Juvenile Salmonid Passage and Survival Through Turbines

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INTRODUCTION

Hydroelectric dams on the Columbia and Snake Rivers have substantially affected downstream-migrating juvenile salmonids. Raymond (1988) and Williams (1989) summarized the effects of dams in delaying migration and causing direct mortalities from atmospheric gas supersaturation and passage through turbines. Bell (1981) estimated turbine passage mortalities of 8 to 19% for juvenile salmonid populations based on research conducted primarily in the 1950s and 1960s.

As a result of expected cumulative mortalities to juvenile migrants passing through turbines, considerable research has been directed toward developing structures to guide fish away from turbines into juvenile collection or bypass systems at all Columbia and Snake River dams. However, the effects on fish survival of changed hydraulic conditions resulting from installation of these guidance devices in turbine intakes have not been studied. Moreover, past turbine survival tests have sometimes lacked standardization and replication of test conditions and were performed under operational and pool conditions that differ from the present. Therefore, using turbine survival estimates derived from past data and applying them to current studies may not be wise, since the data are based on a few selected studies under passage conditions that may no longer exist.

This paper addresses some of the issues concerning juvenile salmonid passage and survival through hydroelectric turbines in the Columbia and Snake Rivers. It presents a summary of survival estimates and their application to existing river conditions. In addition, it reviews the methodologies and technologies used in calculating survival rates and makes recommendations for future work. Discussion is limited to Kaplan turbines since they are the principal turbine type in the juvenile migration corridor. A comprehensive review of the literature was neither intended nor performed. Rather, the synthesis and analysis of pertinent data from selected publications formed the core for much of the following discussion and subsequent recommendations.

BACKGROUND

Causes of Injury and Mortality

Fish passing through turbines can be injured by physical impact with wicket gates, stay vanes, or turbine blades, or by rapid pressure changes in localized zones of cavitation and decompression. Injuries can also result from shear effects caused by the boundary between two different levels of flow and turbulence (Eicher Associates 1987). Long and Marquette (1967) identified several areas within turbines that may be of special concern. These included the space between stay vanes and wicket gates and the space at the base of the blade, on either side of the shaft or between the blade tip and discharge (distributor) ring (Fig. 1). Additional areas of concern are the trailing edge of the runner blade and the end or hub of the runner, because of the possibility of low pressures. Cavitation, turbulence, and shear forces are the general risks encountered by fish passing these areas. Cada (1990) suggested that the area with the most

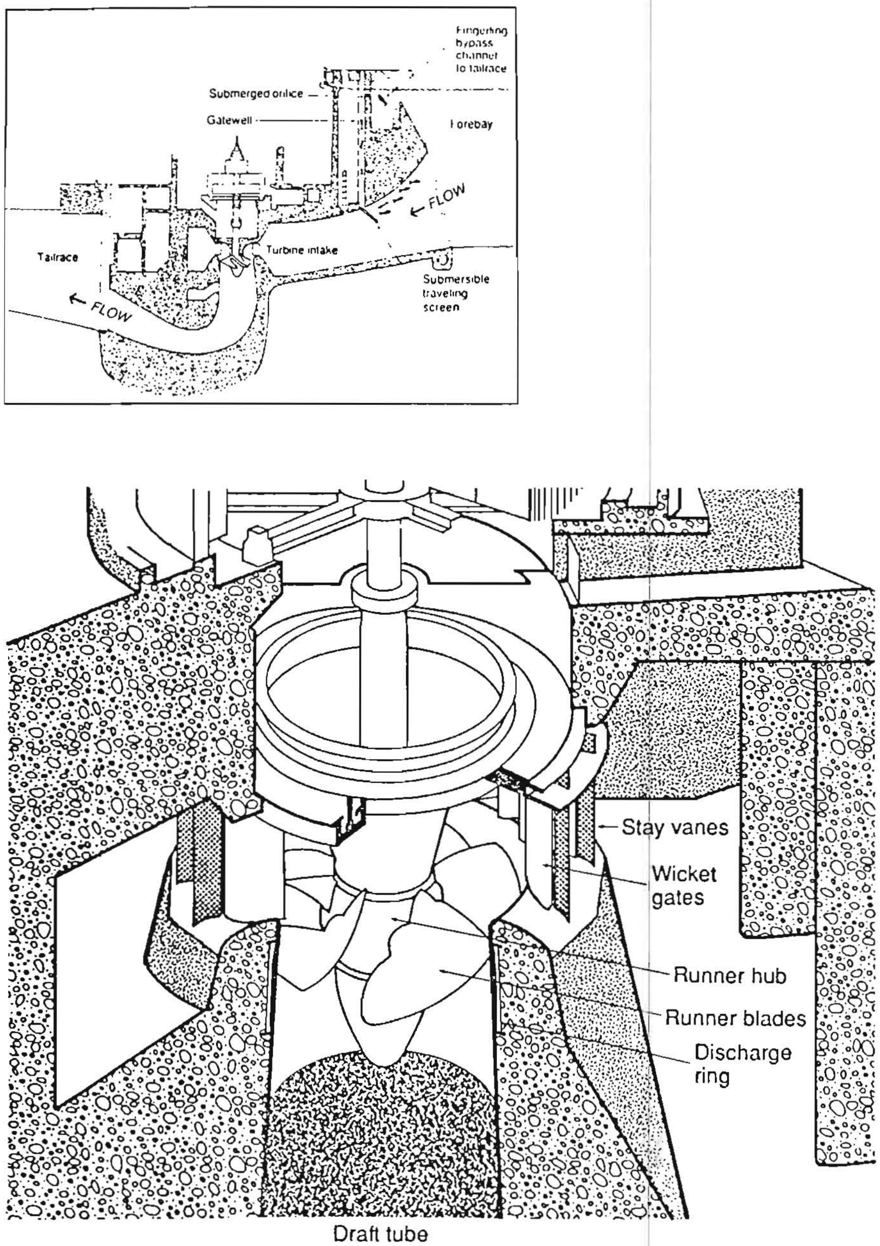

Figure 1.--Location of principal turbine areas that may affect fish passage.

potential for mortalities may be behind the turbine blade because of the momentary decompression that occurs in that area.

Attempts to identify specific causes of injury and mortality have been hampered by the difficulty of observing actual fish passage within the turbine. Definitive relationships between injury types and their causes are difficult to establish, with the possible exception of swim bladder ruptures. However, it is likely that most injuries and mortalities are principally the result of pressure changes and mechanical damage according to the assessments of Stokesbury and Dadswell (1991) in their turbine passage study on American shad (*Alosa sapidissima*), alewives (*A. pseudoharengus*), and Atlantic herring (*Clupea harengus*).

Furthermore, the magnitude of injury and mortality appears to be inversely related to turbine efficiency (Oligher and Donaldson 1966, Groves 1972, Bell 1981). Turbine efficiency is in turn determined by the wicket gate opening, the blade angle setting, and especially by the relationship between runner and tailwater depth (Bell et al. 1967).

Besides causing direct, physically disabling stress, injuries, and mortalities, turbine passage may disorient fish or increase their vulnerability to predation and disease. In fact, the relative importance of direct and indirect mortality needs to be determined under different passage conditions. There has been considerable discussion as to whether the stress from turbine passage is indiscriminate, affecting all fish equally (Brett 1958), or discriminate, affecting some fish but not others (Ruggles 1980, 1985). It is most likely a combination of the two. Some fish may be subject to specific localized pressure conditions or contact with mechanical obstructions, whereas the whole population is likely affected by the rapid acceleration and deceleration experienced during turbine passage. As yet unidentified are the extent of stress-related mortalities and the effects of cumulative stresses (i.e., the resultant stress from multi-dam passage) on fish health, condition, and long-term survival. For example, Sigismondi and Weber (1988) determined that stress effects were cumulative for juvenile chinook salmon (*Oncorhynchus tshawytscha*) and resulted in equilibrium loss, abnormal behavior, and longer recovery periods after handling.

Methods for Estimating Survival

Studies to evaluate turbine passage have generally compared the recapture rates of marked fish released into turbine intakes with those of marked fish released in the vicinity of the draft-tube exit or tailrace. A variety of different techniques have been used to aid in the recovery of marked fish. These include external devices such as balsa box enclosures, cloth bags with balloons (Donaldson 1954), polystyrene floats (Johnson 1970), and recently, an inflatable tag (HI-Z Turb'n Tag[1]) (Heisey et al. 1992). All of these devices, though highly visible, may affect fish passage through the turbine. Test and control fish have also been marked with tattoos, freeze brands, coded-wire tags, and more recently, passive integrated transponder (PIT) tags. Stier and Kynard (1986) and Giorgi

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[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

et al. (1988) also used radio tags to track fish passage. However, with radio tags, there were concerns regarding the inability to distinguish between live and dead fish during the tracking process, and the effects of tag size and fish size on vertical distribution. Moreover, the size of the available radio tags limited their use to fish larger than the general outmigration population of chinook salmon.

One strategy for the recovery of test fish has been placement of nets in the immediate turbine outfall area. Fyke nets, if positioned correctly, can capture the majority of fish exiting a turbine draft tube. Similarly, large nets that strain the entire flow from a draft tube have been used. These direct capture methods, because of their potential in recovering the majority of passed fish, have the advantage of providing information on the quantity and type of injuries. Also, releases of control fish into the draft tube exit or directly in front of the recovery gear can provide estimates of the majority of recovery gear bias.

However, there are several disadvantages of the direct capture method: nets can be costly; test fish are exposed to the effects of both turbine passage and recovery gear; passage effects over several dams may be additive; and for the majority of applications in the Columbia and Snake Rivers, large nets enclosing draft-tube exits are impractical, given the volume and flow of water under normal operating conditions.

A second strategy of recovery involves sampling for test and control fish farther downstream with scoop traps, fyke nets, gatewell collection devices at downstream dams, and downstream beach seines. The primary advantage of this method lies in its relative low cost. The major disadvantage is the large number of fish needed for release, since recovery proportions are very low. A secondary disadvantage is that random mixing of test and control fish at the recovery sites is assumed but cannot be guaranteed. The method also assumes that losses due to delayed mortality and predation, as consequences of turbine passage, can be factored out, using results from the control releases.

Adult recoveries have also been used to assess survival, but use has been limited because of the long waiting period prior to recovery and the extremely large numbers of test and control fish that must be released to provide sufficient numbers of adult returns.

Turbine Survival Studies at Columbia and Snake River Dams

Holmes (1952) initiated survival studies for fish passing turbines in the Columbia River system in 1938. These studies continued through 1944, with the release of fin-clipped subyearling fall chinook salmon at Bonneville Dam and subsequent recovery of adult fish. Because some of the releases were made in the forebay, turbine passage survival (range between 85 and 89%) may have been underestimated. Weber (1954) estimated survival of 96.1% of subyearling chinook salmon released into turbines at the same dam. Survival was estimated without benefit of a control group, and was based on the fyke-net recovery of 2.1% of the test fish.

Schoeneman et al. (1961) presented the results of a multi-year study at McNary and Big Cliff Dams involving subyearling and yearling chinook salmon. Results from studies at the latter dam, although on the Santiam River and not on the Columbia River, were considered representative of main-stem Kaplan turbines. Fish identified by tattoo marks were released into the turbine intakes and below the dams and recovered with downstream scoop traps. No significant differences were detected between release groups recovered at either dam. No significant differences were observed between year classes, or between different turbines within McNary Dam. The data for both dams were therefore pooled, and resulted in an estimated combined turbine passage survival of 89% (95% confidence interval [CI] = 87-91%). Mortalities and injuries were reportedly the result of cavitation effects and contact with turbine components.

Long et al. (1968) released yearling hatchery coho salmon (*O. kisutch*) below the ceiling of a turbine intake (Unit 2B) at Ice Harbor Dam and also into the turbine discharge front and backrolls. Recaptures from purse seining in the Ice Harbor Dam tailrace and dipnetting out of gatewells at McNary Dam were used to assess survival. The authors reported an estimated turbine survival between 81 and 90%, with a substantial loss due to predation.

In a subsequent experiment at Lower Monumental Dam with hatchery coho salmon, Long et al. (1975) estimated an overall survival of 80% with a range of 76 to 83%. Test fish were branded and released at various locations in Turbine 3 and controls were released downstream into the frontroll. Recoveries were made at the Ice Harbor Dam fingerling collection system and at McNary Dam gatewells. Predation was not mentioned as a factor.

The first direct estimate of mortality for spring chinook salmon and steelhead (*O. mykiss*) was provided by Oligher and Donaldson (1966) from Big Cliff Dam. Recapture nets were fastened directly to the turbine draft tubes. Different gate openings at different heads were examined, and survival was estimated at approximately 95% when the turbines were operated at highest efficiency.

Raymond and Sims (1980) examined hatchery fall chinook salmon passage at John Day Dam. Freeze-branded fish were released into the turbine intake and 3.2 km downstream from the dam, 30 m from the shore, in groups of 120,000 and 121,200, respectively. Turbine operations were at full load. The authors estimated a survival of 87% (95% CI = 81-92%) in fish recovered at the Dalles Dam sluiceway.

Lower survival estimates were derived by Giorgi and Stuehrenberg (1988) for yearling spring chinook salmon released at Lower Granite Dam. Three groups of PIT-tagged fish from the Rapid River Hatchery were released into Turbine 3, and a similar number of control fish were released downstream of the same unit's discharge boil. River discharge was characterized as no spill, low flow. Fish were detected by the Little Goose Dam PIT-tag detectors, and turbine passage survival was estimated at 83% (95% CI = 74-92%). Three explanations for the lower than usual estimates were provided: 1) spring chinook salmon yearlings might be more susceptible than other species to the effects of turbine passage; 2) turbine efficiency and other turbine passage conditions might have been less conducive for survival than in other studies; and 3) the duration and distance traveled by the released fish were considerably longer in this compared with other studies, increasing the opportunity for additional mortality.

The most recent turbine survival studies were presented by Ledgerwood et al. (1990) for subyearling fall chinook salmon released from Bonneville Dam Second Powerhouse. This multi-year project compared survival among turbine, spillway, and bypass releases with corresponding releases downstream from the dam. Seining and recovery at a site 100 km downstream from Bonneville Dam yielded near-term results, while adult returns and contribution to the fishery are anticipated to yield long-term survival estimates for the different release groups. Relative turbine passage-survival estimates were derived from multiple releases of fish at four locations: 1) 1 m below the turbine intake ceiling (simulating the absence of submerged traveling screens [STS]); 2) 1 m below the effective depth of the STS emplaced in a turbine intake; 3) at the frontroll of the tailrace section of the turbine; and 4) 2.5 km downstream from the dam. Differences in survival between fish released at the two turbine locations would indicate the difference between the effects of passage near the runner hub (no STS; higher survival) and passage closer to the runner blades (below STS; lower survival).

Recoveries from releases at the frontroll would indicate tailrace passage effects, and those from downstream releases would represent control fish without passage effects. The results for three study-years indicated that there were no significant differences between lower and upper turbine releases and that although the frontroll release averaged a 3% higher recovery rate than the two turbine releases, the difference was not significant. However, survival of the downstream release group was significantly higher than that of other groups, indicating a substantial near-dam effect.

In summary, turbine passage-survival studies for the Columbia and Snake Rivers began in the 1940s and have continued on a sporadic basis to the present. The results are summarized in Table 1. Point estimates of survival have been variable, ranging from 80 to 97-98%. The average passage survival, based on the nine point estimates, is approximately 90%. This approximates the 85% turbine passage-survival estimate (combined direct and indirect mortality) that has generally been applied to fish passage models and other applications. Of the nine studies mentioned in this report, only two (Giorgi and Stuehrenberg 1988, Ledgerwood et al. 1990) have been conducted within the last 10 years. Since the 1950s, turbine passage-survival estimates havebeen derived for Bonneville, John Day, McNary, Ice Harbor, Lower Monumental, and Lower Granite Dams.

These studies have generally been conducted to determine passage survival but were not designed to clarify cause and effect relationships and mechanisms. In the context of Eicher

Table 1.--Turbine survival estimates for Columbia and Snake River salmonids.

Authors	Dam	Species	Recovery method	Survival (%)
Holmes 1952	Bonneville	Subyearling chinook salmon	Adult returns	85-89
Weber 1954	Bonneville	Subyearling chinook salmon	Fyke nets	96.1
Schoeneman et al. 1961	McNary & Big Cliff	Subyearling and yearling chinook salmon	Scoop traps	89 (95% CI= 87-91)
Oligher and Donaldson 1966	Big Cliff	Yearling chinook salmon and steelhead	Direct recapture	95.0
Long et al. 1968	Ice Harbor	Yearling coho salmon	The Dalles Dam sluiceway	81-90
Long et al. 1975	Lower Monumental	Yearling coho salmon	Ice Harbor & McNary Dams	80.0 (Range 76-83)
Raymond and Sims 1980	John Day	Subyearling chinook salmon	The Dalles Dam sluiceway	87 (95% CI= 81-92)
Giorgi and Stuehrenberg 1988	Lower Granite	Yearling chinook salmon	Little Goose Dam	83.1 (95% CI= 74.1-92.2)
Ledgerwood et al. 1990	Bonneville PH 2	Subyearling chinook salmon	Downstream seines	97-98

Associates (1987), the investigations have been informative rather than exploratory in that the objective was to determine typical mortality levels rather than to assess the effects on fish survival from changing turbine operations. Variables such as species, age and size of fish, release methods and locations, recovery methods (location and efficiency), in-river flow regimes, and turbine configurations have not been consistently investigated, largely because of the restricted goals and scopes of the projects. Consequently, the results of those studies cannot be integrated to provide any predictive capability. Further, with the exception of recent Bonneville Dam studies (Ledgerwood et al. 1990), the studies were not directed toward answering questions about possible changes in turbine passage survival after the installation of guidance devices. Neither did those studies address the effects of flow regimes through turbines with different lengths or differently configured guidance devices or the effects of increased predation and the changing composition of hatchery and wild fish.

CONSIDERATIONS FOR FUTURE WORK

Marking Techniques

Among the existing marking techniques, PIT tags continue to hold the most promise for rapid and accurate individual fish identification. Their advantages include interrogation of live fish without handling, positive identification of uniquely tagged fish without the possibility of human error, availability of a system-wide data-base, and relative lack of effects on behavior and other traits of tagged fish. Major disadvantages are higher costs, limited detection distance, and the inability, for the most part, to interrogate fish other than in bypass systems at dams or water diversion facilities. Coded-wire tags may be satisfactory for long-term studies with adult recoveries but are otherwise limited for individual fish identification and recovery of tags without sacrifice. Freeze-brands suffer from low and variable recovery rates due to human error in brand application, reading, and interpretation (McCutcheon and Giorgi 1990). Radio-tracking has promise in tracking fish movement, but tag size relative to fish size and the inability to mark and track large numbers of fish remain serious problems.

A new marking methodology that has been promoted recently for turbine passage survival studies is the HI-Z Turb'n Tag (Heisey et al. 1992). With use of the tag, direct recovery of live, injured, and dead fish immediately after passage through turbines may be possible, providing the tag remains intact and attached to the fish. The HI-Z Turb'n Tag potentially shares the limitations of older, externally attached tags such as the polystyrene float; persistence of the externally attached tag is questionable because tags are attached via pins through the dorsal musculature, and may affect swimming ability or behavior. Also, the location and size of the tag may alter normal fish passage through the turbines. However, if these limitations can be addressed successfully, the potential for direct recovery of tagged fish for absolute determinations of survival and degree of morbidity or mortality would enhance fish passage research.

In recent years, statistical methodologies that are principally focused on release-recapture models have been formalized to address turbine survival studies (e.g., Burnham et al. 1987). In combination with PIT-tag identification at downstream detector sites and some knowledge of fish guidance efficiencies and projected survival rates, sample sizes can be established for the desired precision of the survival estimator. For example, Table 2 was prepared to determine sample sizes necessary to compare survival of yearling chinook salmon released either in the sluiceway or in the turbine at Ice Harbor Dam. Variables included sluiceway survival, turbine survival, survival to McNary Dam, and fish guidance efficiency (FGE) at McNary Dam. The following equation is applied to obtain the requisite sample sizes:

$$n = \frac{(z\alpha/2 + z\beta)^2 \, [p_1(1 - p_1) + p_2(1 - p_2)]}{(p_1 - p_2)^2}$$

where $z\alpha/2$ and $z\beta$ are standard normal variates corresponding to α and β (for $\alpha = 0.05$ and $\beta = 0.20$) and p_1 and p_2 are recovery percentages for releases at locations 1 and 2, respectively. Sample sizes necessary to attain survival estimators with satisfactory precision have been significantly reduced through the availability of individual fish identification methods such as the PIT tag. With further development, this may also be possible with the HI-Z Turb'n Tag. Other marking technologies in the research and development phase that could enhance turbine survival investigations include an extended-range PIT-tag and an acoustic PIT-tag.

Table 2.--Sample sizes (n) necessary to compare survival of yearling salmon released at Ice Harbor Dam either in the sluiceway or in the turbines (for α = 0.05 and β = 0.20); p_1 and p_2 are recovery percentages for releases at the sluiceway and the turbines, respectively.

Sluiceway survival	Turbine survival	Survival to McNary	FGE at McNary	p_1	p_2	n
0.98	0.99	0.95	0.75	0.68	0.68	74,244
0.98	0.99	0.95	0.65	0.59	0.59	110,036
0.98	0.99	0.90	0.75	0.65	0.64	87,169
0.98	0.99	0.90	0.65	0.56	0.56	124,950
0.98	0.97	0.95	0.75	0.68	0.66	8,338
0.98	0.97	0.95	0.65	0.59	0.57	12,275
0.98	0.97	0.90	0.75	0.65	0.63	9,760
0.98	0.97	0.90	0.65	0.56	0.54	13,915
0.98	0.95	0.95	0.75	0.68	0.65	3,031
0.98	0.95	0.95	0.65	0.59	0.56	4,434
0.98	0.95	0.90	0.75	0.65	0.61	3,538
0.98	0.95	0.90	0.65	0.56	0.53	5,018
0.85	0.99	0.95	0.75	0.59	0.59	109,826
0.85	0.99	0.95	0.65	0.51	0.51	151,092
0.85	0.99	0.90	0.75	0.56	0.56	124,727
0.85	0.99	0.90	0.65	0.49	0.48	168,287
0.85	0.97	0.95	0.75	0.59	0.58	12,252
0.85	0.97	0.95	0.65	0.51	0.50	16,791
0.85	0.97	0.90	0.75	0.56	0.54	13,891
0.85	0.97	0.90	0.65	0.49	0.47	18,682
0.85	0.95	0.95	0.75	0.59	0.56	4,426
0.85	0.95	0.95	0.65	0.51	0.49	6,043
0.85	0.95	0.90	0.75	0.56	0.53	5,010
0.85	0.95	0.90	0.65	0.49	0.46	6,717

Biological Considerations

Size, species, health and condition, and degree of smoltification may all affect fish passage and survival. Fish size may influence the probability of contact with turbine structures such as runner blades (Von Raben 1964), the strength and behavior of the fish (Bell 1981), and the incidence of injuries from shear forces between two bodies of water with large differences in velocity (Groves 1972). Different species of fish may have different vertical distributions in the water column (Raymond and Bentley 1964; Long 1968, 1975; Swan et al. 1983). This might affect the percentage of fish guided away from turbines into gatewells or the pathway through the turbine (Long and Marquette 1967). Muir et al. (1988) determined that degree of smoltification affected fish guidance, and that less smolted fish had a greater tendency to pass through turbines rather than bypass systems. Fish health and condition may affect fish guidance, and the physiological state of the fish post passage may affect survival. The susceptibility of post-passage fish to predation, given the magnitude of the predation problem in dam tailraces, can lead to serious losses (Long et al. 1968).

In the absence of direct recovery methods, the assumptions of equal non-treatment mortality and the random mixing between test and control fish must be met for valid statistical analysis. Despite precautions taken to eliminate all possible differences, test and control populations will differ because of their prior experience with or without turbine passage. Because of indirect mortalities sustained by the test group as a result of the delayed effects of passage injury or predation, direct turbine mortalities will be difficult to assess, even with a control population. A fish, temporarily disoriented because of turbine passage, might normally survive the tailrace environment and proceed to the next dam if it were not consumed by a predator because of its weakened state. A mid-river release in conjunction with turbine and tailrace releases similar to those reported by Ledgerwood et al. (1990) could be used to partition turbine passage effects and tailrace effects.

Other Considerations

Physical variables affecting fish passage through turbines include the presence or absence of guidance devices within the turbine intakes and their effects on flow dynamics. These devices may affect flow through the intake, the wicket gate position, the forebay and tailwater levels, turbine efficiency, river discharge and temperature, tailrace characteristics including frontroll and backroll, position of the draft tube, presence of slack-water, and degree of powerhouse loading (Bell et al. 1967, Bell 1981). Eicher Associates (1987) presented an example of a list of turbine and experimental characteristics that should be useful in describing and standardizing turbine survival experiments.

Specific turbine designs and operating regimes can lead to different injury types. However, the cause-effect relationship will continue to be ill-defined given the present design of turbine survival experiments involving full-scale dams and indirect methods of recovery. There is a need to determine injury types related to turbine passage to lead toward improvements in turbine design and operations.

CONCLUSIONS

This review of past research brings to light certain key issues regarding turbine passage and survival. These include:

1) Turbine passage-survival estimates for Columbia and Snake River dams are based on relatively few studies (nine in this review). These survival estimates, taken as a whole, average approximately 90% per dam.

2) Experimental methodologies, including release and recovery methods and choice of fish species, source, size, and general condition, varied from project to project.

3) Most turbine survival estimates were based on conditions which no longer exist because fish guidance devices were not yet installed at the time of these studies, turbine units were operated solely for power in the past, the composition of migrant fish populations has changed, and predation has been recognized as a significant source of mortality.

4) Turbine survival studies for Columbia and Snake River dams were narrow in scope and therefore lacked the discriminatory power to determine injury types or causes of injuries.

5) Passage conditions have been altered to the extent that indirect or delayed mortalities may now be the predominant factor in overall survival.

6) Fundamental relationships between physical (i.e., turbine criteria and hydrographic conditions) and biological variables

(i.e., fish species, size, condition, and health), as they relate to turbine passage and survival, have not been established.

RECOMMENDATIONS

1) Develop biological design criteria for turbine design and operation.

Biological criteria for major turbine-passage related variables should be determined. The effects of rapid changes in pressure and turbulence, and changes in velocity relative to fish species, size, physiological state, and source should be examined. Passage routes under real and simulated, optimal and sub-optimal, conditions should be evaluated.

In-river, full-size dams are inappropriate arenas for the determination of biological design criteria for turbine design and operation. Long and Marquette (1967) suggested that safe turbine passage will require several modifications to turbines, each perhaps resulting in a "small increase in survival." Given that the total improvement in survival will probably be 10% or less, their statement remains valid. Therefore, because existing turbine-passage survival testing methodologies lack the sensitivity to detect small differences among effects, first attempts should be performed with computer modeling techniques and simulation methods. Existing and future designs should be evaluated; results should then be confirmed with turbine models and prototype systems under controlled operating conditions such as those described by Cramer (1960). Testing should then proceed to an intermediate-sized dam with full-sized turbines and controllable conditions such as those at Big Cliff Dam, where direct recovery methods also could be performed. Final evaluation should be performed at appropriate dams in the Columbia and Snake Rivers using standardized testing methodologies.

The development and potential application of new technologies such as light detecting and ranging (LIDAR) and gated video may permit direct observation of fish passage through turbines. Only then will it be possible to establish definitive relationships between injury types and their causes, and subsequently, to determine biological criteria.

2) Determine survival of fish passing through turbines at all dams with guidance devices in place.

Concurrent with the development of biological design criteria, research should be proceeding in several other directions. One of the most urgent needs is the verification of turbine survival estimates for all dams in the Columbia and Snake River systems. Under present operating schemes, this will require evaluation with and without normal and extended STSs. To compare results from different dams, operating conditions such as forebay and tailwater elevations and blade angles, as they relate to sigma, specific speed, and efficiency, should be standardized between dams as much as possible. Species, size, condition, physiological state, and source of fish should be evaluated carefully. If feasible, the same stock of fish should be used to evaluate survival at different dams. Given the standardization of conditions, the generality or specificity of the results could be determined. Finally, release and recovery methods should be standardized.

The application of promising new developments which might permit direct recovery, such as the HI-Z Turb'n Tag (Heisey et al. 1992), should be investigated. However, evaluation of such new developments should follow a systematic and consistent plan to eliminate as many confounding variables as possible. For example, studies solely involving the passage of tagged fish through turbines cannot be relied upon exclusively for determinations of feasibility and suitability of tags for survival estimations. A comprehensive evaluation should involve a series of tests, such as those performed by Giorgi et al. (1988) in their study of the use of radio-tags for juvenile salmonids. A similar testing program for the HI-Z Turb'n Tag could contain such elements as:

a) The effects of pressure changes from simulated turbine passage on the survival of tagged vs. control fish;

b) Tag loss rates under simulated turbine passage; and

c) The effects of tag size and weight on different sizes (or species) of salmonids for swimming behavior and stamina, and the resultant effects on fish guidance efficiency.

Until a direct recovery method other than direct recapture via nets is adopted, indirect recovery methods should be used. A principal element in the protocol should be the use of PIT tags for fish-marking. Under certain conditions, the effects of multi-dam passage could be evaluated. All attempts should be made to separate turbine effects from tailrace (principally predation) effects. The paired-release approach, with releases of test fish in the turbine intake followed by control fish in the tailrace and downriver (as reported by Ledgerwood et al. 1990), appears the most feasible approach presently available. Because of the difference in condition between test and control fish as a result of turbine passage, a refinement to the approach would incorporate some prior stress to the control fish. The nature and application of the stressor would require additional investigation. Interception of test and control fish prior to the next downstream dam may be necessary if it appears that the random mixing may not occur.

REFERENCES

Bell, M. C. 1981. Updated compendium on the success of passage of small fish through turbines. Report to U.S. Army Corps of Engineers, Contract DACS-68-76-C-0254, 204 p. (Available from U.S. Army Corps of Engineers, North Pacific Division, Portland, OR 97208.)

Bell, M. C., A. C. DeLacy, and G. J. Paulik. 1967. A compendium on success of passage of small fish through turbines. Report to U.S. Army Corps of Engineers, Contract DA-35-26-Civeng-66-16, 54 p. (Available from U.S. Army Corps of Engineers, North Pacific Division, Portland, OR 97208.)

Brett, J. R. 1958. Implications and assessments of environmental stress. In P.A. Larkin (editor), The Investigation of Fish Power Problems, p. 69-93, University of British Columbia, Vancouver, B.C., Canada.

Burnham, K. P., D. R. Anderson, G. C. White, C. Brownie, and K. H. Pollock. 1987. Design and analysis methods for fish survival experiments based on release-recapture. Am. Fish. Soc. Monogr. 5:1-437.

Cada, G. F. 1990. A review of studies relating to the effects of propeller-type turbine passage on fish early life stages. N. Am. J. Fish. Manage. 10:418-426.

Cramer, F. K. 1960. Fish passage through turbines, model turbine experiments. U.S. Army Corps of Engineers, Progress Report 1:1-9. (Available from U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, WA 99632.)

Donaldson, I. V. 1954. Effect of structures at main Columbia River and certain other dams on downstream migration of fingerling salmon. Report to U.S. Army Corps of Engineers, 83 p. (Available from U.S. Army Corps of Engineers, Portland, OR 97208.)

Eicher Associates, Inc. 1987. Turbine-related fish mortality: review and evaluation of studies. Report to Electric Power Research Institute, AP-5480. Research Project 2694-4, 194 p. (Available from Electric Power Research Institute, 3412 Hillview Avenue, Palo Alto, CA 94304.)

Giorgi, A., and L. Stuehrenberg. 1988. Lower Granite pool and turbine survival study, 1987. Report for Department of Energy, BPA, Contract DE-A179-87BP34270, 30 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Giorgi, A. E., L. Stuehrenberg, and J. Wilson. 1988. Juvenile radio-tag study: Lower Granite Dam 1985-1986, Report for Department of Energy, BPA, Project 85-35, 50 p. (Available from Northwest Fisheries Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Groves, A. B. 1972. Effects of hydraulic shearing actions on juvenile salmon. U.S. Dep. Commer. Nat. Mar. Fish. Serv. Northwest Fisheries Center, Seattle, WA, 7 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Heisey, P. G., D. Mathur, and T. Rineer. 1992. A reliable tag-recapture technique for estimating turbine passage survival: application to young-of-the-year American shad (Alosa sapidissima). Can. J. Fish. Aquat. Sci. 49:1826-1834.

Holmes, H. B. 1952. Loss of salmon fingerlings in passing Bonneville Dam as determined by marking experiments. Unpubl. manuscr., 6 p. (Available from U.S. Fish and Wildlife Service, 9317 Highway 99, Vancouver, WA 98665.)

Johnson, F. A. 1970. A device for fish recovery during turbine-passage mortality studies. Prog. Fish-Cult. 32(4):236-239.

Ledgerwood, R. D., E. M. Dawley, L. G. Gilbreath, P. J. Bentley, B. P. Sandford, and M. H. Schiewe. 1990. Relative survival of subyearling chinook salmon which have passed Bonneville Dam via the spillway or the second powerhouse turbines or bypass system in 1989, with comparisons to 1987 and 1988. Report to U.S. Army Corps of Engineers, Contract E85890024/E86890097, 64 p plus Appendixes. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Long, C. W. 1968. Diel movement and vertical distribution of juvenile anadromous fish in turbine intakes. U.S. Nat. Mar. Fish. Serv. Fish. Bull. 66(3):599-609.

Long, C. W. 1975. Final report on vertical distribution of fingerling salmonids in turbine intakes of the Bonneville first powerhouse. Report to U.S. Army Corps of Engineers, Portland District, Portland, OR, Contract DACW-57-75-F-0569, 11 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Long, C. W., R. F. Krcma, and F. J. Ossiander. 1968. Research on fingerling mortality in Kaplan turbines -1968. Research report, U.S. Bur. Commer. Fish., Seattle, WA, 7 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Long, C. W., and W. M. Marquette. 1967. Research on fingerling mortality in Kaplan turbines. Research report, U.S. Bur. Commer. Fish., Seattle, WA, 37 p. (Available from Northwest Fisheries Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Long, C. W., F. J. Ossiander, T. E. Ruehle, and G. Matthews. 1975. Survival of coho salmon fingerlings passing through operating turbines with and without perforated bulkheads and of steelhead trout fingerlings passing through spillways with and without a flow detector. Report to U.S. Army Corps of Engineers, Portland District, Portland, OR, Contract DACW68-74-C-0113, 8 p. (Available from Northwest Fisheries Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

McCutcheon, C. S. and A. E. Giorgi. 1990. An assessment of freeze-brand and PIT-tag recovery data for juvenile salmonids at McNary Dam, 1988. Report for Department of Energy, BPA, Project 87-130, 28 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Muir, W. D., A. E. Giorgi, W. S. Zaugg, W. W. Dickhoff, and B. R. Beckman. 1988. Behavior and physiology studies in relation to yearling chinook salmon guidance at Lower Granite and Little Goose Dams, 1987. Report to U.S. Army Corps of Engineers, Contract DACW68-84-H-0034, 47 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Oligher, R. C., and I. J. Donaldson. 1966. Fish passage through turbine tests at Big Cliff hydroelectric plant. U.S. Army Corps of Engineers, Walla Walla District, Progress Rep. 6:1-15. (Available from U.S. Army Corps of Engineers, Walla Walla District, Walla Walla, WA 99362.)

Raymond, H. L. 1988. Effects of hydroelectric development and fisheries enhancement on spring and summer chinook salmon in the Columbia River Basin. N. Am. J. Fish. Manage. 8:1-24.

Raymond, H. L. and W. W. Bentley. 1964. Use of turbine intake gatewells for sampling of migrant juvenile salmonids. Research report, Fish-passage research program. U.S. Bur. Commer. Fish., Seattle, WA, 10 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Raymond, H. L. and C. W. Sims. 1980. Assessment of smolt migration and passage enhancement studies for 1979. Report to U.S. Army Corps of Engineers, Contract DACW-68-78-C-0051 and DACW-57-79-F-0411, 48 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Ruggles, C. P. 1980. A review of the downstream migration of Atlantic salmon. Canadian Tech. Rept. 952, 39 p.

Ruggles, C. P. 1985. Can Injury be minimized through turbine design? Hydro Review 4(4):70-76.

Schoeneman, D. E., R. T. Pressey, and C. O. Junge, Jr. 1961. Mortalities of downstream migrant salmon at McNary Dam. Trans. Am. Fish. Soc. 90:58-72.

Sigismondi, L. A., and L. J. Weber. 1988. Changes in avoidance response time of juvenile chinook salmon exposed to multiple acute handling stress. Trans. Am. Fish. Soc. 117:196-201.

Stier, D. J., and B. Kynard. 1986. Use of radio telemetry to determine the mortality of Atlantic smolts passed through a 17-MW Kaplan turbine at a low-head hydroelectric dam. Trans. Am. Fish. Soc. 115:771-775.

Stokesbury, K. D. E., and M. J. Dadswell. 1991. Mortality of juvenile clupeids during passage through a tidal low-head hydroelectric turbine at Annapolis Royal, Nova Scotia. N. Am. J. Fish. Manage. 11:149-154.

Swan, G. A., R. F. Krcma, and F. Ossiander. 1983. Studies to improve fish guiding efficiency of traveling screens at Lower Granite Dam. Report to U.S. Army Corps of Engineers, Contract DACW68-78-C-0051, 20 p. (Available from Northwest Fisheries Science Center, 2725 Montlake Boulevard E., Seattle, WA 98112-2097.)

Von Raben, K. 1964. Regarding the problem of mutilation of fishes by hydraulic turbines. Die Wasserwutschoff 4:97-100, 1957. (Translated by the Fisheries Research Board of Canada, Translation Series No. 448, 4 p.)

Weber, K. G. 1954. Testing the effect of a Bonneville draft tube on fingerling salmon. Unpubl. rep. U.S. Fish Wildl. Serv., Seattle, WA (reported by Eicher Associates, 1987).

Williams, J. G. 1989. Snake River spring and summer chinook salmon: can they be saved? Regulated Rivers 4:17-26.