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EVALUATION OF THE EFFECTS OF TURBULENCE ON THE BEHAVIOR OF MIGRATORY FISH

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U.S. Department of Energy
Bonneville Power Administration
Division of Fish and Wildlife

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1. INTRODUCTION

The fundamental influence of fluid dynamics on aquatic organisms is receiving increasing attention among aquatic ecologists. For example, the importance of turbulence to ocean plankton has long been a subject of investigation (Peters and Redondo 1997). More recently, studies have begun to emerge that explicitly consider the effects of shear and turbulence on freshwater invertebrates (Statzner et al. 1988; Hart et al. 1996) and fishes (Pavlov et al. 1994, 1995).

Hydraulic shear stress and turbulence are interdependent natural hydraulic phenomena that are important to fish, and consequently it is important to develop an understanding of how fish sense, react to, and perhaps utilize these phenomena under normal river flows. The appropriate reaction to turbulence may promote movement of migratory fish (Coutant 1998) or prevent displacement of resident fish. It has been suggested that one of the adverse effects of flow regulation by hydroelectric projects is the reduction of normal turbulence, particularly in the headwaters of reservoirs, which can lead to disorientation and slowing of migration (Williams et al. 1996; Coutant et al. 1997; Coutant 1998). On the other hand, greatly elevated levels of shear and turbulence may be injurious to fish; injuries can range from removal of the mucous layer on the body surface to descaling to torn opercula, popped eyes, and decapitation (Neitzel et al. 2000a,b). Damaging levels of fluid stress, such turbulence, can occur in a variety of circumstances in both natural and man-made environments.

This report discusses the effects of shear stress and turbulence on fish, with an emphasis on potentially damaging levels in man-made environments. It defines these phenomena, describes studies that have been conducted to understand their effects, and identifies gaps in our knowledge. In particular, this report reviews the available information on the levels of turbulence that can occur within hydroelectric power plants, and the associated biological effects. Furthermore, this report describes an experimental apparatus designed to test the effect of turbulence on fish, and defines its hydraulics. It gives the results of experiments in which three different fish species were exposed to representative levels of turbulence in the laboratory.

2. DEFINITIONS

In this section we define terms and expressions of fluid and flow properties that are useful to understanding the hydrodynamic environment associated with hydroelectric power plants. Some of the mechanisms, such as turbulence, which is the subject of this research project, and shear stress, are believed to be harmful to fish at high levels. It is important to understand the nature of these mechanisms and how they act on turbine- and spillway-passed fish. This will facilitate development of the appropriate biological response curves between the independent variable (velocity, turbulence shear stress, or force) and the dependent variables characterizing the flow (fish response, disorientation, injury, or mortality). These mechanisms provide a link between fluid properties that can be measured or estimated in a test facility and possible biological effects that will be quantified.

Force

Force, F, is defined as the rate of change of momentum with respect to time or the product of mass multiplied by acceleration, and is expressed in Newton (N or $kg{\cdot}m/s^2$). For a fish striking a wall, the force would be the mass of the fish multiplied by the deceleration. A massive fish rapidly decelerating from 10 m/s to 0 m/s would experience more force hitting the wall than a small fish moving in the low-velocity boundary layer along the wall. This same relationship is true if, instead of a wall, the fish encounters another water mass of different velocity. Important factors that govern the effect of force are (1) size of the fish (larvae have lower mass than adults so they strike the wall/water mass with less force), (2) life stage (larvae are more sensitive to a given amount of force than adults), (3) the way in which the fish strikes the wall or water mass (whole side of the body vs. head-on). This last factor leads to a consideration of pressure. Pressure is force per unit area, applied perpendicular to the body surface, expressed in N/m^2. If all the force (fish's mass multiplied by acceleration/deceleration) of striking the wall is focused on one small point (eyeball), there will be much greater pressure and injury than if the entire side of the fish's body strikes the wall. The force associated with the different water mass could be distributed relatively uniformly over the whole body, or experienced as a pinpoint jet. The location and amount of a fish's body upon which the forces are focused have a bearing on the resultant damage. This aspect of force distribution over the fish's body is beyond the scope of this study.

Reynolds Number

Forces acting on a flowing fluid include inertial, gravitational, viscous, and pressure, among others. Dynamic similitude in hydraulics uses mathematical expressions relating these forces, in a normalized form, to describe a physical process. The result of using dimensional analysis to describe a flow process produces meaningful dimensionless numbers, such as Reynolds and Froude numbers. Each of these numbers highlights the relative importance of the dominant force influencing that process (Rouse 1946). For example, the Froude number highlights the relative importance of gravitational forces in steady non-uniform flows, and the Reynolds number highlights the relative importance of viscous action within the flow field.

Using the fluid properties, such as velocity, density, and viscosity, and a characteristic length in the flow field, we can obtain expressions for relative importance of inertial and viscous forces. The ratio of inertial to viscous forces gives the dimensionless Reynolds number (Rouse 1946; Flammer et al. 1982; Vogel 1994). The ratio of the fluid dynamic viscosity, μ, to its density, ρ, is often referred to as the kinematic viscosity, $\nu = \mu/\rho$, in the widely used form of the Reynolds number:

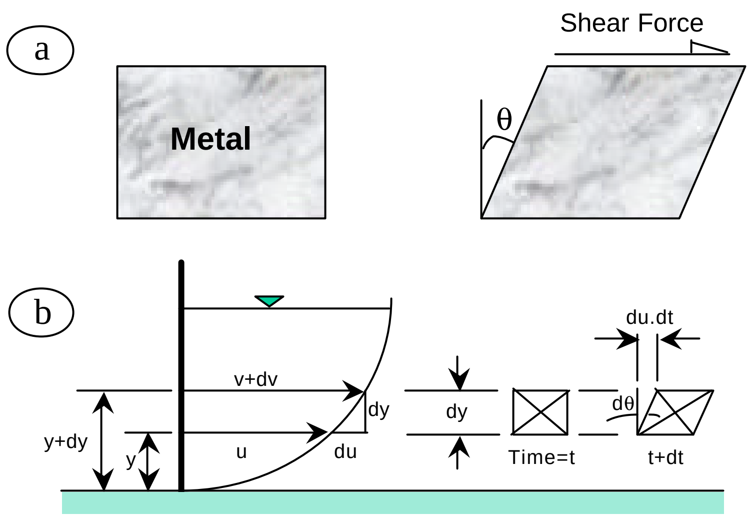
$$\mathrm{Re} = \frac{L \cdot U}{n} \qquad (1)$$

where U is the mean velocity of the fluid, ν is the fluid's kinematic viscosity, and L is a characteristic length. In the case of a full flowing pipe, L is its diameter, or, for a solid immersed in a fluid, L is the characteristic length taken to be the greatest length of that solid in the flow direction.

Because the Reynolds number is proportional to a product of length and velocity within the flow field, its value can range widely in nature. The Reynolds number of a whale swimming at 10 m/s is 14 orders of magnitude greater than that of a bacteria swimming at 0.01 mm/s (Vogel 1994). The Reynolds number is used as a parameter to describe the laminar versus turbulent nature of a flow. At a Reynolds number of about 1,500 or less, the flow tends to be laminar. Above this value, flows become turbulent. A discussion of the nature of turbulence in different parts of the turbine system is provided in Section 3.

Hydraulic Shear Stress

Force acting parallel, or tangential, to a surface is referred to as shearing force. When a tangential force (shearing force, F_V) is applied to a solid, the cohesive forces between its molecules try to maintain its shape. As the shape of the solid changes, the cohesive forces increase; until the solid is permanently deformed, see Figure 1a. However, the cohesive forces resisting shear in a liquid are significant only when adjacent layers are moving at different velocities (Flammer et al. 1982). This is to say the rate of change of velocity, u, with respect to distance away from a boundary, y, is greater than zero (i.e. *du/dy* ... 0), see Figure 1b. Shear stress in a liquid, therefore, depends greatly on its viscosity.



Rate of strain of a fluid element due to effects of viscosity

Figure 1. Schematics showing the distortion due to shear forces in **a**) metals; and due to viscous forces in **b**) fluids.

Viscosity, μ, is a fluid property, which indicates the fluid's internal resistance to relative motion between its adjacent layers. This means that the shearing force, F_V, is proportional to this rate of change of velocity of the flow with respect to distance, (i.e. $F_V \propto du/dy$). The ratio *du*/*dy* is also called the *rate of strain or rate of deformation* of the fluid (Rouse 1946). Viscosity, μ, is defined as the proportionality constant between shearing stress, τ, (which is the shearing force divided by the area, i.e. $\tau = F_V/A$) and the rate of strain of the fluid (or rate of deformation) (*du*/*dy*). This is to say, $\mu = (F_V/A)/(du/dy)$.

Therefore, by rearranging the terms, the shear stress, τ, for viscous laminar flows is defined as:

$$\tau_{\text{laminar}} = \mu\left(\frac{du}{dy}\right) \qquad (2)$$

It turns out that the relationship in (2) describes shear stresses in laminar flows, where viscous effects are substantial and the Reynolds' number, $R_e = u{\cdot}d/\nu$, is equal to 1,500 or less (White 1992). In the formula for R_e, *u* is velocity in m/s, d is a characteristic length in m, and ν is the kinematic viscosity in m^2/s. In nature, fluid particles move and, therefore, deform in all directions. Hence, the fluid's rate of strain in a three-dimensional flow field can be expressed as ($du/dy + dv/dx + dw/dz$).

In most hydraulic systems, such as streams and hydropower systems, flows are turbulent (Nezu and Nakagawa 1993). The total shear stress is, therefore, affected by the instantaneous fluctuations in the flow field. Turbulence and shear stress are interdependent, obtaining the turbulent shear stress requires a term that describes the apparent viscosity of the flow (also called eddy viscosity, ε). This eddy viscosity is added to the dynamic viscosity, *m*, of the fluid to obtain the turbulent shear stress. Therefore, for turbulent flows, Eq. (2) is modified to become:

$$t_{\text{turbulent}} = (m + e)\left(\frac{du}{dy}\right) \qquad (3)$$

Unlike μ, the eddy viscosity *e* is not a fluid characteristic and there are no tables that give values for ε. Eddy viscosity is dependent on how vigorous the turbulence is, and must be found by experimentation. If the flow is entirely laminar, *e* is zero and Eq. 2 reduces to Eq. 1. For fully turbulent flow, effects due to dynamic viscosity are negligible ($m << e$), and Eq. (2) reduces to:

$$t_{\text{turbulent}} = e\left(\frac{du}{dy}\right) \qquad (4)$$

Shear stress is, therefore, a property that involves a velocity gradient (*u*, measured in m/s). Water velocity is important for transporting organisms or their food and for creating aquatic habitats in a natural stream. In artificial conduits, where velocities are fairly uniform, a fish moving at 0.2 m/s or 20 m/s will not be injured or disoriented. However, when water velocities gradients change on scales comparable to the size of a fish, damaging shear stresses can occur in any hydraulic system.

Shear stress occurs when two water (a viscous fluid) masses or layers of different velocities are adjacent to each other. As mentioned above, shear stress is directly proportional to the rate of change in water velocity over distance (rate of strain of the fluid). That is to say, if velocities of two adjacent water masses differed by 3 m/s over a distance of 0.1 m, the resultant rate of strain would be 30 m/s/m. However, if water were a non-viscous fluid the fish would just spin freely in the flow field and would not experience any harm (other than maybe dizziness).

Hydraulic Turbulence

At high water velocities and because of edge effects and surface roughness of structures, given that water is a viscous fluid, flows in a hydropower turbine system are turbulent, rather than laminar. The tendency of water molecules to resist shear forces, due to the presence of viscosity, causes them to move irregularly. The shear stresses within a flow field tear the fluid into highly energetic, irregular, and three-dimensional eddies, with scales ranging from the size of the flow passage down to unity (Miller 1990). These eddies exist randomly in space and time in turbulent shear flows (Nezu and Nakagawa 1993). Turbulent flow occurs when fluid particles move in a highly irregular manner, even if the fluid as a whole is traveling in a single direction. That is, there are intense, small-scale motions present in directions other than that of the main, large-scale flow (Vogel 1994). Unlike laminar flow, which is most easily described by exact equations, turbulent flow can only be defined statistically (Gordon et al. 1992; Nezu and Nakagawa 1993); descriptions of the overall motion within turbulent flows cannot be taken as describing the paths of individual particles (Vogel 1994).

Within a turbine system, natural river, or laboratory test apparatus, flows are so turbulent it would be difficult to separate the effects of normal forces that cause pressure from tangential forces that cause shear stress. The fluid stresses exerted on the fish will be a combination of the normal and tangential forces.

It is believed that fluid stresses are not uniformly applied to a fish; a fish encountering high-velocity water head-on is more likely to experience more shear stress on the head than on the tail. Also, resistance of a fish to shear stress and turbulence maybe size-specific; e.g., small rainbow trout may be less resistant than large rainbow trout. Resistance is certainly species-specific (e.g. eels are more resistant than shad) and probably life stage-specific (e.g. adults are more resistant than larvae; non-smolted chinook salmon juveniles are more resistant than chinook salmon smolts).

Turbulence Intensity

The pattern of turbulence within a turbulent flow field continuously changes with time (Rouse 1946). Therefore, in order to describe the turbulence in that flow field a continuous record of the instantaneous velocities at the point of interest must be kept; that is essential to perform the necessary statistical analyses. Using the instantaneous velocities turbulence can be described by a measure called *turbulence intensity* (Gordon et al. 1992).

The local velocity in a turbulent region is composed of a temporal mean value plus a component that represents the turbulent fluctuation about the mean. The turbulence intensity is a measure of the magnitude of the turbulent fluctuations about the mean. When a series of instantaneous velocity measurements are made at a point, the turbulence intensity at that point can be expressed as the root mean square of these measured values.

$$\text{Root Mean Square } = \sqrt{\frac{\sum_{i=1}^{n}\left(v_i - v_{ave}\right)^2}{n}} \qquad (5)$$

where v_i is the instantaneous velocity measurement, v_{ave} is the mean velocity of the flow, and n is the number of instantaneous velocity measurements. Eq. 5 yields a value for turbulence that is expressed in terms of velocity units, e.g., m/s. This formulation has been reported in studies by Pavlov and Tyuryukov (1993) and Skorobogatov et al. (1996).

An alternative, but similar, expression of turbulence intensity is found by dividing the standard deviation of the velocity (s) by the mean velocity:

$$K_t = \frac{s}{v_{ave}} \qquad (6)$$

This dimensionless ratio is an expression of the relative intensity of turbulence. It has been used, for example, by Lacoursiere and Craig (1990) and a series of Russian papers (Pavlov et al. 1982; Pavlov et al. 1994; Lupandin and Pavlov 1996). When multiplied by 100, K_t is reported as a percentage.

Turbulence Scale

The size of the turbulent fluctuations, i.e. *turbulence scale*, is also an important consideration (Nowell and Jumars 1984; Peters and Redondo 1997). Globally, turbulence of biological interest can occur in scales as large as 10^4 m or more in the ocean down to microscopic scales affecting the movements and feeding of individual planktonic organisms. Turbulence exists at a wide variety of scales in a river, from the swirling motion created when a salmon scoops out a redd (scales smaller than the size of the fish) to large pulses of flow in a river (scales much larger than a fish). Similarly, within a hydropower turbine turbulence occurs at different scales (Figure 2). Smaller-scale turbulence, which occurs throughout turbine passage, can distort and compress portions of the fish=s body. Larger-scale turbulence may be most pronounced in the draft tube and tailrace, where water flow is decelerating, expanding into a larger passage, and has a swirl imparted on it by the turbine runner. Fixed structures in the draft tube (walls and support piers) may cause secondary flows, i.e., flows moving in opposite directions from the main flow moving out of the draft tube and into the tailrace. Similarly, the configuration of the tailrace can also cause backflows (Atailrace roll") that impede the downstream movement of turbine-passed fish. These chaotic flow conditions (small-scale turbulence, larger-scale flow pulses, vortices, and secondary flows) will distort and spin the fish, and at the least may cause disorientation. It has been suggested that this turbulence-caused disorientation, while perhaps not injuring the fish directly, may leave turbine-passed fish more susceptible to predators in the tailrace.

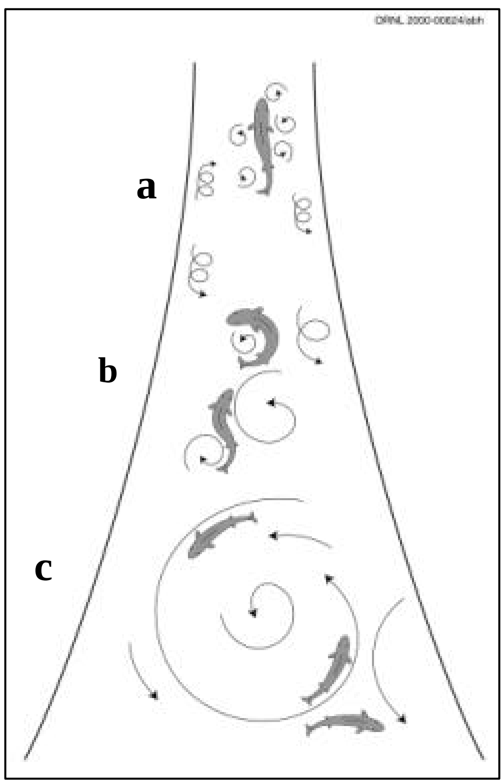


Figure 2. Turbulence scales compared to the size of a fish.

Shear force, shear stress, and turbulence are inextricably linked. For any but the smallest pipes and lowest velocities (in which laminar flows occur), shear stress will cause turbulent eddies. Similarly, turbulent flows, by definition, will create shear forces and shear stresses, because parcels of water that are moving in different directions and with different velocities will interact.

In terms of adverse effects on fish there are areas within a turbine in which either shear stress or turbulence predominate. Near a solid-liquid boundary (for example, the runner blade or turbine wall), water velocity decreases very rapidly from the mean velocity of the bulk flow, say 15 m/s, to the non-slip velocity of zero at the solid surface. Some of the energy associated with the large shear stress in this boundary layer is shed as turbulent vortices, but the damage to the fish caught in the boundary layer is caused less by chaotic motions of water particles (turbulence) than by the fact that a portion of its body is proceeding downstream at a different velocity than another portion, leading to distension, compression, bending, torsion, and localized damage. Turbulence is certainly present in the boundary layer, but its adverse effects are overshadowed by the high values of shear stress (Figure 2 a and b).

Elsewhere in the turbine system, larger-scale turbulence may overshadow the effects of localized shear stress. In the draft tube outlet and tailrace, where flow is expanding and slowing, velocity differentials are lower compared to those associated with boundary layers within the turbine. Consequently, the shear stresses will be lower as well and are less likely to exert forces great enough to damage fish. In these areas, however, turbulence may be quite high and of a scale larger than that of the fish. In that case, the motion of the fish's body will also be chaotic, like the water surrounding it. Turbulence scale is important because the forces associated with tiny turbulent eddies will cause localized damage (bruises, scale loss) (Figure 2a). Turbulence at a larger scale, e.g., several times the size of the fish, will agitate and spin the fish (Figure 2c). It is believed that residence in an area of large-scale turbulence for enough time will cause the fish to become disoriented, lose equilibrium, have a reduced swimming capacity, and potentially become more susceptible to predators.

3. SHEAR STRESS AND TURBULENCE IN THE HYDROPOWER SYSTEM

Shear Stress and Turbulence in Rivers

Levels of shear associated with average flows in natural streams are generally small (Table 1). For example, many stream salmonids inhabit low velocity resting positions from which they make short forays into adjacent faster water to feed on drifting invertebrates. Hayes and Jowett (1994) measured the velocity differences encountered by large brown trout in these normal feeding forays and estimated rate of strain exposures no greater than 5.0 m/s/m. Velocity changes experienced by 15 to 30-cm-long brook trout feeding in a Michigan stream resulted in strain rates of 0.6 m/s/m or less (Fausch and White 1981). In relatively low-turbulent flows, these values would produce shear stresses of less than 1 N/m^2. Lancaster and Hildrew (1993) measured near-bed shear stresses in small streams; shear stresses were less than 1 N/m^2 at moderate discharges and less than 7 N/m^2 at high discharges. Statzner and Müller (1989) reported 90 measurements of shear stress values at the bottoms of 3 streams. Estimates of shear stress were generally less than 200 N/m^2; most data points were less than 30 N/m^2.

Table 1. Estimates of shear stress (N/m^2) in natural and altered aquatic systems.

Environment	Shear stress (N/m^2)	Reference
Water column in a trout stream, average flow	< 1.0	Fausch and White (1981)
Small streams, near bed	<1-7	Lancaster and Hildrew (1993)
Medium-sized streams, near bed (90 measurements)	most <30, but some >200	Statzner and Müller (1989)
Flash floods, small basins	61-2600	Costa (1987)
Floods, large rivers	6-10	Costa (1987)
Bulb turbine draft tube	500-5,421	McEwen and Scobie (1992)
Near ships' hulls and wakes	7.6-40.4	Morgan et al. (1976)
Near barge propeller	$\geq$ 5,000	Killgore et al. (1987)

On the other hand, Costa (1987) calculated the shear stresses associated with maximum rainfall-runoff (flash) floods in 11 small basins in the United States. Mean shear stress values ranged from 61 N/m^2 to 858 N/m^2. He also alluded to unpublished shear stress estimates from four other flash floods in small basins that ranged from 1500 to 2600 N/m^2. By comparison, large rivers, such as the Mississippi and Amazon, produce shear stresses of 6 to 10 N/m^2 in flood. Costa (1987) noted that shear stresses are often higher in small basins than in large basins because shear stresses depend not only on discharge but also on hydraulic radius, energy slope, and mean velocity.

It is well known that fish sense and respond to shear stress and turbulence in natural waters. Fish can sense variations in pressure and water velocity on the body surface, especially by means of their lateral line and inner ear (e.g., review by Dijkgraaf 1963). However, what is less well understood are the patterns (if any) of response to these stimuli.

Much of the Russian literature has been focused on the ability of non-migratory fish to maintain position in low velocity, moderately turbulent flows, rather the effects of high, potentially damaging levels of turbulence. For example, Pavlov et al. (1982; 1994) found that increasing the turbulence intensity decreased the fish's critical velocity, i.e., the maximum velocity at which a fish can sustain itself in a stream. They concluded that energy expenditures will be greater for fish attempting to maintain position in streams with turbulent flows because such streams possess more kinetic energy. Surprisingly, Lupandin and Pavlov (1996) found that starved fish tended to select turbulent flows over non-turbulent flows (both water velocities and turbulence were low), possibly because of increased feeding opportunities. Non-migratory fish chose different levels of turbulence, depending on species (rheophilic vs. limnophic groups) and also previous experience (Skorobogatov et al. 1996). When given a choice, fish that inhabit rivers (e.g., gudgeon and grayling) selected water flows with relatively strong turbulence whereas lake-dwelling fish (e.g., crucian carp) preferred low turbulence.

Pavlov and Tyuryukov (1993) compared the reactions to water currents of dace that were intact or had their lateral line or inner ear disabled. Fish whose lateral lines were disabled by means of a topically applied anaesthetic were still able to maintain proper orientation in both laminar and turbulent flows, but may have had a reduced ability to detect irregularities in the velocity field and to avoid obstacles. On the other hand, compared to unstressed fish, dace that had their inner ear disrupted by centrifugation (10-minute period of swirling flow) were unable to maintain normal orientation in turbulent flows and avoid obstacles. Both of these effects, i.e., the disorientation arising from exposure to swirling flows and the diminished ability to sense and avoid objects in the water, could be expected to increase the fish's susceptibility to predators.

Coutant and Whitney (2000) suggested that turbulence in rivers is used by anadromous fish to speed downstream migration. They believe that migrating juvenile salmon may seek out features of unsteady flow (e.g., turbulent bursts, vortices, and waves) in rivers to find regions of higher velocity than that of the bulk flow. Such features of turbulence as vorticity cannot be measured directly, but must be derived from integrating measurements of velocity at multiple points; Hanke et al. (2000) suggested that the fish's lateral line could serve this purpose. Although the response of juvenile salmonids to natural turbulence has not been extensively studied, Coutant (1998) pointed out that anadromous fish evolved in turbulent rivers, and it would be surprising if they did not take advantage of opportunities to utilize the kinetic energy from turbulence to reduce the metabolic energy needed for swimming. If true, this idea would suggest that there are optimal levels of turbulence for migrating salmonids. If turbulence is too high (as within a turbine draft tube, tailrace, or spillway), it could damage or disorient the juvenile fish. If it is too low (as within a stagnant reservoir), missing are not only the downstream guidance cues and transport function associated with the bulk flow, but also the ability to capitalize on energy associated with large scale, low intensity turbulence.

Shear Stress and Turbulence Associated with Ships

Large vessels, such as commercial barges, can increase shear stress and turbulence in rivers. Mazumder et al. (1993) measured variations in longitudinal, lateral, and vertical water velocities in the Illinois River, both under natural conditions and in response to passing barges. The movement of a barge in a restricted channel displaces water, creates surge waves in front of the bow, and generates turbulence (both from water displacement by the hull and action of the propeller). They found that the barge generated larger eddies and more turbulent transverse shear than the natural flows of the river. Maximum values of shear stress from barge passage occurred near the shore, and decreased to near zero in the central zone between the shore and the barge.

In order to assess the effects of shipping on fish eggs and larvae in the Chesapeake and Delaware Canal, Morgan et al. (1976) used rotating concentric cylinders to create shear zones in 30.5-cm-diameter chambers. Striped bass and white perch eggs and larvae were introduced into the layer of water between the cylinders, and consequently exposed to calculated shear stresses ranging from 7.6 to 40.4 N/m^2 for periods of 1 to 20 minutes. Both eggs and larvae were sensitive to these low levels of shear stress. For example, shear stresses of 35 N/m^2 killed an average of 38 percent of the white perch larvae in 1 minute, 52 percent in 2 minutes, and 75 percent after 4 minutes exposure. The authors developed a set of regression equations, which related the amount of shear stress to expected mortality among these fish early life stages. They concluded that shear forces generated by the hull of a large vessel would be unlikely to kill fish eggs and larvae over a brief exposure time. They did not attempt to estimate shear forces and turbulence associated with a ship=s propeller.

Maynord (2000) estimated that shear stress associated with the hull of a high-speed, five-barge-long commercial tow on the Upper Mississippi-Illinois Waterway System (UMR-IWWS) would be greater than 250 $dynes/cm^2$ in only 5 percent of the water mass beneath the tow. Shear stress would be greater than 135 $dynes/cm^2$ in 50 percent of the region beneath the tow. Vessel passage times (= exposure times for fish) would be around 1-2 minutes. Applying the bioassay data from Morgan et al. (1976), he estimated that hull shear (not including that caused by the propellers) associated with a typical UMR-IWWS tow could cause an average of 9 percent mortality among fish eggs and larvae.

Killgore et al. (1987) examined the effects of turbulence on survival of paddlefish yolk-sac larvae in the laboratory. Paddlefish larvae were placed in circular containers and exposed to differing frequencies and intensities of turbulence created by water jets. Turbulence in the laboratory chambers was expressed in terms of both water velocities (cm/s) and pressures ($dynes/cm^2$). The investigators found that turbulence intensity was more lethal than frequency of disturbance. Low turbulence (1,774-1,902 $dynes/cm^2$; 177-190 N/m^2; 21.5-22.8 cm/s) caused 3 and 13 percent short-term mortality, whereas high turbulence (6,219-6,421 $dynes/cm^2$; 622-642 N/m^2; 56.5-59.3 cm/s) resulted in 87 and 80 percent short-term mortality. Longer-term direct mortality, indirect mortality, and physiological stress were not examined. Based on these laboratory studies and field measurements of pressures near commercial barges (which sometimes exceeded 50,000 $dynes/cm^2$ [5,000 N/m^2]near the propellers), Killgore et al. (1987) suggested that turbulence generated in the immediate vicinity of commercial vessels could cause mortality among paddlefish larvae.

Recognizing that shear stresses and turbulence caused by tow boat propellers are much larger than those induced by the hull, Killgore et al. (2000) exposed fish eggs and larvae to a scale model propeller in a recirculating water channel. In their experiment, observed mortalities resulted from a combination of fluid stresses (shear and turbulence) and propeller blade impact. Sensitivity varied with species and life stage, but was directly related to the calculated magnitude of shear stress. Significant mortalities were observed for most species at the highest shear stress levels; for example, 83 percent of lake sturgeon larvae were killed by exposure to 4,743 dynes/cm^2. High shear stresses can occur in the zone between the propeller blades, the zone downstream of individual blades, near the hub, and within and around the perimeter of the propeller-induced jet. The authors concluded that fluid stresses in the zone of influence of tow boat propellers can be a major source of mortality for larval fishes and a relatively minor source of mortality to fish eggs and juveniles.

Shear Stress And Turbulence Inside Turbines

The spatial change of velocity inside a turbine varies greatly. It is most pronounced near the boundaries. The highest values of shear stress are therefore found close to the interface between the flow and solid components, such as the turbine blade leading edges, stay vanes, and wicket gates. Present views suggest fish sustain injuries, sometimes lethal, when they are in 'damaging' shear stress zones within the turbine system; injuries are believed to be dependent on fish species and size, and their orientation upon entry of the shear zone (USACE 1995). „ada et al. (1997) gives a summary of attempts of various researchers to verify the limits of shear stress at which a fish of certain size and species sustains injury using laboratory experiments. In order to find these limits some researchers introduced fish to a varying velocity submerged water jet, some used up to 36.6 m/sec (Groves 1972; SWEC 1975; Turnpenny et al. 1992). Other researchers sent fish through a 35.5 cm pipe ending with varying size nozzles (Johnson 1970a; 1970b; and 1972). Results varied according to the test fish size, species, and methodology used.

Typical velocity changes across shear zones inside turbines are on the order of 9.1 m/sec, which is higher than velocity gradients inside Kaplan turbines (USACE 1995). Vortices within the flow cause shear stress. These can be found inside turbines due to leakage near wicket gates and runner blades (USACE 1995). Shear stress zones should be minimized to enhance fish survivability. Vortices exist in the draft tube swirl. They cause shear stresses and may be a primary source of shear stress damage to fish in Francis turbines (USACE 1995).

Shear Stress and Turbulence at Hydroelectric Power Plants

McEwen and Scobie (1992) estimated that shear stresses within a reference bulb turbine could average over 500 N/m^2; maximum values were estimated to be 3,740 and 5,421 N/m^2 for "on-design" and "off-design" conditions, respectively. On the basis of these calculations, Turnpenny et al. (1992) designed a laboratory apparatus that could expose fish to localized shear stresses of this magnitude. They introduced fish into a high-velocity water jet submerged in a tank of static water, then examined the fish for injuries and long-term mortality. Jet velocities tested ranged from 5 to over 21 m/s, resulting in maximum shear stresses ranging from 206 to 3,410 N/m^2.

Salmonids (Atlantic salmon, rainbow trout, and brown trout) tested at the lowest shear stresses (maximum values of 206 and 774 N/m^2) experienced little scale loss, no loss of mucous coating, no other apparent injuries, and no mortality up to 7 days after the single exposure. Greater jet velocities and shear stresses resulted in more injuries and lower long-term survival (Turnpenny et al. 1992). For example, at the highest shear stresses tested (maximum value near the jet of 3,410 N/m^2), localized loss of mucous cover and some eye damage (corneal rupture; pop-eye; hemorrhaging in the eye) was noted; survival was around 90 percent 7 days after the test. Fish that died after exposure to the higher shear stress levels were heavily coated with fungus, probably because the loss of mucous increased their susceptibility to fungal infections.

Clupeids (shad, herring) were much more susceptible to shear stresses in the experiments of Turnpenny et al. (1992). All fish tested in the apparatus, even at the lowest maximum shear stress of 206 N/m^2, died within 1 hour. Many clupeids suffered eye damage, eye loss, torn and bleeding gills, and substantial loss of scales and mucous layer. At the other end of the scale, eels suffered no evident damage, other than some loss of mucous coating, and no 7-day mortality even at the highest shear stress levels tested.

Turnpenny et al. (1992) observed visible creases on the body surfaces of some fish entrained in the turbulent jet, which led to crushing of internal organs and internal hemorrhaging. Eye damage (corneal rupture, pop-eye, or red-eye) or eye removal were also common injuries among the fish exposed to these localized shear stresses. Finally, osmotic imbalance caused by loss of much of the mucous layer and underlying scales is believed to be the reason for the sensitivity of clupeids to even low levels of shear. Eels, which have substantial mucous layers, were not injured by high shear stresses.

Groves (1972) exposed juvenile salmon (total lengths ranging from 3.5 to 13.5 cm) to a water jet submerged in a tank of static water. In his experimental protocol the jet was brought to full speed (mean calculated velocities ranged from 9 to 37 m/s) and the fish were immediately introduced to the tank near the nozzle. Each test lasted only for the time needed to introduce the fish, usually less than a second. Thus, exposure to shear in this experiment was a brief, one-time exposure to high velocity water at the edge of the jet. The actual velocities and shear stresses experienced by fish were not measured. Some of the tests included high-speed photography to track the fishes' movements, and all tests examined the resultant types of injuries and mortality. Juvenile salmon were unaffected by exposure to the lowest velocity jet tested, 9 m/s. As jet velocities increased the rates of disorientation, visible injury, and mortality also increased (Groves 1972). Fish disabled (disoriented) but without visible injury usually regained normal capacities in 5 to 30 minutes. Visible injuries were mostly in the head region and included bulged or missing eyes, broken and ripped gill covers, and torn gills. Whereas visible injuries and mortalities were zero at 9 m/s, velocities of 15 m/s caused injuries in 2 to 59 percent of the fish in the test batches. At any given jet velocity, injury rates were inversely related to the size of the fish, i.e., 3-cm salmon were more often injured than 13-cm-long salmon.

Injury from the water jet was related to the part of the fish contacted and to the position of the fish relative to the jet flow direction at the time of contact (Groves 1972). Greatest injuries occurred when the jet contacted the head region and was moving from the rear towards the head of the fish. Larger fish were less affected if the jet initially contacted some other portion of the body than the head, or if the fish was facing into the jet stream. On the other hand, smaller fish were damaged irrespective of their orientation. Groves attributed this size-related difference in injury rates to the proportion of the fish's surface area struck by the jet. The jet struck a relatively larger portion of a small salmon's body, and at the higher velocities some were literally torn apart. Larger fish had a proportionately small portion of their bodies contacted by the margin of the jet, so injuries tended to be more frequent when initial contact was with more protruding or less rigidly attached parts of their head region, such as the gill structures and eyes.

Heisey et al. (2000) catalogued the injuries they observed on fish that had passed through hydroelectric turbines in the Pacific Northwest. In 10 studies, a loss of equilibrium was noted in 0.4 to 4.1 percent of the turbine-passed fish (depending on project), which they attributed to the effects of turbulence. Commonly, between 1 and 2 percent of the mid-blade-passed fish experienced loss of equilibrium. In the most recent study of turbine passage survival at Bonneville Dam First Powerhouse, 1.2 percent of the turbine-passed fish exhibited loss of equilibrium (Normandeau Associates et al. 2000). Passage route (i.e, whether the fish passed through the runner near the hub, near mid-blade, or near the blade tip) did not appear to affect the incidence of equilibrium loss.

Davidson (2000) described the nature of turbulence that is believed to occur within different parts of a hydroelectric turbine. His descriptions related to a typical Kaplan turbine installation on the Columbia River, but general characteristics apply to a large number of hydropower plants. The eight AHazard Passage Zones,@ starting at the turbine intake and ending in the draft tube outlet (Figure 3), are:

Zone 8 - *upstream of the submerged intake (fish) screens.* The water has low velocities (5 to 7 fps), low turbulence, and low potential for fish injury. Also, the horizontal components of the trash rack (upstream from the fish screens) can cause large turbulent wakes that propagate as much as 30 feet downstream and can affect velocity distributions.

Zone 1 - *immediately downstream of the fish screens*. The zone is characterized by an uneven velocity distribution (caused, in part, by the screens), high turbulence in the wake of the screen, and moderate velocity shear.

Zone 2 - *upstream from and within the scroll case*. Within the scroll case, velocities range from 8 to 15 fps, and flow is turbulent if fish screens are in place. Immediately upstream from the scroll case large, recirculating rollers may be created that cause an interchange of flow between bays and my create holding areas for fish.

Zone 3 - *wicket gates and stay vanes*. Water velocities accelerate rapidly in this region from 9 to 30 fps. Shear stress can be very high, especially near surfaces.

Zone 4 - *runner*. Very high velocities (and shear) occur near surfaces. Turbulence associated with the trailing edge of the runner and hub and blade tip gaps may be very high. Turbulent vortices are shed from the hub.

Zone 5 - *downstream of the runner to the draft tube*. Water velocities decrease in this expanding area from about 40 fps to 20 fps. All fish pass through this area of potentially high shear and high intensity turbulent vortices coming off trailing edges of the runner, gaps, and the runner hub.

Zone 6 - *draft tube*. The cross-sectional area continues to expand in this zone, resulting in decelerating flows, high turbulence, and very non-uniform velocity distributions within each barrel (section) of the draft tube. Adding to the chaotic nature of the flow, larger draft tubes have support piers that split the swirling flow (often unevenly) leaving the runner, causing turbulence and secondary (reverse) flows.

Zone 7 - *draft tube outlet to tailrace*. With increasing cross-sectional area, flows decelerate to an average of about 7 fps. This area is characterized by very non-uniform velocity distributions (in terms of both magnitude and direction of flow), large-scale turbulence, and potentially formation of a backroll that can trap fish in the tailrace. Hydraulic conditions here are expected to disorient, rather than directly injure, fish.

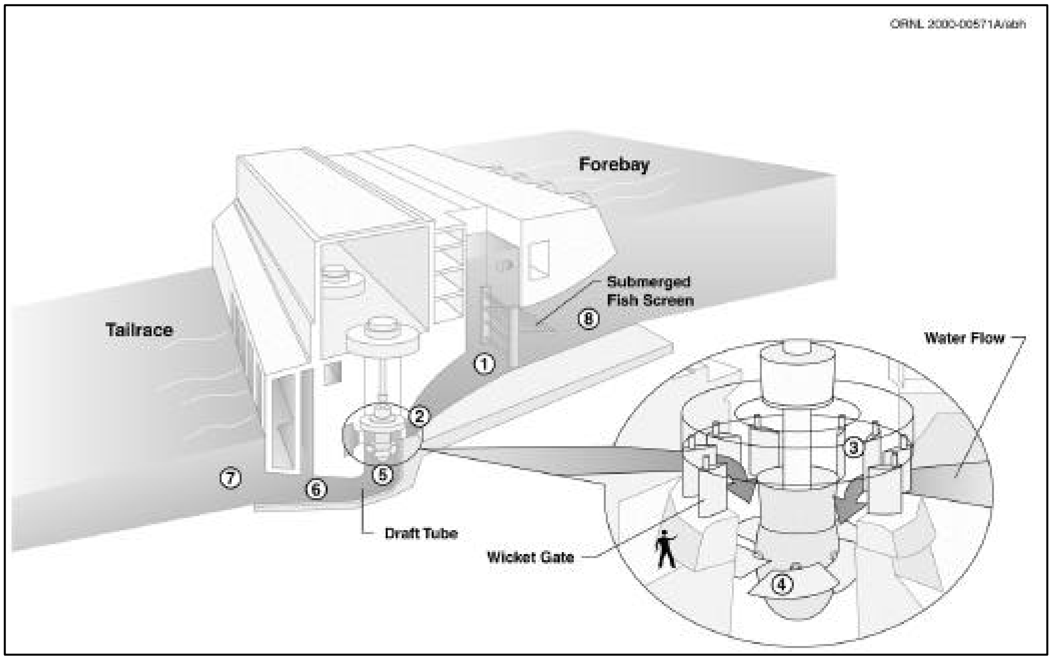


Figure 3. Eight Hazard Passage Zones associated with passage through a hydroelectric turbine. Based on Davidson (2000).

Much of the interest in studying the adverse biological effects of turbulence is focused on Zones 6 and 7, where turbulence is high and dominates other fish injury mechanisms. Draft tubes are designed to handle the maximum (nameplate) flow through a turbine. Unlike Kaplan turbines, in which wicket gate positions and blade angles are coordinated in order to operate efficiently under a range of hydraulic heads and flows, the geometry of draft tubes does not change with changes in flow. Compared with adjustable blade turbines, then, under most operating conditions, flows are transported through the draft tube inefficiently. These inefficiencies are dissipated as turbulence; in the upper draft tube (Zone 6), the tangential (sideways) velocity, which is proportional to turbulence, can be 50 percent of the axial (downstream) velocity (Rod Wittinger, personal communication). The energies associated with these turbulent flows can be expected to impact entrained fish.

There are numerous draft tube designs, ranging from a straight conical diffuser to configurations with bends and bifurcations (Gulliver and Arndt 1991). Diffuser designs are often tradeoffs that seek to minimize construction cost and effort while avoiding flow separations, unstable flow, excessive swirl, and vibrations that can affect turbine efficiency.

Water discharged from dams via spillways can reach velocities of tens of meters per second, which can create high values of shear stress and turbulence, especially near solid surfaces. At high velocities (12 to 15 m/s or more), surface irregularities can cause flow separations that are sufficient to lower water pressure below the local vapor pressure and cause cavitation (Chanson 1989). These extreme flow separations can occur within flow-expansion tunnels (such as draft tubes), along the floor of the spillway, near baffle blocks and other structures in stilling basins, and in association with vortices near gates and gate slots (Hamilton 1983). Flow separations that can cause cavitation might also be expected to exert damaging shear stress on fish being transported in these flows. The effects of spillway discharges on fish have not yet been rigorously examined. However, in 38 tests done at 6 hydroelectric projects in the Columbia River basin, Heisey et al. (2000) observed visible injuries among 0 to 7.0 percent of spilled/bypassed fish. No loss of equilibrium was seen in 23 of the 38 tests, but in the other 15 tests loss of equilibrium ranged from 0.1 to 4.7 percent among spilled fish.

In this study we expect to "explore" the possibility and means of studying the effects of turbulence on fish inside the laboratory. However, the time and funding resources allocated for this project made it unfeasible to run adequate number of experiments to obtain conclusive results.

4. EXPERIMENTAL STUDIES

Objectives and Hypotheses

The aim of this study was to assist in the understanding of the effects of hydraulic turbulence on downstream migratory juvenile fish. The objective was to create varying levels of turbulence that resemble conditions found downstream of a hydropower turbine, subject juvenile fish to these predetermined turbulence conditions, then test if there is a biological response. We attempted to create turbulent conditions that caused no direct injuries or mortality, but may change the fish' s behavior or reduce their swimming capacity or escape ability.

Examples of the hypotheses that were tested include:

1) Exposure of fish to known levels of turbulence for a period of 10 minutes may induce minor injury to some species.

2) Exposure of fish to known levels of turbulence for a period of 10 minutes does not reduce startle response in rainbow trout, but has a measurable effect in terms of increasing reduction in startle response with increasing turbulence for juvenile Atlantic salmon and hybrid bass.

3) Recovery of reduction in startle response from effects of turbulence at these scales is complete within 24 h for the species tested.

There could be a large number of these testable hypotheses, depending on the number of test conditions created in a similar experiment, the number of fish species/sizes to be tested, and the number of biological response variables to be measured.

Experimental Apparatus

A full understanding of the biological effects of turbulence at hydropower plants requires a combination of three approaches: laboratory experiments, computer modeling, and field studies. Controlled, replicable laboratory experiments can be used to develop biological criteria, i.e., the levels below which turbulence associated with turbine and spillway passage will not cause either direct or indirect mortality. Computational fluid dynamics (CFD) models can be used to predict turbine areas that were found (in laboratory studies) to have damaging levels of turbulence. Finally, field studies maybe used to verify predictions of laboratory and CFD studies.

Unfortunately, none of the above-mentioned methodologies has yet been used to describe the flow conditions within a tailwater of a turbine just downstream of the draft tube exit. In order to determine the appropriate tailwater conditions to test in our experimental apparatus, we contacted leading experts in the fields of hydraulics associated with hydroelectric power plants. These experts include university professors, government employees, and industry representatives. They informed us that to date such turbulence information is available only for the turbine system components found upstream of the tailrace, such as draft tube, scroll case, penstock, etc. Hydropower turbine tailrace field conditions are extremely chaotic and may be dangerous for researchers to study in the field. In addition, documenting tailrace turbulence intensities and scale in the field would require a special instrument to be deployed at various locations within a predefined grid system, for adequate periods of time at each location.

The absence of instantaneous velocity information needed to characterize field tailrace turbulence has made it challenging for us to develop turbulence design criteria for our laboratory apparatus. Therefore we decided to design a hydraulic system that simulates turbine draft tube exit and tailrace pool conditions. We used an array of nozzles that emitted jets with predetermined velocities to create the varying turbulent conditions.

We made our turbulence generating hydraulic system capable of providing a range of turbulence intensities and scales, we believe will encompass conditions found in hydropower tailraces. Owing to the present lack of information on tailrace turbulence characteristics, we designed the apparatus described below that can accurately and repeatedly reproduce a variable turbulent environment that encompasses shear stresses comparable to some of those given in Table 1.

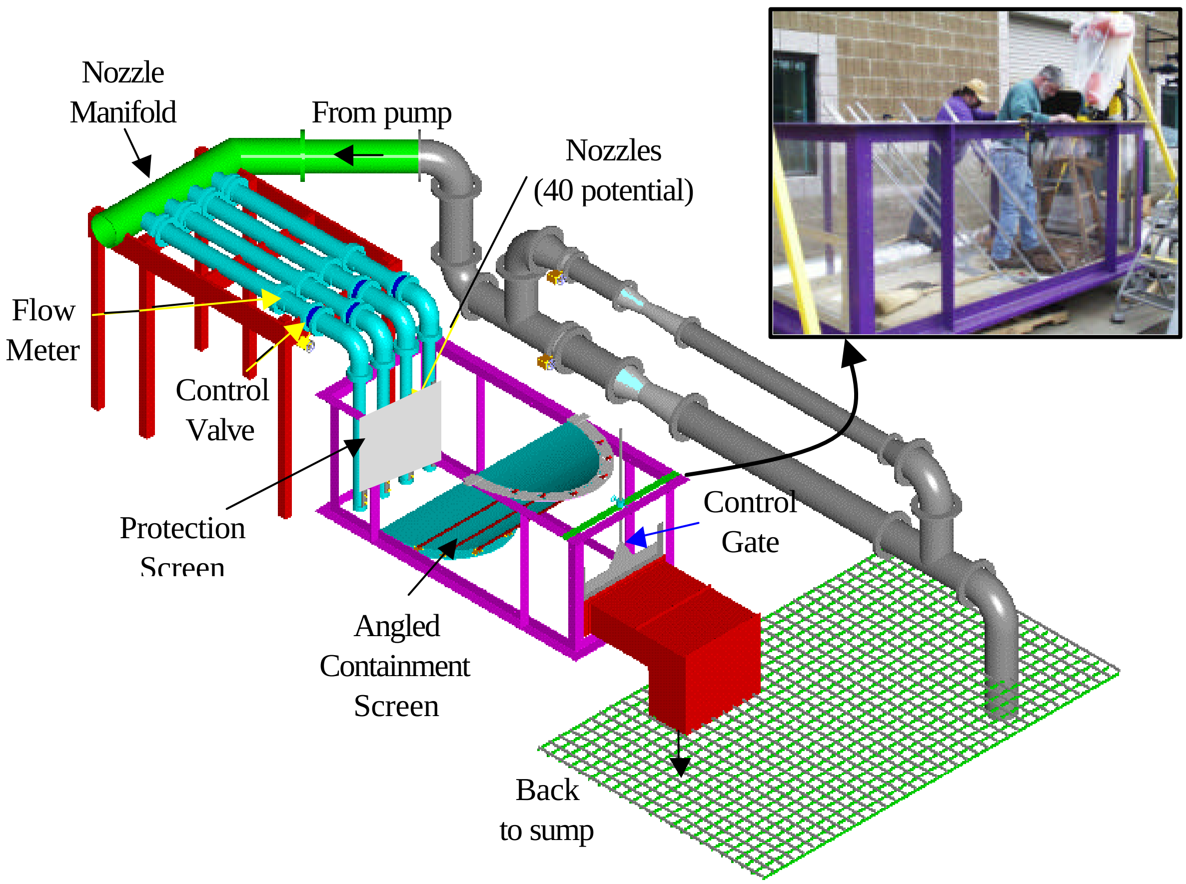


Figure 4. Experimental apparatus showing the turbulence tank and its supply and discharge piping at the USGS-Conte Anadromous Fish Research Center, Turners Falls, Massachusetts. Insert photos show the main tank under construction.

The turbulence tank was made out of steel members and Plexiglas sides and bottom. It measured 4 feet wide by 10 feet long by 4 feet deep (122 cm wide x 300 cm long x 122 cm deep). Water was supplied via a flow introduction manifold with four individual supply pipes, flow control valves, flow meters, and 10 nozzles per supply pipe. An adjustable control gate to the exit channel controlled water level within the tank. The large unobstructed area inside the tank could be construed as a tailrace downstream of a hydropower turbine (Figure 4). The ‘test chamber’ consisted of half of the tank volume. A smooth inclined adjustable elliptical perforated plastic screen formed the downstream end of the chamber. An arched aluminum frame, arching from one side of the chamber to the other, structurally supported the screen. Arching the screen in the horizontal and vertical planes eliminated sharp corners that may be used as sanctuaries by the test fish within the chamber. The arching of the screen also made the chamber hydraulically smooth by reducing corners that would cause turbulent eddies and stagnation zones. Also, a coated wire screen (1/2 inch mesh) was placed 6 inches downstream of the nozzles forming the upstream end of the test chamber. This was done to protect the fish from being directly struck by the jets. The main frame of the turbulence tank was made of welded steel. The side and bottom were made of clear Plexiglas to facilitate non-intrusive observations and videotaping of the test fish from outside. The entire turbulence tank was kept inside an enclosure with a black curtain to facilitate control of lighting and prevent disturbance of the fish by human movement during testing.

The flow introduction arrangement was made modular. Flow was introduced via an array of nozzles at the upstream end of the turbulence tank. The varying numbers, sizes, and arrangement of flowing nozzles were used to vary the turbulence intensity and scale. Forty nozzles were placed in rows of 4 horizontally and 10 vertically with the largest nozzle size being ¾ inches in diameter. The nozzles were supplied with water via metered 4-inch diameter PVC pipes. The supply pipes and nozzles were isolated from the chamber by means of a smooth perforated screen, with the nozzles protruding through it (Figure 5).

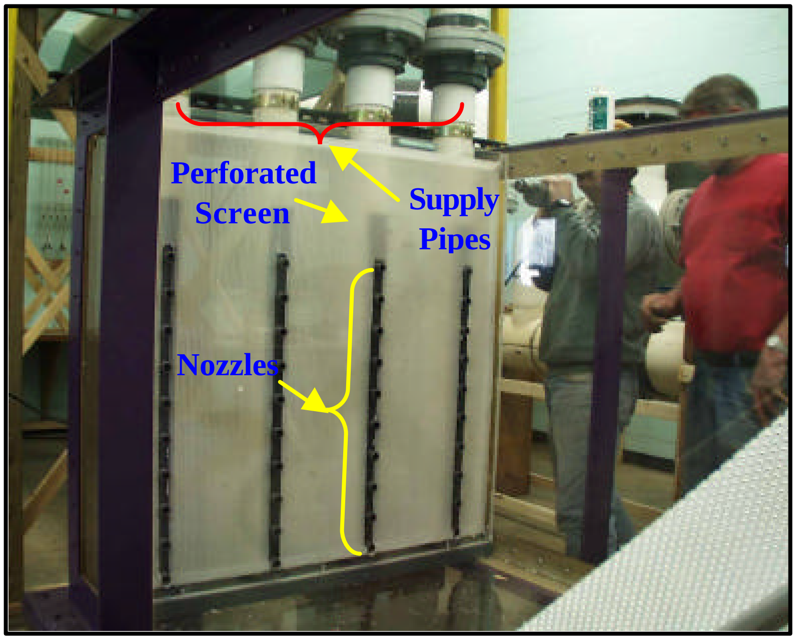
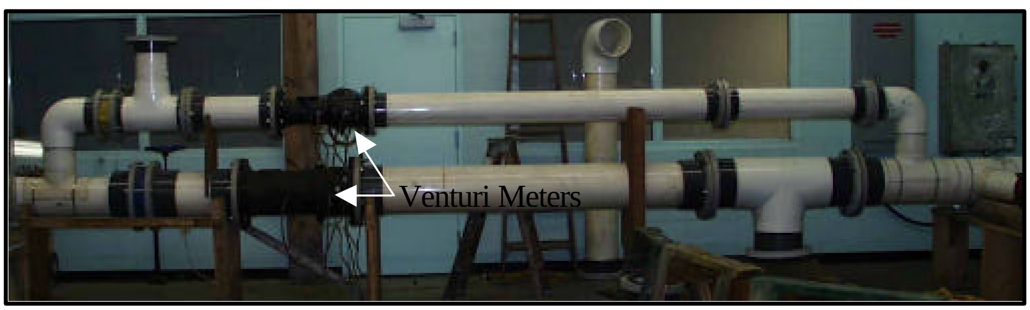


Figure 5. Flow introduction via nozzle arrangement; showing the 40 nozzles and a perforated screen used for fish exclusion from the supply pipes.

Water was supplied to the tank via a 77 horsepower pump capable of delivering about 7 cfs (cubic feet per second) at 68 feet of head (Figure 6a). The pump was located inside a 14 ft wide by 32 ft long by 14 ft deep sump inside the hydraulic laboratory at CAFRC (Figure 6b). The turbulence tank was also set up to receive water from two smaller submersible pumps (2.8 cfs at 40 ft head each) located in the same sump. Figure 6c shows the piping used to convey the water from the sump pumps along with the calibrated Venturi meters used to measure the flow. Each individual 4 inch nozzle header was equipped with a pitot static probe to balance the flow rates to all nozzles. The sump inside the hydraulic lab was filled with Connecticut River water via the Cabot Power Canal adjacent to CAFRC. Control valves located downstream in the pump discharge lines and near the nozzle supply lines were used to adjust the flow. An adjustable slide gate located at the end of the turbulence tank controlled the water surface elevation inside the chamber. Water was discharged back into the sump after passing through the chamber. Temperature, dissolved oxygen, and turbidity were monitored to maintain constant water quality throughout the experiments.

a

b



c

Figure 6. Photographs showing a) the sump pump, b) the sump, and c) the piping used to supply water to the turbulence tank.

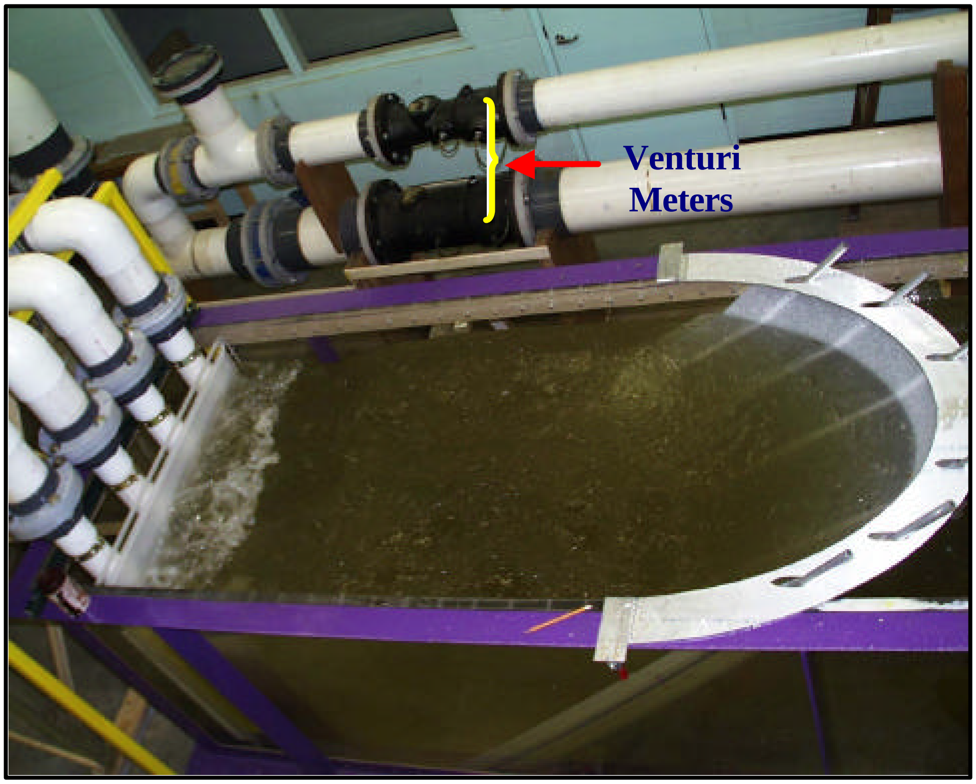


Figure 7. Photograph showing the turbulence tank filled with water.

Hydraulic Evaluation

Velocity Measurements

In order to estimate turbulence intensity inside the chamber instantaneous velocity measurements were taken continuously over time at points within a grid system. The top of the turbulence tank was outfitted with a rail system to support a carriage carrying two Acoustic Doppler Velocimeters (Model Sontek ADVLab). The carriage system was motorized to accurately document different hydraulic test conditions at which fish were tested. Water level was kept constant throughout all tests.

The spacing of points on the measurement grid was chosen to be 2 in (5 cm) along all axes, which was based on the size of the test fish of approximately 6 in (15 cm). Inflow to the tank was set for the test conditions by using calibrated Venturi flow meters (with 0.25% accuracy).

The design velocities for the nozzles were set to be 14, 25, and 35 feet per second (fps) to produce low, medium, and high turbulence, respectively. This was done by leaving the bottom five nozzles open in all four nozzle headers. The photograph in Figure 7 shows the turbulence tank in operation. In this 'system shakedown" run all nozzles were left unobstructed and the tank was filled to its capacity. The system is ready for calibration and testing.

The three directional velocities were measured. The x component of the reference axis for the velocity grid was lengthwise along the tank, the y component across the width of the tank and the z component the water depth. The test area encompassed the protection screen just downstream of the jets to the inclined elliptical containment screen (Figure 4). A 3-D grid with 2-inch spacing on each axis was chosen for velocity documentation. (The number of velocity points varied with the traverse location in the x direction (along the tank) decreasing with respect to the boundaries of the inclined elliptical screen. A maximum of 22 velocity points in the y direction and 14 points in the z direction upstream of the inclined screen were measured. These decreased to 12 horizontal and 2 vertical depths at the end of the test area. Velocity was measured at a total of 5,876 points within the test area at each flow condition. Only low and medium flow conditions were documented. High flow conditions rendered the meters useless due to high velocities (outside meter's range of 8 feet per second) and entrapped air.

The principle workings of the velocity meters were based on the Doppler principle. A short pulse is transmitted along a vertical axis and transducers in receiving arms record an echo from the measuring area (a 0.015 $inch^3$ of water volume about 2 inches from the transmitter). A personal computer was used to condition, process and analyze the frequency shift from the transmitted pulse and the received echo. This velocity probe's three rigid arms, 120 degrees apart, receive a signal from a transmitting transducer located in the center shaft (Figure 8). The important advantage of using this type of meter was because the probe does not interfere with the flow at the exact measurement location. The meter was set at its maximum scanning rate of 25 Hz.

A 3-D traversing system was constructed to support and motion the ADV meters to acquire velocity data (Figure 9). The x and z component axis were manually operated and the y axis automated. A partially automated system was all that was possible due to the physics of the acoustical system and the limits of its software. Linear bearings rails were installed on top of the tank and a beam used to traverse the width of the tank supported the probes and was attached to the rails for travel longitudinally along the tank. A screw and stepper motor were installed on the beam with the meters attached to the screw for automated movement in the y direction. One ADV meter was used for each half of the tank. The meters were spaced horizontally on the screw based on the width of the measurement section along the length of the tank. Each meter was attached to an adjustable holder in a slide assembly for vertical movement in the z direction.

Data were acquired using software supplied by Sontek. Velocity measurements were recorded at 25 Hz. A minimum acquisition time of 3 minutes was used for each point on the grid. Exploratory velocity measurements indicated that the 3 minutes was a sufficient time period for a representative average velocity. At fixed intervals on the y axis the velocity measurement period was 5 minutes. Measurements with a 5 minute period were chosen for time series analysis of the velocity data. A velocity traverse was initiated by setting the traverse mechanism at a position on the x axis and setting the meter at a the desired depth. The two ADV meters were moved along the traverse system in the y direction by using a motion control program developed for the turbulence tank. Depending on the traverse location the meters would record data for either 3 or 5 minutes then automatically move two inches and record data and so on until all measurements were completed at that x location and depth. The traverse system would then be reset at the next x location along the tank and the software would start recording data again. The software provided by the ADV meters' manufacturer, Sontek, filed the velocity data on the computer hard drive.

Hydraulic Data Reduction

Velocity data taken along each traverse in the y direction were recorded continuously to a file. Winadv (Wahl 2001) was used for post-processing the stored data. Bubbles in the highly turbulent flow regime caused acoustic noise and poor signal quality in the Doppler based backscatter system used by the ADV meters. In the absence of particles in the flow a poor echo developed and a low "signal-to-noise –ratio" (SNR) and is measured. Low correlation values are an indication of a high number bubbles or a low SNR. All velocity points were post-processed with low limits recommended by the meters' manufacturer, a correlation parameter of 70 and a SNR of 15 db were used. Measured velocities with parameters lower than these were not used. Processed data were then copied to a spreadsheet. The time and number of scans for each point in the traverse were identified, separated and the spatial locations noted in separate columns. Average velocities, standard deviations, turbulent intensities, Reynolds stresses, and vorticity were then calculated.

The magnitude of the velocity vector at each grid point and instant in the time interval was calculated from the resultant of each velocity component by:

$$V = \sqrt{u^2 + v^2 + w^2} \tag{7}$$

Where u, v, and w are the velocity components in the three dimensions and V is the resultant velocity at a given grid point in a given instant of time. The average velocity at each point was calculated using:

$$\overline{V} = 1/n\sum_{i=1}^{n} V_i \tag{8}$$

Where the bar over the V indicates the mean value and n is the number of instantaneous velocity measurements. The root mean square (rms) for each velocity component is a measure of turbulence intensity, and it was calculated by using:

$$V'_{rms} = \sqrt{\frac{\sum_{i=1}^{n}\left(V_i - \overline{V}\right)^2}{n}} \tag{9}$$

Turbulence in the tank was characterized by two quantities, the size and the intensity of the fluctuations. Although the mean velocity over time at a point was constant the instantaneous velocity components fluctuated. The size of these instantaneous fluctuations are given by u', v', w' where:

$$\begin{aligned} u &= \overline{u} + u' \\ v &= \overline{v} + v' \\ w &= \overline{w} + w' \end{aligned} \tag{10}$$

The intensity of velocity fluctuations was found by using equation (9) to calculate the rms. We also assumed that fluctuations among the different velocity components change in unison. Therefore, we calculated the resultant turbulence intensity from the individual rms values in the three directions to find a resultant rms by:

$$V'_{rms} = \sqrt{u'^2_{rms} + v'^2_{rms} + w'^2_{rms}} \tag{11}$$

Thereafter, we compared the level of turbulence at different locations by calculating the resultant turbulent intensity at each grid point by using:

$$TI = \frac{V'_{rms}}{\overline{V}} \times 100\% \tag{12}$$

Where *TI* is the turbulent intensity at a point over the period of measurement. In turbulent flows velocity fluctuations exchange momentum between adjacent layers of fluid. This rate of change of momentum produces a shear force. Osborne Reynolds was the first to discuss turbulent shear stress. The term Reynolds shear stress in the x-y plane is defined as:

$$-r u' v' \tag{13}$$

Because eddy motion is three-dimensional the Reynolds' stresses were calculated for all three planes. However, we present the results in the z direction; as the Reynolds' stresses were most prominent in that direction. The units of Reynolds' stresses are similar to pressure or hydraulic shear stress; they are force per unit area. We believe that this is a good measure of turbulence severity when correlating turbulence with fish. We also realize that the turbulent kinetic energy is another measure of turbulence that we could have calculated. However, the Reynolds' stresses are more indicative of the effect of turbulence on the fish's body.

Also, secondary currents and large scale eddies driven by the turbulent flow regime were created in the test section. The secondary currents do not carry the primary velocity and their rotation was considered the average angular velocity of two mutually perpendicular line elements. Rotation of any fluid element w about the other two coordinate axes was obtained as follows:

$$w_z = \frac{1}{2}\left(\frac{\partial u}{\partial x} - \frac{\partial u}{\partial y}\right) \tag{14}$$

The three components $w_{x,} w_{y,} and w_z$ can be combined in the form:

$$w = w_x i + w_y j + w_z k \tag{15}$$

Which results in,

$$w = \frac{1}{2}\nabla \times \mathbf{v} \tag{16}$$

We also used *Vorticity* as a measure of the rotation of the fluid element as it moves in the flow field. *Vorticity* was defined as a vector having a value twice the rotation vector and was calculated by:

$$curl\mathbf{v} = \nabla \times \mathbf{v} = \left(\frac{\partial v_z}{\partial y} - \frac{\partial v_y}{\partial z}\right)\vec{i} + \left(\frac{\partial v_x}{\partial z} - \frac{\partial v_z}{\partial x}\right)\vec{j} + \left(\frac{\partial v_y}{\partial x} - \frac{\partial v_x}{\partial y}\right)\vec{k} \tag{17}$$

where $\mathbf{v}$ is the velocity vector and $\vec{i}$, $\vec{j}$, and $\vec{k}$ are the unit vectors in the x, y, and z direction.

The flow field of interest in the turbulence tank rotated around the y-axis and it was the one calculated by:

$$\nabla V(x,z) = \frac{\partial v_z}{\partial x}(x, z) - \frac{\partial v_x}{\partial z}(x, z) \tag{18}$$

Because the measured velocity vectors were on a discrete grid, the differentiation can be approximated by a finite difference. For example, for position (x, z) the *Vorticity* was calculated by:

$$\nabla V(x,z) = \frac{v_z(x+dx,z)-v_z(x-dx,z)}{\Delta x} - \frac{v_x(x,z+dz)-v_x(x,z-dz)}{\Delta z} \qquad (19)$$

Biological Studies

Test Fish

Three species of fish were used in tests: hybrid bass (striped bass *Morone saxatilis* × white bass *M. chrysops*), juvenile rainbow trout (*Onchorhynchus mykiss*), and Atlantic salmon parr (*Salmo salar*). All species were cultured in tanks and obtained from commercial aquaculture facilities (hybrid bass: Fins Technology, Montague, Massachusetts, USA) or hatcheries (rainbow trout: Sunderland Fish Hatchery, Sunderland, Massachusetts, USA; Atlantic salmon: White River Hatchery, U.S. Fish and Wildlife Service, White River, Vermont, USA). Size, weight and holding/testing temperature characteristics of the three test species are given in Table 2.

Fish were transported from culture facilities in a 1000 L truck-mounted tank and transferred by dipnet to 650 L holding tanks in the CAFRC facility at a density of 6 to 10 fish per tank. Tanks were supplied with flow-through water from the adjacent Connecticut River at an average rate of 8 L/min, at ambient river temperature. Tanks were covered with 1.27 cm bar mesh plastic screening to prevent fish from jumping out of tanks. Fish were fed once per day on a diet of 3/32" 42% protein, 16% fat trout feed, and were kept on a natural diel light cycle. Testing of all fish was performed within 1 week to a month after transport. Tanks were visually checked daily for mortalities or diseases; any dead or unhealthy fish were removed immediately from tanks.

Testing Protocol

At the start of a test, fish in holding tanks were subjected to an initial pre-exposure startle response trial (SRT). A wooden silhouette of a potential avian predator (cormorant; wingspan 61 cm) mounted on a 1 m long wooden pole was passed by hand over the holding tank at a speed of approximately 1 m/sec and a height of 0.5 m above water level. Care was taken so that fish could see the silhouette and pole only, not the observer holding the pole. Startle responses of the fish were recorded by a digital video camera (model Canon Elura 2; 640 x 480 pixel resolution, 30 frames/sec) mounted over the holding tank. All SRTs were performed at ambient daylight levels (810 lux), and the predator silhouette was contrasted against a white ceiling background. Videotapes were archived for later evaluation (see *Evaluation of Video Data* below).

Immediately after the pre-exposure SRT, the turbulence tank was filled to the desired level (76 cm) and flows set to produce the desired turbulence condition (low, medium, or high). For control groups, the turbulence tank was filled but flow was maintained only at the minimal level in order to maintain the test water level (usually only 40 L /min). The entire group of fish from the holding tank (6 to 10) was dipnetted and transferred into the turbulence tank via a plastic bucket containing approximately 12 L of water. Fish were released into the turbulence tank by gently lowering the bucket into the tank so that water levels of the tank and bucket were equal, then inverting the bucket. Flows in the turbulence tank were maintained for 10 min after fish release. Behavior of fish in the turbulence tank was recorded via digital video. At the end of the 10 min exposure period, flow was shut off to the turbulence tank and the water level was maintained at 75 cm. Fish were then subjected to six SRTs while inside the turbulence tank, each spaced 10 sec apart. Fish were then returned to the holding tank by the dipnet/bucket method. Bruising, scale loss, or other injuries were recorded as fish were netted out of the turbulence tank.

SRTs were repeated and video-recorded on the test group of fish after they had been returned to the holding tank every 5 min for 30 min, and at additional times of 1 hr, 24 h, and 48 h after testing in the turbulence tank. After 48 h, fish were removed from the holding tank, measured, (FL, nearest mm), and weighed (nearest g). Fish were not re-used in testing thereafter. Mortalities and post-exposure injuries were recorded.

Table 2. A summary of fish species used during testing at the various test conditions, including test results.

Species	Turbulence	Nozzle Velocity (fps)	# of Trials	Total # of Fish	Average Length and SD (cm)	Average weight and SD (g)	# Damaged	# Immediate Mortalities (in the test)	# Delayed Mortalities (24 hr)	# Delayed Mortalities (48 hr)	Water Temperature (ºC)
hybrid bass	Control	0	6	56	17.19 (2.26)	66.46 (25.64)	0	0	0	0	24.73 (0.40)
hybrid bass	Low	14	3	28	17.34 (2.35)	70.26 (29.94)	2	0	1	0	24.07 (0.93)
hybrid bass	High	32	4	38	17.16 (2.12)	65.76 (23.03)	14	0	4	0	24.09 (0.95)
Rainbow Trout	Control	0	8	74	19.13 (1.23)	79.62 (13.94)	0	0	0	0	15.56 (1.34)
Rainbow Trout	Low	14	6	53	19.20 (1.21)	79.16 (13.79)	2	0	0	0	15.28 (1.33)
Rainbow Trout	Medium	25	7	62	18.99 (1.07)	77.99 (12.51)	13	0	0	0	15.59 (1.35)
Rainbow Trout	High	32	6	57	19.01 (1.02)	78.16 (12.40)	12	0	0	0	15.88 (1.28)
Atlantic salmon	Control	0	4	28	17.78 (1.36)	62.84 (10.25)	0	0	0	0	9.57 (0.41)
Atlantic salmon	Low	14	5	34	17.61 (1.19)	62.89 (10.08)	0	0	0	0	9.48 (0.05)
Atlantic salmon	Medium	25	5	33	17.31 (1.41)	59.44 (10.92)	3	0	0	0	8.96 (0.21)
Atlantic salmon	High	32	5	30	17.41 (1.33)	58.38 (10.29)	11	0	0	0	9.08 (0.15)

The average DO in the holding tanks was 9.20mg/l, and in the turbulence chamber was 10.09mg/l.

Evaluation of Video Data

Videotapes were played back in real time and displayed on a 51-cm color monitor. Only one investigator analyzed videotapes. Responses of each fish during each SRT were ranked and recorded on a scale of 0 to 3; 0 = no reaction, 1 = visible reaction (e.g. body twitch), but no movement > 1 body length (BL), 2 = fish startled and moved > 1 BL, but reaction did not occur within 1 sec of passing of the silhouette, 3 = fish startled and moved > 1 BL and reaction was within 1 sec of passing of the silhouette. Other behaviors were also recorded for each fish, including swimming depth (on bottom, above bottom), schooling (at least 3 fish within 2 BL of each other), disorientation (listing, inverted swimming, collision with walls), and territoriality (aggressive behavior directed towards other fish). Data were recorded on datasheets and later entered into a computer database, Microsoft Access.

Videotapes of fish during turbulence exposure were also reviewed and general observations on behaviors and orientations were noted.

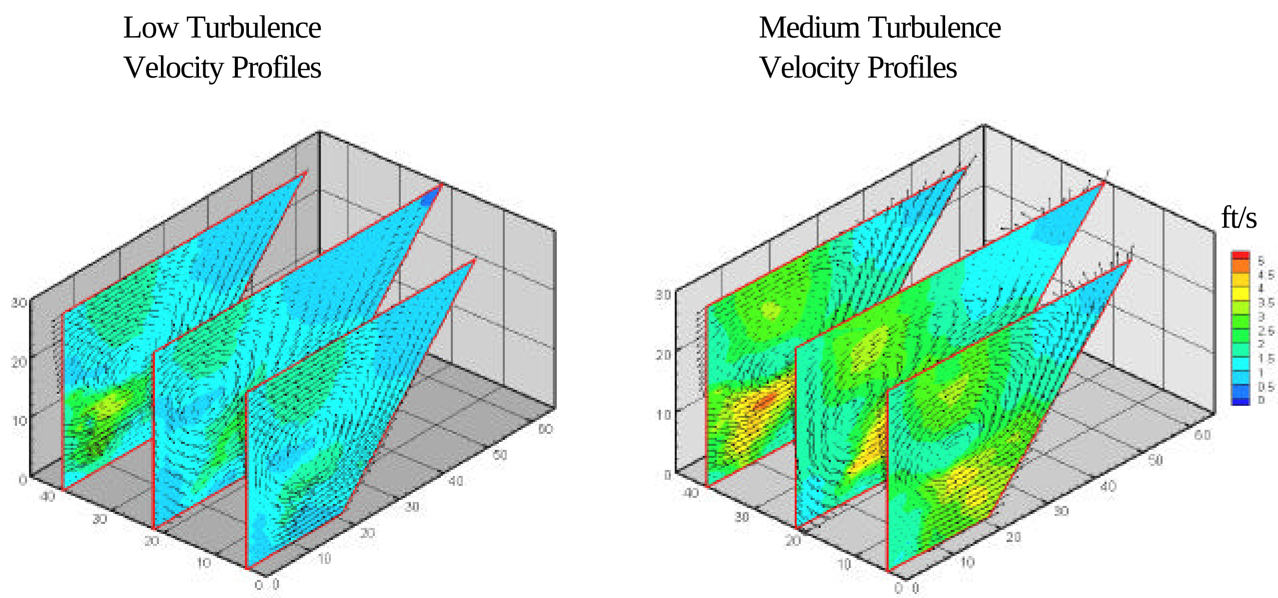
Data Analysis

Response levels recorded for each fish during the SRTs were averaged for the entire test group. The difference between the pre- and post-exposure mean responses, ΔR, was calculated. A one-way analysis of variance (ANOVA) based on ranks of ΔR was performed for each species and test location (turbulence tank and holding tank). Additionally, because both ΔR and turbulence condition can be viewed as continuous variables, a test for trend in ΔR with increasing turbulence condition was performed using Kendall's τ (tau) to test for the significance of correlation between these two variables (Conover 1971) for each species and test location.

5. RESULTS AND DISCUSSION

Turbulence Tank Hydraulics

Plotting the time-averaged velocities within the turbulence tank revealed the desired flow pattern that was expected from opening the bottom five nozzles in all four drop pipes. Figure 8 a & b shows the roller and upwelling inside the test chamber at the low and medium turbulence conditions (14 & 25 fps nozzle velocities, respectively). This may be the type of flow behavior seen at the downstream end of a turbine draft tube where fish are found just after passage through the turbine. Velocities reached 2.5 to 3 fps in the bottom of the tank and were up to 2 fps in the opposite direction in the top part of the tank at the low turbulence condition (Figure 8 a). Time-averaged velocities were up to 5 fps and 3 ft/s in the bottom and top parts of the tank, respectively at the medium turbulence condition (Figure 8 b). At the high turbulence condition, velocities exceeded 8 fps at the bottom, the flow was highly turbulent, and aerated with too many bubbles for the ADV meter to work properly.



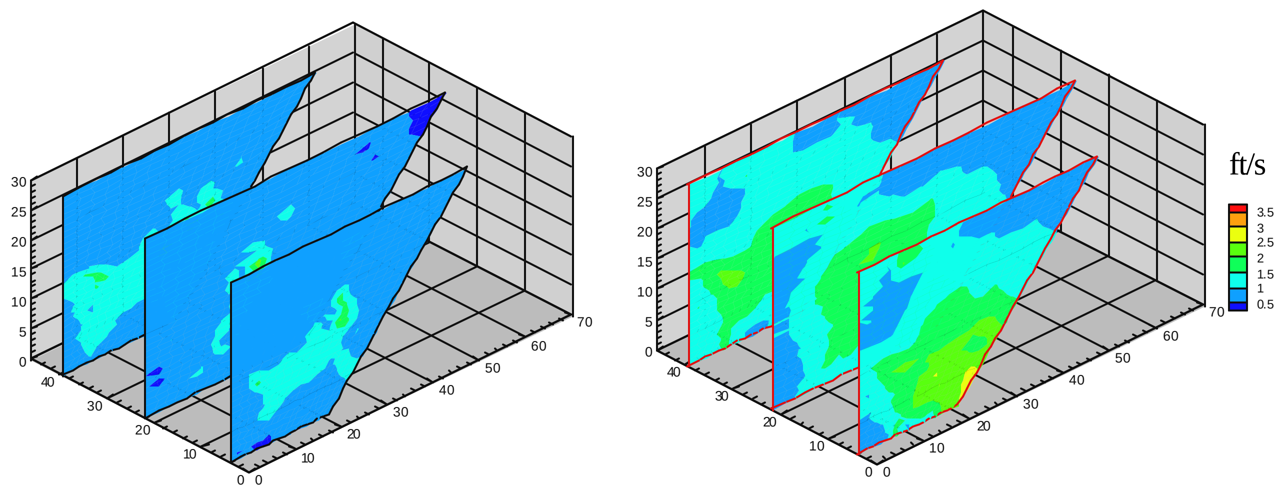
a) **b)**

Figure 8. Velocity profiles at three planes within the turbulence tank a) at the low turbulence condition, where nozzle velocities were 14 fps, and b) medium turbulence condition, where nozzle velocities where 25 fps.

The instantaneous velocities that were measured over time were used to calculate the root mean squares (rms) of velocity at all grid points (using equation 9) in order to describe the turbulence around the mean velocities inside the test tank. The plots in Figure 9 a and b show the rms values for low and medium turbulence conditions, respectively. It is clear that the instantaneous velocity fluctuations from the mean velocity are larger in the medium condition than the low one. The ADV meter recorded very high fluctuations during the high turbulence condition, but they were outside the meter's range.

Low turbulence rms

Medium Turbulence rms



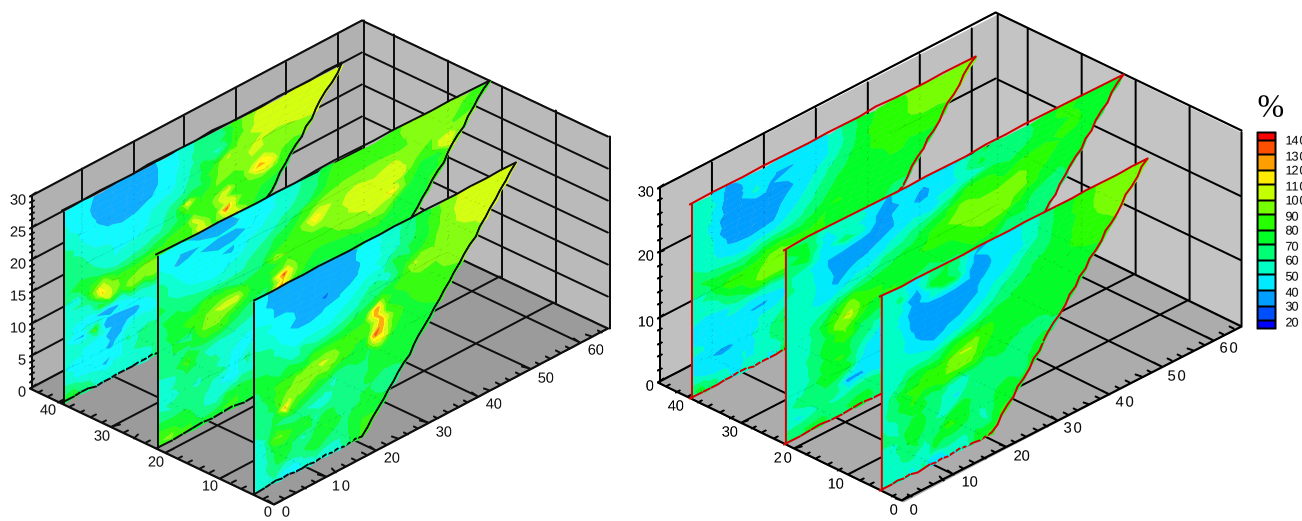
a)

b)

Figure 9. Root Mean Square (rms) of velocity profiles shown at three planes within the turbulence tank at the a) low and b) medium turbulence conditions.

However, when the Turbulence Intensity (*TI*) calculations were performed at the same velocity grid points, which were found by using equation 12, they showed that the low and medium turbulence conditions had very similar turbulence regimes, as described by the *TI* values (Figure 10 a and b). This indicated that the "percent of fluctuations" of the instantaneous velocities from the mean value over time during the low and medium turbulence conditions did not differ significantly. This was due to having large fluctuations associated with the higher mean velocity value and low ones with the low velocity at the medium and low conditions, respectively. That is, velocity fluctuations were proportional to the time-averaged velocities.

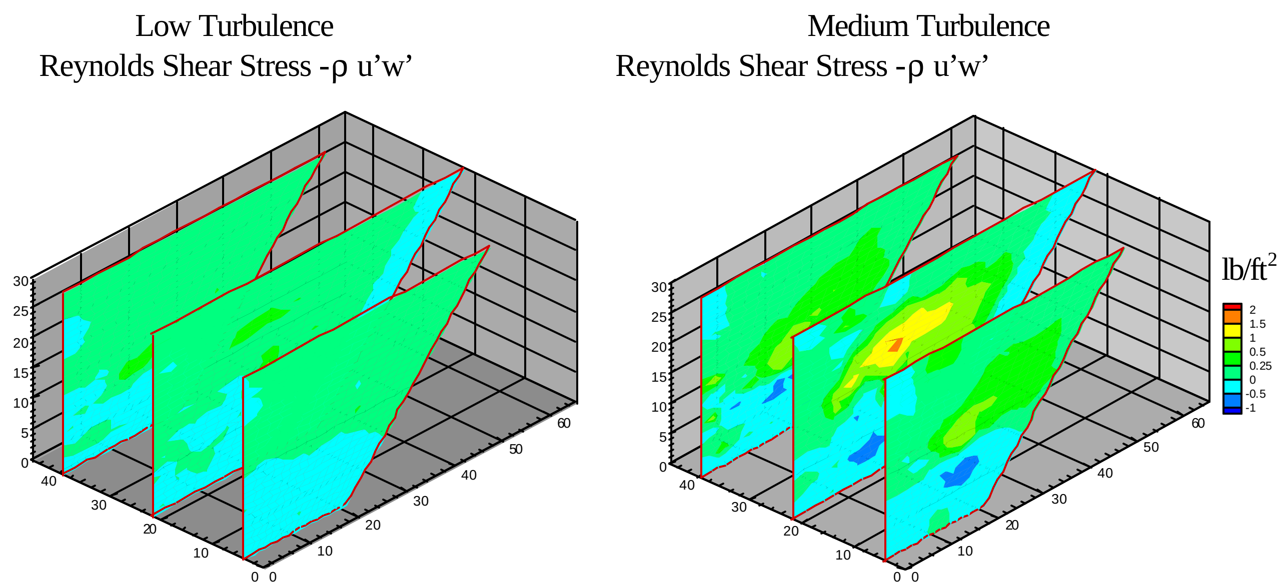
Low Turbulence *TI* Medium Turbulence *TI*



a) **b)**

Figure 10. Turbulence Intensity profiles at three planes within the turbulence tank at the a) low turbulence condition and b) medium turbulence condition.

The profiles of the Reynolds' shear stresses in the x-z plane, calculated by using $-\rho u'w'$, are shown in Figure 11 a and b. These too figures show that both turbulence conditions have similar patterns of flow and turbulence regimes, with increased stresses at the medium turbulence condition. The Reynolds' shear stress can be used as an indicator of the turbulence strength related to fish because it has units of force per unit area. Figure 11 shows that the Reynolds' stresses, higher at medium turbulence, are on the same order of stresses found in streams during a flash flood (50 N/m^2, see Table 1).



a) **b)**

Figure 11. Reynolds' shear stresses profiles at three planes within the turbulence tank describing a) low turbulence condition and b) medium turbulence condition. The units here are lb_f/ft^2, and can be converted to N/m^2 by multiplying by ~48 $N/m^2/\ lb_f/ft^2$.

To illustrate the Reynolds' shear stresses Figures 12 and 13 show these at a single point within the turbulence tank at the low and medium turbulence condition, respectively. The instantaneous velocities shown in the top plate of each figure were taken at the same point over approximately 5 minutes. Shear stresses were higher due to the high fluctuation of turbulent velocities about the mean velocity in the medium turbulent condition. Shear stress values are clearly dependent on the magnitudes of the instantaneous velocities. The Vorticity plots in Figure 14 also show that the flow rotated faster and more frequently at the medium than it did at the low turbulence condition.

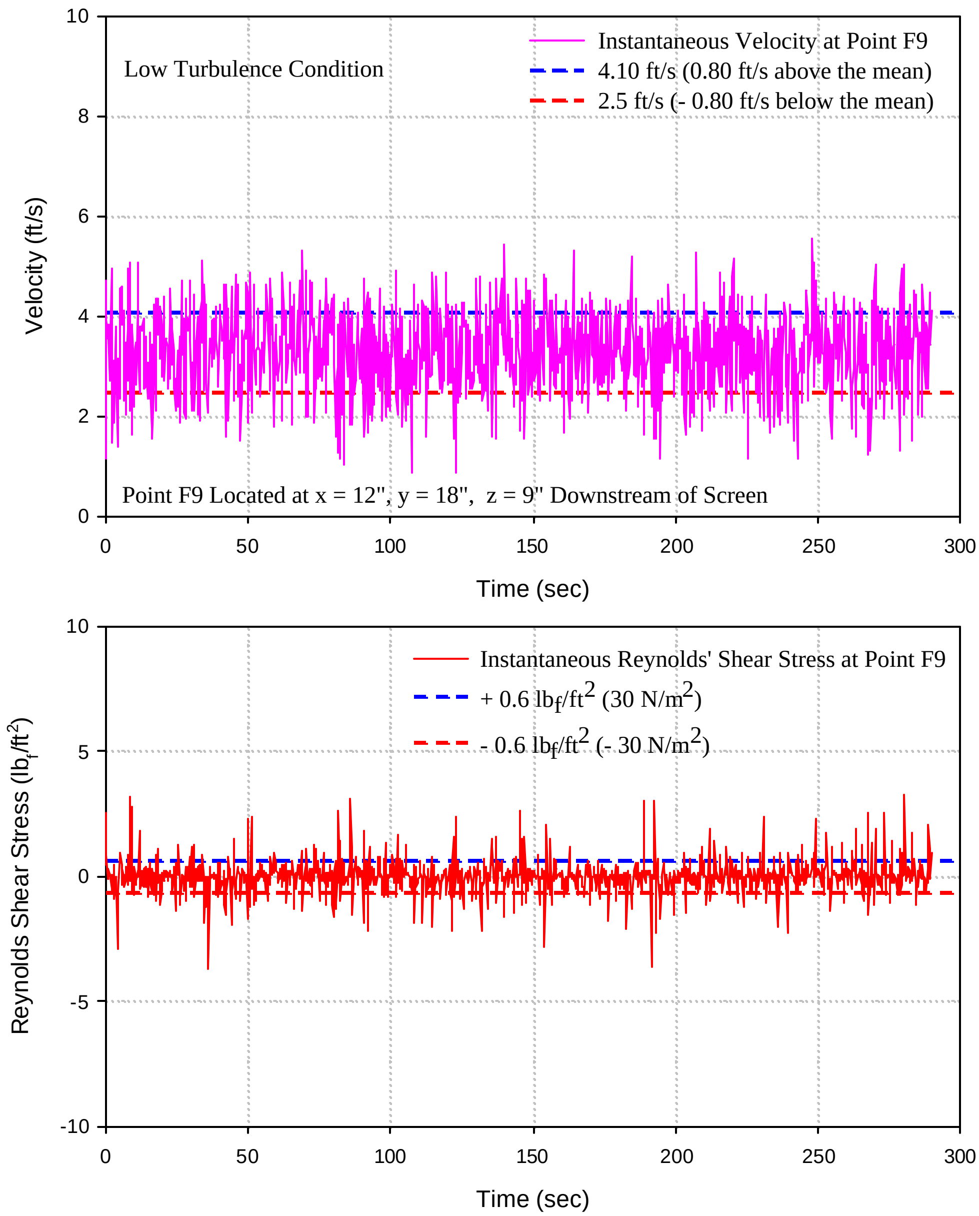


Figure 12. Plots of low turbulence instantaneous velocities (Top Plate) and Reynolds' Shear Stress (Bottom Plate) at a single point in space within the turbulence tank. The point is 12" downstream of the protection screen.

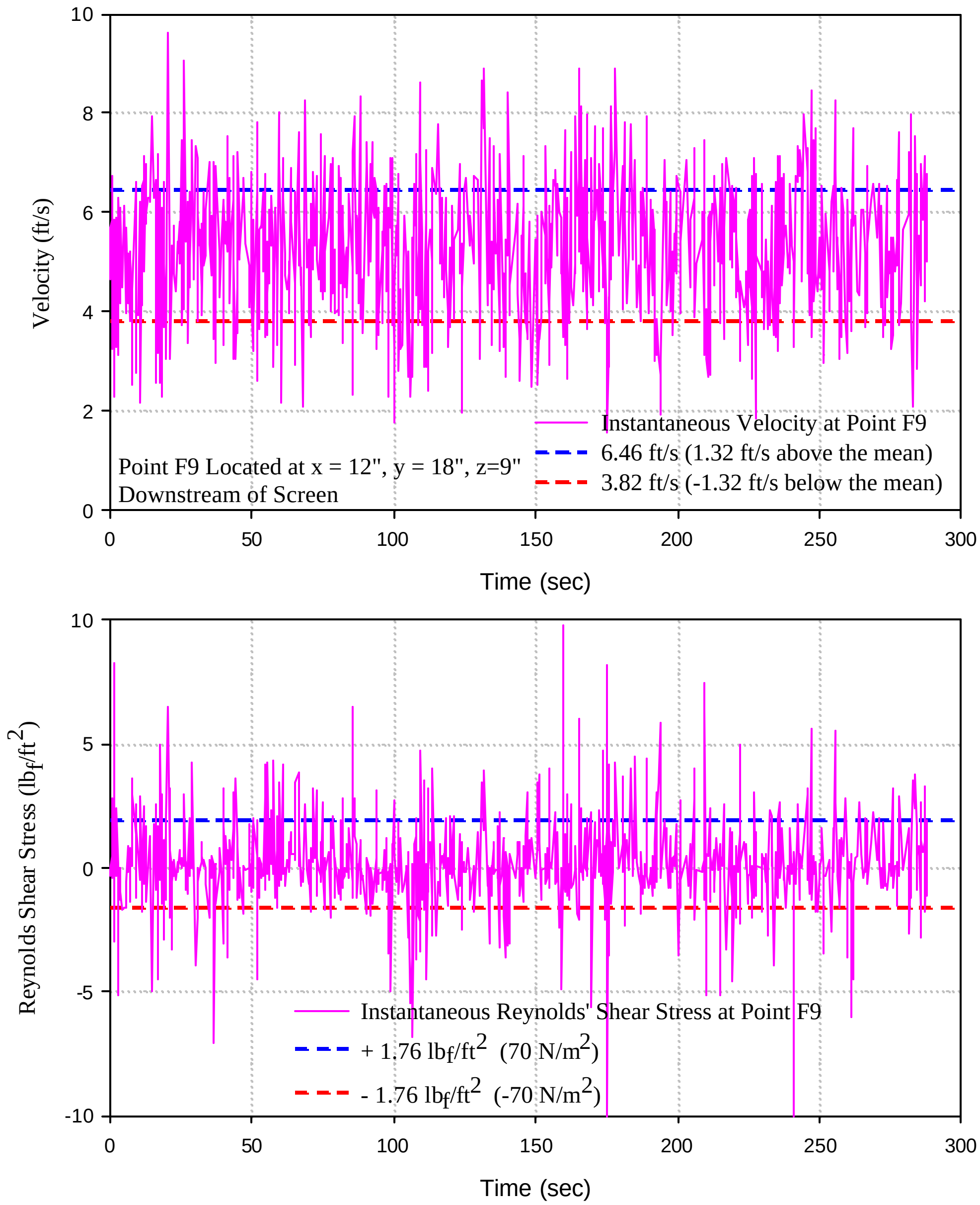
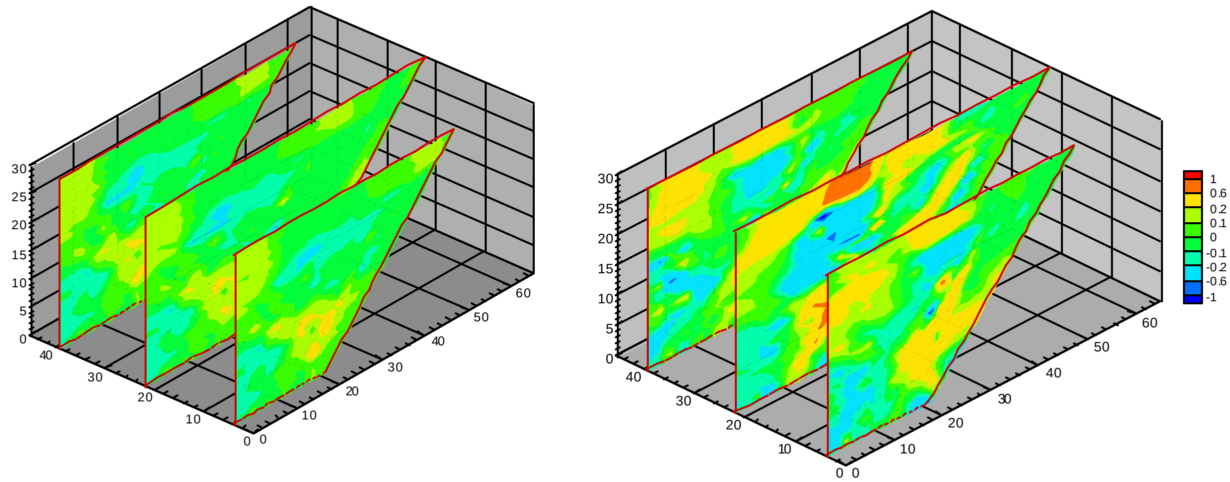


Figure 13. Plots of medium turbulence instantaneous velocities (Top Plate) and Reynolds' Shear Stress (Bottom Plate) at a single point in space within the turbulence tank. The point is 12" downstream of the protection screen.

Low Turbulence Vorticity Medium Turbulence Vorticity



a) **b)**

Figure 14. Vorticity profiles at three planes within the turbulence tank describing a) low turbulence condition and b) medium turbulence condition. The units here are similar to units of frequency, 1/sec.

Behavioral Observations

All species had difficulty maintaining orientation in the turbulence tank during exposure to the medium and high turbulence condition; this effect was more pronounced at the high turbulence condition. Although fish attempted to swim in the turbulent flow, their bodies would be buffeted by the turbulence such that they were oriented at all angles, including inverted. At low turbulence fish were able to swim and maintain vertical orientation, usually at the bottom of the turbulence tank. At the conclusion of a turbulence exposure, fish generally swam to the bottom and rested there with a normal vertical orientation, although some exhibited listing behavior, where their bodies tilted to one side at an angle of up to 30 degrees from vertical. Other post-treatment behaviors included schooling (bass more than others), attempts to swim through the Plexiglas wall or floor (bass and trout), or territorial behavior (trout; fin nipping). Salmon did not react at all to the predator while in the turbulence tank. Control salmon swam to the bottom immediately after release and then exhibited listing behavior during the 10-min exposure period. We noted that after exposure, most fish had a very high respiratory rate, which was likely due to bouts of strong swimming in response to turbulence and their attempts to maintain orientation.

Injury and Mortality

Injuries of test fish ranged from 0% in control groups (all species) to as high as 37% (hybrid bass; 14 of 38 test fish; high turbulence condition; Table 2). Percent of injuries generally increased with increasing turbulence condition for all species. However, it is difficult to assess whether injuries were caused by turbulence itself or by abrasion of fish against the walls, floor, and screens of the turbulence tank. Based on the nature of the injuries (primarily scale loss) we suspect that abrasion was a primary factor, although turbulence itself may have a minor effect.

There was no post-exposure mortality of rainbow trout or Atlantic salmon. Mortality of hybrid bass within 24 h of exposure was 0% in controls but increased with increasing turbulence (3% at low turbulence, 10% at high turbulence condition). There was no mortality between 24 and 48 h post-exposure. Again, we cannot rule out the possibility that mortalities resulted from contact abrasions, rather than from turbulence *per se*.

Effects of Turbulence

Short-Term Change in Reaction

Mean pre- vs. post-exposure change in reaction (ΔR) differed among species and locations. Both salmon and hybrid bass showed reduced response to the simulated predator at greater levels of turbulence (Figure 15). However, these differences were not statistically significant for any species (p values > 0.3), as analyzed by the ANOVA based on ranks test. We attribute this nonsignificance to relatively low sample size and resultant low statistical power of the test, rather than any real nonsignificant difference between responses. The trend was significant (Kendall's τ, $P < 0.05$) in both the turbulence tank (immediately after exposure) and the holding tanks (1 min to 48 h after exposure) for hybrid bass; for salmon, diminished response to the bird silhouette was only significant in the holding tank. The absence of an effect for salmon in the turbulence tank appears to be due in part to a strong reaction to transfer of the fish to the novel tank itself, as indicated by the strongly negative ? R values under the control (zero turbulence) condition (Figure 15). The strong initial reaction to transfer to the turbulence tank did not appear to be present in the other two species, suggesting interspecific differences in sensitivity to transfer to novel environments.

Although significant effects were observed among salmon and hybrid bass, turbulence had no observable effect on reaction of rainbow trout. These results may be somewhat biased due in part to the high degree of variability under the control condition. Also, it should be noted that all test species were cultured, and the hatchery or aquaculture rearing environments likely possessed differences in turbulent conditions in which these species had been originally acclimated. Although suggestive of species-specific differences, the data are not sufficiently robust to identify these inter-specific differences; further study is needed before conclusions of no effect can be drawn.

Long-Term Recovery of Response

For all species, mean pre-exposure reaction in holding tanks was generally high (between 2.0 and 3.0; Fig. 14.). Post-exposure reactions in holding tanks were generally lower than pre-exposure reactions for the first 60 min after exposure to turbulence, but appeared to increase to pre-exposure levels within 24 h. However, there was no consistent association between the degree of reduction of the response and level of turbulence intensity throughout this post-exposure period. The reduction in response was also present in control groups suggesting that handling had a significant effect on post-exposure response. However, recovery of response within the 60 min post-exposure period appeared to be longest for the high turbulence condition in trout and salmon, suggesting some effect of turbulence on response recovery at high turbulence levels.

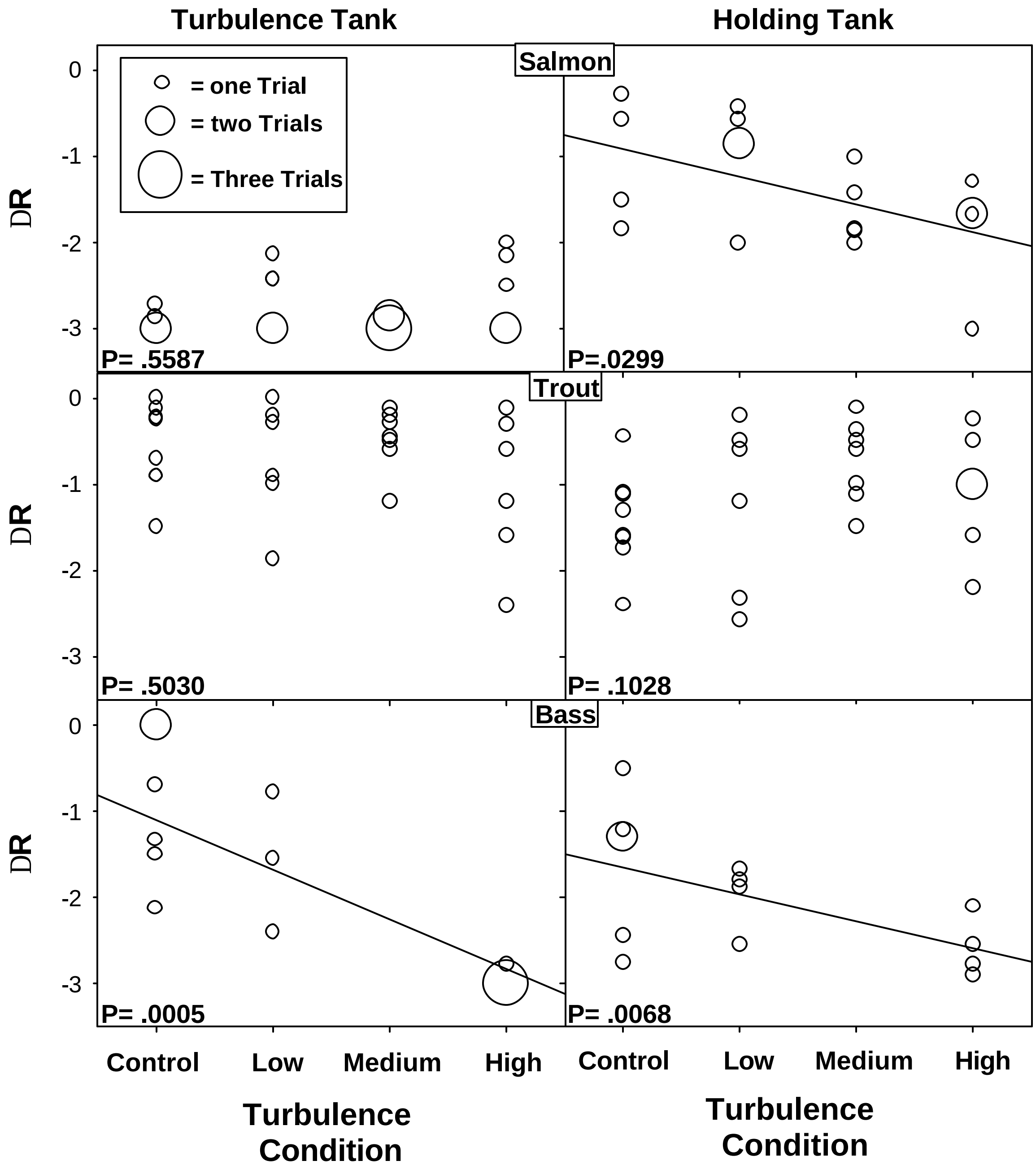


Figure 15. Relationship between startle response and turbulence condition for three test species, as measured in the turbulence and holding tanks. Startle response is expressed as ? R, the difference between the pre- and post-exposure response score (larger negative values of ? R indicate a reduction in response post-exposure).

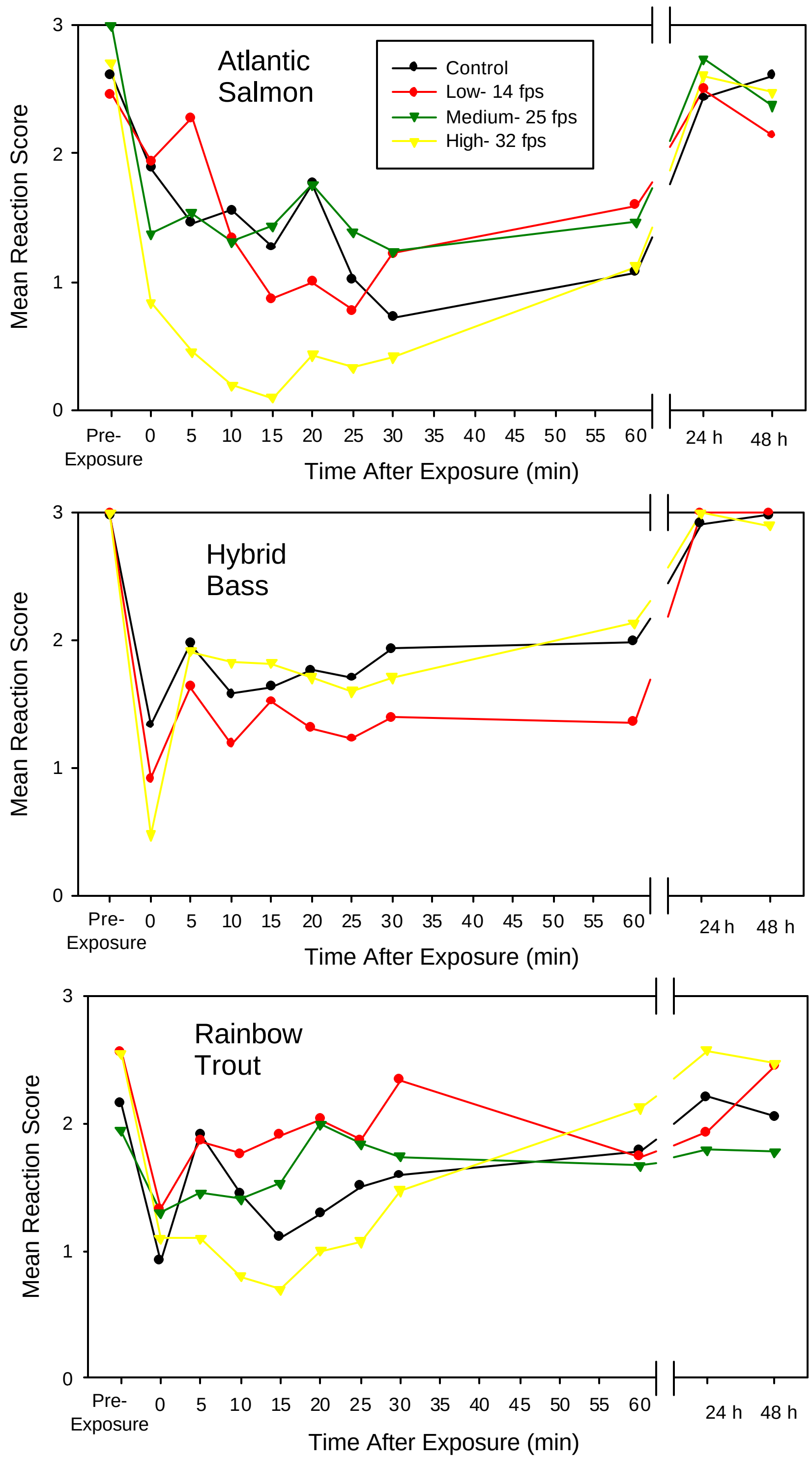


Figure 16. Mean reaction scores pre- and post-exposure to turbulence conditions (1 h, 24 h, 48 h; note break in x-axis scale) for three species in holding tanks.

6. FUTURE RECOMMENDATIONS

- *Reduce or account for variability in the data.* This can be achieved by testing only species with low variability in response, or by conducting more control and treatment runs, potentially on individual fish rather than groups.
- *Improve experimental design to minimize handling effects.* A mechanism or experimental apparatus to measure startle response before and after exposure to turbulence would be ideal, however we found this to be technically challenging due to: 1) inherent (and unknown) effects of handling on startle behavior; and 2) long period of time required to acclimate fish to the turbulence chamber after transfer.
- *Improve resolution of data collection*. Our experimental protocol tested individual fish, but because individuals could not be identified between pre- and post-exposure conditions, we had to express response as a mean for the group. Had we been able to identify change in response of individual fish, sample size would have increased several-fold, yielding improved ability to detect turbulence effects, as well as ability to block data within tanks. An alternative might also be to expose fish to turbulence individually (which would have been very time-consuming with our apparatus), perhaps by introducing turbulence into holding tanks containing one fish only.

7. BIOCRITERIA FOR EFFECT OF TURBULENCE ON FISH BEHAVIOR

The aim of this study was to improve the understanding of the effects of hydraulic turbulence on juvenile fish. By creating varying levels of turbulence that resemble conditions found in the field, subjecting juvenile fish to these predetermined conditions, then testing if there is a biological response, we established a preliminary protocol for measuring effects of turbulence on volitional avoidance behavior. We attempted to create turbulent conditions that caused no direct injuries or mortality, but may alter a fish' s behavior, reduce their swimming capacity or otherwise reduce the ability of a fish to detect and avoid predators or other hazards (e.g., collision with stationary objects).

This study has demonstrated that turbulence can influence the startle response of fish, and the effect can be produced and measured in the laboratory setting. Three generalized biocriteria for turbulence effects for the species tested can be established from these results:

1) Exposure to an average turbulence with Reynolds' shear stresses that are higher than 50 N/m^2 for a period of 10 minutes may induce minor injury to some species, but does not incur significant mortality over 48 h post-exposure period.

2) Exposure to an average turbulence with Reynolds' shear stresses that are higher than 30 N/m^2 for a period of 10 minutes does not reduce startle response in rainbow trout, but has a measurable effect in terms of increasing reduction in startle response with increasing turbulence for juvenile Atlantic salmon and hybrid bass. The degree of reduction in startle response measured would likely put the fish at risk of predation or other hazards.

3) Recovery of reduction in startle response from effects of turbulence at these scales is complete within 24 h for the species tested.

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