.

Because acceleration has high predictive power for injury rates (Deng et al. 2005), the probabilities of specific biological responses to acceleration were computed. Using binomial logistic regression, the probability of minor injury or worse was found to increase quickly starting at an acceleration magnitude of 500 m/s^2 and reached nearly 100% at $1,200 \text{ m/s}^2$ (Figure 6). For major injuries, the probability started to increase quickly at an acceleration level of 700 m/s^2 and reached almost 90% at $1,500 \text{ m/s}^2$ (Figure 7). Threshold or critical levels of fish acceleration were also determined based on the probability of injury as a continuous function of the acceleration of the fish. For example, the 15% probability of minor and major injuries corresponded to fish acceleration levels of 519 m/s^2 (95% confidence interval = $322\text{--}613 \text{ m/s}^2$) and 757 m/s^2 (95% confidence interval = $592\text{--}868 \text{ m/s}^2$), respectively (Table 2). Ranges for these estimates were determined on the basis of the lower and upper curves bounding the 95% confidence interval.

Discussion

The jet entry velocities for the onset of minor, major, and fatal injuries are consistent with the findings of

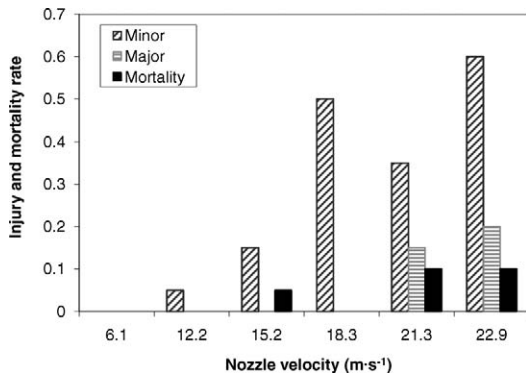


FIGURE 4.—Injury and mortality rates at different mean nozzle exit velocities (m/s), expressed as the proportion of juvenile Chinook salmon with minor injuries, major injuries, or mortality (i.e., both direct and indirect mortality).

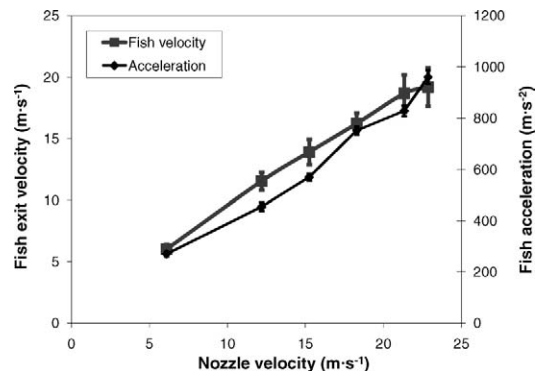


FIGURE 5.—Mean exit velocities (m/s) and maximum acceleration levels (m/s^2) of juvenile Chinook salmon as a function of nozzle velocity (m/s).

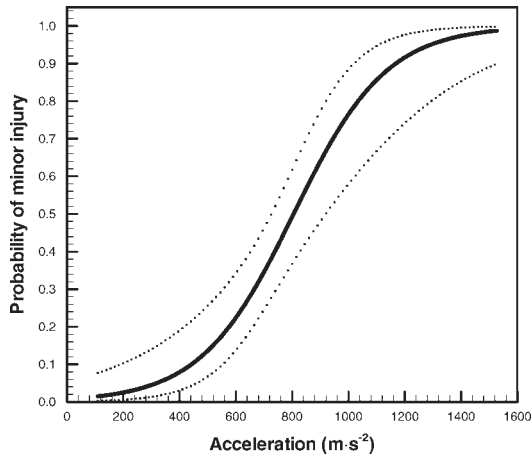


FIGURE 6.—Fitted probability of minor injury or worse in juvenile Chinook salmon as a function of acceleration (m/s^2), with 95% predictive confidence intervals (dotted lines), as derived from binary logistic regression.

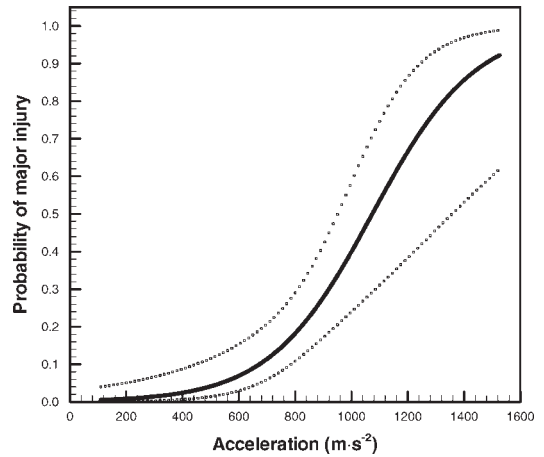


FIGURE 7.—Fitted probability of major injury in juvenile Chinook salmon as a function of acceleration (m/s^2), with 95% predictive confidence intervals (dotted lines), as derived from binary logistic regression.

Johnson et al. (2003), who reported that jet entry velocities of up to 15.2 m/s provided benign passage conditions for the sizes and physiological states of juvenile salmonids tested under a similar exposure mechanism. Head or body bruises were the most common injuries. For comparison, the onset of minor, major, and fatal injuries of the test fish exposed to the slow-fish-to-fast-water mechanism (Deng et al. 2005) occurred at lower jet velocities of 12.2, 13.7, and 16.8 m/s, respectively. In addition, injuries associated with the operculum were the most common injuries and began to occur at significant levels at 12.2 m/s.

Generally, the thresholds for fish injury under the fast-fish-to-slow-water mechanism were higher than those of fish under the slow-fish-to-fast-water mechanism for both minor and major injuries. For example, the 10% probability of minor injury corresponded to fish acceleration levels of 442 m/s^2 (95% confidence interval = $192\text{--}554 \text{ m/s}^2$) for the fast-fish-to-slow-water mechanism and 180 m/s^2 (95% confidence interval = $20\text{--}310 \text{ m/s}^2$) for the slow-fish-to-fast-water mechanism. These findings were not significantly different because of the wide bound of the 95% confidence intervals. However, the acceleration threshold of major injury for the fast-fish-to-slow-water mechanism (673 m/s^2 ; 95% confidence interval = $448\text{--}785 \text{ m/s}^2$) was significantly higher than that for the slow-fish-to-fast-water mechanism (340 m/s^2 ; 95% confidence interval = $210\text{--}440 \text{ m/s}^2$). This observation is consistent with the findings of Johnson et al. (2003) that injury rates would be significantly lower when juvenile fish are entrained in fast-moving water before exposure to turbulent shear

flows in the relatively slow water of the tailwater region of a dam.

The two different exposure mechanisms (slow-fish-to-fast-water and fast-fish-to-slow-water scenarios) have direct applications to understanding fish injury and mortality rates during passage at hydropower dams because they simulate the severe hydraulic events fish usually experience in those environments. For example, during spillway passage, juvenile fish are entrained in and oriented to the fast-moving water before they enter the turbulent shear flow zone in the transition zone region between spillway chute and tailrace; this situation is similar to the fast-fish-to-slow-water mechanism. For comparison, during turbine passage, juvenile fish are generally swimming horizontally along the flow before the entrance to the highly turbulent runner region. Because the flow around the turbine runner is downward, fish are exposed to the turbulence and shear at the periphery of the turbine mechanical and structural components; this example is similar to the slow-fish-to-fast-water mechanism.

In contrast to jet entry velocity, which represents the flow field characteristics, fish acceleration is specific to each individual fish and also is the most predictive

TABLE 2.—Acceleration magnitudes (m/s^2) corresponding to injury probabilities of 5, 10, and 15% for juvenile Chinook salmon exposed to the fast-fish-to-slow-water mechanism (95% confidence intervals are shown in parentheses).

Injury type	5%	10%	15%
Minor injury	319 (0–462)	442 (192–554)	519 (322–613)
Major injury	536 (194–674)	673 (448–785)	757 (592–868)

parameter for the observed injuries. For actual applications, the acceleration information can be estimated by releasing numerical Lagrangian particles into flow fields derived through computational fluid dynamics (Richmond et al. 2004), computed from fish movement simulated by using numerical individual-based fish models (Scheibe and Richmond 2002; Goodwin et al. 2006). In addition, predictions made by the models can be measured directly by tracking fish from underwater dual-frequency identification sonar movies (Handegard and Williams 2008). The thresholds and relationships for fish injury in terms of acceleration can be applied to evaluate the impact of potential severe hydraulic events on fish, resulting in safer operation of existing hydroelectric facilities and facilitating the design of alternative routes of passage.

Because only a limited number of fish were available for testing, the possible impacts of increased predation on fish that had become disoriented from the exposures could not be evaluated. Several studies have documented that predation occurs in the tailrace region of dams and is attributed to the disorientation of fish as they pass through turbines or over spillways. Previous tests at our facility documented that rainbow trout (15.5 cm) were more susceptible to predation than control fish at jet entry velocities of less than 12.2 m/s (Neitzel et al. 2004). Other fish species (including the American shad, kokanee *O. nerka* [lacustrine sockeye salmon], and Pacific lamprey *Lampetra tridentata*) are also known to be entrained at hydroelectric dams (Neitzel et al. 2004), but results from our test fish are not directly transferable to those species. Therefore, future studies could examine the effects of the orientation of approaching fish and the responses of different species.

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References

- Čada, G. F. 2001. The development of advanced hydroelectric turbines to improve fish passage survival. *Fisheries* 26(9):9–23.
- Coutant, C. C., and R. R. Whitney. 2000. Fish behavior in relation to passage through hydropower turbines: a review. *Transactions of the American Fisheries Society* 129:351–380.
- Deng, Z., G. R. Guensch, C. A. McKinstry, R. P. Mueller, D. D. Dauble, and M. C. Richmond. 2005. Evaluation of fish-injury mechanisms during exposure to turbulent shear flow. *Canadian Journal of Fisheries and Aquatic Sciences* 62:1513–1522.
- Goodwin, R. A., O. M. Nestler, J. J. Anderson, L. J. Weber, and D. P. Loucks. 2006. Forecasting 3-d fish movement behavior using a Eulerian-Lagrangian-agent method (ELAM). *Ecological Modelling* 192:197–223.
- Handegard, N. O., and K. Williams. 2008. Automated tracking of fish in trawls using the DIDSON (dual frequency identification sonar). *ICES Journal of Marine Science* 65:636–644.
- Hu, W. W., G. X. Wang, W. Deng, and S. N. Li. 2008. The influence of dams on ecohydrological conditions in the Huaihe River basin, China. *Ecological Engineering* 33:233–241.
- Johnson, G. E., B. D. Ebberts, D. D. Dauble, A. E. Giorgi, P. G. Heisey, R. P. Mueller, and D. A. Neitzel. 2003. Effects of jet entry at high-flow outfalls on juvenile Pacific salmon. *North American Journal of Fisheries Management* 23:441–449.
- McCullagh, P., and J. A. Nelder. 1989. *Generalized linear models*, 2nd edition. Chapman and Hall, New York.
- Neitzel, D. A., D. D. Dauble, G. F. Cada, M. C. Richmond, G. R. Guensch, R. P. Mueller, C. S. Abernethy, and B. G. Amidan. 2004. Survival estimates for juvenile fish subjected to a laboratory-generated shear environment. *Transactions of the American Fisheries Society* 133:447–454.
- Odeh, M., and G. Sommers. 2000. New design concepts for fish friendly turbines. *International Journal of Hydropower and Dams* 7:64–71.
- Richmond, M. C., T. J. Carlson, J. A. Serkowski, C. B. Cook, and J. P. Duncan. 2004. Characterizing the fish-passage environment at the Dalles Dam spillway. *In* G. Sehlke, D. F. Hayes, and D. K. Stevens, editors. *Critical transitions in water and environmental resources management – proceedings of 2004 world water and environmental resources congress*. American Society of Civil Engineers, Reston, Virginia.
- Scheibe, T. D., and M. C. Richmond. 2002. Fish individual-based numerical simulator (FINS): a particle-based model of juvenile salmonid movement and dissolved gas exposure history in the Columbia River basin. *Ecological Modelling* 147:233–252.
- Turnpenny, A. W. H. 1998. Mechanisms of fish damage in low-head turbines: an experimental appraisal. Pages 300–314 *in* M. Jungwirth, S. Schmutz, and S. Weiss, editors. *Fish migration and fish bypasses*. Blackwell Scientific Publications, Oxford, UK.
- Turnpenny, A. W. H., M. H. Davis, J. M. Fleming, and J. K. Davies. 1992. Experimental studies relating to the passage of fish and shrimps through tidal power turbines. *Marine and Freshwater Biology Unit, National Power, Fawley, Southampton, Hampshire, UK*.
- Zar, J. H. 1999. *Biostatistical analysis*, 4th edition. Prentice Hall, Upper Saddle River, New Jersey.