Analysis of Fish Response to Flows in the 1991 Pasco Flume Experiments

by James J. Anderson

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Introduction

This report analyzes data collected to evaluate factors affecting juvenile salmonid guidance efficiencies. The study is being conducted by Williams, Gessel and Stanford of NMFS[1]. The hypothesis of the study is that low fish guidance efficiency (FGE) at Columbia River dams may, in part, be due to fish diving when they encounter changes in water velocities. This behavior would cause fish to move deeper in the water column allowing them to pass below the bypass screens (Fig. 1). It is not clear though what flow conditions would produce such zones of avoidance or how fish might respond in them.

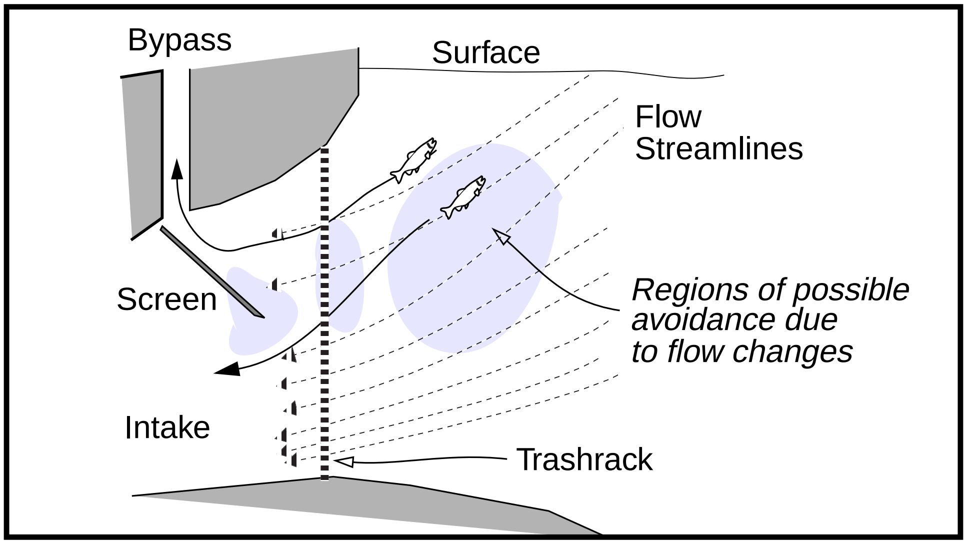

Fig. 1. Hypothesis of fish avoidance by moving across flow streamlines.

This hypothesis is described mechanistically by a model based on the geometry and hydraulics at a dam and the behavior of fish in response to flows (Anderson 1991). The model suggests that avoidance swimming speed and direction and the point in the flow where avoidance is initiated are critical factors determining FGE.

The purpose of the NMFS study is to obtain information on the character of the flow that induces avoidance behavior and the nature of the response. The experiments if successful will identify flow features that elicit avoidance and provide estimates of behavioral parameters for use in the model.

This report presents an analysis of the flume study and an approach to extract the needed information from the experiments. In addition, recommendations for future experiments are presented.

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[1] National Marine Fisheries Service, Seattle

Experimental design in 1991

The response of fish to changes in flow were conducted in the Pasco oval flume. Fish were released into a flow and their responses to a barrier of different porosities were recorded with video cameras (Fig. 2).

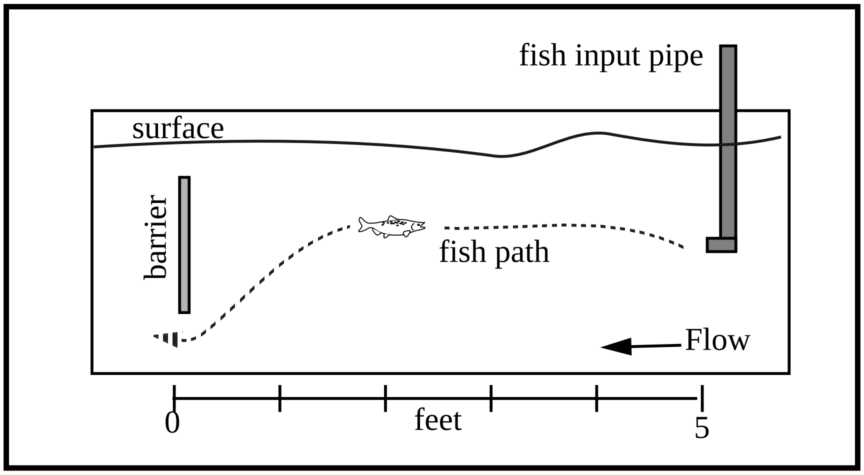

Fig. 2. Schematic of flume used in study showing fish path.

In addition to recording fish paths, the flow distribution in the flume was measured with a current meter. The study was conducted with yearling and subyearling juvenile chinook salmon. Barriers with four porosities were tested (100%, 53, 35, and 0% porosity). The Waterways Experimental Station (WES) determined flow with a Doppler LASER current meter. Flow streamlines were presented as vector plots and time history samples at selected points n the flume.

In this report one fish trajectory was analyzed. Using the WES data to estiamte flows fish behavior responses are estimated and related to changes in flow velocities. The analysis was on a video track make on July 10, 1991 using a barrier with 53% porosity. No information was provided on the tape as to the species but from its size and the date of the experiment it appeared to be a subyearling chinook.

Analysis approach

The approach used in the analysis was to separate fish movement into two parts: one due to the water flow and one due to fish behavior in response to the stimulus the fish encountered in the flume. The idea was to identify fish swimming velocity and then determine if the changes in swimming speed correlated with changes in flow. The existing data was not sufficient to establish statistically significant results but it was sufficient to illustrate the analysis methodology.

Flow Analysis

The WES meter provided point source measurements from which streamlines were constructed which represent theoretical particle paths and the velocity of particles along the paths. Although this technique provides average flow conditions it is unclear if estimating trajectories from the point source measurements is suitable for the analysis. Ideally, to separate flow and behavioral contributions of fish movement we require paths of neutrally buoyant particles moving in the vicinity of a fish. In any case collecting both point and path measurements will provide the best description of the flow in the flume.

For analysis of the 1991 data the streamline vector contours provided by WES were converted into a hypothetical particle path. The theoretical position of a water particle at each 0.1 *s* increment was determined by the velocity along the streamline. Next, a smooth path was determined using an S-PLUS smoothing algorithm[1]. In the procedure *X* and *Y* positions of the particle were smoothed against time. In Fig. 3 the smoothed vertical position of a fish is illustrated along with the data points. The smoothing function provides an apparently higher level of resolution since fish and fluid move in a smooth continuous manner allows for interpolation of positions between observation points.

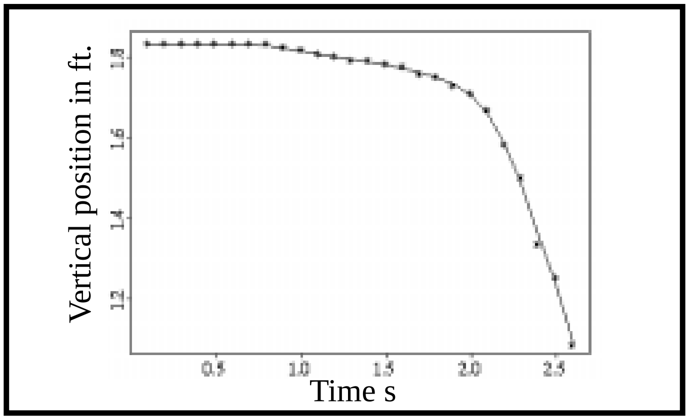

Fig. 3. Smoothed *Y* position of a particle moving along a streamline over time. Line is smoothed function, data are (*).

From individual *X* vs. time and *Y* vs. time a smoothed *X* vs. *Y* path was made (Fig. 4).

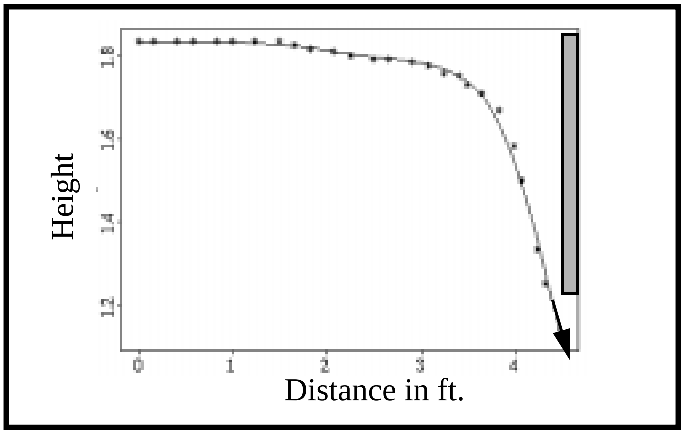

Fig. 4. Path of water particle along streamline in flume. Barrier is illustrated in figure along with data points (*).

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[1] Smoothing based on cubic B-spline (smooth.spline) available in S-PLUS (StatSci, 1991)

From the smoothed positions velocity as a function of time or positions was determined from the time derivative of position by the equations:

$$
\begin{aligned}
U\left(t + \frac{\Delta t}{2}\right) &= \frac{X(t + \Delta t) - X(t)}{\Delta t} \\
V\left(t + \frac{\Delta t}{2}\right) &= \frac{Y(t + \Delta t) - Y(t)}{\Delta t}
\end{aligned}
\qquad (1)
$$

The resulting vertical velocity of a flow particle over time is illustrated in Fig. 5.

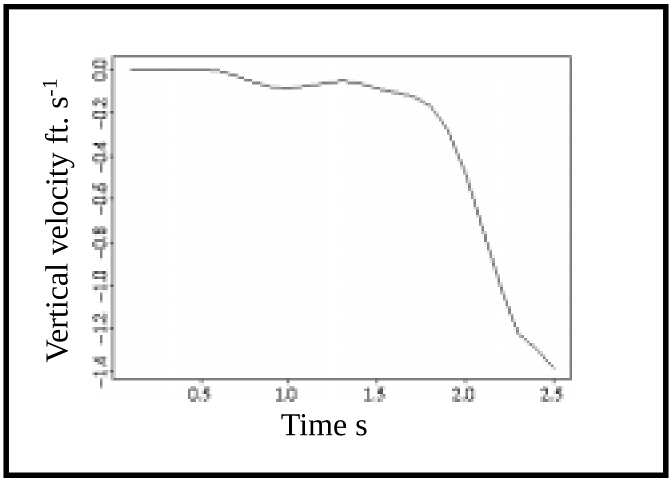

Fig. 5. Velocity of a particle in the *Y* direction vs. time.

The particle speed along the streamline is determined from:

$$S = \sqrt{U^2 + V^2} \qquad (2)$$

The speed of the particle plotted against *X* distance from the release point is illustrated in Fig. 6. The barrier distance was 4.5 ft.

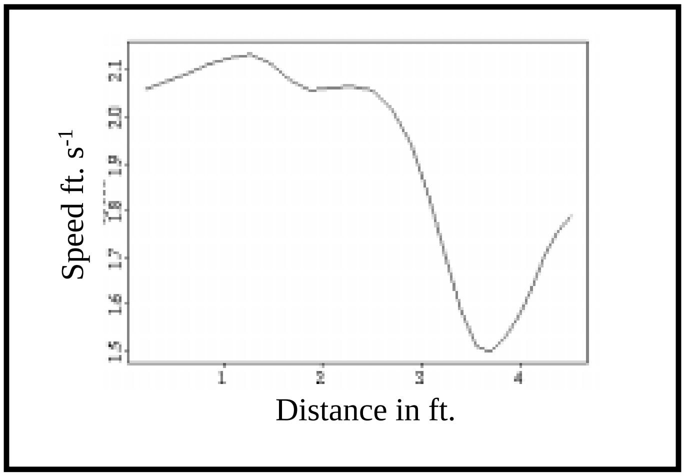

Fig. 6. Flow *U* velocity along *x* coordinate.

Notice that the particle appears decelerates as it approaches the barrier and then accelerates as it passes it.

The water particle acceleration is calculated from the equation:

$$A\left(t + \frac{\Delta t}{2}\right) = \frac{S(t + \Delta t) - S(t)}{\Delta t} \tag{3}$$

This is illustrated in Fig. 7.

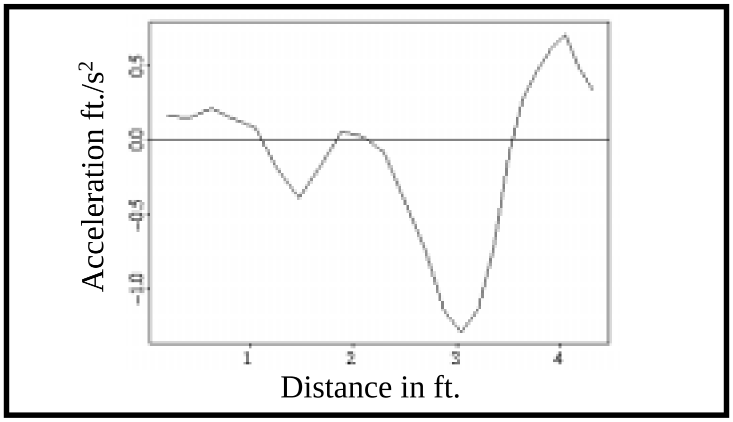

Fig. 7. Acceleration as a function of distance. Barrier is at 4.5 ft.

Fish Analysis

The fish path, velocity and acceleration were analyzed in a similar fashion to the flow data. First, fish position was smoothed against time for the *X* and *Y* coordinates. The smoothing, illustrated in Fig. 8 and Fig. 9, shows the position of the fish in the vertical and horizontal directions as a function of time for both observations (*) and the smooth fit.

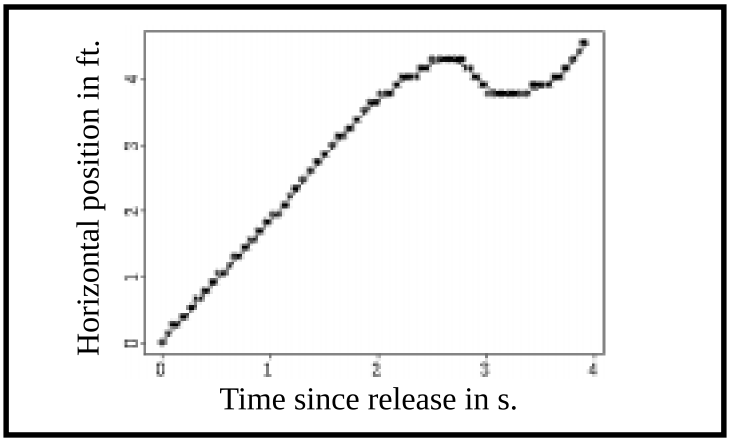

Fig. 8. Actual positions (*) and smoothed path of fish in *X*.

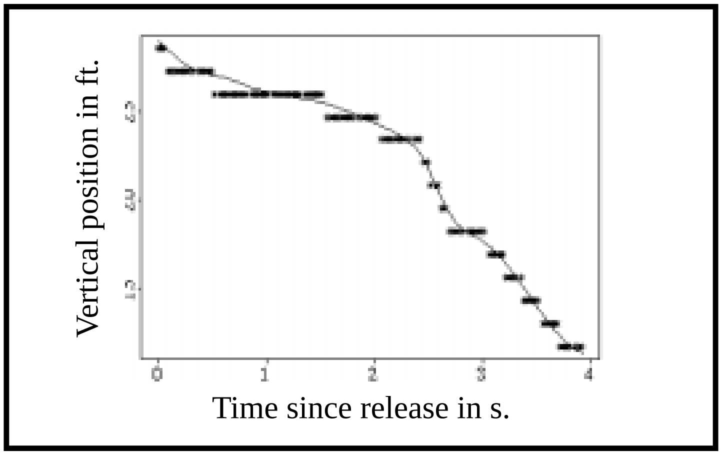

Fig. 9. Actual positions (*) and smoothed path of fish in *Y.*

The smoothed fish path in *X* and *Y* is illustrated in Fig. 10.

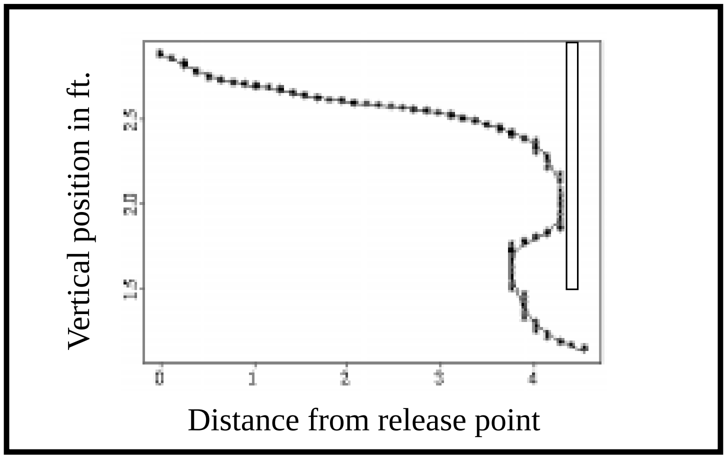

Fig. 10. Data points (*) and smoothed path of fish in *X* and *Y.*

From the fish path the velocities, accelerations and speed was computed. Fish speed is illustrated in Fig. 11 as a function of distance from the release point.

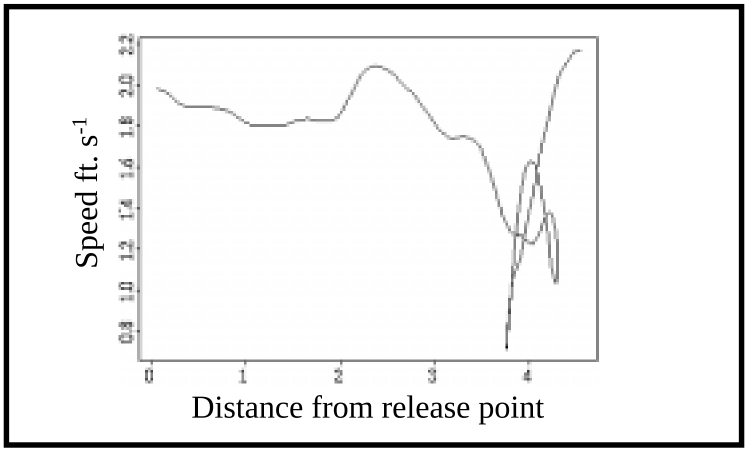

Fig. 11. Fish speed with distance from release.

The above figure shows absolute fish speed. Our interest is in the swimming velocities resulting from the behavior. To compute this value we subtract the flow velocity components from the fish velocity components yielding fish swimming velocity components as a function of time or distance. The equations are:

$$\begin{aligned} U_{swim} &= U_{fish} - U_{flow} \\ V_{swim} &= V_{fish} - V_{flow} \end{aligned} \tag{4}$$

The resulting vertical swimming velocity of the fish from Eq(4) is illustrated in Fig. 12 and Fig. 13 below.

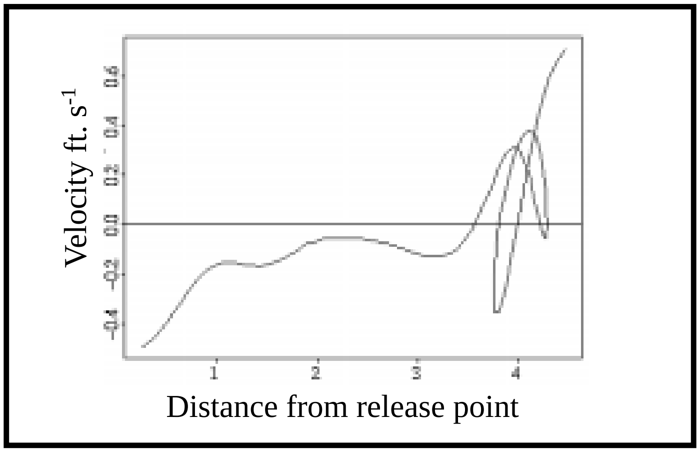

Fig. 12. Vertical swimming velocity vs. distance in flume.

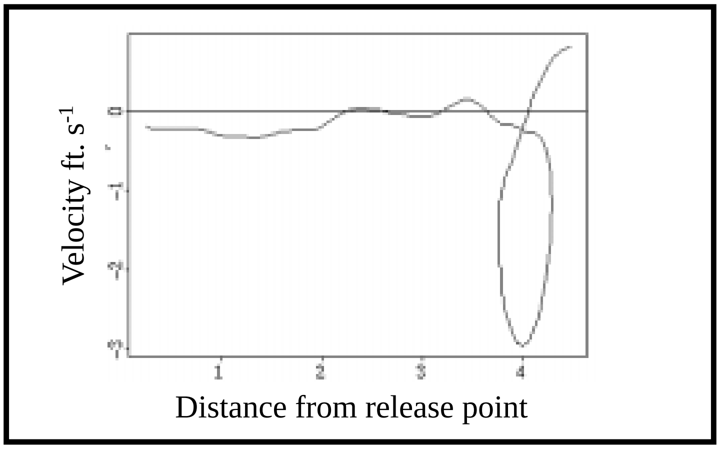

Fig. 13. Horizontal swimming velocity vs. distance in flume.

Notice that when the flow is removed, horizontal velocity is essentially zero and vertical velocity is slightly negative for the first 4.5 feet of the fish's path. At 4.5 ft. the fish encountered the barrier. This is also evident in swimming speed illustrated below (Fig. 14).

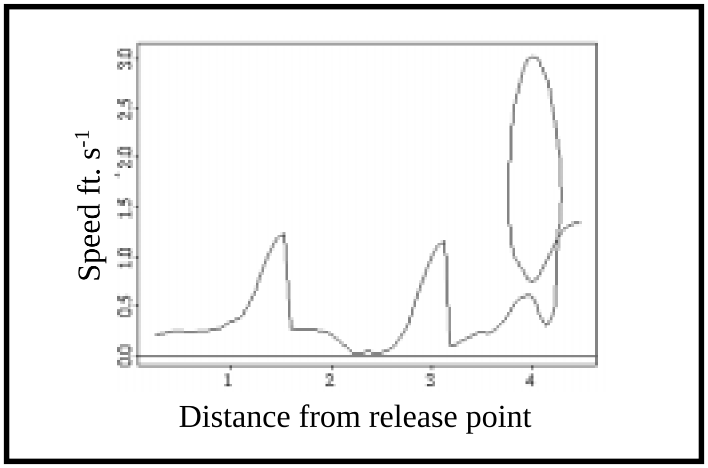

Fig. 14. Swimming speed vs distance in flume. Note avoidance response is initiated at a distance of 4 ft.

The angle of swimming can be estimated from the velocity components using the equation:

$$\theta = \mathrm{atan}(V_{swim}, U_{swim}) \tag{5}$$

The angle of swimming vs. distance from release is illustrated in Fig. 15. The angle of 0° occurred when the fish moved downstream with the flow downstream. Angles of about -90° occurred when the fish actively swam upstream. In these cases the effective fish swimming angle was up to 90° below the horizontal. The data suggest that in its escape the fish, oriented upstream, swam downward. Just before encountering the barrier it moved upward.

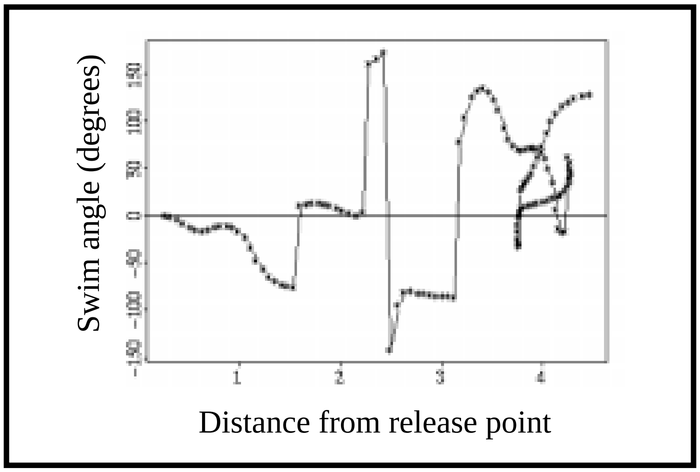

Fig. 15. Angle in swimming behavior. 0° is downstream, 150° upstream and downward.

The pattern of angle change is correlated with swimming speed (Fig. 16). It is not clear how much of this correlation is an artifact of the computations since both angle and speed apply the same basic velocity data.

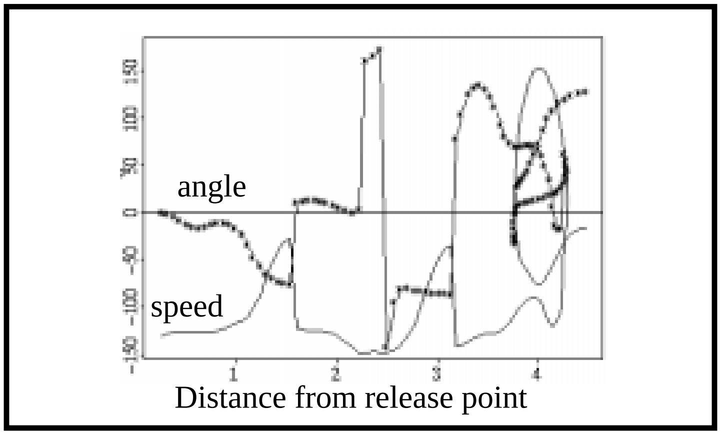

Fig. 16. Correlation of swimming speed and angle.

The data in Fig. 12 and Fig. 15 suggest that the fish initially moved slightly downward in the flume. This observations is supported by the fact that nearly all fish in the flume studies passed beneath the barrier instead of above it. This analysis, although preliminary, suggests that before fish initiate an avoidance response to the barrier they actively moved downward at a velocity of about 0.2 ft. s^{-1} and an angle of near 90°.

Discussion

From the observations on the behavior of fish in the flume study we hypothesize that fish respond to changes in the water velocity. This is supported by studies on the sensory biology of fishes (Kalmijn 1988). Studies indicate that for low frequency motions the strength of the neurological signal produced by inertial detectors in the fish inner ear (otolith) is directly proportional to the acceleration of the fish body. Thus, there is a biological mechanism to base a relationship between swimming behavior and water accelerations.

This hypothesis is supported since increased swimming speed appears to correspond with a deceleration in the flow field (Fig. 17). Such a deceleration is expected to be associated with a flow blockage by the barrier.

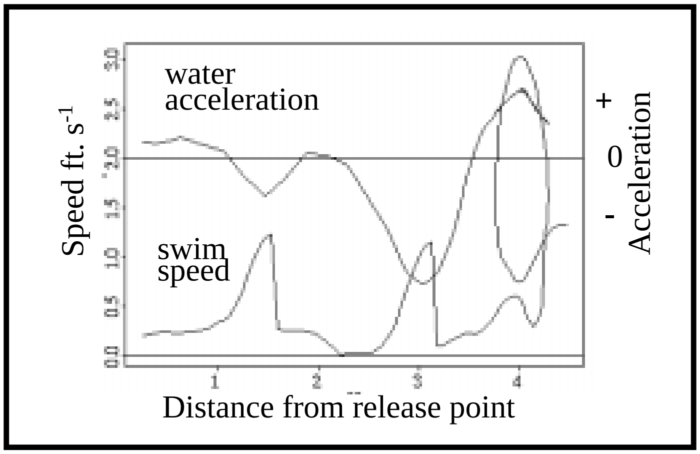

Fig. 17. Fish swimming speed and flow acceleration.

The relationship between swimming speed and water acceleration can be further illustrated by plotting the two properties directly (Fig. 17). It appears that a swimming response was initiated with flow decelerations. The actual relationship between fish swimming velocity and acceleration is complex. Flow accelerations will cause changes in fish acceleration, which in turn induce changes in swimming. This results in changes in fish acceleration. In addition, not only does fish behavior alter the fish acceleration field directly the resulting change in position will put the fish into a different flow field. The result is a complicated relationship between swimming velocity and water acceleration. In spite of these complications a relationship might be identified but more careful measurements will be required to determine if a speed-acceleration relationship is statistically significant.

Conclusions on data analysis

This analysis of the Pasco 1991 flume experiments provides preliminary information suggesting the following:

- Water and fish velocities and accelerations can be resolved by tracking fish and neutrally buoyant particles in the flume.
- Using a time date generator during the video taping is required.
- The fish positions can be traced within a few centimeters.
- Fish analyzed in the experiments (subyearling chinook and a 53% porosity barrier) appeared to have two main behaviors.

  1. Far field behavior: a gradual downward swimming (~ 0.2 ft. s^{-1}) prior to encountering changes in flow at the barrier.

  2. Near field behavior: a strong downward swimming (~ 2 ft. s^{-1}) upon encountering the barrier.
- Avoidance responses in the far fields appeared to have angles up to -90° or directly downward.

NMFS Objectives

The primary 1991 objective of NMFS was to evaluate juvenile fish migrant behavior relative to changes in water velocities. How behavior might be related to flow was not detailed in the NMFS proposal but there appears to be sufficient information from the 1991 study for a preliminary analysis. The NMFS efforts need to be focused on identifying trajectories of water and fish from which actual fish behavior can be extracted.

The stated 1992 objective, to repeat the experiments under selected light conditions, seems premature. First, the existing data from 1991 needs to be analyzed using the techniques outlined in this report. A hypothesis relating fish velocities and movements to flow accelerations needs to be developed. This is a nontrivial task since a time referenced trajectory of each fish must be obtained. Although it is difficult to develop an exact experimental design for 1992 without an analysis of the 1991 data, the analysis of one fish in this report and the path data already conducted by NMFS suggest some modifications to the study. These are detailed below.

Recommendations

Visual affects

A criticism of the experiments is that fish also respond to visual stimuli which complicate the analysis of responses to flow. Although this criticism can only be alleviated by removing all visual signals, as a first step the visual stimuli should be controlled so it does not change with changes in flow. Once the response of fish to flow is understood then experiments can be conducted on blind fish or fish under low light levels to determine if major conclusions of flow experiments change when visual cues are eliminated.

Flow control

The experimental setup of the Pasco flume appeared to produce sufficient flows to induce changes in fish behavior. The paths of fish were quite smooth suggesting the level of turbulence in the tank did not significantly affect results. To better control the flow distribution about the barrier, the following flume modification is suggested (Fig. 18).

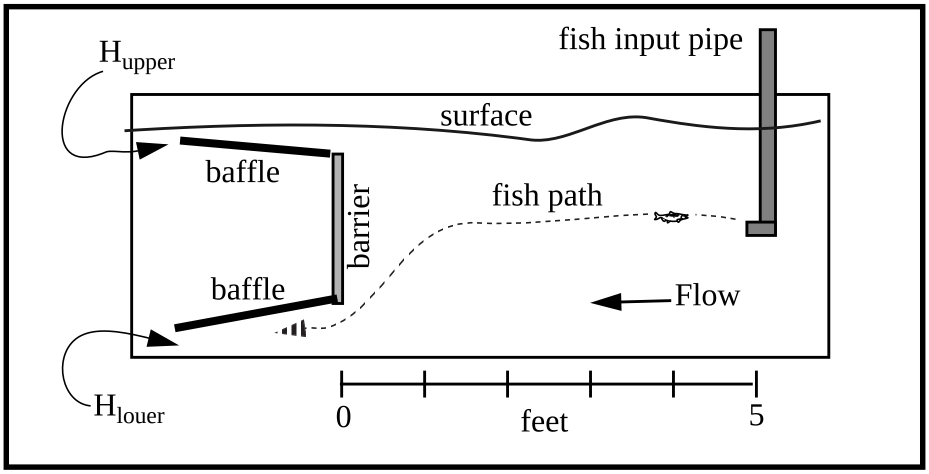

Fig. 18. Suggested flume design to control flows.

Two baffles would fit behind the barrier. Adjustable openings in the baffles, designated H_{upper} and H_{lower}, would direct the flow above or below the barrier while the visual configuration experienced by the fish would be unchanged. With this configuration it would be possible to direct neutrally buoyant particles to pass either above or below the barrier. This configuration might be used to study if downward motion is related to flow or behavior.

Video tracking

Resolution of fish paths requires a clear video record including a high resolution time date generator. Using the existing camera, frames were taken every 0.03 to 0.07 seconds providing resolutions of between 1 to 5 cm in the fish position. This resolution might be adequate to resolve the velocities and accelerations.

A time date record can be superimposed on the video after recording with a time date generator[1].

The background color and lighting used in the 1991 studies made continuous tracking of fish difficult. Additional work is required to obtain a clear video image. A white background should be provided on the tank side. Adequate levels of light should be used so each fish can be tracked on a frame-by-frame basis.

The background should have a grid so fish positions is easily referenced in the video records.

A parallax problem appeared in the 1991 films resulting from the video camera being at an angle to the screen. The experiments should be set up to reduce this problem (Fig. 18).

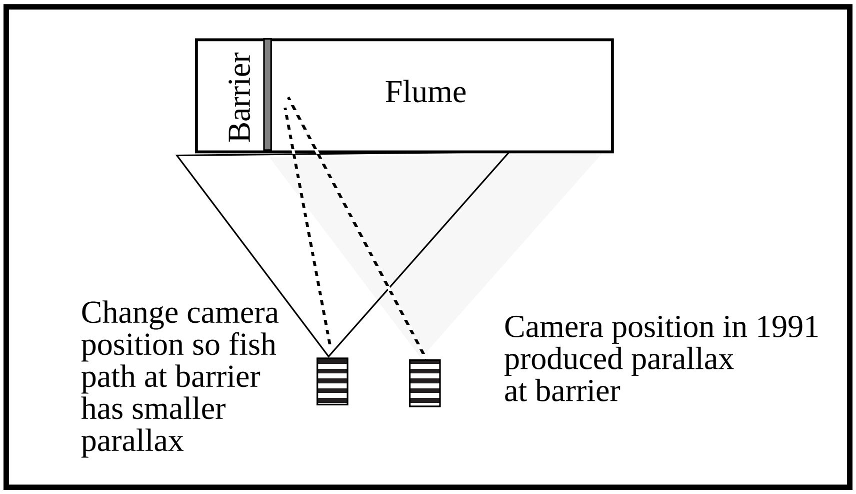

Fig. 19. Suggested future and 1991 camera positions.

Water path and velocity

The velocity information required for the analysis is best measured as trajectories of particles moving with the flow. This is the technique used to measure fish velocities. It is not clear that point measurements of velocity provided by WES are sufficient for the analysis although an understanding of the average flow conditions in the flume would help interpret and understand flow trajectories. I suggest that anesthetized fish of the same species and size be released along with the experimental fish and that water velocity and acceleration then be computed using the procedures outlined in this report.

The timing of release of anesthetized fish is important for comparison with test fish. Since anesthetized fish will move quickly through the flume several fish must be released with each test fish. The idea is to insure that at each point along a test fish’s path an anesthetize fish is in the same location and so the paths of the two fish can be compared.

Protocols for this analysis will have to be developed at the flume. In addition, the data will have to be analyzed to determine maximum allowable distances between test and anesthetized fish to adequately resolve the flow field around test fish.

As an alternative to using anesthetized fish to measure the flow fields it may be possible to use spheres that circulate in the water system.

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1. A time date generator for the study can be provided by the UW.

Experimental preliminaries

Although the design for further experiments needs to be modified as work proceeds there are several guidelines for the process:

- determine an adequate video recording environment prior to experiments. This will require analyzing fish tracks to make sure they can be followed over the entire path and that parallax problems are minimized;
- determine a relationship between the flow field and baffle openings prior to fish experiments. It should be possible to characterize the flow field in terms of basic measures such as the position of streamline divergence, percent of flow above and below the barrier, and flow acceleration/deceleration values;
- data should be analyzed as experiments proceed characterizing thresholds of response in relation to the flow acceleration field.

Experimental design

The 1991 Pasco experiments suggest at least two key hypotheses:

- fish exhibit a gradual downward movement under low acceleration in the far field (a distance from the barrier);
- fish exhibit a strong avoidance response in the near field acceleration (close to the barrier).

I suggest experiments be developed to study both of these hypotheses.

Behaviors in the far field

To study the possibility that fish dive when encountering flow decelerations, field observations of fish movement are needed prior to the response at the barrier. In the 1991 experiments, nearly all fish drifted down in the flume after release and eventually went below the barrier. To follow up on this observation, behaviors with different far field acceleration distribution should be studied. The far field acceleration field might be altered with the two baffles settings, H_{upper} and H_{lower}. An analysis of far field fish and flow paths might reveal a pattern in which fish switch from downward to upward movement in response to the far field acceleration field.

A goal is to develop a relationship showing how the percentage of upward and downward moving fish changes with alterations in flow field measurements such as acceleration.

Behavior in the near field

The 1991 study suggested that fish respond to a deceleration at the barrier. This hypothesis can be tested by altering the point and intensity of flow field acceleration and determine how avoidance responses of the fish change. Preliminary flow experiments are needed to measure and change the acceleration field in the flume.

Two experimental designs can be considered.

1. fix the accelerations field and determine if the fish avoidance response always occurs at some level of acceleration;
2. change the intensity and distribution of the acceleration field and determine if the avoidance response changes position or is extinguished below some threshold.

A goal is to develop a relationship between response probability or intensity and the characteristics of the flow acceleration field.

Application of Study

The results of the Pasco flume experiments should have application to the design of bypass systems at dams. In a qualitative sense, they will help evaluate the hypothesis that changes in flows in front of screens and in the forebay induce behaviors that contribute to low FGE. The experiments should help identify what factors are important in determining avoidance behaviors. Specifically they can be used to evaluate the hypothesis that fish dive when the flow decelerates.

If quantitative results can be extracted from the experiments, it might be possible to apply the predictive model FGE (Anderson 1991). In this model FGE is related to hydraulic and geometric properties of a dam and behavioral properties of fish. The model has three critical behavioral parameters that might be readily extracted from flume experiments: the angle, speed, and distance of an escape response. The angle and speed of escape might be inferred from the far field behavior of fish in the flume. That is, from the behavior of the fish before they encounter the barrier. The distance from the dam that a behavior is elicited will require an understanding of how flow interacts with swimming behaviors. Developing such a relationship is more tenuous and also requires information on the flow field at the face of a dam itself.

References

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