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Turbulent Attraction Flows for Juvenile Salmonid Passage at Dams

Charles C. Coutant

Environmental Sciences Division
Publication No. 4798

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ABSTRACT

Induction of mild turbulence and increased water velocity in slowly moving water in dam forebays is proposed to attract downstream-migrating juvenile salmonids to dam bypasses. Attraction flows have been used successfully for decades at the downstream ends of fish ladders to attract adult salmonids to fish ladder entrances. Similar hydraulic concepts for simulating a turbulent stream have generally not been implemented to divert juvenile migrants into dam bypasses and away from damaging turbine intakes. Turbulence appears to be a feature of normal flow in natural rivers that guides and assists juvenile salmon migration. It is hypothesized that enhancement of turbulence in selected zones of quiescent dam forebays would spatially expand the opportunities for fish to discover entrances to fish bypasses (such as surface-flow bypasses). A "trail of turbulence" could lead fish to surface bypass entrances. Enhanced turbulence at bypass entrances and within bypass channels could also improve the effectiveness of juvenile salmonid guidance and retention in the bypasses. Turbulence could be enhanced by passive (using existing flow momentum or head directed by vanes) and active (pumped water jets or propellers) methods, which can be tailored to specific situations.

1. INTRODUCTION

Passage of downstream-migrating juvenile salmonids through dams without death or injury is one of the major challenges for providing multiple uses of mainstem regulated rivers such as the Columbia and Snake (OTA 1995). Pacific salmon (*Oncorhynchus* sp.) and steelhead (*O. mykiss*) in the Columbia River basin that spawn in the upper mainstem or headwater tributaries must pass through up to nine dams for completion of their life cycle. Although detailed bioengineering research in the early days of dam building (1930s and 1940s) developed successful combinations of physical structures and hydraulics to attract and pass adults upstream through fish ladders (Clay 1961; Collins et al. 1962; Weaver 1963; Bell 1990), similar success with guiding and bypassing juveniles in dam forebays before they enter turbine intakes has not been achieved. Delays of migration in the slowly moving waters of dam forebays appear to be a main factor in prolonging migration times of some juvenile salmonids in the impounded lower Snake River (Venditi et al. 1997). Dam breaching is being considered seriously to avoid migration delays at dams (Harza 1996).

An important feature of fish ladders for adults is an attraction flow at the base of a dam (Clay 1961). Using pumped water or water from the reservoir, hydraulic jets create zones of increased velocity and turbulence that simulate large volumes of water emerging from the base of the ladder, even though the main ladder flow is small (Fig. 1). These attraction flows mimic the turbulence and water movement of the natal river and entice the adult salmonids to enter the ladder. The ladders themselves are a series of simulated pools, waterfalls, and high-velocity chutes that maintain highly turbulent flow. These common hydraulic features of numerous ladder designs encourage most adult salmonids to continue onward through the ladder.

In contrast, bypass systems for juvenile salmonids have not employed attraction flows other than the inflow currents that are drawn by hydraulic head to enter turbines, spillways, trash sluices, or other passage routes. Early bypass devices used surface spills or variable-depth submerged orifices such as the "Merwin Trap" (Stockley 1959) or pumps such as floating migrant collectors at Baker River, Washington, dams (Wayne 1961; Quistorff 1966) to create hydraulic head differences and thus generate attraction flows for outmigrants that pulled the fish into a bypass portal or enclosure. Each device apparently tried to simulate the volume and velocity of a natural stream without concern for natural turbulence. Early studies of turbulent water jets to deflect juveniles to bypasses at water intakes (Bates and VanDerWalker 1964) were not further applied to fish guidance despite positive results.

The most common "bypass" system today in the Columbia River basin uses submerged traveling screens to remove juveniles from the deep turbine intakes (Mighetto and Ebel 1994). These bypasses operate counter to the fish's natural tendency to remain near the water surface, and probably account for much of the delay in migration at the forebays. To more closely match surface orientation of migrants, bypasses with surface entrances are being tested (Sweeney et al. 1997; Johnson et al. 1997b).

To facilitate new "surface-flow bypasses" or "surface collectors" that make use of the fish's surface orientation, considerable effort has focused on defining the hydraulic features of the regions where flow moves toward a particular dam portal (the portal's "flownet"; Johnson et al. 1997a). These flownets are generated by the differences in hydraulic head between the reservoir and the portal, and the water is pulled toward the portal with gentle acceleration and smooth flowlines (Fig. 2). Fish are presumed to detect the flownet and follow flowlines to the portal. Dam operations (e.g., turbine operations or spillway use) have been modified experimentally to alter the relative positions of the flownets leading toward turbines and alternative fish passage routes. Different bypass entrance sizes and shapes, including baffles, have been examined for the flownets they create, which affect the discovery and use of the bypass by fish.

Flownets are passive and generally not very turbulent. They arise gradually in the forebays of dams where impounded waters are quiescent compared to an unimpounded river (even though bulk flow

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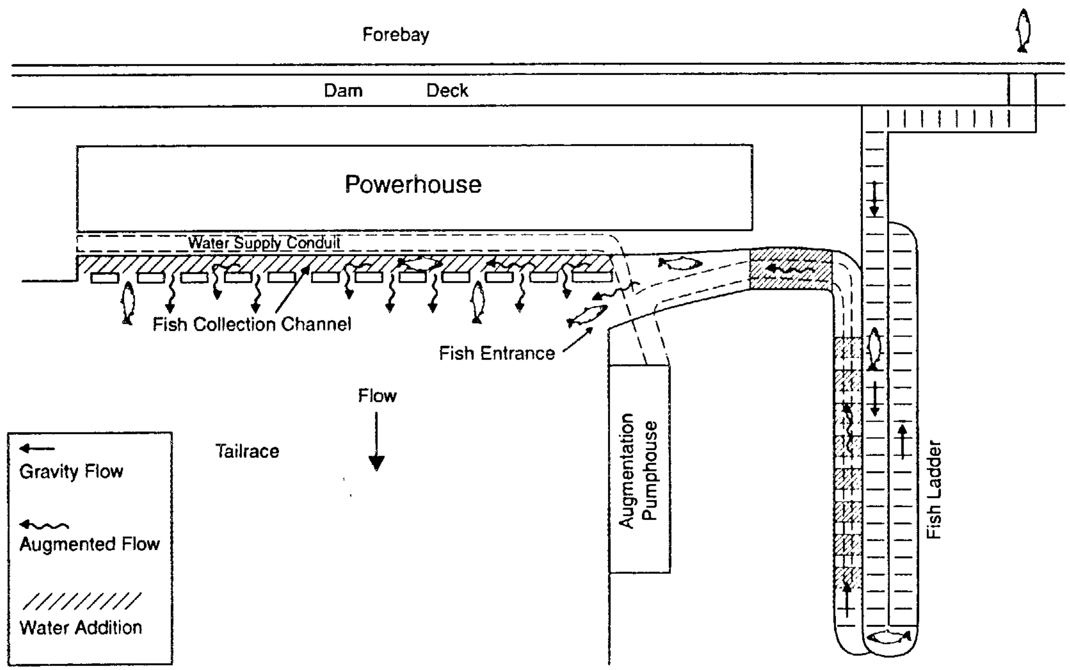

Figure 1. The attraction flow system for adult salmon migrants at the downstream entrance to the south fish ladder at Ice Harbor Dam, Snake River. Attraction water is pumped from the tailwater into the lowest segment of the fish ladd and the collection channel above the turbine discharges (hatched zones). The water that attracts adult salmon into and up the ladder is a mixture of water direved by gravity from the ladder and the pumped additions. (Adapted from blueprints supplied by D. Hurson, U.S. Army Corps of Engineers).

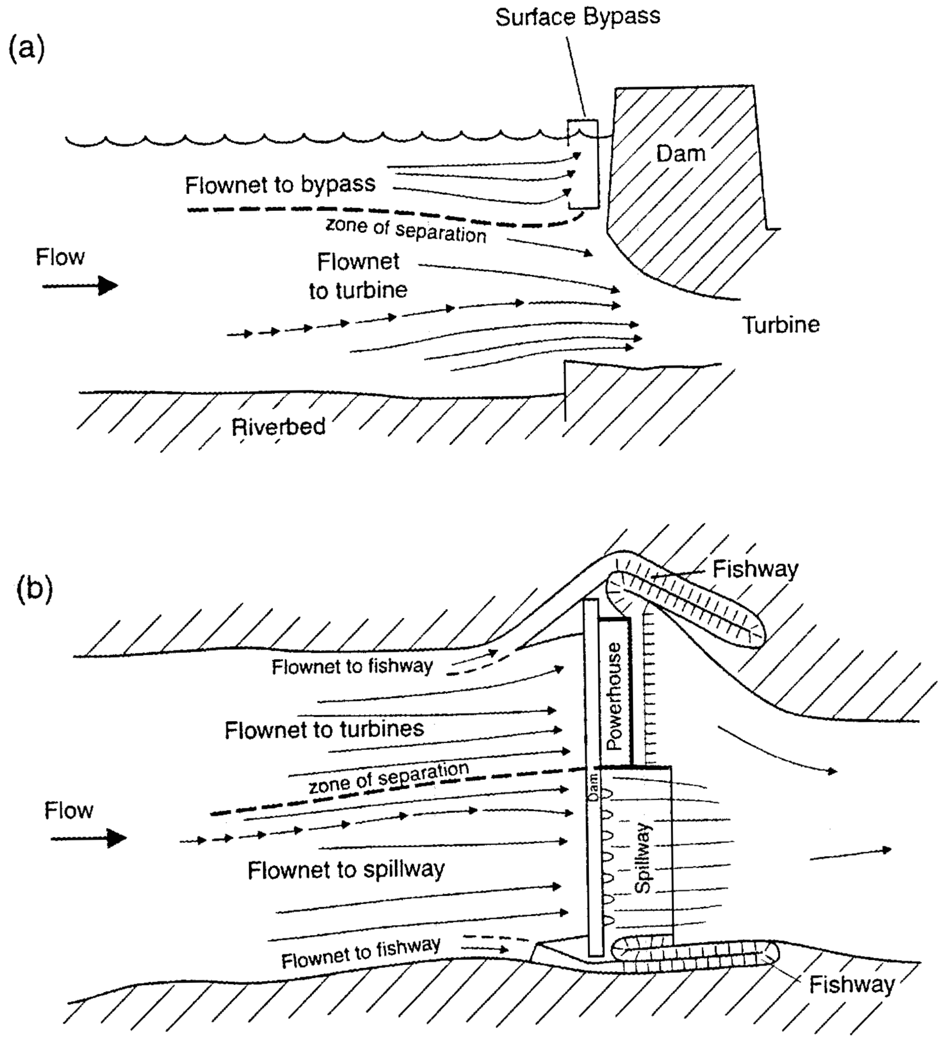

Figure 2. Typical vertical (a) and horizontal (b) flownets in the forebays of a mainstem dam. Flownets are the flow streamlines drawn to a particular dam portal. One streamline in (a) and (b) illustrates the increasing velocity (longer arrows) as the portal is approached. Zones of separation (heavy dashed lines) divide the trajectories of particles heading toward different portals. After Johnson et al. 1997a.

may still be recognizable). Flow velocities typically increase slowly in a linear direction as the dam portal is approached (Fig. 2). Turbulence within the flownet has not been the focus of study as attention has been directed toward defining average velocity fields in the direction of the portals and the location of the "zone of separation" between two flownets (Johnson et al. 1997a).

Although the flownets near bypass entrances appear to attract migrants, their effectiveness diminishes with increasing distance. Johnson et al. (1997a) distinguished three zones in forebays of Columbia River basin mainstem dams: a near field within about 10 meters of the portal, an intermediate field (10-30 m), and a far field (>30 m). Bulk flow dominates the far field, flownets separate toward various portals in the intermediate field, and specific portal conditions dominate in the near field. Rainey (1997) noted that there is little opportunity for fish to discover the entrance when they are outside the near field of a bypass flowing at about 2 m/s. Mechanisms for expanding the "opportunity for discovery" are a high priority for surface bypass development (Johnson et al. 1997a; Rainey 1997).

Flows within bypass channels near their entrances have generally not been engineered to keep juveniles in the bypasses once they have entered, as has been done for adult fish ladders. Studies of several prototype surface flow bypasses have shown that a large proportion of the juveniles that enter bypass structures reverse course and pass through dams by another route (Pevan et al. 1996; Johnson et al. 1997a; Stevenson et al. 1997).

The purpose of this paper is to suggest that a missing component for guiding juvenile salmonids toward and through bypass systems at dams is a turbulent attraction flow. The turbulent component may be especially important for surface flow bypasses, which otherwise seek to match the natural preferences of juvenile salmonids for surface and flow orientation, in accord with developing more "normative" fish passage conditions that match our understanding of the functional features of a natural system (R. Williams et al. 1996; Coutant 1997). Further, this paper suggests that levels of mild turbulence appropriate for guiding fish could be created near bypass entrances by both passive mechanisms that alter existing water movements in flownets and active methods that use pumped water jets (as used in attraction flows at fish ladders) or propellers at distances where flownets are weak. The paper presents a general hypothesis that could be tested at fish passage prototypes and experimental bioengineering facilities.

2. TURBULENCE IN NATURAL RIVERS

Natural rivers, even large ones, are turbulent. Even a casual observer is aware of eddies at rocks or bridge pilings that continue for many meters downstream, "boils" where water surges to the surface creating horizontally spreading surface patches, and "rips" that separate fast-moving waters of the channel from slower-moving water at the edges or at mouths of side channels or sloughs. Flow over bottom sills or boulder fields generates standing waves and chutes of faster-moving water. Less apparent are waves propagated downstream by changes in flow volume or other disturbances, which interact with topographic features and add to turbulence. This is the natural environment of a downstream migrating juvenile salmon. Many of these features are treated in detail in textbooks of applied hydrology and fluid dynamics and are summarized here.

Fluid dynamics of water flowing in rivers (open channels) is a field of physical sciences that matured 15 to 20 years ago (Liggett 1994) but that has not been brought to bear adequately on questions of juvenile salmon migrations or fish guidance. Study of the physical biology of fluid flow has generally been concerned with static (attached) life in moving fluids, such as the shapes of organisms in flowing waters (Vogel 1994), or design of swimming animals for propulsion, lift, and minimizing drag (Webb 1994; Triantafyllou and Triantafyllou 1995). Yet mobile, migrating salmonids undoubtedly interact with the complex fluid dynamics of riverine environments. The basic mathematical expressions of features of water flow, elevation, and velocity in rivers can be found in textbooks such as Chow (1964), Cunge et al. (1980), Abbott and Basco (1989), and Chaudry (1993). Recent work has combined this basic understanding into computational fluid dynamics (CFD) models useful for designing engineering works for fish passage (e.g., Sinha et al. 1998).

Several features of fluid dynamics of open channel flow (that is, flow in channels with solid sides and bottoms and a water surface exposed to air) may influence juvenile salmon migration. Water rarely moves as uniform flow along a streamline. Flow is most uniform when the depth and width are constant along the direction of flow and the bottom is smooth, a situation unlikely to occur in natural rivers frequented by salmon. Similarly, natural streams rarely have steady flow, in which the velocity at a point does not change with time. The normal pattern for a stream, viewed at the scale of a 50- to 200-mm fish, is to have velocities and directions of flow (vectors) that change in often complex ways, whether viewed while moving along a longitudinal reach or from one stationary point over time. With changes in velocity and direction, usually as vortices, come changes in water pressure. These complex changes in velocity, direction, and pressure are collectively considered turbulence and have several causes in a river.

Streams of water have different turbulent structures depending upon the interactions of flowing fluid and solid objects (e.g., Laufer 1951, 1954). Although the field of fluid dynamics has been greatly concerned with generation of turbulence at fluid-solid interfaces (for resolving such questions as drag in mobile vehicles), the environmental interest for fish migrating in rivers is with so-called free turbulent flows. Free turbulent flows are characterized by the phenomenon of intermittency, first noted in a jet by Corrsin (1943) and later more clearly recognized and studied in detail in the wake of a cylinder by Townsend (1949) and in two-dimensional channel flow by Laufer (1951). It is now known that intermittency is present in flows like wakes, jets, and those near a free surface of a boundary layer, and that the intermittancy is a prominent feature of turbulent structure (Laufer 1954).

One large feature of riverine turbulence is the turbulent burst. A turbulent burst is the high-speed, turbulent ejection of fluid and suspended solids away from the sediment bed, often after encountering a streambed obstruction (Leeder 1983). Over distances of 4 to 5 times the water depth, accelerated flow events occur that act toward the bed and concurrent rapid fluid movements away from the bed (Fig. 3). The rising burst of flow propagates downstream in the water column as a 3-dimensional flow feature and is seen at the water's surface as a roughly circular upwelling or "boil." A view of the surface of a swiftly

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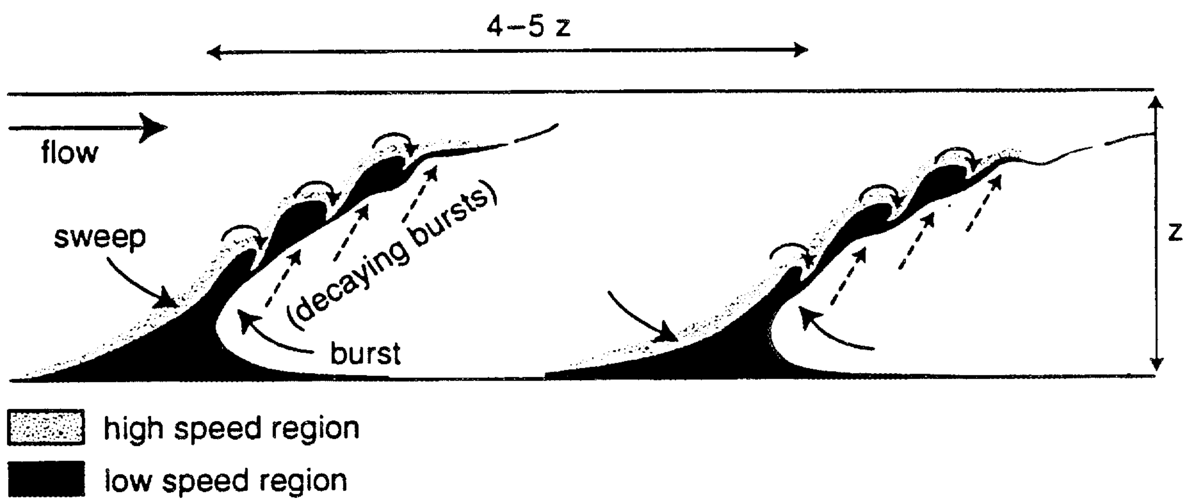

Figure 3. Anatomy of a typical turbulent burst, showing high-speed turbulent ejection of fluid and suspended particles away from the bed of a river. Zones of increased water velocity occur at the leading edges of bursts as they rise toward the water surface at a rate faster than general water movement. After Leeder 1983.

moving river such as the unimpounded Columbia at Hanford, Washington, is of a patchwork of these boils. Water velocities in the leading edge of boils exceeds that of the general surrounding water. Bursts have been studied for their importance in moving sediment, but not fish. Unsteady bedload transport is driven by "bursting-type" cycles in the sea (Thoren et al. 1989), and Carling (1992) has suggested that riverine sediment transport is also related to the inherent turbulent structure of rivers. These velocity bursts are a function of flow rate, water depth, and bottom roughness; reduction of flow velocity and increase in depth (as in impoundments) would terminate such turbulent structures. It seems reasonable that salmonids emigrating in rivers would have evolved to make use of the zones of accelerated velocity in these turbulent bursts to assist them in downstream movement.

Vortices in wakes are another feature of turbulent flow, in which the propagating mechanism for the 3-dimensional flow feature usually acts initially in the horizontal plane rather than the vertical (as in bursts). Rows of vortices are shed behind solid bodies and trail behind in a wake (Fig. 4). If the body is in midstream, there is a wake of roughly parallel vortices, forming first on one side of the body and then the other. Each vortex rotates horizontally in the opposite direction of the preceding and succeeding ones. If the body is a projection from shore, the vortices trail in single file in what is often referred to as a shoreline "rip." In either case, water velocities on the outside of the wake of vortices are more rapid than the general (average) water flow. Migrating juvenile salminids may have evolved to seek and enter these higher velocities.

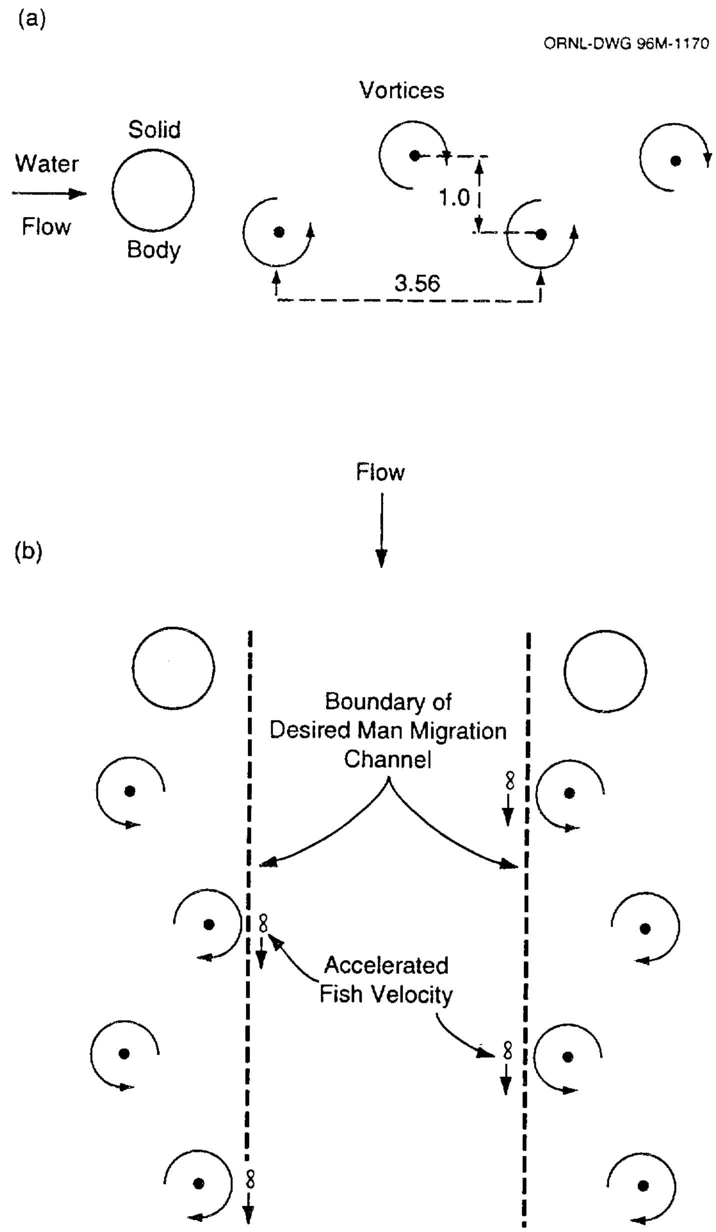

Figure 4. Vortices in a river trailing downstream from a physical obstruction. (a) A double row of vortices from a single obstruction. Distance between sequential vortices is generally about 3 1/2 times the lateral spread. (b) A set of vortices from paired obstructions in a channel, with a zone of accelerated flow between obstructions.

3. RESPONSES OF JUVENILE SALMONIDS TO TURBULENCE

It was in this turbulent environment that juvenile salmonids evolved their downstream migrations. Although there has been little direct study of the orientation of juvenile salmonids to the well-understood features of turbulence, it is reasonable to assume that they normally used the enhanced velocities of turbulent microenvironments to assist their downstream migration (Triantafyllou and Triantafyllou 1995; R. Williams et al. 1996). Every bit of assistance from a downstream vector of turbulence would mean less metabolic energy to be expended in swimming. It would be surprising, indeed, if fish did not take advantage of opportunities for recapturing kinetic energy from turbulent wakes, waves, and bursts. Triantafyllou and Triantafyllou (1995) concluded that fish instinctively exert precise and effective controal of the flow around their bodies to extract energy. In fact, most studies of juvenile salmon orientation during outmigration show them positioned head upstream so as to use their energy most efficiently in maintaining orientation with flow rather than in active downstream swimming (Smith 1982; Cada et al. 1997). In the physical sciences, the extraction of energy from unsteady flows using a stationary foil is called the Katzmayr effect, after the German engineer who first studied it (Triantafyllou and Triantafyllou 1995).

Turbulence has generally not been considered as an attractive feature for guidance of downstream migrants largely because early experiments showed fish avoided areas of turbulence near bypass intakes (Brett and Alderdice 1958). Even recent studies have found that structures like trash racks at bypass portals can cause fish to be repelled, which is often attributed to "turbulence." Rapid changes in direction and velocity of water movement at louvers have been used to repel juvenile salmonids and guide them to bypasses. The hydraulic principle behind louver fish guidance systems is a rapid change in direction (and velocity) of water as it passes through louvers oriented nearly perpendicular to water flow (review by Taft 1986). Fish detect the changed flow conditions at some distance upstream of the louvers and follow the angled bank of louvers to a bypass system. The many studies that have evaluated guidance efficiency of louver systems did not measure turbulence *per se* but may show the influence of it. For example, Ruggles and Ryan (1964) observed clear behavioral changes in sockeye smolts in their experimental flume when velocities (and we can speculate turbulence, also) were changed. At low velocities (to about 40 cm/s) and presumed low turbulence, smolts actively swam downstream and exhibited an in-and-out exploration of the bypass entrance; at about 75 cm/s smolts moved about rather randomly; at 115 cm/s and probably higher turbulence, smolts were all oriented tail-first moving downstream and were guided to a bypass.

Researchers in the Soviet Union have investigated the influence of flow turbulence on fish behavior since the late 1970s, but only some of this literature is available in English (Shtaf et al. 1983; Skorobogatov and Pavlov 1991). Much of their emphasis has been on nonmigratory species (roach *Rutilus rutilus* and minnow *Phoxinus phoxinus*) and their ability to maintain position in turbulent flows rather than their use of turbulence to assist migration. One significant result for salmon is the demonstration that the horizontal movement of drifting young fish is facilitated by narrow channels with higher turbulence (Pavlov et al. 1995). Turbulence appeared to assist the fish in their daily cycle of horizontal movements alternating between near-shore (day) and stream-channel (night) occupancy, similar to the normal daily cycle of underyearling chinook salmon in the Columbia River basin.

Few experiments have been carried out to examine the responses of downstream-migrating juvenile salmonids to 3-dimensional changes in water velocity at distances within 10 to 20 body lengths. Studies of damaging turbulent shear caused by high-pressure water jets (Groves 1972) are not relevant to the much milder turbulence being considered here. Johnson (1996) reviewed numerous laboratory and field studies of smolt orientation to water velocity, spanning over 40 years, with the conclusion that evidence for movement to higher velocities was mixed.

A sampling of research suggests that fish can discriminate higher velocities that would be found in small turbulent eddies. Dijkgraaf (1933) showed that blinded fish in midwater could orient to a small jet of water. McKinnon and Hoar (1952) observed that chum and coho salmon showed a preference for the stronger of parallel laminar currents. Gregory and Fields (1962) found that juvenile coho and chinook salmon were capable of discriminating very low velocities without visual stimulation (in the order of 0.02 feet per second or 0.4 m/min.). Recently, J. Williams et al. (1996) reported experiments with yearling and underyearling chinook salmon outmigrants in an experimental flume with water moving at 0.7 to 0.8 m/s. These fish were recorded as they reacted to the presence of a physical barrier inserted in their path (Fig. 5). The fish avoided low velocities in front of the barrier and actively swam (oriented head upstream) to position themselves in the high-velocity flow lines above and below the barrier. The fish detected and responded to velocity differences of about 10 cm/s with a detection distance of approximately 10 cm. The detection distance approximated the length of the fish's pressure-sensing lateral line. Anesthetized controls confirmed that the response by alert fish was an active one and not merely a function of fluid dynamics around the barrier. No observations were made in the turbulent zone downstream of the barrier. Quite possibly the mixed results of studies of velocity orientation by smolts are the product of lack of concern for the guiding effects of small-scale turbulence.

At least one field study may have inadvertently shown the beneficial effects of a turbulent attraction flow. A log boom at Lower Granite Dam on the Snake River was shown by Swan et al. (1985), using fyke nets, and Wilson et al. (1991), using radiotelemetry, to guide yearlings of chinook salmon and steelhead toward the dam spillway. The boom was acutely angled from the south shore of the forebay across the powerhouse entrance, terminating at the juncture of powerhouse and spillway. Hydroacoustic surveys of turbine intakes with and without the boom definitely showed a higher abundance of migrants at the turbines nearest the termination of the boom when the boom was in place, especially in daytime (Kuehl 1986). Although the boom provided little physical barrier to movement of fish passing under it in the upper water column, one can speculate that a zone of turbulent water was created along the boom, which may have provided cues for guidance along the boom.

Juvenile salmonids have a highly developed lateral line system for detecting changes in water pressure. More is known about its anatomy than about its function in a natural environment, however (Bleckmann 1986; Popper and Platt 1993). As suggested by the review of R. Williams et al. (1996), this sensory system could be the mechanism whereby downstream migrants facing upstream guide themselves along the microregions of highest velocity in a turbulent hydraulic environment. They might thus easily discover and follow turbulence generated in dam forebays at the entrances to surface bypasses.

It is difficult to extract information about possible fish behavior in turbulent flows from the literature because flow structure generally has been simplified to measures such as mean water column velocity (e.g., Johnson 1996). Highly sensitive acoustic doppler current profiler data that could give information on turbulence have been averaged both in time and dimension (e.g., depth) and high-velocity "errors" discarded to remove all evidence of small-scale variations (turbulence). Not surprisingly, the sanitized velocity data are not well correlated to fish distribution, even at locations such as Wells Dam where there is good fish guidance to bypass entrances (Johnson 1996). Realistically, the relationships will not be clarified or quantified until measurements and data analyses appropriate to understanding turbulence at the scale of migrating fish are undertaken (such as Stacey and Monismith 1997). In the meantime, considerations for management can be given on the basis of likely responses based on indirect evidence.

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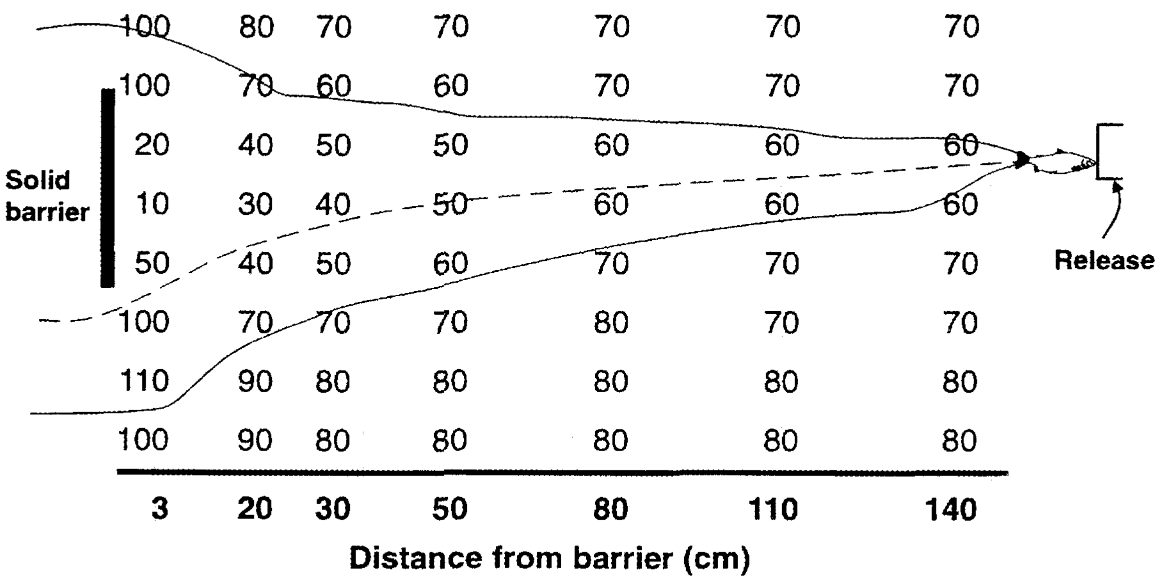

Figure 5. Average trajectories of alert yearling chinook salmon that moved tail-first above and below a solid barrier (solid lines) in an experimental flume, superimposed over average water velocities (cm/s). The trajectory of an anesthetized salmon that moved under the barrier is shown for comparison (dashed). After Williams et al. 1996.

4. INDUCTION OF TURBULENCE

I propose that the "opportunity for discovery" (Rainey 1997) be enhanced in the intermediate and far fields of dam forebays by creating a "trail of turbulence" leading to bypass entrances. In essence, the turbulent features of currents in a natural, unimpounded river would be simulated in a relatively narrow path in the surface waters of the forebay's far and intermediate fields. Fish guidance would be "normative" (Coutant 1997) by making use of the normal orientation mechanisms of river-migrating fish to turbulent flow. A trail of turbulence could be engineered in several ways, both active and passive. A linear series of multiple devices, active and passive, would likely be most effective for establishing the "trail" in areas such a dam's forebay.

The idea of guiding downstream migrants by creating river-like currents aimed in the direction of a bypass entrance has some precedent. A search of U.S. patent files uncovered an expired 1984 patent by D. L. Koch (Patent Number 4437431: "Method and apparatus for diversion of downstream migrating anadromous fish") for a surface bypass system in which water jets were proposed to generate "artificial stream conditions...within the forebay of dams used for hydroelectric facilities." The jets were to create an artificial stream current in the path of fish in the reservoir, direct the migrating fish in such a manner that they sense the artificial stream current, are attracted to it, and enter it. The jets were directed at a funnel-like bypass entrance in a dam forebay and were to push fish from the forebay into the funnel and then through the bypass piping. The patent encompassed the entire bypass system, and the exact features of the current-inducing jets near the entrance were not described in detail.

More recently, Truebe and Truebe (1997 draft and in press) have proposed and tested a "current inducer" directed toward a surface bypass. Field testing of a surface bypass for Atlantic salmon juvenile migrants in New Hampshire (Upper Penacook Hydroelectric Project on the Contoocook River) indicated that migrants were not drawn to the bypass but followed currents to the turbine intake. The bypass entrance was located where there were few surface currents beyond its immediate vicinity. A mechanically generated current was aimed at the bypass entrance and across the top of the turbine flow from a point along the shoreline upstream of the powerhouse. Current was generated by two 2-horsepower, low-speed submersible electric motors driving 1-meter-diameter (3-foot) propellers mounted in a screened frame. Propellers were calculated to be more energy efficient than water jets (J. Truebe, pers. comm.). One propeller was positioned horizontally with its centerline 76 cm (30 in.) below the water surface while the other was tilted upward. Whereas the bypass had been ineffective without the current inducer, tests with the artificial flow yielded bypass efficiencies of 93 and 80 %. The emphasis of design and testing was to induce water movement (velocity, momentum) toward the bypass, although photographs indicate that highly turbulent flow was created by the propellers. Both turbulent cues for orientation and water momentum for transport probably contributed to the positive results.

4.1 PASSIVE DEVICES

Control structures placed in a reservoir might use the momentum of existing flow fields to induce turbulence and changes in water velocity that could guide and aid fish movement toward bypasses. For example, a pair of simple concrete cylinders placed at the edges of the main channel in a forebay would induce vortices in the direction of a bypass that could be sufficient to guide fish movements (Fig. 4). If such cylinders were placed at intervals along one side of a reservoir, a useful channel velocity might be continued from upstream riverine reaches well into the dam forebay where downstream directionality of fish movement disappears and fish begin a back-and-forth searching behavior (Venditti et al. 1997). Submerged berms and dikes are commonly used to direct river flows. Few navigable rivers are without these structures intended to maintain navigation channels through induction of turbulent scour of bottom sediments.

The submerged vane is a control structure that also has found application in redirecting water velocities to aid sediment movement (Odgaard and Wang 1991a). This structure may also be capable of redirecting velocity patterns to aid juvenile salmon migration into bypasses. As applied to sediment management, the vanes are small, flow-training structures (foils), installed near the riverbed and designed to modify the near-bed flow pattern and redistribute flow across the channel cross section (Fig. 6a). They are installed at an angle of 15-25° with the flow and their initial height is 0.2-0.4 times the local water depth at design stage. The vanes generate a secondary circulation of flow not unlike other midstream obstacles, but with additional avenues of control through angle, size, and number of vanes. A single vane generates a vertical vortex of flow that would push surface water to the center of a channel (where fish migrate) and sediment toward the sides. Vanes in groups generate larger, combined vortices (Fig. 6b). When aligned on opposite sides of a channel, sets of vanes can constrict the flow to a more defined channel (Odgaard and Wang 1991b; Fig. 6c). The functionality of vanes in rivers has been evaluated experimentally (Marelius and Sinha 1998) and numerically (Sinha and Marelius in press).

Although there have been many applications of submerged vanes to sediment control, there has been no experimentation with their use as fish-assisting devices. One can visualize using both vertical and horizontal vanes suspended in flow fields in many orientations to simulate natural turbulent bursts and vortices directed toward bypass entrances. The vanes should be effective wherever there is sufficient momentum in the bulk flow to power the changes in flow direction, velocity, and turbulence.

4.2 ACTIVE DEVICES

Active induction of turbulence may be necessary for effective fish cueing or attraction to dam bypasses where ambient water flow and channel topography are insufficient to generate useful turbulence and there is insufficient momentum to use passive devices. Flownet flows induced in bypass structures are generally insufficient to extend flow cues far enough into the quiescent waters of the reservoir for fish to discover and orient to them.

An active approach was advocated by Koch (patent) and Truebe and Truebe (1997). A small amount of pumped water (relative to the bypass flow) could produce turbulent flow cues through hydraulic mixing of an induced jet with surrounding water (Fig. 7). The physics of turbulence in an unconstrained fluid jet is well established (Laurence 1956). A pumped water jet (single or in arrays) is highly controllable in volume and direction, and it can be positioned easily in the water column. However, the jets must be designed so that damaging effects of turbulent shear are avoided (Groves 1972). It may be preferable to use propellers (as Truebe and Truebe 1997), paddle wheels, or similar mechanical devices. Computer models for the near-field mixing of water jets (such as the CORMIX model developed for mixing of waste discharges; Jirka et. at., 1996) could be used to custom design a series of water jets to form a trail of turbulence through a dam forebay and into a bypass entrance. Considering the high potential for such approaches, high priority should be given to both computational and experimental studies of relative effectiveness and energy efficiency of alternative devices.

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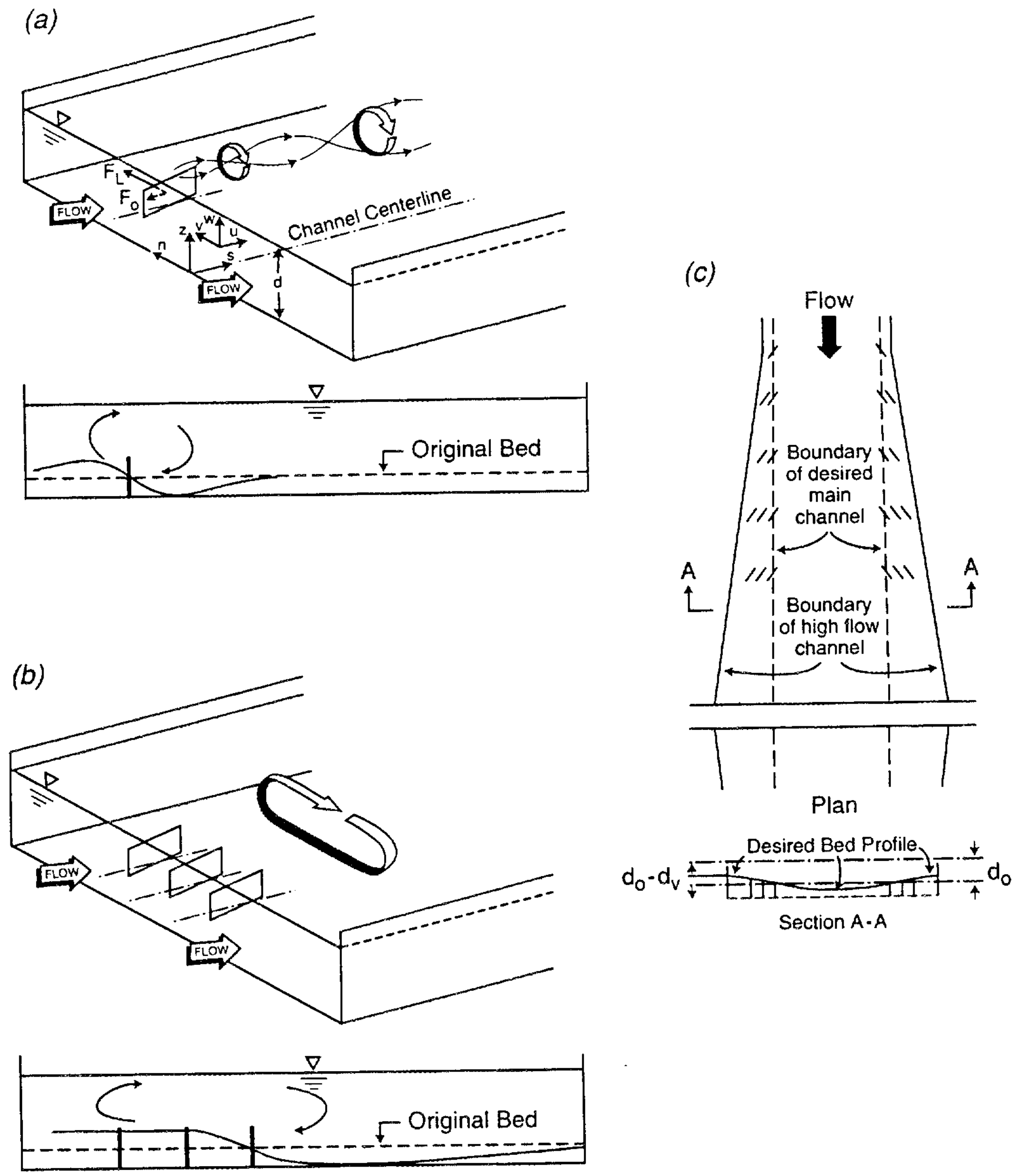

Figure 6. Flow induced by submerged vanes to control sedimentation and clear river channels. (a) Schematic perspective view of flow around a single vane at the side of a channel, showing vertical vortices. The lower panel of (a) shows the circulation pattern in channel cross section. (b) The larger vortex pattern created by a set of closely spaced vanes, shown in perspective and cross section. (c) Multiple vanes installed at the sides of an expanding water body to constrict the higher-velocity channel. After Odgaard and Wang 1991 a and b.

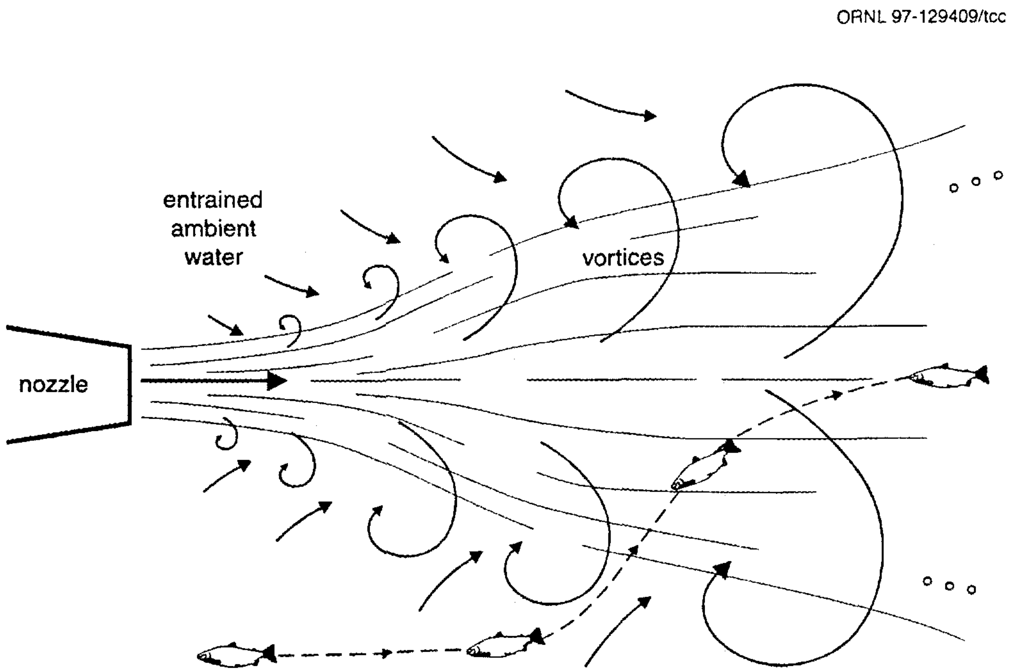

Figure 7. Two-dimensional view of turbulent mixing of a hydraulic jet into a standing or slowly moving fluid. Ambient water is entrained into a series of vortices at the edge of the jet. The momentum of the water at the nozzle is imparted to the sum of jetted and entrained fluid. Downstream-migrating juvenile salmon would discover the jet as they are entrained with surrounding water (dashed trajectory) and likely maneuver to remain in the highest velocity zones as they follow the jet's overall trajectory.

5. APPLICATION

Specific designs for locating and installing passive and active devices to create a trail of turbulence would be necessary for each fish bypass facility, largely because each dam is laid out differently. However, the concept of simulating hydraulic turbulence and momentum in waters through which fish are to be guided should have general application. There appear to be three principal applications: (1) deployment in open waters of a quiescent main reservoir, (2) deployment in the intermediate- and near-field approach to fish bypass entrances (e.g., within 30 m of the bypass entrance), and (3) deployment in the bypasses themselves, to continue the mild turbulence into and through the bypass to prevent fish from sensing a changed environment and swimming back out.

Water nozzles or vanes could be placed near the bottom of a desired surface migration pathway and angled upward, thus closely simulating turbulent bursts (Fig. 8). The turbulent flow effects could be concentrated in the near surface waters usually populated by downstream-migrating fish by suspending vanes or jets at mid-depth. Such a mid-depth placement in a dam forebay could deflect migrants that might otherwise sink into turbine intakes. An added advantage of upward-angled turbulence and flow induction would be the elevation of somewhat cooler water into a dam forebay where a pool of warm water often accumulates.

Design specifications for the hydraulic structures needed to create a useful trail of turbulence at a given facility could be developed several ways. Computational fluid dynamics modeling (computer simulation) could be the most cost effective. However, hydraulic physical models could be used in which scale-model prototypes are constructed and the effects of alternative arrangements would be observed through dye tracers or other visual observations.

Passive and active methods could be employed as part of an integrated system to enhance migration of fish through reservoirs and into fish bypass structures (Fig. 9). Iowa vanes or other baffles could be installed at upstream locations to make use of remaining river momentum and impart turbulence and increased microvelocities. Where momentum is too low to be managed effectively, water jets or propellers could be employed to provide turbulent flow zones to guide fish. When sufficient velocity from hydraulic head has been attained close to or within a bypass, passive methods may again be suitable. These measures for fish attraction to bypasses might be integrated with repulsion measures at turbine intakes, such as strobe lights (Johnson and Plosky 1997; Plosky and Johnson 1997) or sound (Carlson and Popper 1997).

This normative fish guidance concept could enhance fish migration at critical low-velocity locations in reservoirs while preserving cultural benefits of hydropower, navigation, and flood control of mainstem dams. Since 1980, taxpayers and electric ratepayers have invested about $3 billion to stem the decline of Pacific salmon in the Columbia River basin, with little success. In 1997, the lowest number of juvenile salmon ever recorded migrated from the Snake River spawning grounds to the ocean. Two scientific reports (NRC 1996; R. Williams et al. 1996) and the Corps of Engineers (Harza 1996) have converged on a key approach to reviving fish runs: replication of natural river habitat that once nurtured salmon. A key feature of the natural migration habitat is the fast, turbulent flow that likely guided and assisted downstream migrations of juveniles.

One alternative for replication of riverine habitat is to breach four dams on the Snake River (and perhaps other dams; Harza 1996), thus returning the river to near-original flow conditions. This approach would likely have large repercussions in the regional economy. It is estimated to reduce average regional hydropower production capacity by approximately 1231 megawatts of renewable energy or near 5% of the region's total generating capacity, which is needed especially on days of peak demand (Fazio 1998). Replacement power would likely come from fossil fuels that generate carbon dioxide and contribute to

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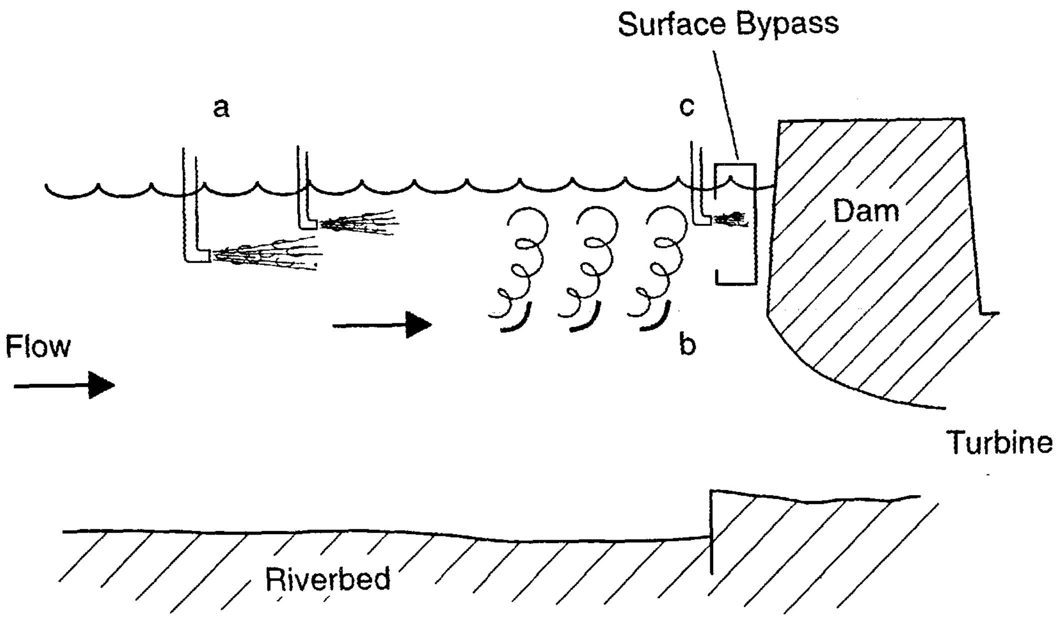

Figure 8. Diagrammatic Placement of jets (a,c) and vanes (b) in a vertical section of a dam forebay to generate turbulence in surface waters to aid bypass discovery by juvenile salmon. Jets at (a) provide turbulent orientation in the slowly moving forebay at a distance from the bypass. Vanes at (b) simulate turbulent bursts in upper layers by passively using the increased velocity of water just below the zone of separation and heading toward the turbine. Water jets at (c) direct fish into and in the bypass. Actual placement would depend on physical configuration of the forebay and bypass.

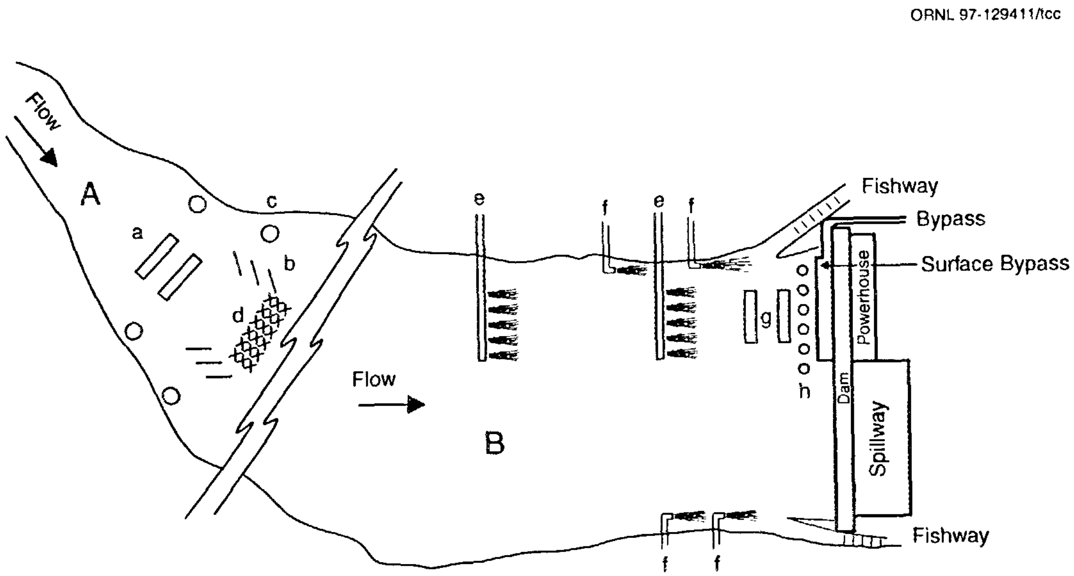

Figure 9. Diagrammatic, plan view of an integrated system of passive and active devices to impart more normative turbulent conditions in a quiescent reservoir and dam forebay. In the upper reservoir (A) where cross-sectional area expands and velocity decreases, the remaining river momentum can be used passively to create surface turbulence for salmon guidance by horizontal (a) and vertical (b) vanes, pilings (c), or submerged berms (d). In a quiescent dam forebay (B) surface turbulence aimed at the bypass can be created actively with banks of jets in diffuser arrays (e) or alongshore (f) where adult migration from fish ladders may also be guided. Near the dam, surface turbulence can again be generated passively with horizontal vanes (g) by using the increased velocities as water nears the turbine entrances (Fig. 8). Fish may be deterred from diving into turbine intakes by banks of flashing strobe lights (h) or other repellant placed below the vertical zone of flow separation.

global warming. It would also reduce river navigation ($500 million/year in grain shipments alone) and irrigation. Dam breaching on the Snake River would cost an estimated $153 million/year for 5 years (minimum), and is under serious consideration by the Corps of Engineers (Harza 1996). If the precedent of dam breaching for fish migrations is adopted in other river basins, the economic loss to hydropower, navigation, and flood control could be large. With international attention on global warming from emissions of greenhouse gases, the loss of renewable hydroelectric power generation could have global consequences. In contrast, the concept of fish attraction flows using controlled turbulence provides an alternative way to replicate critical fluid dynamics of rivers in dam forebays and fish bypasses that could prevent these estimated economic losses.

6. NEEDED WORK

Neither the basic biology of salmonid migration in turbulent waters nor the potential value of inducing suitable turbulence and flow at bypass entrances is well enough known for attraction flow facilities to be designed and installed everywhere without additional study. Enhanced fish guidance to and within juvenile salmonid bypass systems is expected to be of critical importance for the federal Columbia River basin hydropower system because other systems that rely just on flow fields induced by the hydraulic head of bypass portals have not proven fully successful (Rainey 1997). Thus, the effort to understand the interaction of biology and hydraulics appears justified. It seems crucial that an integrated system of turbulent attraction flows be evaluated and tested before long-standing decisions are made (now planned for 1999) about the future operation of the Columbia River hydropower system, including dam breaching.

Contact with researchers in the former Soviet Union who began studies on fish behavior in turbulent waters should be facilitated. Their work may have progressed well beyond what we have available in English. These researchers might be useful consultants for studies and applications in the Columbia River basin.

Biological testing of salmon migration behavior in turbulent water should be conducted in experimental flumes. Recirculating systems such as used by J. Williams et al. (1996) or flow-through designs used so successfully for adult fish ladders at the Bonneville Dam engineering test facility and for juvenile Atlantic salmon behavior at the USGS Biological Resources Division Conte facility at Turners Falls, Massachesetts would each have a place in a planned research program. Such a program should be oriented toward the objective of designing trails of turbulence for fish guidance that increase the opportunity for discovery of bypass entrances.

Advanced, non-intrusive measuring techniques are now available for establishing turbulent flow characteristics near migrating fish. Methods for accurately measuring velocity fluctuations (and consequently turbulence scale and intensity) include laser doppler anemometer (LDA), acoustic doppler velocimeter (ADV), or conventional hot wire anemometer. LDA is most suitable for laboratory applications and is completely non flow-intrusive (but expensive). Several organizations have had a great deal of experience and success in using the ADV for macro-scale velocity measurements near fish bypasses, and this instrument is likely the most practical for field experimental purposes on a finer scale (but it is partially flow intrusive). The third option is a hot wire anemometer which is the least expensive, but flow intrusive. To describe turbulence intensity and scale parameters, velocity fluctuations should be measured at varying locations in the flow field and in proximity to each other (on the size scale of migrating fish). The correlation function can then be determined and finally the turbulence scale is determined based on integration of the correlation function. The best description of these analytical methods are in the classic text by Schlichting (1979).

Computational fluid dynamics modeling should be used to evaluate alternative methods (passive versus active), designs of hydraulic devices, and layouts in dam forebays. Such mathematical modeling would have to be evaluated for its practicality and utility compared to empirical testing at prototype facilities. Physical models of Columbia River dams are already in place at the U.S. Army Corps of Engineers Waterways Experiment Station in Vicksburg, Mississippi and can be employed when they have unique advantages.

Prototype installation and testing of the concept could be implemented by the Corps of Engineers and the Bonneville Power Administration at any of eight federal Snake and Columbia River hydropower projects. Five non-federal hydropower projects on the mid-Columbia River owned and operated by public utility districts would also likely test and (if successful) use this technology, under supervision of the Federal Energy Regulatory Commission. Prototype surface flow bypasses are being developed (tested, planned, implemented, or contemplated) at Lower Granite, Ice Harbor, John Day, The Dalles, Bonneville (I

& II) (all federal) and Wells, Rocky Reach, and Wanapum non-federal dams (Johnson et al. 1997b).

The Corps' principal prototype at Lower Granite Dam would seem to be the most logical location for initial full-scale testing of a hydraulic trail of turbulence. A large, 1100-ft-long, floating, rigid steel structure, the Behavioral Guidance Structure, is currently planned for testing at the site to accomplish the same fish-guidance objective, at much higher cost than is anticipated for induction of a hydraulic trail of turbulence. Smaller dams on tributaries, such as the Cowlitz Falls Dam on the Cowlitz River, could be good early test sites. Small-scale testing with Atlantic salmon (e.g., Truebe and Truebe 1997) should continue with emphasis on evaluation of why prototype systems work from the perspective of interactions of migrating fish with a turbulent zone.

7. CONCLUSIONS

Available evidence points to use of turbulent flows by downstream-migrating salmon for guidance and assistance in migration. In the hydrosystem, normal downstream migration appears to be most disrupted at locations in reservoirs where turbulent flow is least, especially in dam forebays. A major problem with developing effective surface bypass systems at dams is insufficient attraction of migrants to, and their retention in, the bypasses. Nonturbulent flownets as a result of hydraulic head differences between reservoir and bypass are insufficient for migrants to detect and follow the flows to the bypasses. Generation of mildly turbulent flows in the direction of bypasses (trails of turbulence) would appear to be an effective way to guide migrants. Such flows could be generated either passively (with physical structures such as vanes) or actively (with pumped water jets). Further research on this concept and evaluation of the results would appear important for selecting socially acceptable alternatives for operation of the federal Columbia River hydrosystem.

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