

**Fish Behavior in Relation to Modeling Fish Passage Through  
Hydropower Turbines: A Review**

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**Abstract.** We evaluated the literature on fish behavior as it relates to passage of fish near or through hydropower turbines. The goal was to foster compatibility of engineered systems with the normal behavior patterns of fish species and life stages such that entrainment into turbines and injury in passage are minimized. We focused on aspects of fish behavior that could be used for computational fluid dynamics (CFD) modeling of fish trajectories through turbine systems. Downstream-migrating salmon smolts are generally surface oriented and follow flow. Smolts orient to the ceilings of turbine intakes but are horizontally distributed more evenly, except as affected by intake-specific turbulence and vortices. Smolts often enter intakes oriented head-upstream. Non-salmonids are entrained episodically, suggesting accidental capture of schools (often of juveniles or in cold water) and little behavioral control during turbine passage. Models of fish trajectories should not assume neutral buoyancy throughout the time a fish passes through a turbine, largely because of pressure effects on swim bladders. Fish use their lateral line system to sense obstacles and change their orientation, but this sensory-response system may not be effective in the rapid passage times of turbine systems. Effects of pre-existing stress levels on fish performance in turbine passage are not well known but may be important. There are practical limits of observation and measurement of fish and flows in the proximity of turbine runners that may inhibit development of information germane to developing a more fish-friendly turbine. We provide recommendations for CFD modelers of fish passage and for additional research.

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## Introduction

This paper summarizes our evaluation of the literature on fish behavior as it relates to passage of fish near or through hydropower turbines. An evaluation was stimulated by the need to develop more "fish-friendly" turbine systems for hydropower facilities (Brookshier et al. 1995). One aspect of "friendliness" is compatibility of engineered systems with the normal behavior patterns of fish species and life stages in the vicinity of the generation facilities such that entrainment into turbines and injury in passage are minimized. This literature review was part of Oak Ridge National Laboratory's development of biological criteria for the design of advanced hydropower turbines (Cada et al. 1997).

Phases I and II of the U.S. Department of Energy's Advanced Hydropower Turbine System Program involve computational fluid dynamics (CFD) modeling and engineering design studies to develop novel designs for turbines that are less damaging to fish (Sale et al. this volume; Ventikos and Sotiropoulos this volume). For this effort, the modelers and designers need to know how fish move into and through turbines (Figure 1). Biologists need to define whether fish can be simulated in computer and physical models as passive, neutrally buoyant particles distributed throughout the watermass entering a turbine or if they must be represented in ways that reflect specific fish distribution patterns, physical orientations, and directed swimming movements. Fish distribution patterns in a turbine intake would influence the parts of the turbine through which the fish pass (e.g., near the hub or near the blade tips). Physical orientations would affect the likelihood of being struck by a turbine blade. Capabilities of fish for directed swimming movements in the high water velocities of a turbine intake would influence the constancy of distribution patterns and orientations as fish approach the turbine runner. Our review evaluated the knowledge and importance of these considerations.

Physical damage to fish that pass through hydropower turbines is a major source of mortality for many fish populations in the vicinity of hydropower projects (OTA 1995; NRC 1996; Cada et al. 1997). This is especially true for migratory species such as salmon for which the dam is a barrier to movement that must be traversed or the population spawning upstream perishes. Although successful technologies have been developed for passing adult salmon upstream over dams (through simulation in fish ladders of the features of the normal migratory habitat), passage of downstream-migrating juveniles has been difficult to manage and generally not very successful (NPPC 1994; Cada et al. 1994; Francfort et al. 1994).

Both guidance away from turbine intakes and injuries inflicted by the turbine system (including hydrodynamic aspects of the scroll case and draft tube) are influenced, if not determined, by the size-dependent behavior patterns of the entrained species. Most bypass systems for juvenile salmon at major hydroelectric facilities, which involve screening juveniles from deep turbine intakes, seem to have been designed to oppose normal fish behavior in dam forebays. Normal behavior is surface oriented and in the direction of flow (Williams et al. in press). The development of intake screening arose from the observations that fish pulled to unnatural depths of turbine intakes accumulated in the gatewells associated with the tops of the intakes. Recent success with surface flow bypasses (Johnson et al. 1992) can be attributed to those facilities' closer matches to normal migration behavior (Williams et al. in press).

Damage to fish in turbines is not restricted to species that migrate between fresh water and the ocean. Many freshwater residents undergo extensive movements over the course of the seasons. Some of these movements are necessary for successful completion of the life cycle in different portions of a river system. Dams can create obstacles to population success similar to those for ocean-going species. In other cases, local resident fishes in impoundments can be drawn into turbines accidentally as a consequence of their normal feeding and rearing processes in the vicinities of turbine intakes. Thus, it may be useful to consider a diversity of fish behaviors to minimize turbine-induced damages under a wide range of hydropower installations.

Our review briefly introduced the sources of fish mortality from turbine passage, gave a synopsis of earlier literature reviews of fish behavior near turbines with their conclusions, reviewed relevant and current basic scientific information about fish physiology and behavior, reviewed on-site data at dams, and finally provided generalizations and implications for improved design of turbine systems (Cada et al. 1997). Because the majority of *in situ* studies have been conducted with salmonids, this fish group necessarily dominated the empirical aspects of this evaluation. Academic research on the physiology and behavior of fish, in general, provided additional guidance. The primary technological focus was on fixed- or variable-blade, Kaplan-type, vertical shaft propeller turbines, the type found most commonly in the Columbia River basin and at other large hydropower installations.

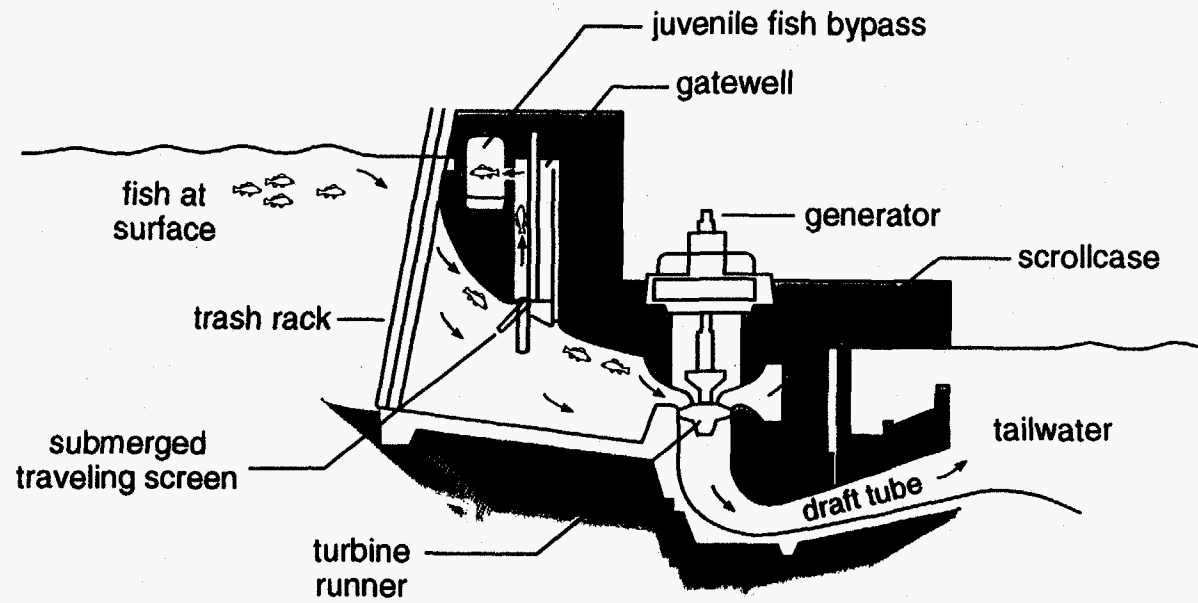


Figure 1. Generalized cut view of a Columbia River basin hydropower powerhouse, showing distribution of downstream-migrating juvenile salmon and fish-passage devices.

## **Behavior of Salmonids**

Early studies of fish mortalities at dams (summarized by Bell 1981) stimulated studies of the behavior of salmonids. Biologists associated with hydropower facilities sought primarily to find ways to direct juveniles away from intakes. They examined the locations of fish in dam forebays (the water just upstream of a dam), the effects of spilling water (and fish) over spillways and the relationships between fish passage and the depths of spill and turbine intakes (Figure 2). Natural and artificial cues (lights, bubble curtains, electric fields, and sound) were evaluated as guidance mechanisms. Early studies established the fundamental behavior pattern of juvenile salmonids as being surface-oriented and following flow. No amount of artificial stimulus has been shown to be sufficiently effective in guiding fish movements otherwise to justify full-scale or prototype testing in the field for application at large hydroelectric projects (Ebel 1981; Mighetto and Ebel 1994; OTA 1995).

Basic research on behavior of juvenile salmonids was also underway during the same time, although often independent of the applied studies. Descriptions of swimming behavior in water flow, orientation of movements, flow cues to migration, and swimming speeds in different environmental situations occupied the interests of basic researchers.

Intensive research on salmonids, both basic and applied, has shown several important considerations for understanding fish behavior as it affects entrainment injury and mortality at turbines. These considerations are: orientation with bulk water flow (toward turbines or alternative pathways), surface orientation of salmonid downstream migrants (the most studied) and other orientations of other species, and body orientation in flow that affects the likelihood of striking a turbine blade or other structures. Basic studies of fish behavior suggest other important considerations, such as buoyancy and stability, obstacle recognition and avoidance, the sensing of acceleration in relation to fish orientation and directed movements, behavior in turbulent flow, and stress responses that may modify normal behavior.

## **Behavior of Non-Salmonids**

The relationships of the salmonid information to behavior of non-salmonids and resident fishes including salmonids is problematical. Juvenile salmonids are attempting to move downstream, and passage through turbines is one route. Resident fishes without the migration urge likely are adapted to resist currents and water flow, the agents that would displace them from their normal habitats. Entrainment of non-migratory species is likely accidental and may relate to the degree to which each species uses habitats closest to the turbine intakes (FERC 1988, 1995). Entrainment probability and fish behavior for resident fishes is likely to be highly site-specific, depending on the habitats and species encountered. The Federal Energy Regulatory Commission has begun to synthesize information obtained in entrainment monitoring studies it has required at small hydropower sites dominated by non-salmonids (FERC 1995).

There is some indication that resident fishes are more vulnerable in autumn and winter than in warm seasons (FERC 1995). Extreme cold or sudden temperature declines can make fishes comatose and they will drift into intakes. FERC (1995) suggested that there is sufficient information about the occurrence of entrainment during periods of cold stress that these episodes could be predicted from weather data. Comatose or moribund fish are unlikely to exhibit any avoidance reactions or controlled body orientation that would cause them to differ from passive particles in transit through turbines.

## **Measurement Concerns**

Although it is desirable to have more accurate information on fish behavior and orientation in turbine intakes, especially as fish approach the turbine runner, there are important limitations for making observations. Realistic expectations of further research are necessary.

Direct observation in physical models is hampered by elements of scale. Although the turbine system can be scaled to a smaller size, the fish cannot. The types of behaviors examined in this report are often not only species-specific, but also size-specific within a species. Use of very small fish (e.g., fry or aquarium species) as surrogates for larger ones compromises the need to observe relevant behavior.

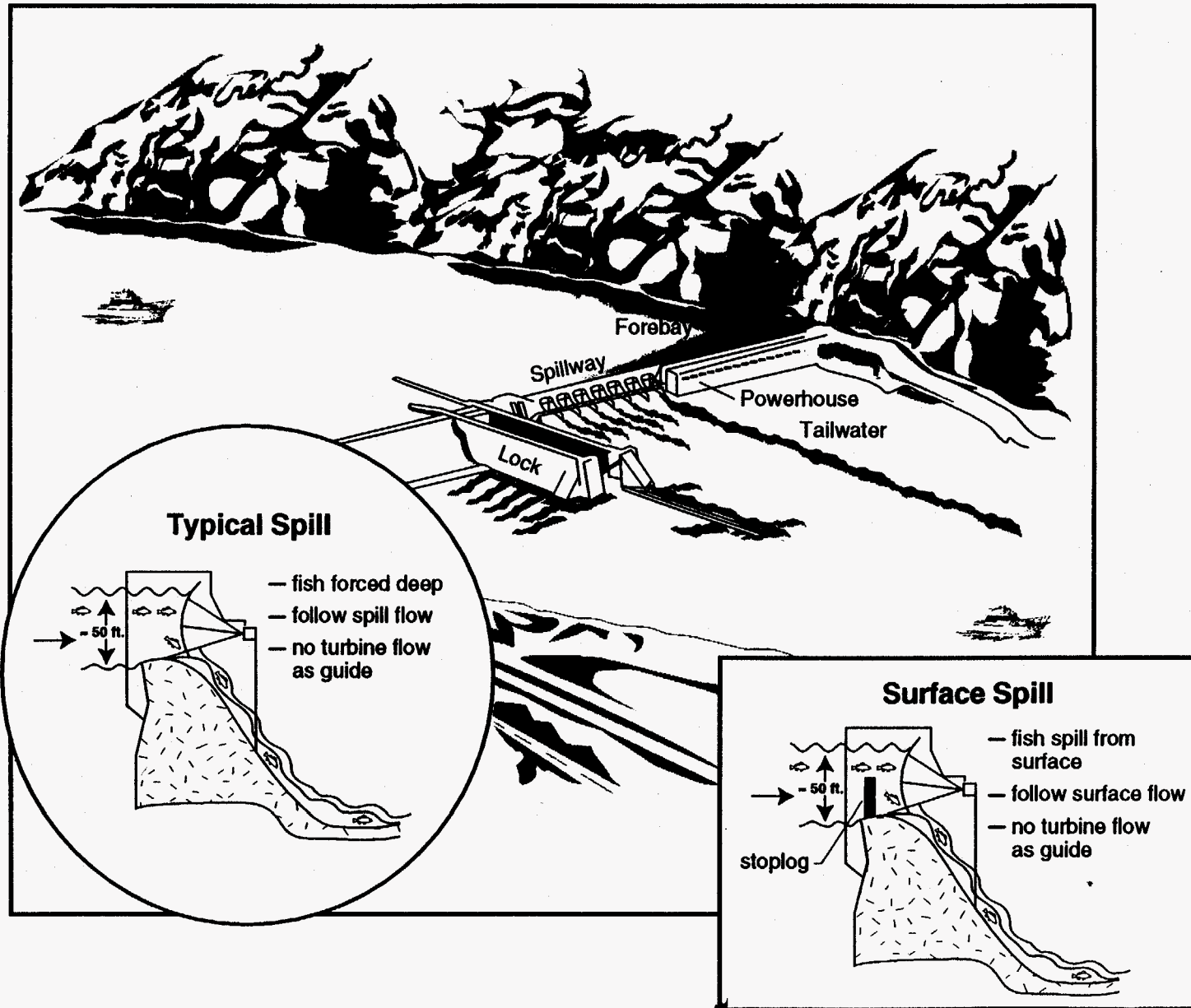


Figure 2. Generalized hydropower facility showing alternative water pathways through powerhouse turbines or spillway. Insets show cut views of a typical spillway and a spillway modified as a surface spillway.

Video observation and recording of fish positions in actual turbine systems seems feasible based on experiences viewing juvenile salmonids at traveling screens at fish bypass systems at Columbia River Basin dams (Nestler and Davidson 1995a,b). The technique has obvious limitations in turbid water, but would be useful in clear-water sites where representative fish species are entrained. However, positioning cameras in the extremely high velocities near the turbine runners without disrupting the fish and water flows that are of interest may prove to be infeasible. Nestler and Davidson (1995a,b) relate placement difficulties with even the slower velocities at the bypass screens.

Hydroacoustics has provided valuable data in turbine intakes at a distance from the runner, but turbine "noise" affects data analysis increasingly as hydrophones are placed near or directed toward the turbine (FWS 1992). The background noise affects the detection of small fish most strongly, and these are the sizes often of concern. Experimentation with different sound frequencies may be necessary before hydroacoustic detection can be used in close proximity to the turbine runners.

Forensic analysis of fish that have been passed through turbines experimentally (subsequent recovery often facilitated by use of balloon tags) may be improved to the point where location and orientation can be inferred more accurately. Balloon tag studies at Rocky Reach Dam on the Columbia River were able to resolve a difference of 1.7% in mortality of smolts passing through turbines with fixed versus variable blades, leading engineers to conclude that the additional injury rate was induced by a small gap between the hub and the blade of the variable pitch turbine (RMC and Skalski 1994). However, many sources of physical damage in turbines result in similar pathologies (Cada et al. 1997). The limits of inference may be too severe for meaningful engineering redesign of turbines.

Without implying too much pessimism, we conclude that the practical limits of observation and measurement of fish and flows in the proximity of turbine runners using existing technologies may inhibit development of much information, including that needed for CFD modeling, that is germane to developing a more fish-friendly turbine.

## **Conclusions and Recommendations**

The main conclusions and recommendations of our review were:

1. Studies with spill in conventional Columbia River spillways affirm the basic flow-following response of juvenile salmonids. There is not a straightforward inverse relationship between the percentage of fish entering the turbine intakes and the percentage of water spilled, although spill generally does remove many fish from the turbine pathway. A major factor affecting whether fish follow bulk water flow is the depth of withdrawal, with surface water having a greater likelihood of carrying fish than deep water. The first priority for a fish-friendly turbine *system* in migratory salmonid waters should be one that bypasses as many downstream-migrating fish as possible along these fish's natural surface-oriented migration pathway away from deep turbine intakes.

2. The basic surface orientation of migrating juvenile salmonids has been abundantly demonstrated. Once in a turbine intake, fish orient to the upper portion of the watermass, often passing along the ceiling where traveling screens have been somewhat effective in removing them from the flow. Horizontal distribution is more uniform, but probably is affected by vortices and other flow instabilities characteristic of a site. Thus, juvenile salmonid entry to the turbine itself will not be uniform across the cross-section of the watermass entering the turbine. Further report evaluation and data collection and analyses are needed to specify fish cross-sectional distribution in a mathematically rigorous way for species, sizes, and intake geometries in order to quantitatively specify fish trajectories through turbines.

3. Fish entering turbine intakes may be oriented in several ways, depending on the species and the migration tendencies of the fish at the time. Underyearling chinook salmon (the smallest migrants) appear to move in a head-upstream manner. They likely maintain that attitude as they enter turbines. Yearlings (the larger fish), especially steelhead, appear to swim rapidly, directed downstream. Yearling chinook salmon may show both types of orientation, but could be oriented head downstream in the accelerating flows of a turbine intake. Further analysis is needed using hydroacoustic and underwater television data, both new and as related to submerged traveling screens, as indicators of species- and size-specific fish orientation as they enter turbines.

4. Schools of juvenile non-salmonid fishes that reside in the open waters of large rivers or tidal estuaries are most vulnerable to entrainment in turbine intakes. Their entrainment is accidental and not related to flow-following behavior. Particularly susceptible freshwater fishes are juvenile gizzard shad and freshwater drum. Few adult gamefishes, which are more oriented to bottoms and shorelines, are vulnerable. Horizontal distribution of entrainment is often not uniform for these species. Susceptible freshwater fishes are generally forage species with high reproductive potential. There has been no special effort to study the orientation of these fishes in turbines. Considerably more justification would be needed for commitment of major expenses for fish-friendly turbines in freshwaters occupied by non-migratory species.

5. A high percentage of non-salmonid entrainment in hydropower turbines, as in steam electric power station intakes, is of forage species that are made comatose by rapid temperature declines or prolonged cold weather in autumn and winter. Fish in these conditions are not likely to exhibit avoidance or orientation behaviors that would cause them to differ from passive particles during transit through turbines. Simulation of many non-salmonids as passive objects seems appropriate.

6. Models of fish trajectories cannot assume neutral buoyancy throughout the time a fish passes through a turbine. Fish without swim bladders that depend on activity to maintain themselves will likely lose control and be negatively buoyant. With numerical values depending on source depth in the forebay, fish with swim bladders will become progressively more dense as they descend to the turbines and then positively buoyant as they are discharged to the draft tube and dam tailwater. The significance of differences from neutral buoyancy and of changes in buoyancy during fish trajectories through a turbine should be established from modeling studies of fish with a range of constant and changing densities.

7. Lateral-line sensing of obstacles occurs rapidly and can affect fish orientation. However, it is unclear whether sensations in turbines will affect fish orientation markedly in the very rapid passage times. Further study of reaction times is needed. Models can tentatively assume that orientation of fish as they enter the scroll case will be retained as they transit the turbine itself (or at least that the fish will not be able to control its orientation in a turbulent environment), under the assumption that reaction times are too long for the rapid flow rates.

8. The use of unsteady fluid flow by fish in migrations is speculative at this point, but may lead to focused research of value to the design of turbine systems, especially draft tubes and tailwaters, that better match the natural migratory behavior of juvenile salmonids. Research on the orientation in and use of unsteady flows by migrating juvenile salmonids is needed.

9. The importance of pre-existing stress levels for fish performance (especially as they affect trajectories) in turbine passage is not known. It is important for modeling of fish trajectories to know whether the behaviors modeled and responses seen are representative or skewed by virtue of a pre-existing stress. Testing of fish behavior in turbines should include background information on pre-existing stress levels, and experiments should use fish in both test and control lots that have been given known amounts of prior stress.

10. Practical limits of observation and measurement of fish and flows in the proximity of turbine runners may inhibit development of much information that is germane to developing a more fish-friendly turbine. Innovative means for obtaining information on fish behavior near turbine runners should be pursued, but there should be realistic expectations about the feasibility of this research.

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