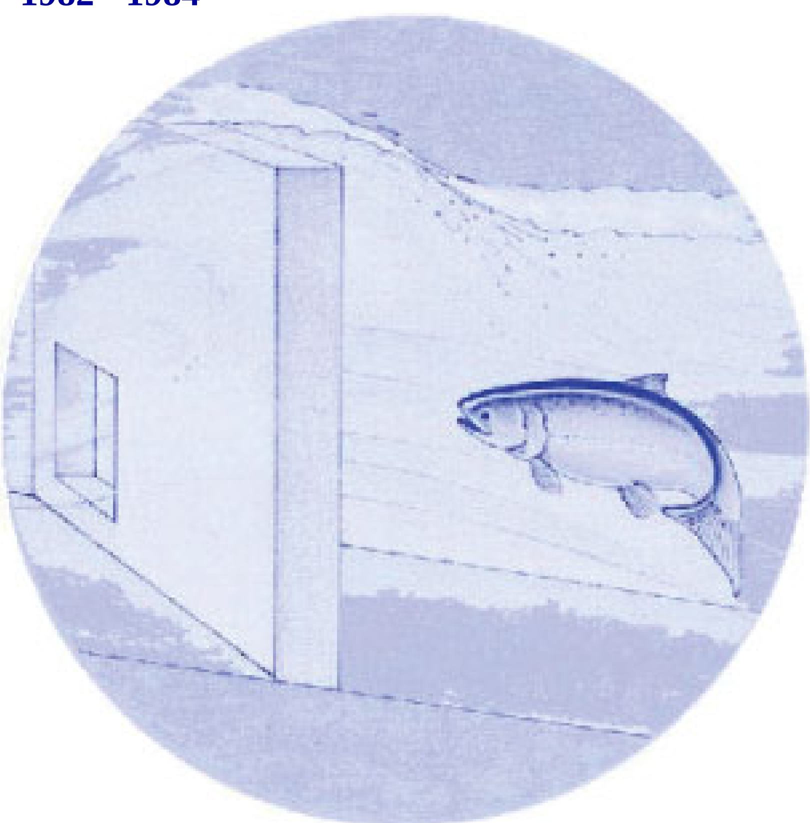
New Concepts in Fish Ladder Design, Volume II of IV

Results of Laboratory and Field Research on New Concepts in Weir and Pool Fishways

Final Report
1982 - 1984



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Bonneville Power Administration
P.O. Box 3621
Portland, OR 97208

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NEW CONCEPTS IN FISH LADDER DESIGN

Final Project Report
Part 2 of 4

Results of Laboratory and Field Research on
New Concepts in Weir and Pool Fishways

Prepared by

Robert G. Aaserude
John F. Orsbom

Washington State University
Department of Civil and Environmental Engineering

Prepared for

Thomas Vogel, Project Manager
U.S. Department of Energy
Bonneville Power Administration
Division of Fish and Wildlife
P.O. Box 3621
Portland, OR 97208-3621

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SUMMARY OF RESEARCH PROJECT REPORTS

Bonneville Power Administration
BPA Fisheries Project 82-14

DEVELOPMENT OF NEW CONCEPTS IN FISH LADDER DESIGN

Conducted at the
Albrook Hydraulics Laboratory
Department of Civil and Environmental Enqineerinq
Washinqton State University
Pullman, Washington 99164-3001

Project Period: June, 1982-October, 1984

1. Orsborn, John F. 1985. SUMMARY REPORT

   A synopsis of the project components was prepared to provide an overview for persons who are not fisheries scientists or engineers. This short report can be used also by technical persons who are interested in the scope of the project, and as a summary of the three main reports. The contents includes an historical perspective on fishway design which provides the basis for this project. The major project accomplishments and significant additions to the body of knowledge about the analysis and design of fishways are discussed. In the next section the research project organization, objectives and components are presented to familiarize the reader with the scope of this project.

   The summary report concludes with recommendations for assisting in the enhancement and restoration of fisheries resources from the perspective of fish passage problems and their solution. Promising research topics are included.

2. Aaserude, Robert G. and John F. Orsborn. 1985. NEW CONCEPTS IN FISHLADDER DESIGN. --Results of Laboratory and Field Research on New Concepts in Weir and Pool Fishways. (With contributions by Diane Hilliard and Valerie Monsey).

   The driving force behind this project, and the nucleus from which other project components evolved, was the desire to utilize fish leaping capabilities more efficiently in fishway design. This report focuses on the elements which were central to testing the premise that significant improvements could be made in water use, costs and fish passage efficiencies by developing a new weir and pool fishway. These elements include: historical review of available information; optimization of weir geometry; fluid jet mechanics; air entrainment; energy dissipation in the pool chamber; and fish capabilities. The new weir and pool chambers were tested in the field with coho and chum salmon.

3. Orsborn, John F. and Patrick D. Powers. 1985. FISHWAYS--AN ASSESSMENT OF THEIR DEVELOPMENT AND DESIGN. (With contributions by Thomas W. Bumstead, Sharon A. Klinger, and Walter C. Mih.)

This volume covers the broad, though relatively short, historical basis for this project. The historical developments of certain design features, criteria and research activities are traced. Current design practices are summarized based on the results of an international survey and interviews with agency personnel and consultants. The fluid mechanics and hydraulics of fishway systems are discussed.

Fishways (or fishpasses) can be classified in two ways: (1) on the basis of the method of water control (chutes, steps [ladders], or slots); and (2) on the basis of the degree and type of water control. This degree of control ranges from a natural waterfall to a totally artificial environment at a hatchery. Systematic procedures for analyzing fishways based on their configuration, species, and hydraulics are presented. Discussions of fish capabilities, energy expenditure, attraction flow, stress and other factors are included.

4. Powers, Patrick D. and John F. Orsborn. 1985. ANALYSIS OF BARRIERS TO UPSTREAM MIGRATION.--An Investigation into the Physical and Biological Conditions Affecting Fish Passage Success at Culverts and Waterfalls.

Fish passage problems at natural barriers (waterfalls) and artificial barriers (culverts) are caused by excessive velocity and/or excessive height. By determining which geometric or hydraulic condition exceeds the capabilities of the fish, the most promising correction can be made to the barrier.

No waterfall classification system was found in the literature which could be applied to fish passage problems. Therefore a classification system was designed which describes: (1) downstream approach conditions at the base of the barrier; (2) central passage conditions as in a high velocity chute or the leap over a falls; and (3) upstream conditions where the fish exits the high velocity chute or lands after leaping past a barrier.

The primary objective was to lay the foundation for the analysis and correction of physical barriers to upstream migration, with fishways being one of the alternative solutions. Although many passage improvement projects are economically small compared with those at large dams, each year millions of dollars are spent on solving these smaller passage problems--and sometimes the money is wasted due to poor problem definition. This report will assist in both the definition of the problem and selection of the most beneficial solution.

ACKNOWLEDGMENTS

(BPA Fisheries Project 82-14)

The financial support for this project was provided by the Bonneville Power Administration, Portland, Oreqon. The project was initiated prior to the time that the Fish and Wildlife Program of the Northwest Power Planninq Council was developed and initiated. The results of this project have already found, and will continue to find, many opportunities for application to the problems addressed in the NPPC Fish and Wildlife Proqram for the Columbia River Basin.

We wish to express our gratitude to numerous active and retired agency personnel and consultants who responded to our desiqn questionnaire and participated in personal interviews. The names and addresses of many are listed in other parts of this report, but those who were especially helpful include:

F. J. Andrew - International Pacific Salmon Fisheries Commission
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Sharon A. Klinqer
Ann E. Martinson
Walter C. Mih
(Co-Principal Investigator)
Valerie Monsey
B. J. Naik
John F. Orsborn
(Principal Investigator)
Patrick D. Powers

NEW CONCEPTS IN FISHWAY DESIGN

ABSTRACT

A comprehensive review of fishway design practice led to a new design concepts that had previously been untested. This concept was based on the observation that fish can be stimulated to leap when presented with certain hydraulic conditions. A laboratory test program was conducted to develop this concept into a new fishway configuration. Field testing revealed that components of the new design improved fish passage. Verification of the initial premise that fish can be stimulated to leap needs further study.

INTRODUCTION

Over the course of the past 20 years, increasing competition between various user groups for fisheries and water resources has spawned a heightened sense of environmental awareness. More recently, this has resulted in a renewed emphasis on restoring fisheries resources, and a new emphasis on conserving water resources. Fishways are unique in that their efficient performance directly affects the satisfaction of both of these priorities. The purpose of this paper is to present the results of a portion of a 2-year study of fishway design.

Fishway design is necessarily a topic of considerable breadth and complexity. The approach taken in this study was thus three-pronged, beginning with a comprehensive literature review. Since fishway design is a subject which is interdisciplinary in nature, fisheries considerations were reviewed in detail in addition to hydraulic theory.

As a result of the literature review, a new fishway design concept was identified that had previously been untested. This concept was based on the observation that fish can be stimulated to leap when presented with certain hydraulic conditions. The second phase of the study was directed towards developing this concept into a new fishway configuration in the laboratory.

The final phase of the study involved field testing of the new fishway configuration with coho and chum salmon. Observations of fish behavior and capability are discussed as they pertain to the performance of the new fishway design.

Although it was concluded that components of the new fishway design improve fish passage significantly, verification of the initial premise that fish can be stimulated to leap requires further study.

EVOLUTION OF DESIGN CONCEPTS

"It now behooves all persons engaged in this great industry, to do everything in their power to devise means to open other streams closed by mill dams or natural falls, for natural breeding, and also to increase the facilities for artificial propagation which, I am satisfied, will be of great value in assisting to keep up the supply of salmon in this river" (Anonymous, 1886).

The need to preserve and enhance natural stocks of resident and anadromous fish has been recognized for at least the past 100 years. Much of this interest has been directed towards fishway design.

The earliest fishways designed and constructed were of the weir and pool type (Figure 1). Termed fishladders, such structures have been in existence since at least 1853, as evidenced by the successful Ballysodare fishladder in Ireland (Pryce-Tannatt, 1938).

In 1861, the British Salmon Fishery Act was passed. Included in the provisions were requirements that fish passes be installed and maintained "in an efficient state" at new dam sites on salmon rivers (Pryce-Tannatt, 1938). Despite the intentions of the law, it is recorded that fishway failures were a problem in the era (Calderwood, 1930). Early design efforts were based more on empiricism and intuition than on scientific endeavor.

Denil is credited with the first systematic scientific investigation of fishway design beginning in about 1908 (McLeod and Nemenyi, 1940). His work culminated in the development of a chute type fishway with large roughness elements (Figures 2 and 3). Variations of his original design are still

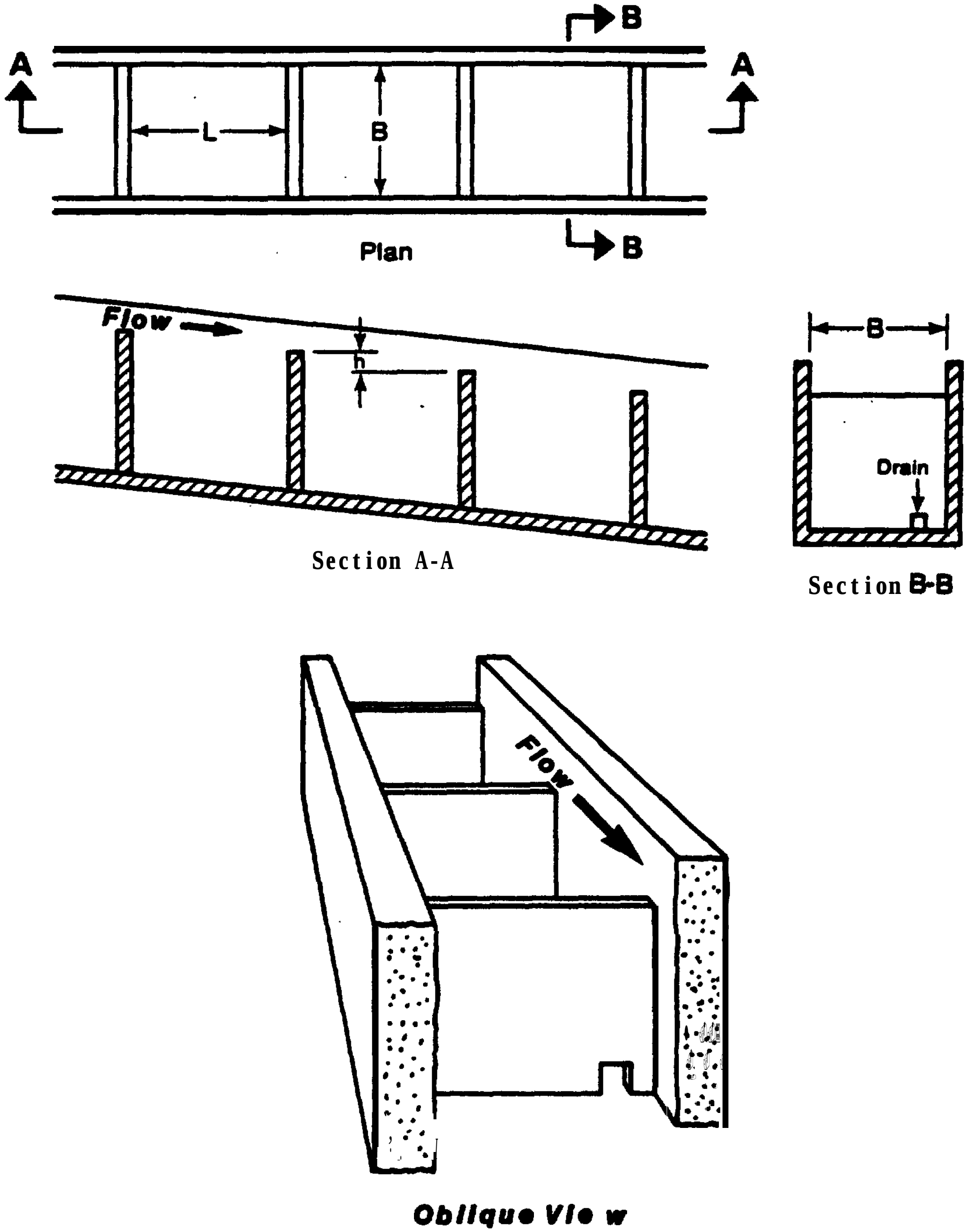

Figure 1.--A schematic of the weir type fishway.

commonly used today. The Alaska steeppass is a form of the Denil fishway concept that has been adapted for application at remote sites (Ziemer,1962).

Perhaps the most significant contribution by Denil is the rational approach to fishway design that he pioneered. He was the first to develop a basis for assessing the mechanical capabilities of fish and matching them to the opposing hydraulic forces within a fishway (Inst. of Civil Engineers, 1942). Denil's work was done in Belgium.

The first systematic American investigation of fishways occurred in 1939-40 (McLeod and Nemenyi). Many fishway types were modeled and live fish were used in the testing. Although the study was largely inconclusive concerning specific recommendations due to its wide scope, there was one significant result. This was the first major fishway study to consider fish behavior. Interestingly, one of the comments concerning fish performance was that "it appeared that the fish learned to climb." This was quite a progression from the mechanical perspective studied previously.

That fish behavior was beginning to emerge as a consideration for fishway design is further evidenced by the following excerpt from the "Report of the Committee on Fish-Passes" (Inst. of Civil Engineers, 1942).

> Migratory fish have certain definite habits and well-marked preferences, which are displayed in their journey to their spawning grounds. One pass may prove entirely successful, whilst for another the fish may show a definite distaste. In designing a fish-pass, therefore, the problem is not merely an engineering and hydraulic one.

This notion of fish behavior and preference was not widely accepted at this time. Within the same report it is written, "the fish is not a conscious being, able to act in anticipation of difficulties ahead."

During 1945-6, a major fishway at Hell's Gate on the Fraser River in British Columbia, Canada, was constructed after extensive hydraulic model

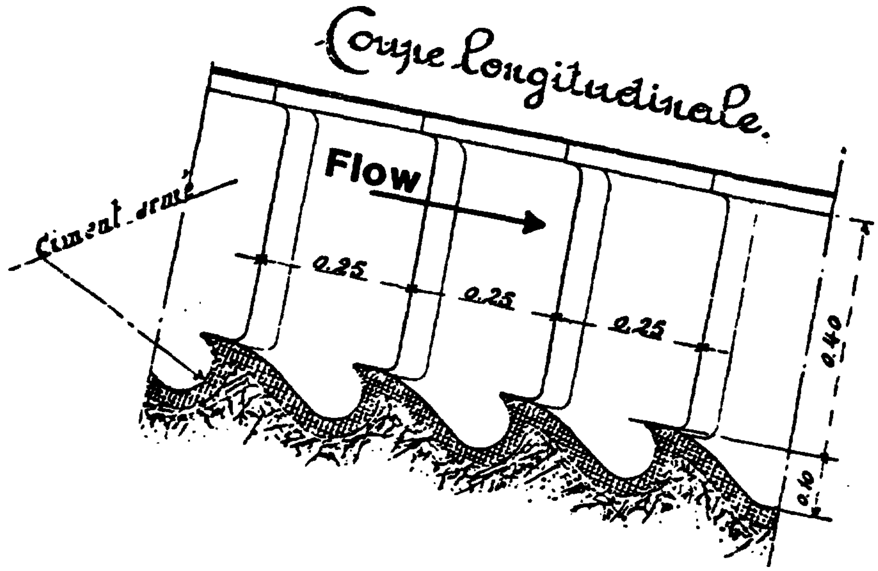

Figure 2.--Side view of the original chute type fishway designed by Denil (after Denil, 1909).

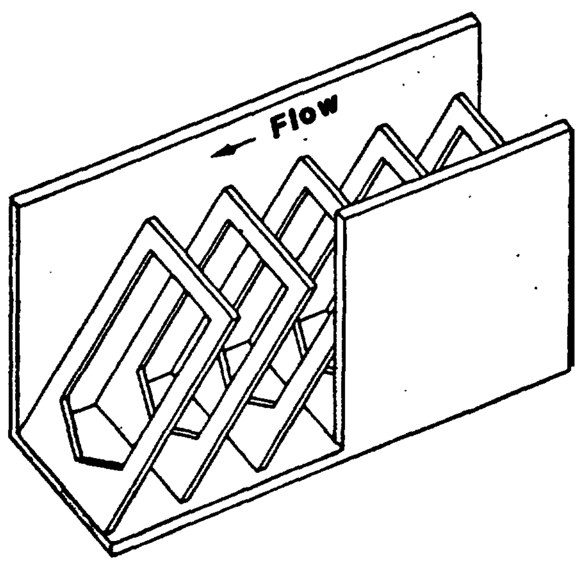

Figure 3.--Oblique view of a commonly used variation of the Denil fishway concept.

tests. This event marked the beginning of a new type of fishway, the vertical slot (Figure 4). Vertical slot fishways are commonly used where large fluctuations in river stage are anticipated, and where fishway flows are unregulated, because they function well over a large range of head.

The biological studies for the Hell's Gate fishway are also noteworthy because the concept of a biological failure to pass fish was openly considered. Factors such as "a trailing rope, the odor of a man, or some other disturbing factor" are mentioned as potentially deterring passage through an otherwise physically passable ladder (Jackson, 1950). Concern for the perspective of the fish grew to such an extent that "psychological factors" governing the motivation of the fish to pass were even mentioned. Jackson (1950) expresses it as the "point a sockeye becomes discouraged, changes its mind, and turns back to hunt for a new route." Spurred by failure, fishway designers were becoming sensitive to conditions which provoke a negative or avoidance reaction in fish.

It was not until the late 1950s that ethology, the objective analysis of behavior, was recognized as having "the possibilities of decoying and guiding fish through appropriate stimulation of their sensory mechanisms" (Hoar, 1958). As this concept gained interest with fish biologists and engineers, research in the field increased. The effects of darkness (Long, 1959), fishway capacity (Elling and Raymond, 1959), fishway slope (Gauley, 1960), flow velocity (Weaver, 1963), and sound (VanDerwalker, 1967) on fish passage rates were studied. This information served to improve the criteria for fishway design.

The first design manual for fishways was published in 1961 (Clay). In the text a fishway is defined as "essentially a water passage around or

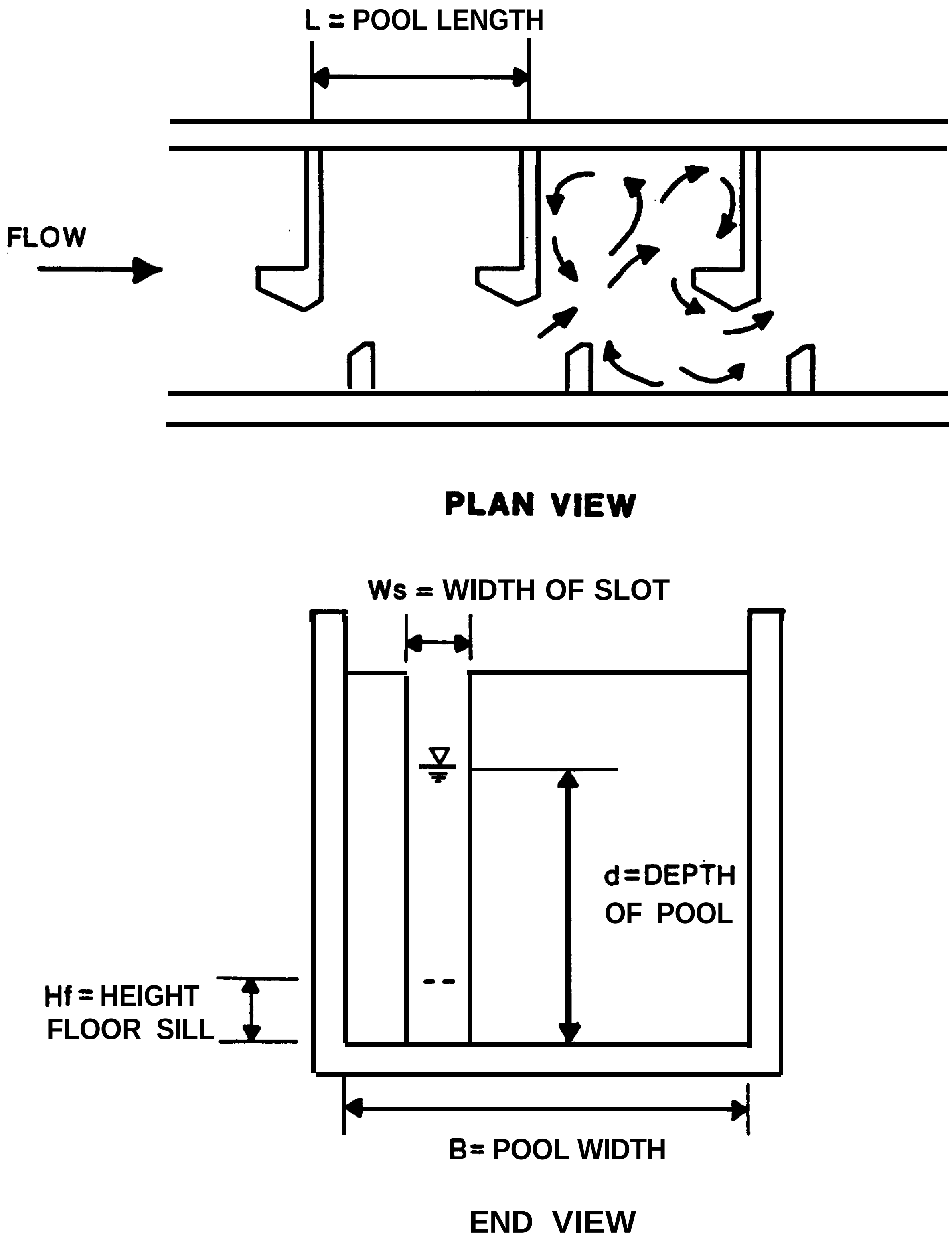

Figure 4.--Schematic of q vertical slot fishway.

through an obstruction, so designed as to dissipate the energy in the water in such a manner as to enable fish to ascend without undue stress." This definition is significant in that it serves to characterize both the current and historical approaches to fishway development.

In 1962, Stuart published a paper titled "The Leaping Behavior of Salmon and Trout at Falls and Obstructions." In this work, Stuart offers an explanation as to why migrating salmon and trout show preference for certain flow conditions in their movement upstream. Stuart concluded that the stimulus for movement appears to be the "force of the impact" of falling water. He noted also that "leaping was initiated when the ratio of kinetic and potential energies was high in the section of water just ahead of the fish. That is, when conditions were such that a standing wave was formed."

The concept that fish could be stimulated or preferred to leap, rather than swim, when confronted with certain hydraulic conditions, was new. Up to this point in time, it was widely believed that fish preferred swimming to leaping, and would opt for the latter only as a last resort. For this reason, as aptly defined by Clay (1961), fishway design efforts had historically focused on providing water passages for swimming. The concept of designing a hydraulic environment conducive to leaping had not received serious consideration, and as Stuart (1962) suggests, "the perfect fish pass has not yet been designed."

Additional evidence appears in the literature that is supportive of the concept of a hydraulic stimulus for leaping. After observing rainbow trout, Webster (1965) writes "they picked a common watery pathway enabling them to take full advantage of the hydraulics of the currents and turbulence below the falls--a path culminating in the spectacular jumps." Bell (1973) notes that jumping, while not being fully understood, "is known to be triggered by shadow patterns or upwelling." Upwelling is symptomatic of the standing wave described by Stuart. It is also interesting that even as early as 1940 (before ethology was in vogue) there is indirect reference to stimulus. In a discussion of pool and jet fishways, it is written that "the overfall type has the advantage of being attractive to the fish" (McLeod and Nemenyi, 1940). Although the' authors do not try to explain this behavior, it requires little effort to conjure up the image of the force of the impact of falling water.

Although Stuart's paper has been in print for over 20 years, his ideas are still new and largely untested. Whether fish are stimulated to leap or move by the force of the impact of falling water is uncertain. It is a perspective that necessarily comes from the fish, whit:h complicates the analysis. Observations of fish behavior do tend to substantiate the premise. It also seems intuitive that a fish must be able to sense the momentum of flowing water not unlike we can if we immerse our hand in a water jet. If this postulate of the stimulus for fish movement can be accepted, then the real task is to develop its application for use in fishway design. The definition of a fishway might then read, "A hydraulic environment so constructed as to dissipate the energy in the water in such a manner as to stimulate fish to ascend without undue stress." It is with the spirit of this definition that the objectives of this study were established. They are:

1. to determine the physical mechanism and magnitude of Stuart's standing wave;
2. to develop a fishway configuration based on the concept that fish can be stimulated to leap; and
3. to assess the performance of the new fishway in the field.

FISHERIES CONSIDERATIONS

Introduction

The idea of taking a fresh look at weir and pool fishladder design principles is exciting for anyone who has had the opportunity to view leaping trout and salmon. Leaps as high as 11 feet 4 inches for salmon have been reported in the literature (Calderwood, 1930). Pryce-Tannatt (1938) suggests that "a sheer fall of 6 feet is probably, to all intents and purposes, about the maximum practicable for the great majority of salmon, even under the most favorable conditions." Although the values reported are maximums, when compared with current design recommendations requiring only one foot of drop between pools (Bell, 1973), the potential for increasing the pool-steps is obvious. In fact, one might question the apparent large disparity between fish capabilities and the requirements imposed upon them. It seems that a large bio-engineering factor of safety is involved. This is usually the practice when working with systems that are poorly understood, inherently variable, or exhibit unpredictable behavior. This seems to be the approach taken towards estimating fish capabilities.

The contention that biological systems are inherently variable cannot be challenged or changed. What can be changed is the level of understanding with which biological problems are approached. With an increased understanding of the factors which influence biological systems, it becomes possible to account for much of the variability, and the behavior of the system seems more predictable. Listed in Table 1 are several of the factors which influence fish capabilities.

Table 1. Factors which influence the swimming and leaping capabilities of fish.

Factor	Influence	Reference
Species of fish	Variable	Bell (1973) Jones et al. (1974)
Stock of fish	Variable	Vincent (1960)
Size of fish	Increased capabilities with increased size	Fry and Cox (1970) Brett and Glass (1973)
Time in the river (Sexual maturity, condition)	Reduction in capabilities with time	Idler and Clemens (1959) Sakowicz and Zarnecki (1962)
Site Geometry, Hydraulics	Optimal conditions exist which promote successful leaping	Stuart (1962) Webster (1965)
Temperature of water	Optimum range exists, above or below performance reduced	Brett et al. (1958) Griffiths and Alderdice (1972)
Lighting	More successful leaping under certain lighting conditions	Stuart (1962)

Even casual inspection of the factors influencing fish capabilities illustrates the potential for variability in the performance capabilities of any species of fish that might be targeted for passage. There is little reason to wonder why swimming capabilities reported in the literature are sometimes in disagreement (Paulik and DeLacy, 1957). Estimating the performance capabilities of a targeted fish necessarily requires a general knowledge of fish capabilities, tempered with project specifics and sound judgement.

Swimming Capabilities

In the design of a fishway, a knowledge of the swimming capability of the targeted species is important so that fishway hydraulics can be provided that do not present a barrier to the fish. Barriers may occur when: (1) flow velocities exceed the swimming capability of the fish, and (2) when the effort required to pass through the fishway fatigues the fish to the point that it is not able to advance its position and falls back. To prevent the first type of barrier a knowledge of the maximum fish swimming speed is required. The second type of barrier requires a knowledge of the relationship between swimming speed and time to fatigue.

Fish swimming speeds have been classified into three categories that reflect the relationship between speed and endurance. These categories are sustained, prolonged, and burst swimming performances (Beamish, 1978). Sustained swimming performances are defined as those speeds that the species in question can maintain for an extended period (greater than 200 minutes) without resulting in muscular fatigue. Prolonged swimming speed is defined for swimming performances of shorter duration (20 seconds-200 minutes) that result in fatigue. Burst swimming speed is defined for yet shorter duration (less than 20 seconds) swimming performances that would be characteristic prior to leaping, darting for prey, or avoiding predators.

Fishway designers are primarily concerned with burst and prolonged swimming capabilities of fish. Knowledge of these two biological criteria should be sufficient to prevent the occurrence of the two types of barriers previously discussed. Table 2 provides the swimming capabilities for several common salmonid species.

Table 2. Nominal upper limits of sustained, prolonged, and burst speeds of adult fish.

Species	Upper Speed for (1) Cruising (2)(Sustained) (fps)	Sustained (Prolonged) (fps)	Darting (Burst) (fps)	Observed Maximum (fps)
<u>Salmon</u>				
Chinook	3.4	10.8	22.4	22.1
Chum[1]	1.6	5.2	10.6	----
Coho	3.4	10.6	21.5	17.5
Pink[1]	1.8	5.6	11.3	----
Sockeye	3.2	10.2	20.6	----
<u>Trout</u>				
Cutthroat	2.0	6.4	13.5	13.5
Steelhead	4.6	13.7	26.5	26.8
Brown	2.2	6.2	12.7	12.8
Atlantic Salmon[2]	4.0	12.0	23.2	26.5

Data primarily from Bell (1973), Beamish (1978), and Dimeo (1977).
Row (1) - Classification of speed in Bell (1973).
Row (2) - Classification of speed in Beamish (1978).

[1]Burst speed estimated from observed leap heights. Sustained and prolonged speeds estimated as ratios of burst speed similar to sockeye salmon.

[2]Burst speed of Atlantic salmon estimated from leap height of 11 feet 4 inches (Calderwood, 1930). Sustained and prolonged speeds estimated as ratios of burst speed similar to steelhead.

Analysis pi Leaping

The mode of locomotion through a fishway can be via swimming or leaping. For a weir and pool fishway, some leaping activity would be expected, depending on the pool step sizes. For this reason, a knowledge of fish leaping capabilities is useful for the design of pool-step increments. One would not want to create a differential elevation barrier by providing pool-steps that were beyond the leaping capability of the target species. Likewise, it is costly to overdesign a fishladder by providing more pools at a lesser differential than is necessary to pass fish.

Estimates of leaping capability are most often made by directly observing leaping fish. Information in the literature regarding leaping capabilities is limited, and often pertains to using observed leap heights to back-calculate swim velocities. Denil (1937) used the following equation to back-calculate the burst speed of Atlantic salmon.

$$y = x \tan \alpha - g\, x^2/(2V_o^2 \cos^2 a)$$

where y = ordinate of rectangular coordinate system the origin of which is the point at which the fish leaves the water,

x = abscissa of coordinate system,

α = angle of leaping trajectory measured from the horizontal,

V_o = initial velocity of fish,

g = gravitational acceleration.

This is simply the equation for a projectile. Another equation that is sometimes used is:

$$HL = V_o^2/2g$$

where HL = leap height.

This is a simplified form of an equation which describes rectilinear motion for uniform acceleration.

Paulik and DeLacy (1957) imply that the equations used to back-calculate swim velocities from leap heights may not be appropriate. They note that "the swimming velocities attributed to salmon as a result of their observed jumping ability may be too high." The concern is that there is a change in forces as the fish leaves the water. They even speculate that "the salmon may accelerate its velocity considerably as it is leaving the water at the beginning of the leap. The water would be used somewhat as a spring board in this maneuver." The following analysis is an effort to respond to the questions raised in the foregoing discussion.

There are five forces which act on a fish that is completely submersed just below the water surface (position 1) (Figure 5). These are the propulsive force (FP) from the fishes tail, the weight (W) of the fish, the buoyant force (FB) of the displaced water, the form or pressure drag (FFD), and the skin drag (FSD). As the fish emerges from the water to the position where the tail has just exited (position 2), there is a reduction in the forces and it can be assumed that only the weight remains (Figure 6). For this analysis it will be assumed that the drag and buoyant forces in air are negligible, the wave drag during emergence is negligible, and that the propulsive force of the fishes tail is fully effective right up to the point of exit (position 2).

To illustrate the analysis it is useful to assume a subject fish. For this purpose, an 18 lb., 3.1 ft. long steelhead trout will be used. From Table 2, the burst speed of a steelhead trout is 26.5 fps. This will be regarded as a terminal velocity reached prior to emergence from the water.

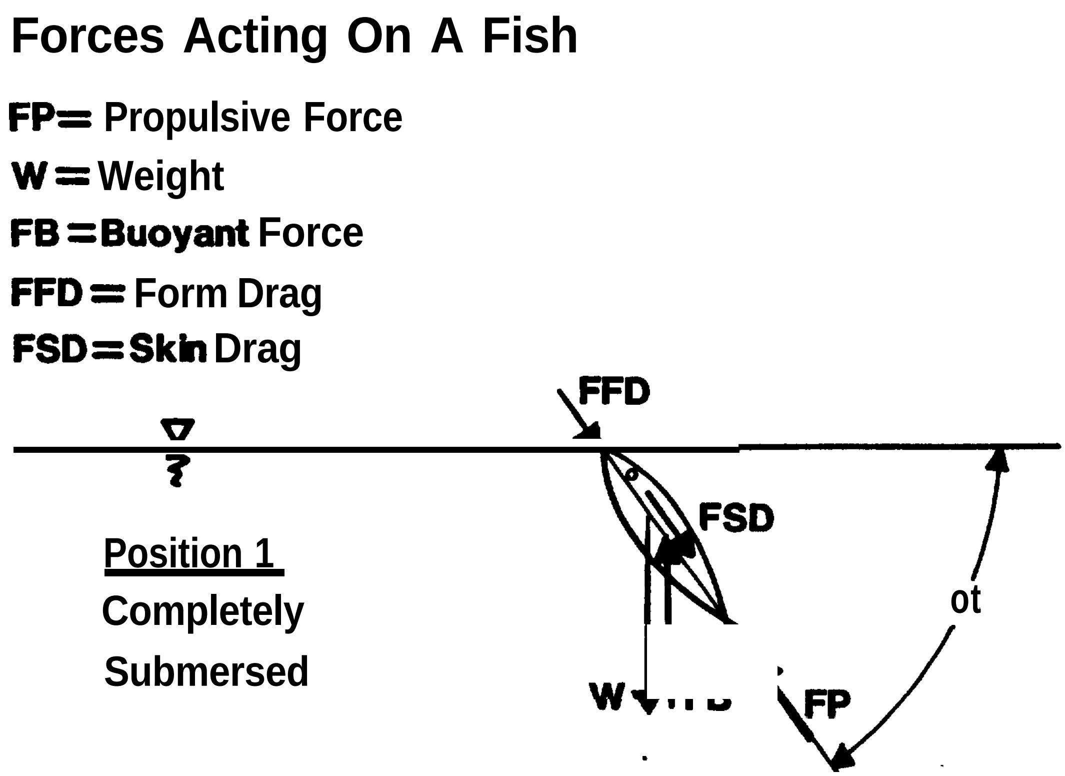

Figure 5.--Schematic of the forces acting on a fish prior to emerging from the water while executing a leap.

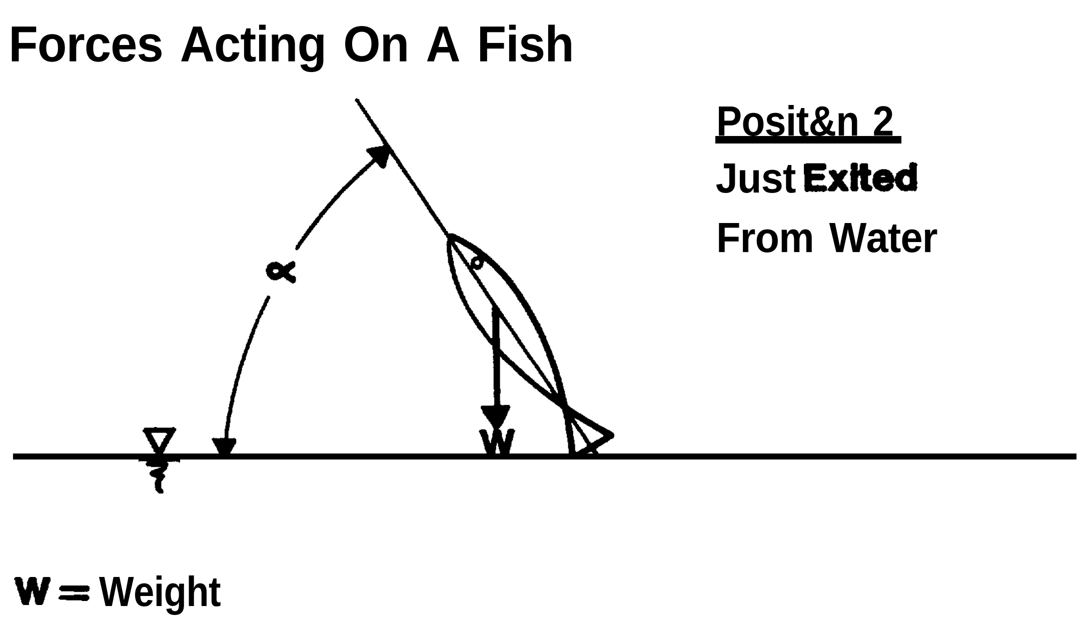

Figure 6.--Schematic of the forces acting on a fish that has just cleared the water during a leap.

The assumption that the fish is neutrally buoyant ($W = FB$) when completely submersed (position 1), is made prior to summing the forces (F) for position 1.

$$\Sigma F_1 = 0 = FP - FFD - FSD$$

It follows that the propulsive force is equal and opposite to the two components of the drag force.

To further the analysis it is necessary to combine the two drag components into a total drag (FD) term.

$$FD = FFD + FSD$$

It is then possible to calculate the total drag from the drag equation.

$$FD = CD(A)\rho(V)^2/2$$

where CD = drag coefficient,

A = a certain drag-related area,

ρ = density of water,

V = burst velocity of the fish.

To determine the drag coefficient, the relationship that a fish's shape is similar to that of a symmetrical airfoil with an aspect ratio (length:depth) of 5 will be utilized. This yields a drag coefficient of 0.06 at a Reynolds number of $4(10)^5$ (Daily and Harleman, 1966). The Reynolds number (Re) is defined as:

$$Re = VL/\nu$$

where V = *the velocity of the fish,*

L = a characteristic length, such as fish length,

ν = kinematic viscosity.

When compared with dead-drag coefficients of salmonids measured in a flume, this value falls within the high side of the range (Webb, 1975). Dead drag measurements yield values that are too low, however, for fish that swim by undulatory propulsion (repeated oscillation of body and caudal fin) (Blake, 1983). This undulatory swimming mode is characteristic of salmonids. It is concluded that the drag coefficient of 0.06 is a reasonable approximation.

The frontal silhouetted area of the fish as viewed from head to tail will be considered as the drag-related area. Other researchers have defined different drag-related areas. Ziemerand Behlke (1966) used $A = L^2$, where L = the length of the fish. Weihs (1974) used the entire surface area of the fish. Experimental data indicates, however, that as a fish exhibits swimming motion, the drag increases by a factor of approximately 3 over that of a rigid body (Webb, 1971). Studies of the muscular efficiencies of various species of fish (Alexander, 1967) indicate the same conclusion of increased drag. Since the drag coefficient is nearly constant for Reynolds numbers above 1000 (Weihs, 1974a), for the drag to increase by a factor of 3, the projected frontal area of the fish would have to increase. Intuitively this seems reasonable because it would be expected that a greater column of water would be disturbed by swimming motion than by movement of a rigid body. The drag-related area of a swimming fish will thus be calculated as 3 times the frontal projected area. For the steelhead used to illustrate the analysis:

$$A = 3(3.5 \text{ inches})(7 \text{ inches})/144 \text{ in}^2/\text{ft}^2 = 0.52 \text{ ft}^2$$

The remaining term in the drag equation is the density of water. For water at 50°F, the density is 1.94 slugs/ft^3. The total drag force can then be calculated as:

$$FD = 0.06(0.51)(1.94)(26.5)^2/2 = \underline{20.8 \text{ lbs}}$$

It follows that the propulsive force is also equal to 20.8 lbs.

Denil (1937) determined that the propulsive force that a salmon can exert at a jump can be estimated as 1.2 W. For a trout the estimate of propulsive force was determined to be 1.4 W. For purposes of comparison Denil's estimates have been calculated for an 18 lb. fish.

$$1.2\ W = 1.2(18\ lbs) = 21.6\ lbs \text{ for salmon}$$

$$1.4\ W = 1.4(18\ lbs) = 25.2\ lbs \text{ for trout}$$

It is likely that an 18 lb. steelhead would behave more similarly to Denil's salmon than trout. The value obtained from the drag equation is reasonably close to Denil's approximation. This serves to validate, as reasonable, the assumptions made in the analysis.

To further the analysis it is necessary to divide the total drag into its two component parts. To do this, it is again necessary to *rely* on the relationship that a fish's shape is similar to that of a symmetrical airfoil with an aspect ratio of 5. For this particular shape, the ratio of the skin drag to the total drag is 0.60 at a Reynolds number of $4(10)^5$ (Daily and Harleman, 1966). The skin and form drag components can thus be calculated.

$$FSD = 0.60\ (20.8\ lbs) = 12.5\ lbs$$

$$FFD = 0.40\ (20.8\ lbs) = 8.3\ lbs$$

It is now possible to analyze the change in forces as the fish moves from position 1 (completely submersed) to position 2 (just emerged from the water). The weight of the fish will be constant, the propulsive force of the fish is assumed constant, the buoyant force is reduced as less water is displaced, and the skin and form drag are reduced as the fish moves from the more dense medium of water to that of air. To obtain specific values for the buoyant force, form, and skin drag, it is necessary to estimate the spatial averages of these forces as the fish emerges from the water.

(No page 21)

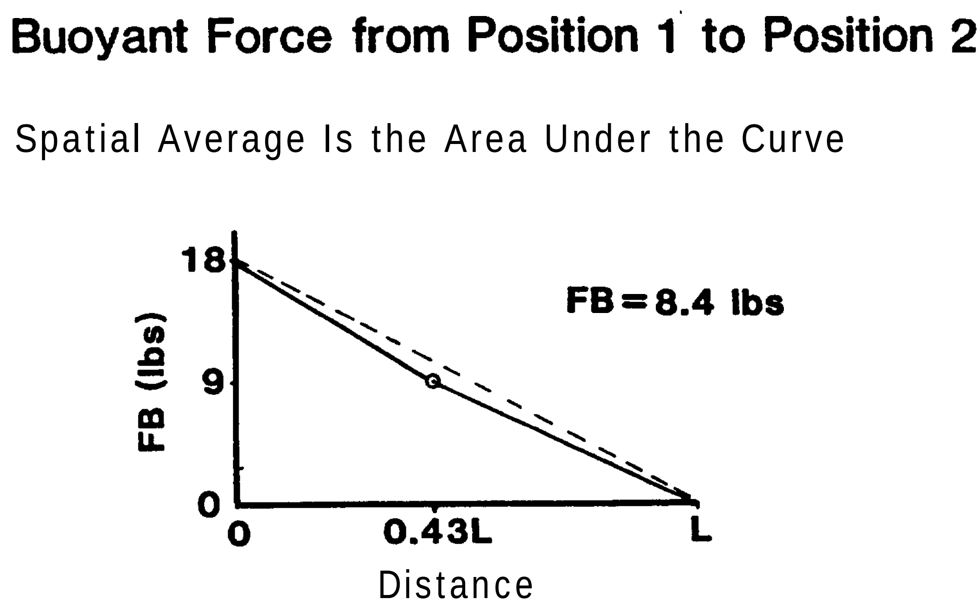

Figure 7.--Plot of buoyant force (FB) versus distance out of the water (fish length (L)) to determine the spatial average of the buoyant force from position 1 to position 2.

a plot of the form drag versus distance out of the water can be made (Figure 8). The area under the curve divided by fish length yields the spatial average for the form drag from position 1 to position 2, which is equal to 0.8 lbs.

With the spatial averages of all the forces determined from position 1 to position 2, it is possible to analyze the acceleration of the fish over this distance. To do this, an assumption of the angle of leaping trajectory must first be made. In this analysis, the angle will be assumed to be 75 degrees from the horizontal. It is then possible to apply Newton's second law and sum the forces.

$$\overset{+}{75^\circ} \quad \Sigma F = ma = FP + (FB \sin 75^\circ) - (W \sin 75^\circ) - FFD - FSD$$

$$= 20.8 + (8.4 \sin 75^\circ) - (18 \sin 75^\circ) - 0.8 - 6.3$$

$$= 4.4 \text{ lbs}$$

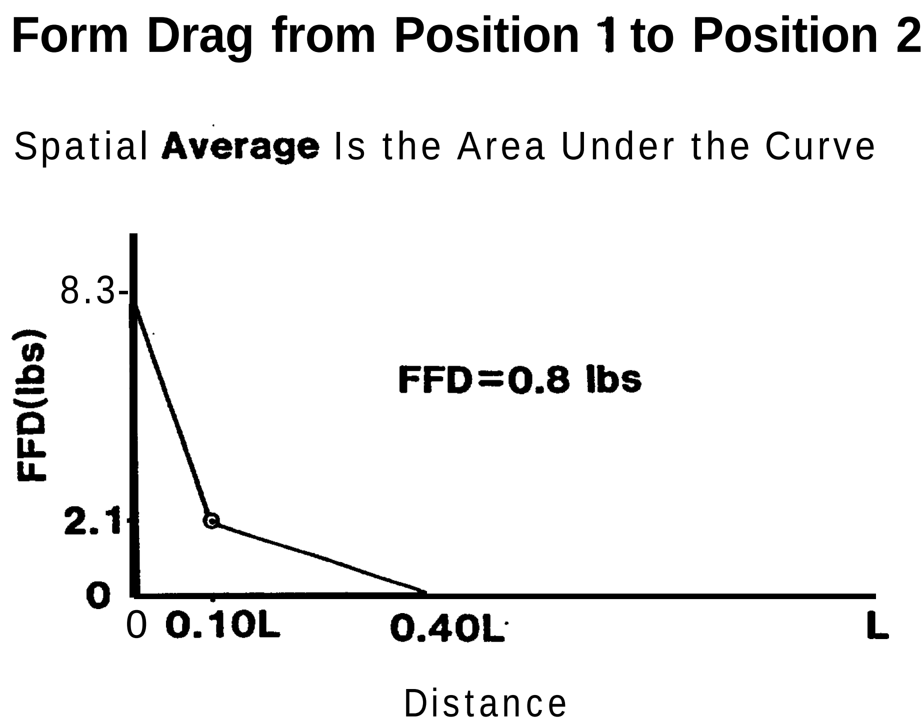

Figure 8.--Plot of the form drag (FFD) versus distance out of the water (fish length (L)) to determine the spatial average of the form drag from position 1 to position 2.

where m = mass of the fish,

a = acceleration of the fish.

It follows that the acceleration from position 1 to position 2 can be obtained.

$$a = F/m = (4.4 \text{ lbs})/(18 \text{ lbs}/32.2 \text{ fps}^2) = 7.9 \text{ fps}^2$$

As suggested by Paulik and DeLacy (1957) some fish, and the steelhead in particular, are capable of accelerating as they emerge from the water.

With the acceleration (1-2) *known, the next step is to determine the* velocity of the fish at position 2. This can be done using an equation of rectilinear motion for uniform acceleration.

$$V2^2 = VB^2 + 2a\,(S2 - S1)$$

where $V2$ = velocity of the fish at position 2,

$(S2-S1)$ = length of the fish (L).

For the steelhead trout of this analysis:

$$V2^2 = 26.5^2 + 2\ (7.9)(3.1-0)$$

$$V2 = 27.4 \text{ fps}$$

So the steelhead begins its leap with a burst velocity of 26.5 fps and emerges from the water at position 2 with the higher velocity of 27.4 fps. Although this increase in velocity does not appear substantial, it increases the leap height significantly because the leap height varies as the square of the velocity.

It is now possible to calculate the leap height of the steelhead when leaping from a still pool. The first step is to obtain the vertical component of the fishes velocity at position 2. Recall the assumption of an angle of leaping trajectory of 75 degrees.

$$\begin{aligned} V2Y &= V2 \sin 75° \\ &= (27.4 \text{ fps}) \sin 75° \\ &= 26.5 \text{ fps} \end{aligned}$$

where $V2Y$ = vertical component of the fishes velocity at position 2.

The leap height of the fish <u>above position 2</u> can then be determined.

$$\begin{aligned} HL &= V2Y^2/2g \\ &= 26.5^2/2\ (32.2) \\ &= 10.9 \text{ feet} \end{aligned}$$

A schematic of the steelhead leaping from a still *pool* appears in Figure 9. It is important to note that the leap height is above position 2. The leaping capabilities of fish should thus be estimated by the following equation.

$$HL = V2Y^2/2g + L$$

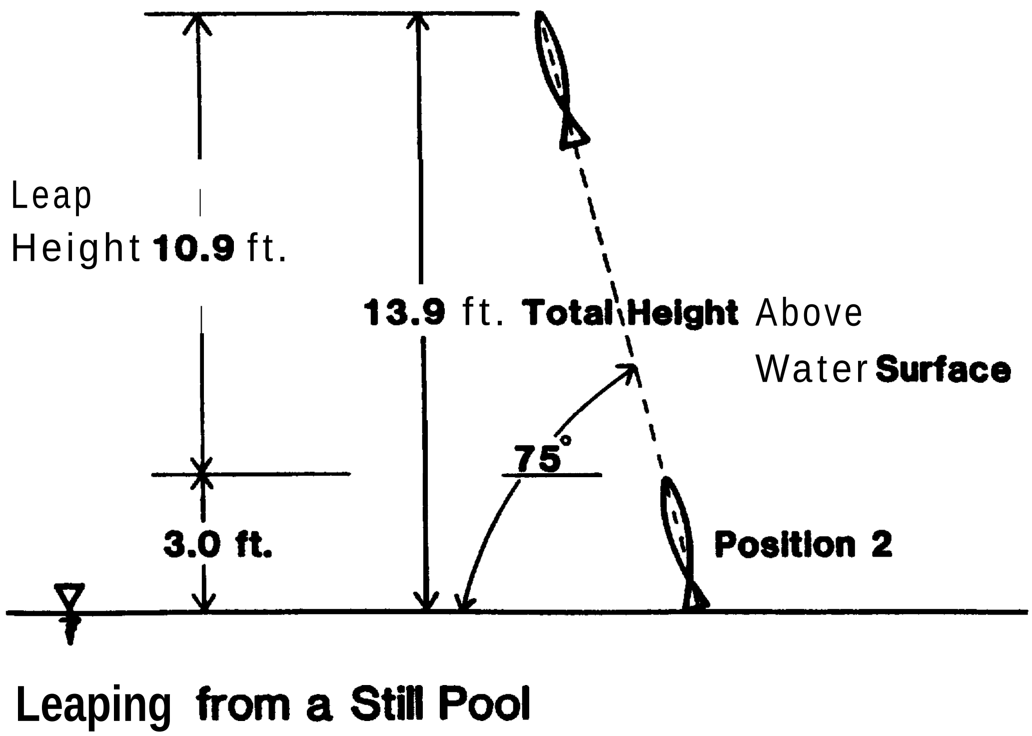

Figure 9.--Schematic of the leaping capability of a steelhead trout from a still pool.

It is the second term, the length of the fish (L), that is missing from equations traditionally used to estimate leap heights. This is why, as Paulik and DeLacy (1957) suggested, back-calculations of swinnning velocity from observed leap heights yield values that are too high (corollary--calculated leap heights from observed burst velocities are too low). Table 3 lists calculated leap heights from a still pool for several species of adult salmonids using an analysis similar to that presented for the steelhead trout. From this analysis it is interesting to note that steelhead trout, sockeye, coho, and chinook salmon, were shown to be capable of accelerating from position 1 to position 2. Chum and pink salmon decelerated from position 1 to position 2, and there was no change for cutthroat

Table 3.--Leap heights from a still pool calculated from burst velocities for several species of salmonids.

Species	Burst Velocity (fps)	Velocity at Position 2 (fps)	Weight (lbs)	Length (ft)	Frontal Area (ft^2)	Leap Height (ft)
Salmon						
Chum	10.6	8.1	10.0	2.5	0.51	3.4
Pink	11.3	11.2	4.0	2.0	0.31	3.8
Sockeye	20.6	22.0	6.5	2.3	0.37	9.3
Coho	21.5	23.0	7.0	2.4	0.37	10.0
Chinook	22.4	22.5	20.0	2.8	0.58	10.1
Trout						
Steelhead	26.5	27.4	18.0	3.1	0.51	13.9
Cutthroat	13.5	13.5	2.2	1.4	0.13	4.0

Burst velocities primarily from Bell (1973), Beamish (1978), and Dimeo (1977). A drag coefficient of 0.06 was used for all species. The drag coefficient for symmetrical airfoils is not sensitive for aspect ratios within the range from 4 to 5.5 at a Reynolds number of $4(10)^5$ (Daily and Harleman, 1966).

trout. The values calculated using this analysis compare favorably with reported observations of leap heights (Table 4).

Leaping activity of salmonids is seldom associated with a still pool. It is more typical to observe them leaping from a pool below a falls. Stuart (1962), in his study of leaping behavior, identified a hydraulic condition as significant for leaping that appeared as a boil or "hump" just downstream of where the waterfall jet entered the pool. He termed the hump the standing wave (Figure 10). Stuart observed that "the fish, without exception, all leapt from the same small area on the 'hump' created by the strong upward current pointed strongly to the importance of this unquestionable aid." An investigation of both the mechanism and magnitude of Stuart's standing wave are within the scope of this study. The objective is to gain

Table 4.--Observed leap heights for several species of salmonids.

Species	Number of Respondents	Range of Heights Reported (ft)
<u>Salmon</u>		
Pink	1	4
Sockeye	2	5-7+
Coho	3	6-10
Chinook		5-10
(generic)	4	3-10
<u>Trout</u>		
Steelhead	5	6-17
(generic)	6	1.5-6

NOTE: Observations reported in a survey of fish leaping capabilities conducted by Dr. J.F. Orsborn Professor of Hydraulic Engineering, Washington State University, 1980, unpublished.

understanding of the phenomenon so that: (1) it can be adapted to fishway design, and (2) so that the magnitude of the "aid" to leaping fish can be quantified. It may then be possible to develop a table of leap heights for fish leaping from a standing wave below a falls.

Bioenergetics

Since anadromous salmon have fixed energy reserves when they begin their upstream migration, the efficient use of their reserves can have an important bearing on whether they spawn successfully. For this reason, it is important that fishways do not delay fish migration.

Although it is likely that the energy expenditure of a fish passing through a properly designed fishway will have little impact on a fish's spawning success, it is interesting to consider the relative energy outlays required by various fishway types. After observing fish pass through

POOL BELOW A 'WATERFALL

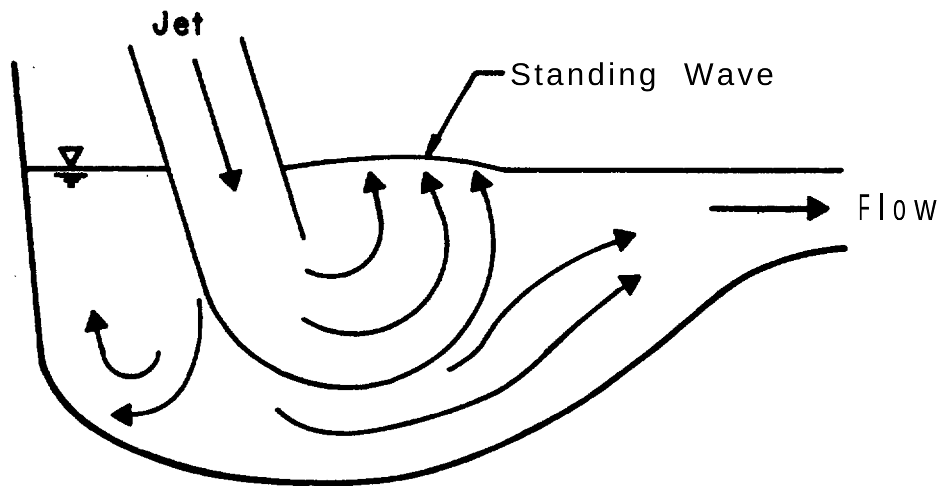

Figure 10 --Sketch showing the side view of a pool below a waterfall.

fishway orifices, Stuart (1962) concluded "that the amount of energy that would be expended by a fish in passing a succession of such orifices must be many times greater than that required to leap over an equivalent series of more natural obstacles." He provided no quantitative information to support this contention. Mih (1983) addressed the question of what is the most bioenergetically efficient mode of ascent by analytically comparing the energy requirements of a fish to ascend: (1) through ports or orifices, (2) up an inclined ramp, and (3) by leaping from a pool. A summary of his analysis appears in Table 5. From the table, it is evident that the analysis is supportive of Stuart's contention.

It is also apparent from Table 5 that leaping offers energetic advantages over swimming up an inclined ramp or through a port above some critical elevation differential (Ah). This is indirectly supportive of the concept that fish prefer to leap rather than swim once a certain minimum stimulus (Δh) has been satisfied. In nature, the path of least resistance offers efficiency, favors survival, and is thus often exercised. Porpoising by dolphins is an example of energetically efficient locomotion (Blake, 1983). It has also been suggested that schooling, in part, is a behavioral adaptation to a more efficient means of locomotion (Weihs, 1974b).

Table 5.--Summary of the energy requirements for a four-pound ascending fish.

Elevation Difference Δh (ft)	Swim Through Ports (ft-lbs)	Swim up a 45° Ramp (ft-lbs)	Leaping from a Still Pool (ft-lbs)
1	7.2	1.6	5.3
2	14.4	6.1	10.7
4	28.9	23.5	21.3
6	43.3	38.6	32.0

After Mih, W. C. 1983. A conceptual, analytical model of the energy requirements of ascending fish. Albrook Hydraulic Laboratory, Washington State University, unpublished.

HYDRAULIC THEORY

Introduction

> Violent air-water mixtures can be seen occurring as a "boil" on the surface although the falling water may be relatively non-aerated. This is the location of the "hump" previously described and it was seen that, instead of hindering the passage of the fish, under certain conditions, it could be of marked assistance (Stuart, 1962, p.32).

Stuart was a biologist by training, and although possibly lacking in the rudiments of hydraulic theory, he was an astute observer. From his description, it is apparent that the "hump" or standing wave referred to is, at least in part, caused by the release of entrained air to the pool surface in the form of an air-bubble plume. With an understanding of the mechanics of this phenomenon it may be possible to adapt its use for fish passage application.

Submerged Jet Theory

The phenomenon of a free jet plunging into a pool is significantly different than that of a submerged jet. The principal difference is the air entraining characteristics of the free jet, which alters the jet diffusion process. Despite these differences, it is useful as a basis to first consider the diffusion of a submerged jet. By superimposing the complication of air entrainment, the free jet diffusion process can subsequently be developed.

As a submerged jet is discharged into a pool, interaction between the jet and the ambient fluid occurs through viscous shear. The effect is to decelerate the fluid just within the jet boundary, and to accelerate the adjacent fluid in the pool. Through this process the velocity core of the jet is gradually diffused, the adjacent ambient fluid is accelerated or entrained, and the overall effect is a gradual transition from a flow of higher to lower kinetic energy.

Albertson et al. (1950), in their study of submerged jet diffusion, divided the diffusion process into two distinct zones (Figure 11). The zone of flow establishment extends from the jet source to the apex of the constant-velocity core. The length of the zone is a function of the initial jet cross-section geometry. Beyond the zone of flow establishment is the zone of established flow. In this zone flow velocities are reduced further as the kinetic energy of turbulence is dissipated through viscous shear.

Continuity requires that a flow circulation pattern develop in the pool to replace the fluid entrained by the jet (Figure 12). Otherwise there would be a fluid build-up at the downstream end of the pool. In a plunging jet, the return eddies that develop to insure continuity are predominately upward in direction (Figure 13). As this flow reaches the pool surface, the vertical component of the velocity head is converted to potential head which appears as a hump, or standing wave, on the pool surface.

$$H = V^2/2g$$

where

V = vertical velocity component of the return eddy,

H = potential head.

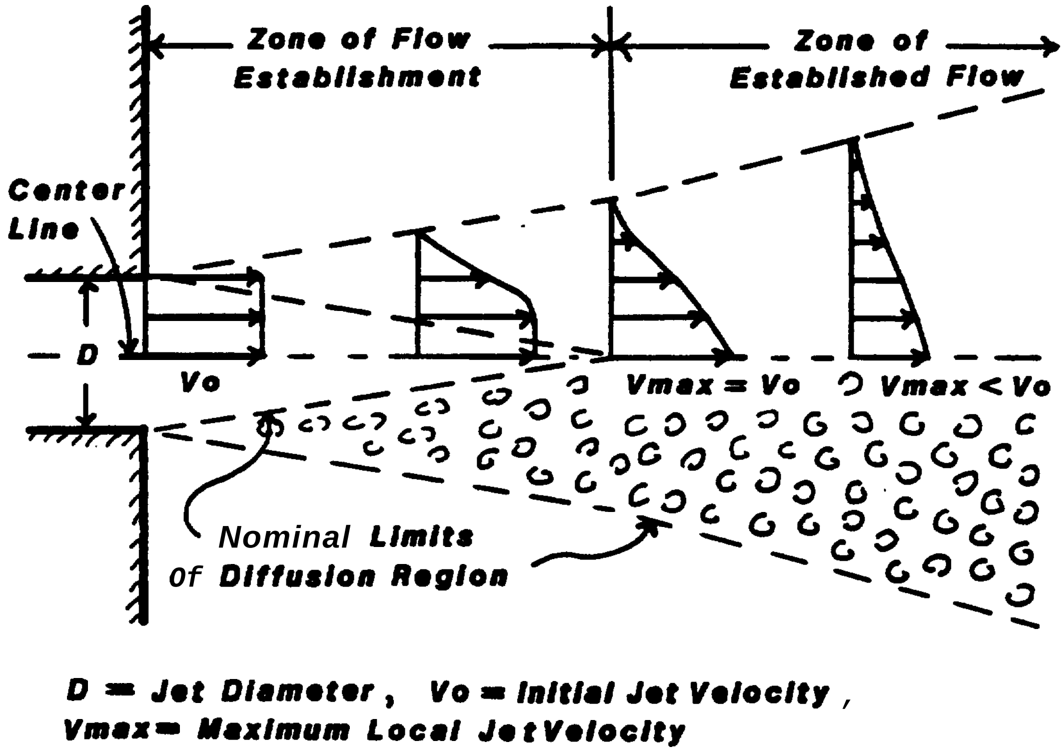

Figure 11. Schematic representation of jet diffusion (after Albertson et al., 1950).

The magnitude of the vertical velocity component of the return eddies, and their relative importance to the formation of the standing wave, are unknown. It is an objective of this study to make such a determination.

Exposed Jet Theory

When a free jet enters a pool, such as at a falls or below a weir, air is introduced into the pool with the jet. This occurs through two mechanisms. The first mechanism is a function of the roughness of the jet surface as measured by the Reynolds number.

$$Re = V_0 L/\nu$$

where

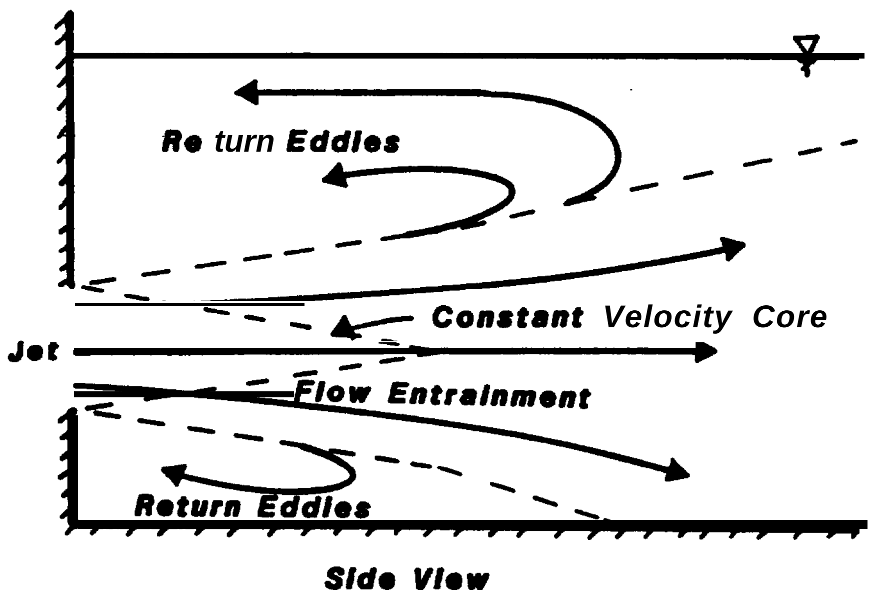

Figure 12.--Schematic representation showing circulation pattern of submerged jet flow, such as from a port.

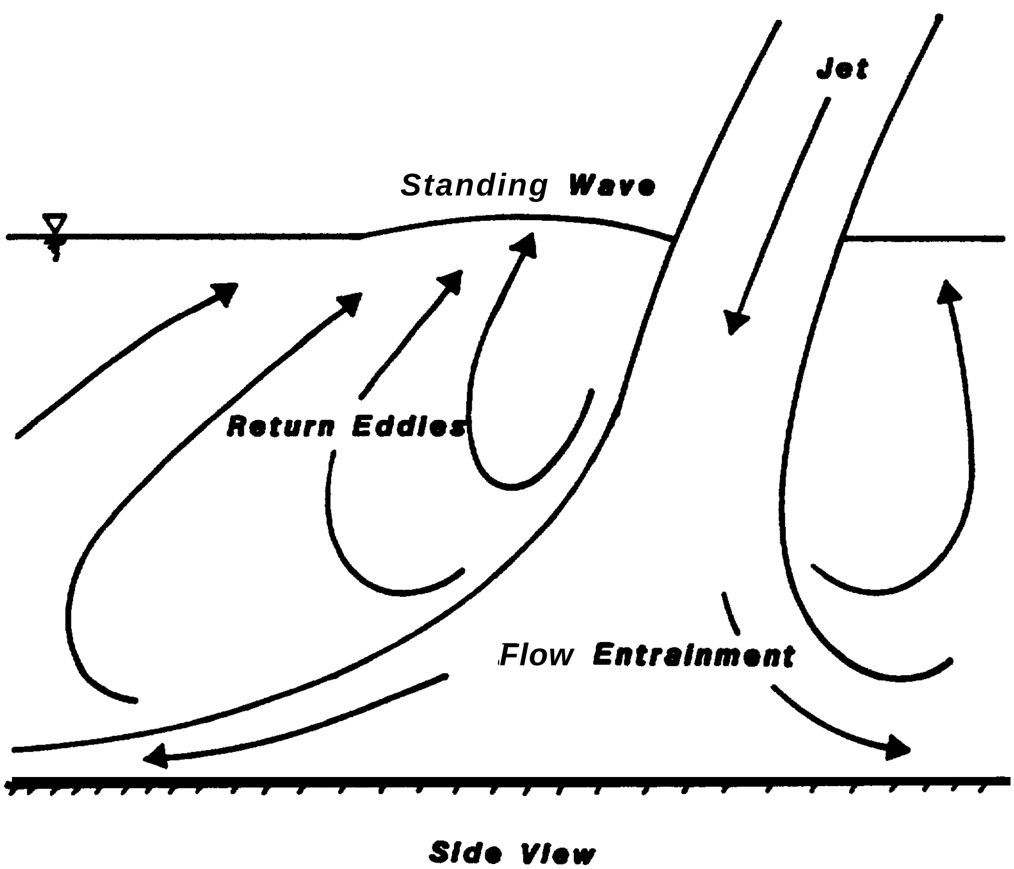

Figure 13.--Schematic representation showing circulation pattern of plunging jet flow.

Re = Reynolds number,

V_0 = jet velocity,

L = characteristic length, diameter, or thickness of the jet,

ν = Kinematic viscosity of the fluid.

At a critical Reynolds number the jet surface becomes rough and small furrows form, opening and closing, in a dynamic process. Air surrounding the jet becomes entrapped in these roughness depressions and is dragged into the pool with the jet. Anderson (1968), using small diameter nozzles and water, observed the onset of jet surface roughening at Reynolds numbers as low as $2.7 \times (10)^4$ for a 0.0417 foot diameter nozzle. Jet surface roughening was observed to occur at higher Reynolds numbers for larger diameter nozzles.

The second mechanism by which air is-entrained in the pool occurs at the jet/pool surface interface. As the jet enters the pool, the pool surface is depressed somewhat by viscous shear. This depression fills with air. Because of turbulent fluctuations in the jet, and erratic flow patterns in the pool, air becomes entrapped and dragged beneath the pool surface. In most cases, this mechanism is probably responsible for the greatest portion of the air entrained in the pool.

The effect of entrained air on the jet diffusion process was described and experimentally verified by Anderson (1968). Two important conclusions were reached: (1) that the rate of the jet centerline velocity dissipation increases with increasing air concentration; and (2) that the transverse velocity profiles are flattened with increasing air concentration as compared to profiles of a submerged jet.

To describe the diffusion process for an exposed jet, Anderson (1968) defined four distinct zones. The first or initial zone is similar to that of a submerged jet because the deceleration effects of the air do not penetrate to the jet centerline. The potential core remains free of air although the surrounding fluid does not. Beyond the first zone the centerline velocity begins to decrease. In this second zone the entrained air is distributed throughout the section and the transverse velocity profile is fully developed. This zone is relatively short. The third zone is defined by another deceleration law and predominates from the section at which the transverse velocity profile is fully developed (end of Zone 2), until the section where a rapid decrease in centerline velocity occurs (beginning of Zone 4). The fourth zone is defined by the increased effect of the buoyancy of the air bubbles. At this depth, the jet velocity has dissipated to the extent that the rise velocity of the air-bubbles is becoming relatively significant.

It is the fourth zone, or perhaps above it, that is particularly interesting concerning fish passage. From this zone a rising air-bubble plume originates. The similarity between an air-bubble plume and a simple buoyant plume was first -discussed by Taylor (1955) in reference to pneumatic breakwaters. As the air-bubbles rise through the ambient water, an induced vertical flow occurs that resembles the process of turbulent diffusion from a submerged source of buoyancy (Cederwall and Ditmars, 1970). At the surface, the induced vertical flow of the air-bubble plume is converted to potential head in an identical fashion as for the vertical component of the return eddies discussed previously. The magnitude of the velocity of the vertical induced flow, and its significance to the formation of Stuart's standing wave, are to be determined in this study.

Application to Fishladder Development

It is evident from the theory that functional relationships exist between certain jet parameters that influence the behavior of a jet as it plunges into a pool. With an understanding of the interactions of these parameters it is possible to predict jet behavior in a qualitative sense. It is particularly desirable to be able to predict the air-entraining and velocity diffusion characteristics of a particular jet shape. Both these characteristics have been identified as pertinent to fish passage.

> The maximum energy of fall, designed for the optimum stimulus for leaping, must be dissipated as nearly as possible below the point of entry in order that: (a) the uplift will be available to the fish, and (b) that the flow into the succeeding pool will have a minimum of turbulence (Stuart, 1962).

It is an objective of this study to develop a weir whose shape and orientation to the flow produces a jet shape with desirable entrainment characteristics for fish passage. The following functional relationships offer guidance to the developmental effort.

1. Length of zone of flow establishment = f (jet diameter)

   The significance of this phenomenon is that the maintenance of jet centerline velocities, perhaps described as the penetration of the jet into the pool, is a function of the jet cross-sectional geometry.

2. Air entrainment = f (jet velocity)

   Anderson (1968) identified air entrainment as a function of the Reynolds number (i.e., velocity). It is reported that 3.6 fps is the minimum velocity required to entrain air (Falvey, 1981). The quantity of air entrained has an obvious bearing on the character of the air-bubble plume which appears as a boil on the pool surface below an overfall.

3. Air entrainment = f^{-1} (jet perimeter (P))

By virtue of the second mechanism of air entrainment discussed previously, it is clear that air entrainment is a function of jet perimeter. It is convenient to compare the air-entraining characteristics of jets of comparable velocity and discharge (velocity X cross-sectional area) by relating air entrainment to jet hydraulic radius.- The hydraulic radius (R) of a jet can be defined as the jet cross-sectional area divided by the jet perimeter.

4. Length of zone of established flow = f^{-1} (air entrainment)

Anderson (1968) concluded that the dissipation of centerline velocities depends on the quantity of air entrained. With increasing air concentrations the rate of velocity dissipation also increases. It follows that the maintenance of jet velocity, described as the penetration of the jet into the pool, is inversely related to air concentration.

THE FISHWAY SYSTEM: COMPONENTS AND FUNCTIONS

A hydraulic system, such as a fishway, consists of various components and functions with complex interactions. To facilitate the understanding of the system it is helpful to identify each component (Figures 14, 15, and 16) and the corresponding functions (Figures 17, 18, and 19). Only with this understanding is it possible to develop and integrate a test program which will provide feedback concerning system response which is meaningful. With understanding and feedback, it is possible to test and adjust the system to achieve the program objectives.

Some pertinent definitions follow:

1. **Weir.**--Routes the flow through the fishway and concentrates the flow momentum prior to the plunge into a downstream pool. Produces a stable standing wave over a range of flows. Also serves as an access opening to upstream pools for leaping fish (Figures 14, 15, and 16).
2. Overflow Yeir.- Extends the range of flows over which the fishway can function (Figure 15).
3. Fi shway Chamber. --Provides water storage capacity and constitutes the base structure of the fishway. The tank geometry influences the hydraulic conditions (energy dissipation, resting space) developed.within the pools of the fishway (Figure 15).

4. **Baffling.**--Dissipates hydraulic energy, directs flow, and guides fish. Influences the overall hydraulics within the pools of the fishway. Contains turbulence upstream of the baffles in each pool when properly located in the fishway chamber (Figure 15).

5. **Downstream Fishway Portal.**--Attracts fish to the entrance structure and provides access into the fishway. Serves as the hydraulic exit (Figure 14).

6. **Upstream Fishway Portal.**--Regulates flow into the fishway and serves as an exit for fish (Figure 16).

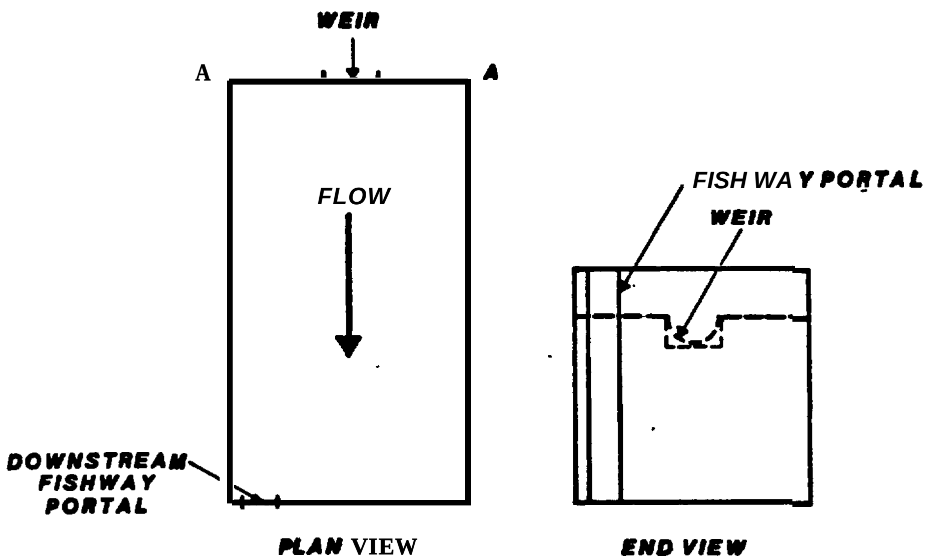

Figure 14.--Schematic of fishway entrance chamber.

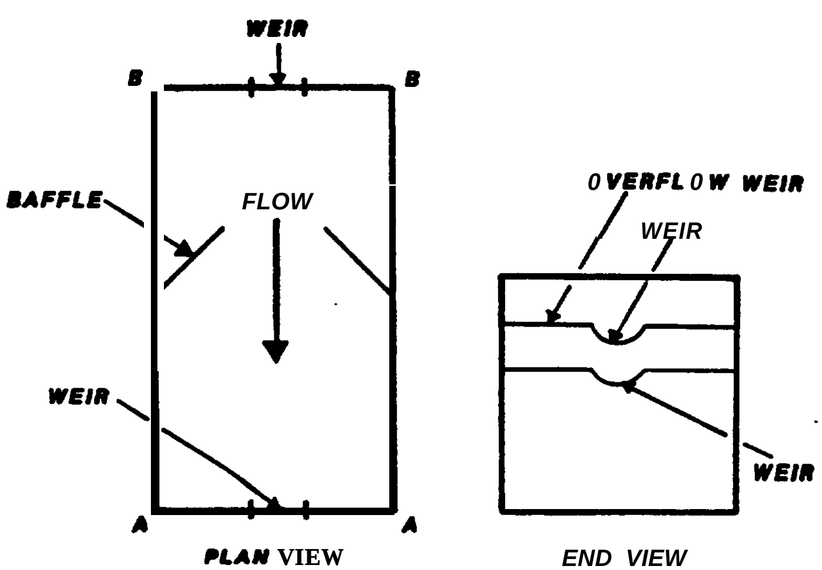

Figure 15.--Schematic of intermediate fishway chamber.

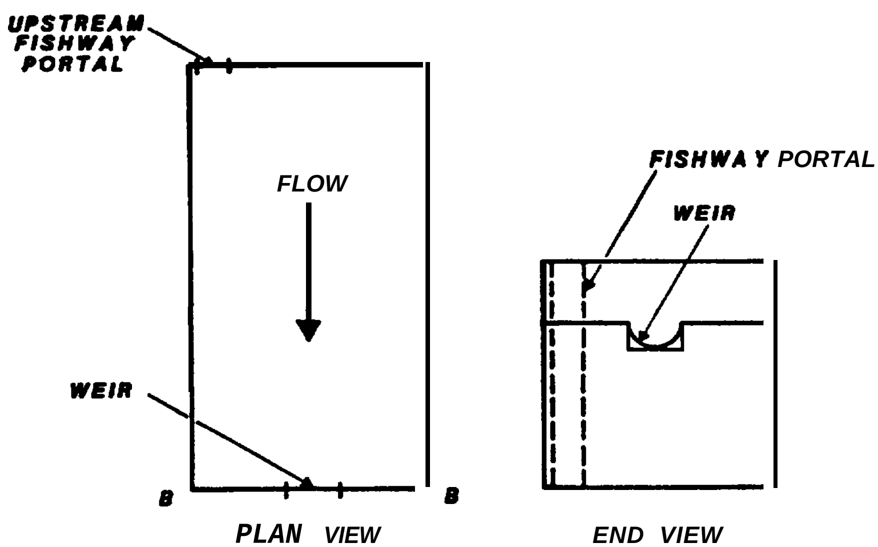

Figure 16.--Schematic of fishway exit chamber.

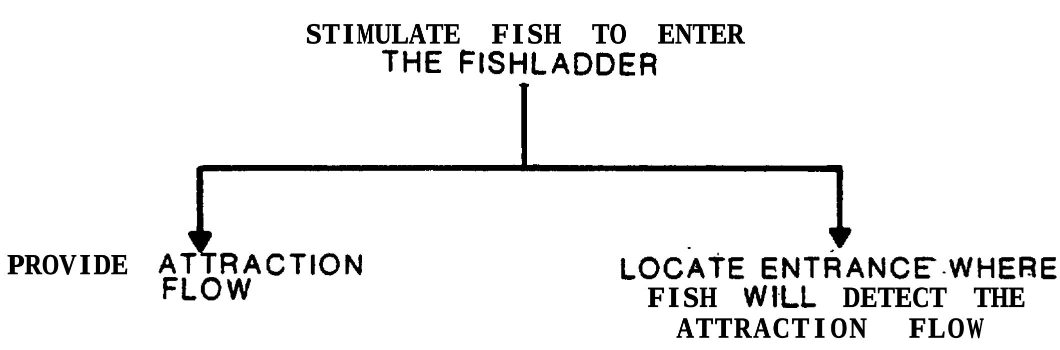

Figure 17.--Subfunction analysis for fishway entrance chamber.

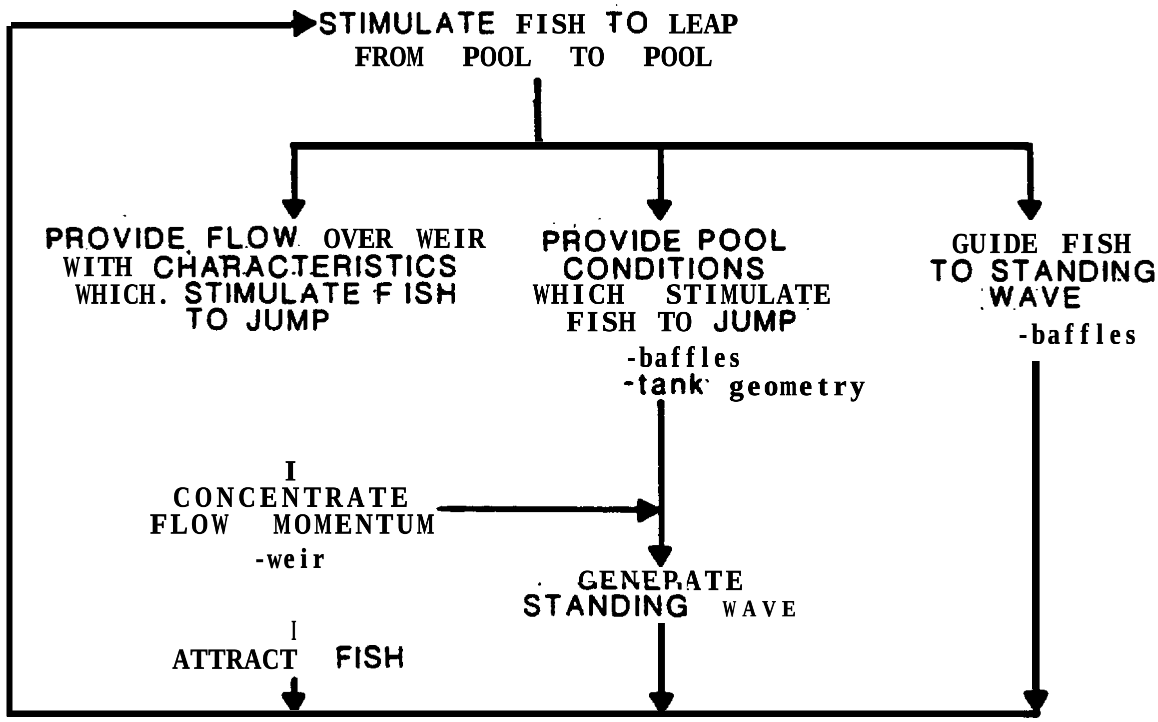

Figure 18.--Subfunction analysis for intermediate fishway chamber.

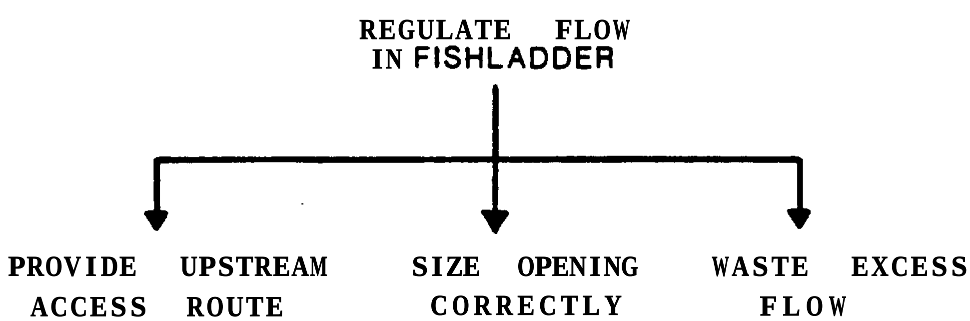

Figure 19.--Subfunction analysis for fishway exit chamber.

CRITERIA FOR FISHWAY DESIGN AND DEVELOPMENT

Introduction

It should be emphasized that in the study of a hydraulic system, such as a fishway, the variables and their respective criteria are often mutually interdependent. It is therefore likely impractical to establish and expect to satisfy rigid criteria in every case. Instead, the requirement is to define criteria in terms of desirable flow features. Firm values only occasionally need to-appear as standards. By experimentation and adjustment it is then possible to optimize the hydraulic conditions in a manner such that all the criteria can be satisfied, and the project objectives realized.

Discussion of Criteria

1. Water Jet

(a) Shape.--The shape of the water jet is important for two reasons. It influences the air entraining characteristics of the jet and it defines the concentration of the flow momentum.

(b) Stability.--By stability is meant the resistance to breakup. For turbulent flow a jet will always disintegrate if given sufficient fall distance (Falvey, 1981). This is primarily a function of the internal turbulence of the jet (Rouse et al., 1951). Jet instability would reduce the concentration of the flow momentum, which is considered undesirable. Flow concentrations are attractive to fish.

2. Standing Wave

(a) Height.- Stuart (1962) concluded that the presence of a standing wave was closely related to a fish's stimulus to leap. The height of the standing wave is an indication of the strength of this hydraulic condition.

(b) Location.- Stuart (1962) concluded that the distance to the standing wave from the obstacle influenced the success of the leap.

(c) Shape and Size.--The shape and size of the standing wave are an indication of the submerged flow characteristics. They may also be an indication of the zone of influence regarding the stimulus for fish to jump.

3. Air Entrained in Plunge Pool.--It is unclear as to what the effect of entrained air in the pool below a weir may be on fish passage characteristics. In Great Britain the practice has been to avoid the superaeration of water in fishways while in Norway the moderate aeration of water is sometimes encouraged (Inst. of Civil Engineers, 1942).

(a) Visibility.- It has been reported that the visual stimulus is important in the orientation of a fish's leap (Stuart, 1962). The quantity of air entrained does affect the visibility within the water medium, but fish sight out of water.

(b) Density.--The density of the water is related to the momentum force by the following relation:

$$F_m = \rho_m QV$$

where F_m = flow momentum force (F),

ρ_m = density of flow medium (FT^2/L^4),

Q = discharge (L^3/T),

V = flow velocity (L/T).

From this relation it is evident that the quantity of air entrained will directly influence the flow momentum force. Since it is hypothesized that the flow momentum force is the releaser for fish movement, it can be reasoned that the quantity of air entrained may influence the action of this stimulus.

Of secondary consideration, in cases of extreme air entrainment, is the possibility that the effectiveness of fish propulsion may be reduced as tail movement meets less resistance in the rarefied medium.

4. General Flow Characteristics Within the Pool.--The general flow characteristics obtained within the pool will in part be a function of the other criteria since the overall fishway hydraulics are mutually interdependent. There are, however, certain flow characteristics, both desirable and undesirable, that can be influenced with the introduction of baffles, guide vanes, or other hydraulic accessories.

(a) Upwelling Flow.--Upwelling flow is known to trigger jumping in fish (Bell, 1973). This is the characteristic flow pattern of the standing wave that will be generated downstream of the weir jet as it plunges into the pool. This standing wave will be the one best location for the fish to initiate their leaps on their passage upstream. It is thus desirable to eliminate all other upwelling areas within the pool so as to avoid orientation problems and unsuccessful leaping activity.

(b) Vorticies.- It is reasonable to assume that vorticies may tax the energy of fish as they struggle to maintain their orientation. In addition, the effect of vorticies on successive weir jets would be to disturb the hydraulics and perpetuate unstable flow conditions. It is thus desirable to attenuate any vorticies that may occur.

(c) Velocity.- It is desirable to provide a clearly distinguishable velocity (flow momentum) gradient towards the standing wave so as to attract fish to the optimal jump location. This can be accomplished with baffling. It is also desirable to reduce the magnitude of secondary velocity jets so that it is unlikely that fish may become oriented away from the desired pathway. Bell (1973) recommends that two feet per second (fps) be used for transportational velocities. This velocity is sufficient for use as a target in this study. It is anticipated, however, that the results of this study will further define the required velocities (flow momentum) necessary to initiate and predict fish movement.

(d) Direction.- Since flow momentum is a vector quantity the direction of the flowlines is important. It is desirable to provide a simple homogeneous flow pattern to encourage the proper orientation of the fish.

(e) Stability.--It is desirable that the general flow characteristics are stable throughout the operational range of flows.

Surging flow is unacceptable in that it would disrupt the flow continuity throughout a series of fishway chambers. This would effectively prevent the optimization of the hydraulics for fish passage.

5. Difference between Pool Elevations .--The primary consideration in establishing the criterion for the height of the fall between pools is that it must be within the leaping capability of the target species. It has been demonstrated that all species of salmonids have the ability to negotiate a three-foot overfall (Collins and Elling, 1961). It has also been reported that six feet can be considered a normal maximum for salmon (species not .mentioned) leaping under favorable conditions (Inst. of Civil Engineers, 1942). Since swimming and leaping capabilities depend on both the species and size of the fish, the proper establishment of this criterion requires specific knowledge of the target fish. For the purposes of this study, it seems prudent to set the maximum difference between pool elevations at three feet. This would provide fish passage conditions within the capability of. most salmonids while still allowing for significant energy dissipation per unit length of facility.

6. Depth of Pool .--Enough depth should be provided to cushion the falling jet sufficiently to prevent excessive turbulence. The relationship between the depth, width, and discharge should be such that velocities are sufficient to stimulate the movement of fish and discourage lingering. Stuart (1962) demonstrated that a relationship exists between pool depth, fall height, and the character of the standing wave generated. It is anticipated that

the interdependence of these variables, and their respective criteria, will be verified in this study.

7. Resting Area.- It has been reported that from 30-50 percent of fishway volume is desirable for resting area (velocity 51 fps) for fish (Bell, 1973). In the development of the fishway a standard for resting area volume will not be established. The resting area volume will be treated as a totally dependent variable.

8. Energy Dissipation.--It has been reported that the maximum design flows for a fishway should be based on an energy dissipation criteria of 4 ft-lbs/sec/ft^3 of water (Bell, 1973). Energy dissipation is of interest to this study but only as a descriptor of the final design. Energy dissipation will thus be treated as a totally dependent variable.

9. Flow Range.- It is desirable that the fishladder be able to operate effectively over as wide a range of flows as possible. The limitation of this study is a working range of 10 cubic feet per second (cfs). With the appropriate design of means to pass excess discharge, either within the fishway (overflow weirs) or externally through a wasteway, it may be possible to extend operations beyond this range.

OBJECTIVES

General

The general objectives of this study were threefold:

1. to determine the physical mechanism and magnitude of the standing wave phenomenon described by Stuart (1962),
2. to develop a fishway configuration based on the concept that fish can be stimulated to leap, and
3. to assess the performance of the new fishway with field tests.

Specific

To achieve the general study objectives, the study was subdivided into several component parts, each with specific objectives. The component studies can be classified into two categories: (1) laboratory, and (2) field. The following is a listing of the component studies and their respective objectives.

Laboratory

1. Preliminary Weir Tests
   - (a) to make a preliminary selection of a weir shape (Figure 20) and orientation angle (Figure 21) for use in further testing,
   - (b) to determine the effect that the orientation of weir training walls (Figures 22 and 23) has on jet shape,
   - (c) to describe the standing waves produced by various jet shapes, and

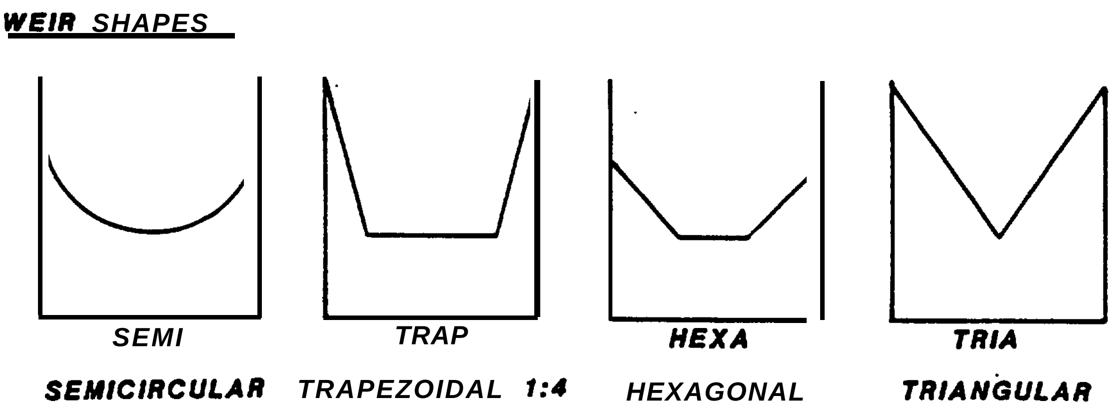

Figure 20.--Schematic of the weir shapes tested.

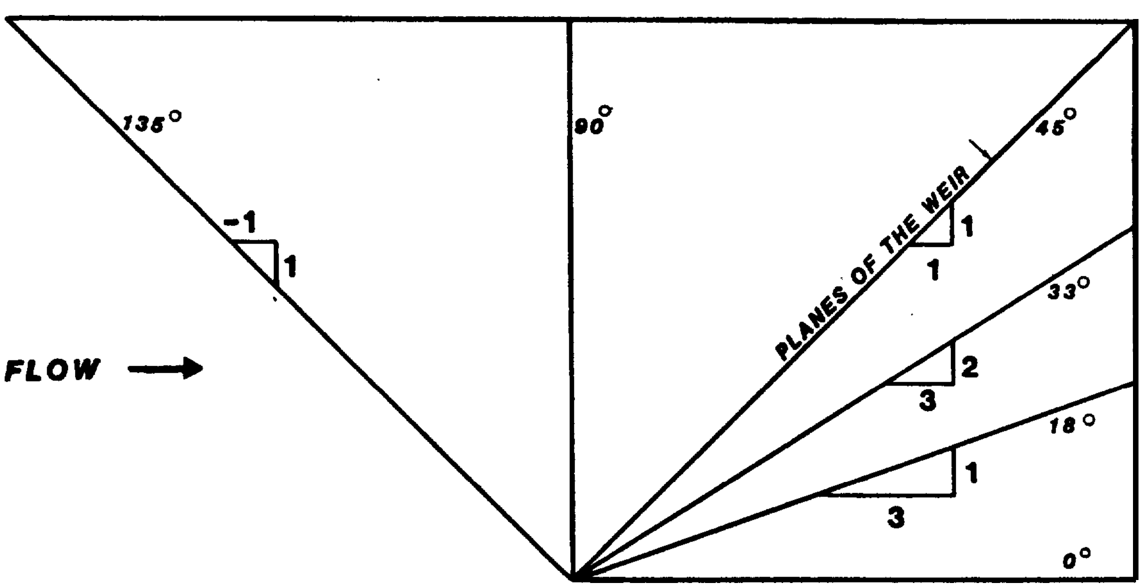

Figure 21.--Side view showing the orientation angles of the plane of the weirs that were tested.

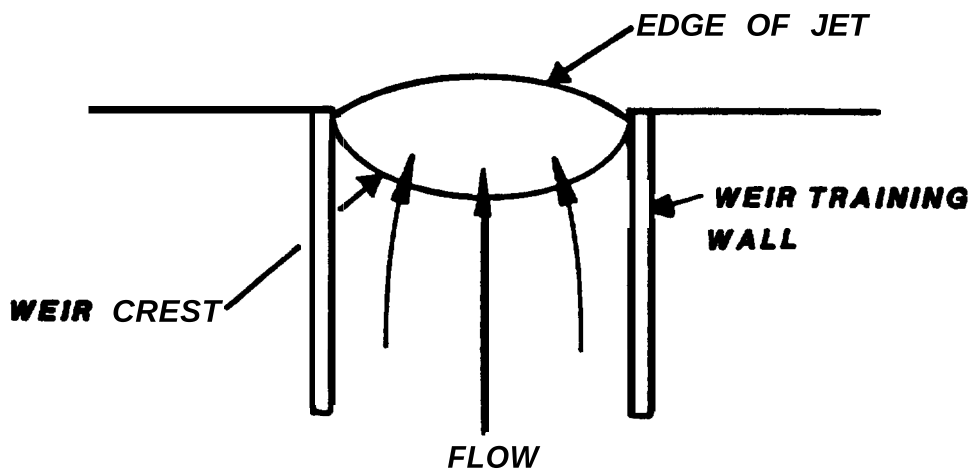

Figure 22.--Plan view showing weir training walls.

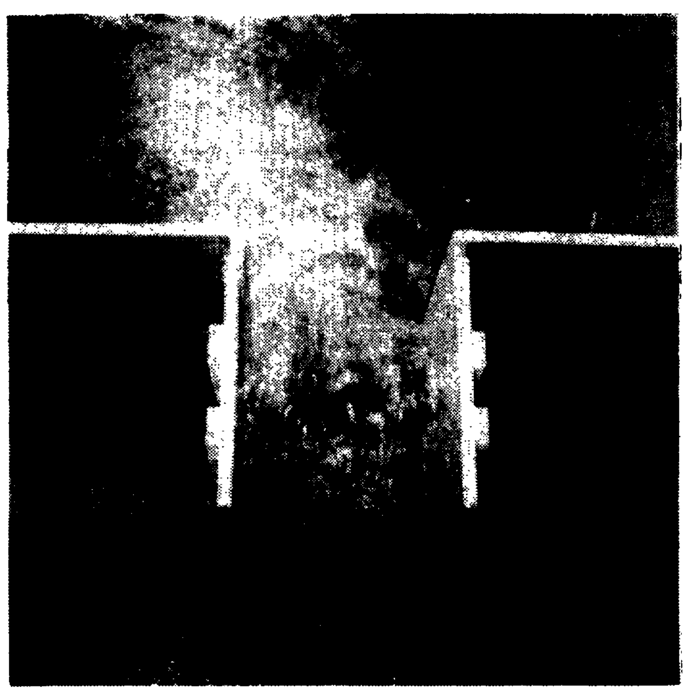

Figure 23.--View of weir training walls
looking downstream from above.

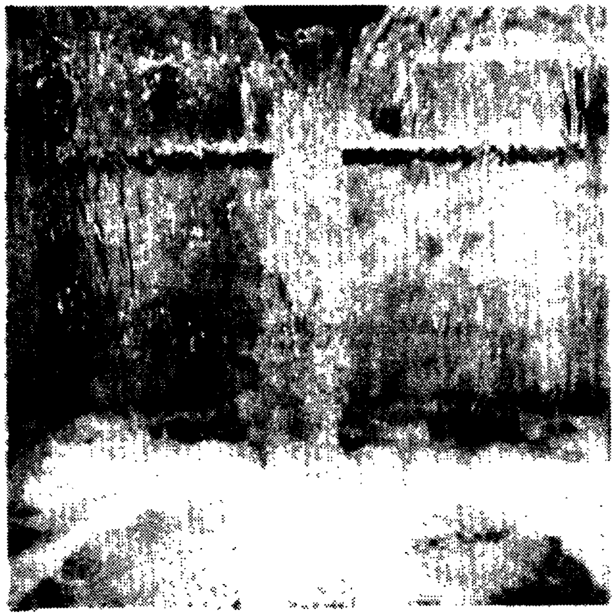

Figure 24.--Front view showing overflow jets on either side of the main weir jet.

(d) to determine the effects of the overflow jets (Figure 24) on pool flow patterns.

2. Baffle Orientation Study

To determine the location[1] (XB) and orientation angle[2] (θ) of baffles (Figures 25 and 26) which produced the best pool flow conditions as defined by the study criteria.

3. Standing Wave Study with a Nozzle

(a) To determine the mechanism governing the formation of standing waves, and

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[1] Distance (XB) downstream in the pool measured from the upstream tank endwall.

[2] Measured inward from the fishway chamber sidewalls.

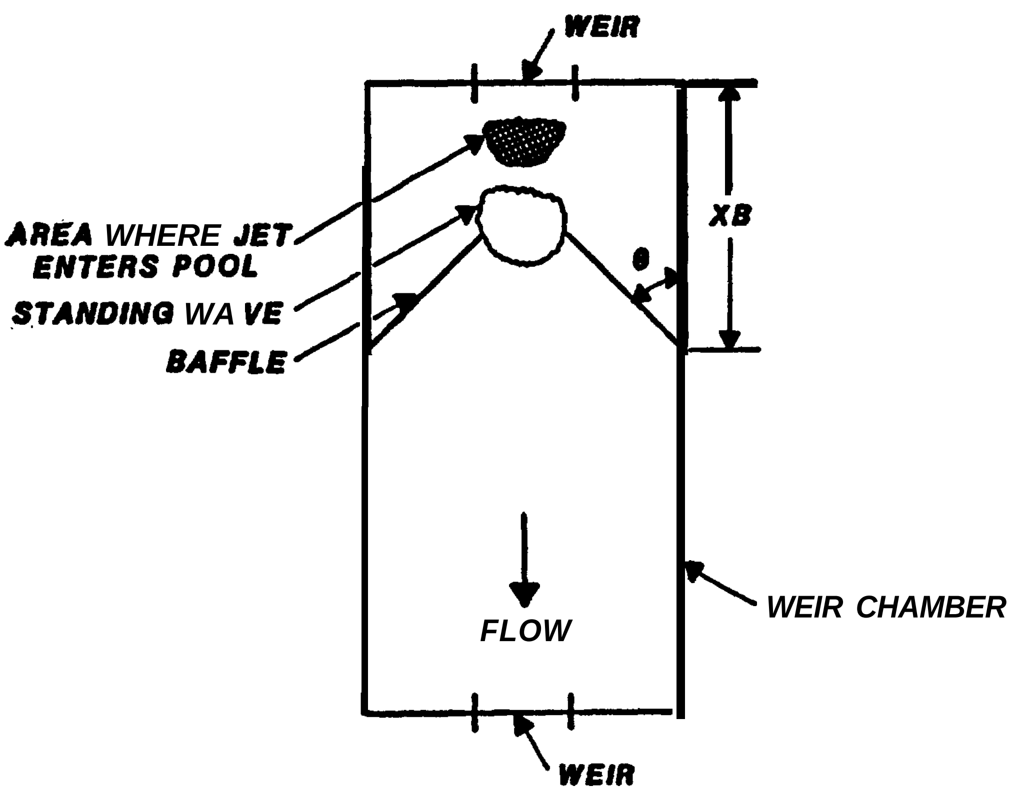

Figure 25.--Plan view of intermediate chamber of fishway showing approximate baffle placement.

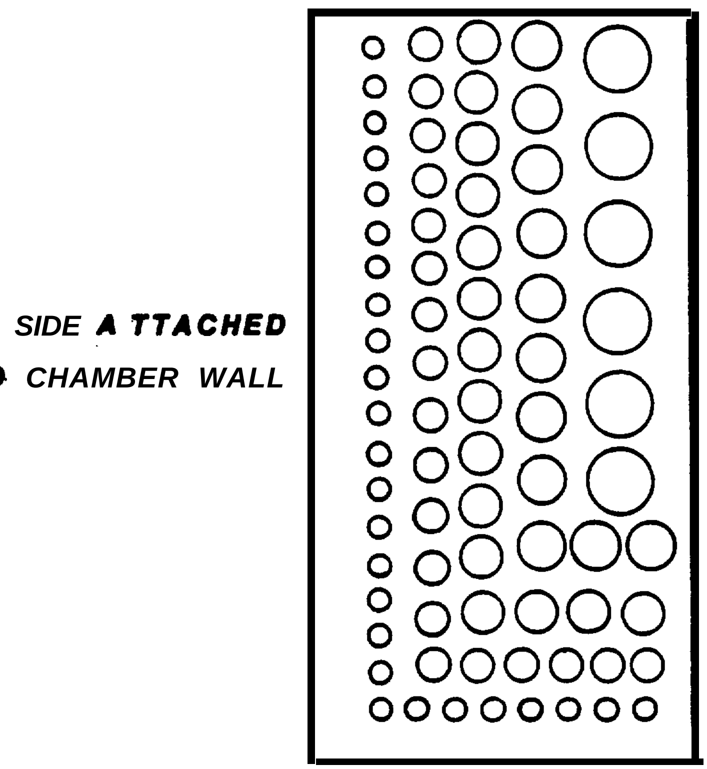

Figure 26.--Schematic of a perforated baffle showing a possible arrangement of holes to dissipate energy and provide a resting space downstream of the baffles.

(b) to measure the magnitude of the vertical velocity component of standing waves.

4. Standing Wave Enhancement Study

(a) To develop a hydraulic appurtenance that directs a plunging jet back towards the pool surface to increase the magnitude of the standing wave,

(b) to measure the magnitude of the enhanced standing wave, and

(c) to determine the location of the device, as measured downstream from the weir bulkhead, that provides the best operating conditions over a range of discharges.

Field

Johns Creek Test Objectives

1. To observe chum and coho salmon leaping and holding behavior in the existing and new ladder units,
2. to adjust the new fishway configuration as necessary based on fish response, and
3. to photograph leaping fish.

MATERIALS AND METHODS

Laboratory

Preliminary Weir Tests

The preliminary weir tests were conducted in a flume 4 feet wide, 6 feet high, and 30 feet long (Figure 27). The test program was divided into three separate stages: (1) main weir selection,[1] (2) weir training wall effects,[2] and (3) overflow weir effects.[2]

The primary variables of each test stage were:

Main Weir Selection

Weir Geometry.--Four weir shapes were tested: (1) hexagonal with one-on-one sideslopes, (2) semicircular, (3) trapezoidal with four-on-one side slopes, and (4) a 68-degree V-notch (Figure 20). The maximum horizontal dimension for each weir was 0.75 feet.

Weir Angle.--The weirs were tested at several orientation angles measured from a horizontal plane and rotated upwards about a horizontal axis perpendicular to the flow. The angles tested were 18, 33, 45, 90, and 135 degrees (Figure 21).

Discharge.--The discharge was varied between 0.1 to 2.0 cubic feet per second (cfs).

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1 Diane Hilliard was the principal researcher on this study component. The work was the basis for her senior paper, "Weir Optimization: A New Concept in Fishladder Design," Washington State University, May 26, 1983, unpublished. This paper includes a reinterpretation of the original data.

2 Valerie Monsey, a civil engineering senior student, was responsible for the dominant portion of the laboratory testing in this study component.

Figure 27.--Test apparatus for the preliminary weir tests.

Tailwater Depth.--The depth downstream of the weir was varied from approximately 0.9 to 3.3 feet in 0.8 foot increments.

Weir Training Wall Effects

Training Wall Skew Angle.--Defined as the rotation of the training wall hypotenuse away from the weir centerline about the downstream point of the training wall (Figure 28).

Training Wall Lean Angle. --Defined as the rotation away from the weir centerline about the bottom edge (hypotenuse) of the training wall (Figure 29).

Discharge. --The discharge was varied between approximately 0.2 to 1.0 cfs in increments for each test series.

Overflow Weir Effects

Total Discharge. --The total discharge (Q) through the flume was varied.

Relative Discharge. --The relative discharge between the semicircular weir (QWW) and the overflow weirs (QOW) was varied.

Although measurements were made to quantify flow characteristics, such as standing wave height and position, the tests were largely qualitative in nature. Much data were obtained by observing a trial and describing, sketching, and photographing the flow features. In this manner, trends were identified, a preliminary understanding of jet and pool dynamics was obtained, and conclusions were reached based on the study criteria. A detailed description of the apparatus and methods of the preliminary weir tests appears in the Appendix.

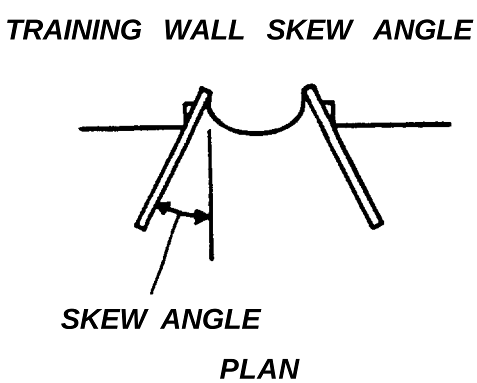

Figure 28.--Training wall skew angle.

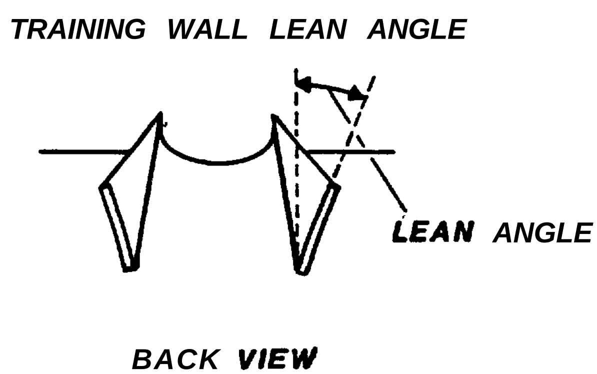

Figure 29.--Training wall lean angle.

Baffle Orientation Study

Apparatus

The test apparatus was a flume 8 feet wide, 6 feet high, and 30 feet long (Figure 30). Water was supplied to the flume through a 20-inch diameter steel pipe by a pump rated at 10 cfs. The flow into the flume was regulated two ways: (1) by wasting excess water through a bypass pipe, and (2) by a gate valve. A velocity diffuser was attached to the pipe inlet. A turbulence dissipator was in the head tank.

A bulkhead was located 9 feet downstream from the pipe inlet. It measured 5.75 feet high, 8 feet wide, and 0.56 feet thick.

Cantilevered from the top of the bulkhead, at 45 degrees from vertical in the downstream direction, was a plywood plate. The plywood plate measured 8 feet wide by 2 feet high. A 32-inch diameter semicircular weir opening was centered in the downstream edge. Attached to both sides of the weir opening were training walls with rounded entrances (Figure 31).

The tailwater pool measured 8 feet wide, 6 feet high, and 15 feet long. The pool depth was regulated by a steel tailwater gate which measured 5.5 feet wide by 5 feet high. The gate rotated from the vertical in the downstream direction about a horizontal axis perpendicular to the flow (about its base). In the top center of the gate was a Cipolletti weir opening with a 2.5 foot crest length and measuring 3.5 feet acrbss the top. A winch and pulley system was used to set the gate position.

One sidewall of the tailwater flume section was constructed of transparent plexiglass. This permitted viewing and photography of the tailwater pool flow patterns.

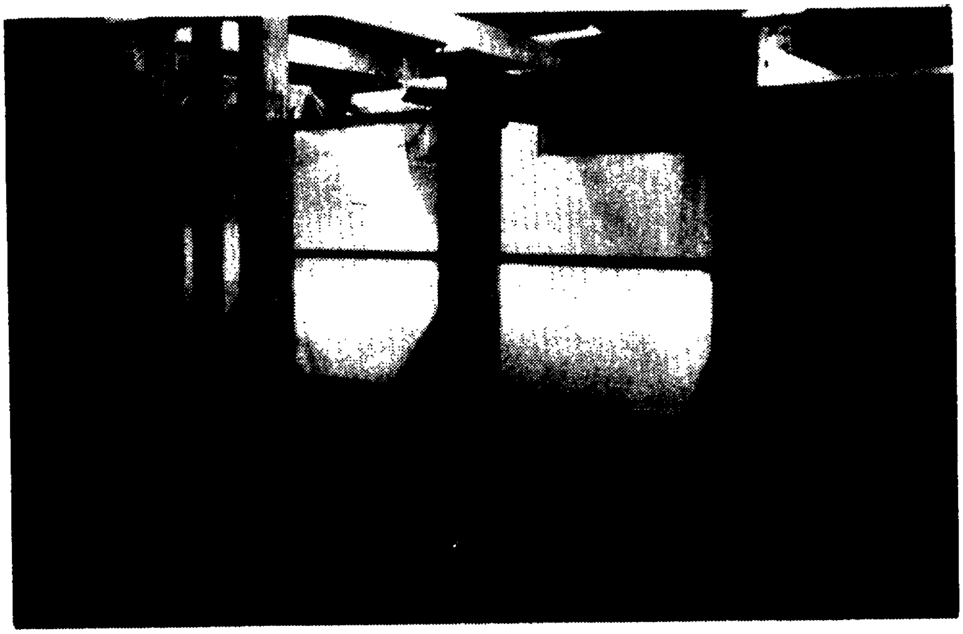

Figure 30.--Test apparatus of the baffle orientation study.

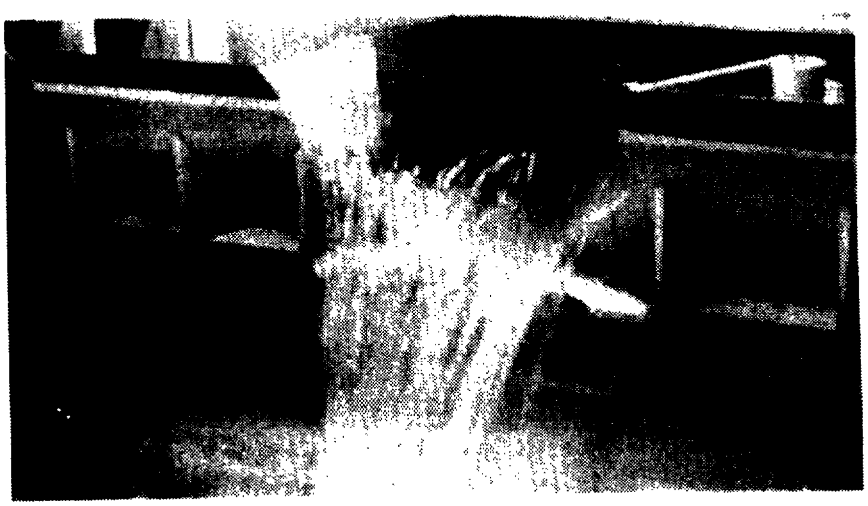

Figure 31.--Semicircular weir (32-inch diameter) with training walls.

Perforated baffles measuring 4 feet wide, 6 feet high, and 3/4 inch thick, were constructed out of plywood and attached to the tailwater pool side walls on hinges (Figure 32). Their position was fixed by clamps at the top, and a peg-in-hole assembly in a baseplate at the bottom.

Two stilling wells were used to monitor the level of the head and tail water in the flume. The headwater level was monitored 4.5 feet upstream of the weir bulkhead. The tailwater level was monitored 2 feet upstremn of the tailwater gate.

The same point gauge assembly described in the preliminary weir tests was used to measure standing wave heights. In addition, an electromagnetic flow meter (Marsh/McSirney Model No. 201 Portable Water Current Meter) was used to measure the vertical velocity component (VSWY) of the standing wave.[3] The position of the standing wave was referenced with a hand-held engineer's tape.

Two Secchi disks mounted on 3/4-inch diameter steel pipe were used as indicators of relative visibility (Figure 33).

Methods

The independent variables in the study were:

Baffle Location.--Defined as the distance (XB) along the flume sidewall to the baffle point of attachment as measured from the upstream weir bulkhead (Figure 25).

Baffle Orientation Angle.--Defined as the angle (θ) measured inward from the upstream flume sidewall (Figure 25).

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[3] The electromagnetic flow meter is applicable to flows which contain air bubbles, although the manufacturer cautions that bubbles may cause the instrument to exhibit a "slightly increased gain." Since errors in velocity measurement of 10 to 20 percent were tolerable, this was not a concern.

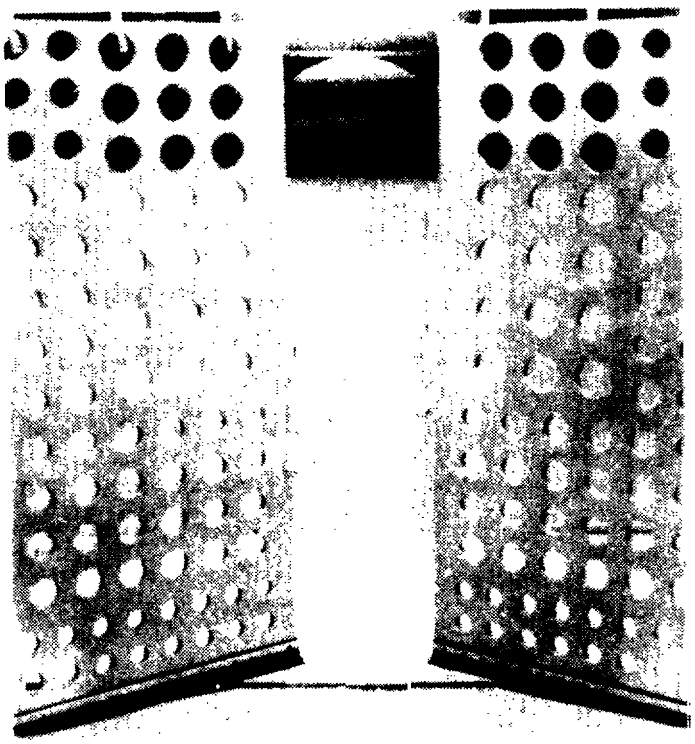

Figure 32.--Perforated baffles used in the baffle orientation study were 4 feet wide and 6 feet high.

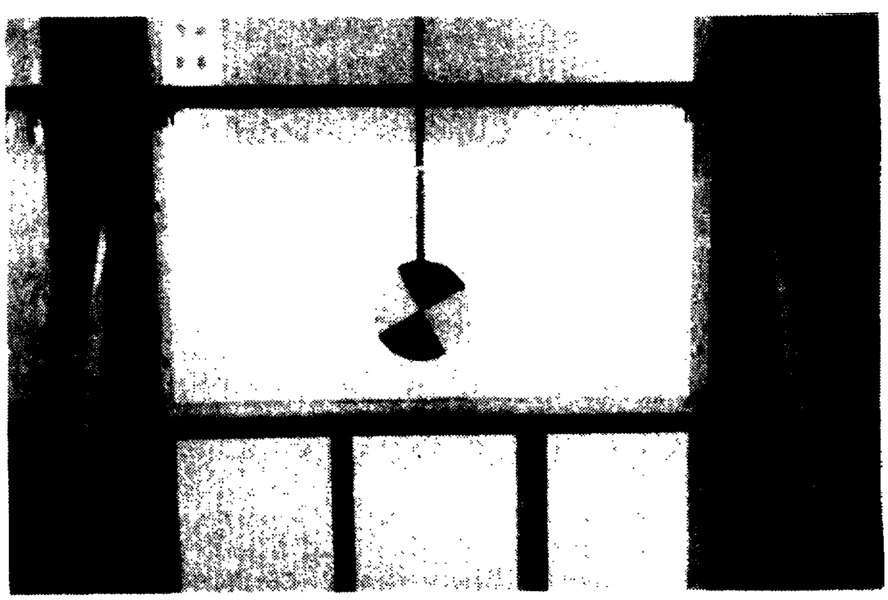

Figure 33.--Secchi disks mounted on 3/4-inch diameter pipe were used to indicate underwater visibility.

The discharge was held constant at 7.4 cfs (semicircle full), the tailwater setting was constant' at 3.44 feet, and the change in water surface elevation (AUSE) was constant at 3.70 feet.

The procedure was systematic and began with a baffle setting of X6 = 6.1 feet, θ = 30 degrees. The pump was activated and the flow regulated so that the semicircular weir was full. With the tailwater weir in the vertical position, the head on the tailwater weir (HTW) was determined via the downstream stilling well. The discharge was then calculated with the following equation.

$$Q = 8.42(HTW)^{1.5}$$

The tailwater level was then adjusted to a depth of 3.44 feet by lowering the tailwater gate. This tailwater setting and discharge were maintained throughout the balance of the testing.

The standing wave height was measured by the same procedure used in the preliminary weir tests. The standing wave position was referenced by measuring the distance from the standing wave to the weir bulkhead with a hand-held engineer's tape. The vertical velocity component of the standing wave flow circulation was measured approximately 0.5 feet below the water surface with the electromagnetic flow meter.

Flow patterns were sketched and defined further with velocity measurements made at various positions in the pool. Attention was focused on identifying eddies, vorticies, and areas of upwelling.

The relative visibility in the water was measured by means of a modified Secchi disk. Modifications were primarily in the means of attachment of the standard disk. This was necessitated because: (1) it was desired to measure the relative visibility in the turbulent upwelling flow of the standing waves; and (2) it was desired to measure the relative visibility in the horizontal plane through the viewing window.

Measurements were made at four sites: (1) vertically through the approximate center of the standing wave; (2) horizontally, one foot below the surface, opposite the standing wave, through the transparent side wall; (3) vertically at a position 10.8 feet downstream of the weir bulkhead on the flume centerline; and (4) horizontally, one foot below the surface, at a position 10.8 feet downstream from the weir bulkhead, through the transparent sidewall. The procedure for making Secchi disk measurements, as described by Lind (1974), was used.

The above procedure constituted one data set. The baffle orientation angle was then increased by 5 degrees and the procedure was repeated. This methodology continued in 5-degree increments until a baffle orientation angle of 50 degrees was reached.

The baffle location (XB) was then moved downstream 0.5 feet. Testing continued through baffle orientation angles from 30 to 50 degrees. This methodology was repeated until the baffles were eventually positioned 8.6 feet downstream from the weir bulkhead.

The procedure was repeated one additional time for the condition of no baffles. This served as a basis for comparison in analyzing the effectiveness of the baffles in providing the desired flow conditions.

Periodically, when a particularly interesting flow pattern presented itself, a diving mask was donned, and the investigators observed the flow conditions from a fish's perspective.

Standing Wave Study with a Nozzle

Apparatus

The test apparatus consisted of a steel head-tank, 2-inch PVC plumbing, and an observation tank with three transparent plexiglas side walls (Figure 34). The local water supply was used through a pressure line into the head tank.

Flow velocities were measured with an electromagnetic flow meter (Marsh/McBirney Model No. 201 Portable Water Current Meter). Distances were measured with a hand-held engineer's tape.

Methods

The independent variables in the study were:

Pool Depth.--The water depth in the observation tank was varied.

Tank Width.--The width of the observation tank was varied with a false backwall.

Nozzle Height.--The height of the nozzle above the water surface was varied.

Nozzle Angle.--Defined as the angle with the downstream horizontal projection, rotated downwards.

Jet Velocity.--The initial jet velocity as measured at the nozzle.

The procedure was systematic and began by opening the water supply valve to fill the head and observation tanks. The water level was then adjusted to the desired depth in the observation tank with the drain valve. The nozzle was set at the desired angle and height above the water surface. The width of the observation tank was initially 1.0 feet.

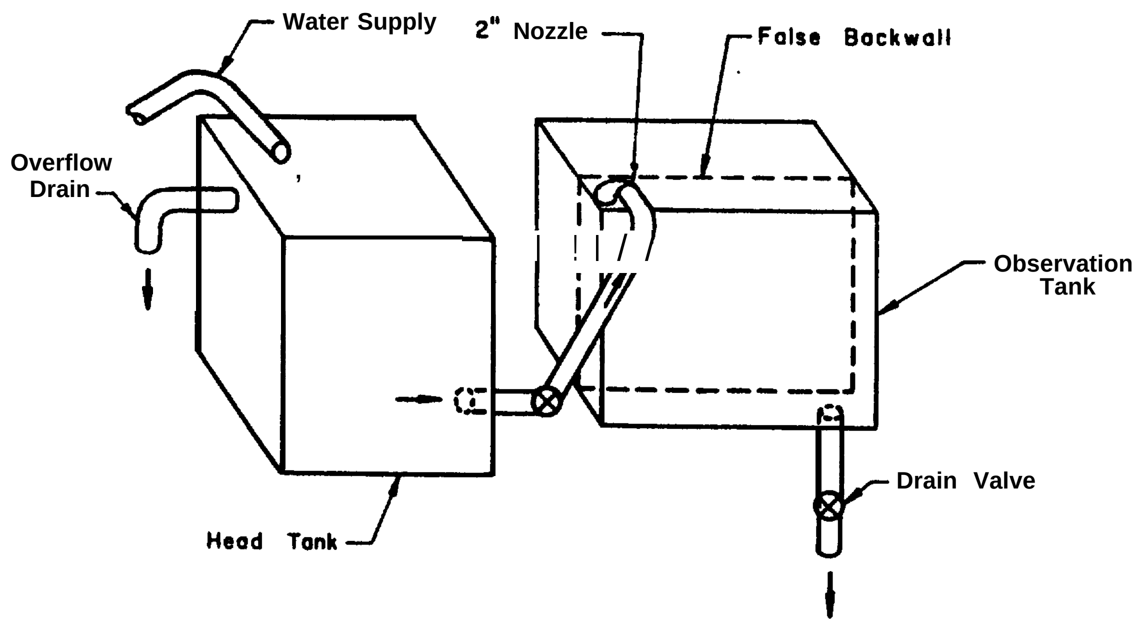

Figure 34.--Test apparatus for the standing wave study with a nozzle.

The electromagnetic flow meter was used to measure the vertical velocity component (VSWY) of the standing wave flow circulation, the initial jet velocity (Vo), and the horizontal velocity component of any return eddies present. The distance to the maximum VSWY reading from the point of entry of the jet into the pool was measured with an engineer's tape. The depth of penetration of the jet into the pool, as defined by the distance to the bottom of the air-bubble plume from the water surface, was also recorded.

Comments regarding air entrainment and flow patterns were noted. The test was photographed.

The above procedure constituted one data set. It was repeated for different combinations of the independent study variables.

Standing Wave Enhancement Study

Apparatus

Same as for the baffle orientation study.

Methods

A hydraulic appurtenance designed to turn the flow momentum towards the surface to enhance the standing wave was developed using a trial and error methodology. The procedure was to design and construct the device, and then test it in the flume. The effect on the standing wave and general flow patterns were observed, and flow velocities were measured (electromagnetic flow meter). If necessary, refinements were made and the device was retested.

Efforts were made to determine the location (XFB) of the device, as measured downstream from the weir bulkhead, that provided the best operating conditions over a range of discharges.

Field

Johns Creek Tests

Facility

The Johns Creek facility is located near Shelton, Washington, on Johns Creek, approximately 3/4 mile above saltwater (Figure 35). Johns Creek flows into the southwest reaches of Puget Sound.

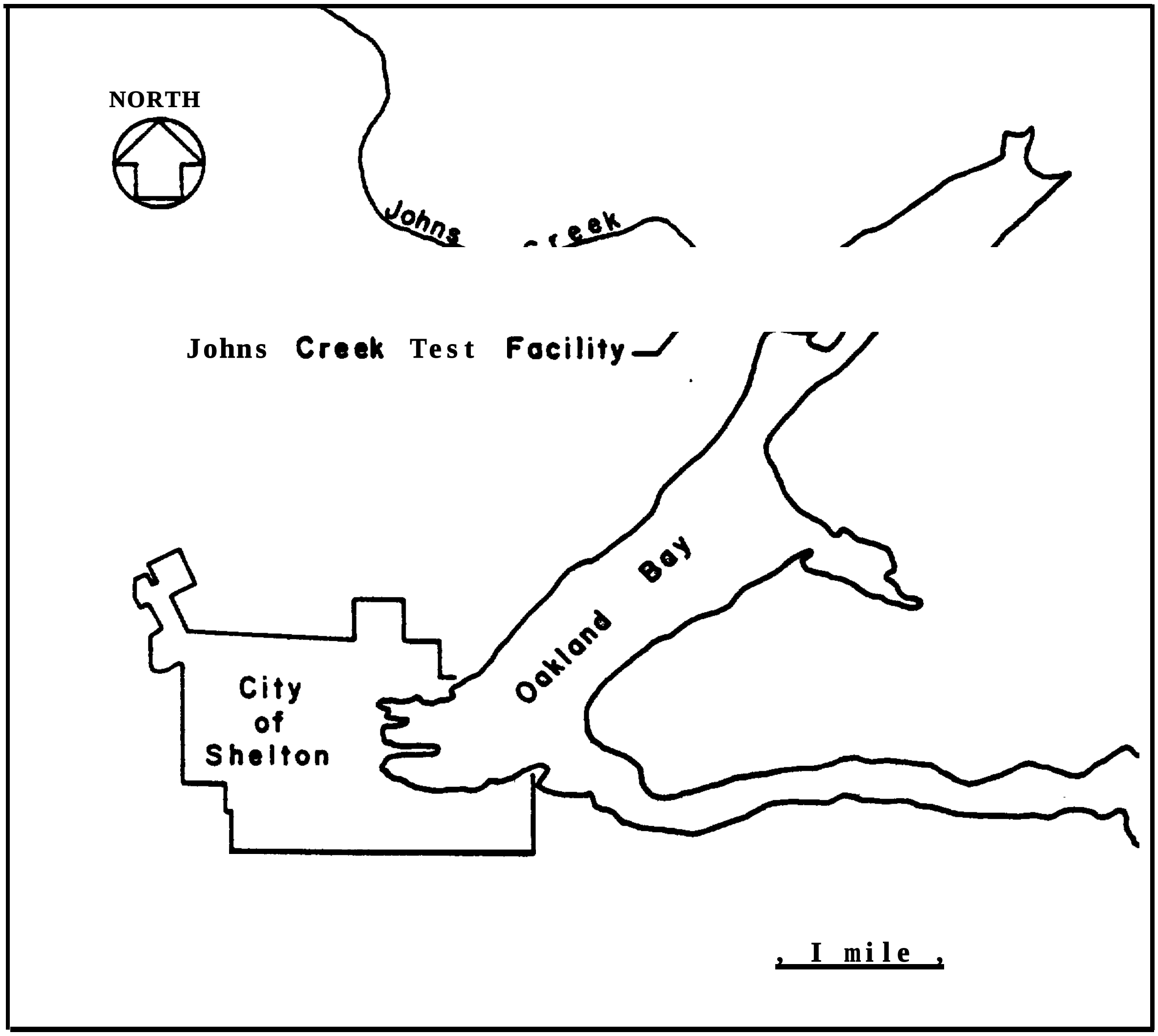

Figure 35.--Vicinity map for the Johns Creek test facility.

The facility is operated by the Washington State Department of Fisheries as a collection site for chum salmon spawners. It consists of a fish holding pond served by an alternating notched weir and pool fishladder (Figure 36). A barrier spans the creek to prevent fish from bypassing the fishladder entrance.

The fishladder consists of a concrete flume approximately 50 feet in length, constructed on a 12.5 percent slope. The flume is 5 feet wide and of variable height, increasing in the downstream direction. Vertical steel channels, spaced on 6 foot intervals, were built into the flume sidewalls to receive stoplogs. The standard fishway chamber measures 5 feet wide, 6 feet long, with a differential pool elevation of 0.75 feet (Figure 36).

The water supply originates from Johns Creek and passes through two settling ponds. Flow regulation is by a system of valves and gates.

Fish

The creek offers runs of both chum and coho salmon during the fall from about mid-September through December. Resident trout are present in the creek also.

Methods

The independent variables in the study were:

Weir Shape.--Several were tried in addition to semicircular.

Weir Size.--Varied from 16 to 24 inches in diameter.

Weir Orientation.--Several weir orientation angles were tried in addition to 45 degrees in the vertical plane.

Baffles.--Several baffle configurations were tried in addition to the configuration suggested by the baffle orientation study. Cells without baffles were also tried.

Standing Wave Enhancement Device.--Tried in several positions.

Differential Pool Elevation.--Varied from approximately 0.75 to 3.0 feet.

Figure 36.--Alternating notched weir and pool fishladder at Johns Creek.

Pool Depth.- Varied to observe the effects on fish behavior and pool hydraulics.

Pod Length.--Both 6- and 12-foot long pools were tried, as controlled by the position of bulkhead slots

Discharge.--Varied to observe the effects on fish behavior and pool hydraulics.

The procedure was to remove the existing fishladder stoplogs and replace them with new stoplogs to reduce leakage. The stoplogs were constructed of variable depths to permit flexibility in the setting of weir crest heights. The top stoplog was specially designed and fitted with a test weir. To reduce leakage further, plastic was nailed in place across the upstream bulkhead surface.

Additional fishway components to be tested, such as baffles or the standing wave enhancement device, were then positioned in the fishladder chamber as the test program required. In this manner, two or three fishladder chambers were retrofitted with test components prior to running water through the fishway.

The water supply gates were then opened, and water was started through the fishway. A waiting period followed to allow fish time to enter.

Water surface elevations, pool depths, and weir crest heights were measured with a 25-foot telescoping fiberglass rod. Flow patterns were sketched and further described with velocity measurements (electromagnetic flow meter).

Discharges were determined by measuring the head on the test weir (HWW) and referring to a stage/discharge curve which had been predetermined at Albrook Hydraulic Laboratory.

Fish holding, swimming, and leaping behavior were observed and photographed. Behavioral observations often suggested design refinements or additional tests. In this manner, the test program was developed further, and the fishway design concept evolved.

To assess the effectiveness of a particular fishway configuration, a leap success ratio was defined as the successful leaps divided by the total leaps. Successful leaps were those in which the fish passed to the upstream pool without falling back. The higher the ratio, the more effective a fishway configuration was deemed to be. Ratios were determined after classifying and tallying all the leaps that occurred in a particular fishladder chamber over some time interval. The length of the time interval depended on the activity level of the fish. It was desirable to observe a sufficient number of leaps for statistical treatment.

LABORATORY RESULTS AND DISCUSSION

Results

Preliminary Weir Tests

Main Weir Selection

Four weir shapes (Figure 20) were tested at several orientation angles (Figure 21) over discharges ranging between 0.1 and 0.2 cfs. The objective was to make a preliminary selection of a weir shape and orientation angle for further testing. The criteria were the circularity of the jet shape produced and the flatness of the stage/discharge relationship. It was reasoned that a more circular jet form would provide the most concentrated flow momentum, which would be attractive to fish. A flat stage/discharge relationship was deemed desirable because it would reduce the magnitude of changes in pool depth with changing discharge. Stuart (1962) identified pool depth as a hydraulic parameter critical to standing wave formation. Hilliard[1] selected the semicircular weir shape oriented at 45 degrees to the horizontal as best satisfying these criteria. This weir was used in subsequent laboratory and field testing with some modifications.

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[1] Hilliard, N.D. 1983. Weir optimization: A new concept in fishladder design. Senior Special Problem, Washington State University, May 26, 1983, unpublished.

Weir Training Wall Effects

A summary of the combinations of the skew angles (Figure 28), lean angles (Figure 29), and discharges that were tested appear in Table 6. The objectives were to determine the skew and lean angles that maximized the circularity of the jet produced by the semicircular weir oriented at 45 degrees, and to gain a preliminary understanding of the standing wave phenomenon.

The following trends regarding jet shape were observed:

1. the greater the discharge, the fuller and more laterally expanded the jet shape;
2. the greater the skew and lean angles of the training walls, the more irregular and dispersed the jet shape, characterized by a pronounced longitudinal expansion (i.e., roostertail) (Figure 37);
3. the less the skew and lean angles of the training walls, the more cohesive and concentrated the jet form (Figure 38).

On the basis of appearance only, it was decided that skew and lean angles of the training walls of approximately 5 and 10 degrees, respectively, produced the jet with the most circular form. The semicircular weir oriented at 45 degrees with said training walls was selected for further testing.

It was also observed that the more irregularly shaped jets appeared to entrain more air and penetrate less deeply into the receiving pool, as defined by their air-bubble plumes, than the more cohesive and concentrated jet forms (Figures 39, 40, 41, and 42).

Table 6. Summary of the combinations of the skew angles, lean angles, and discharges that were tested in the weir training wall effects study.

Skew Angle (degrees)	Lean Angle (degrees)	Test Discharges (cfs)			
		Q1	Q2	Q3	Q4
0	0	0.24	0.44	0.54	0.85
0	6	0.28	0.44	0.56	0.85
0	10	0.24	0.44	0.59	0.95
0	15	0.42	0.59	0.95	em--
0	20	0.36	0.56	----	----
5	0	0.42	0.59	0.85	----
5	a	0.42	0.59	0. a5	w-e-
5	15	0.42	0.59	0.85	-a--
10	0	0.42	0.73	--a-	----
10	20	0.42	0.73	---s	----
20	0	0.43	0.59	m-s-	----
20	10	0.42	0.61	---m	----
(No Training Walls)		0.42	0.61	----	----

Data from tests performed July 12-29, 1983, Albrook Hydraulic Laboratory, Washington State University.

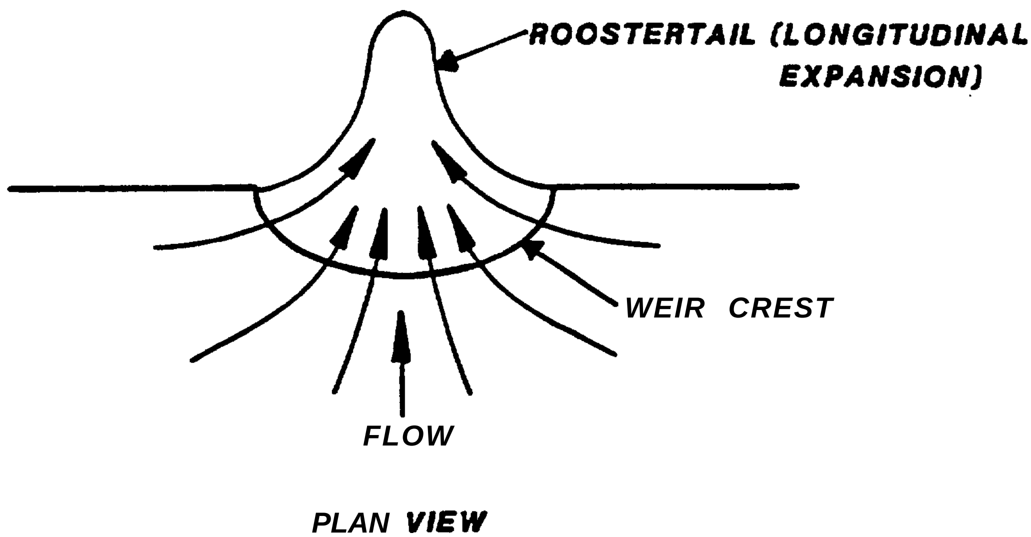


Figure 37.--Plan view of the approach flowlines to the weir without training walls. Note how flowlines converge and form a roostertail. The jet that results is irregular in shape.

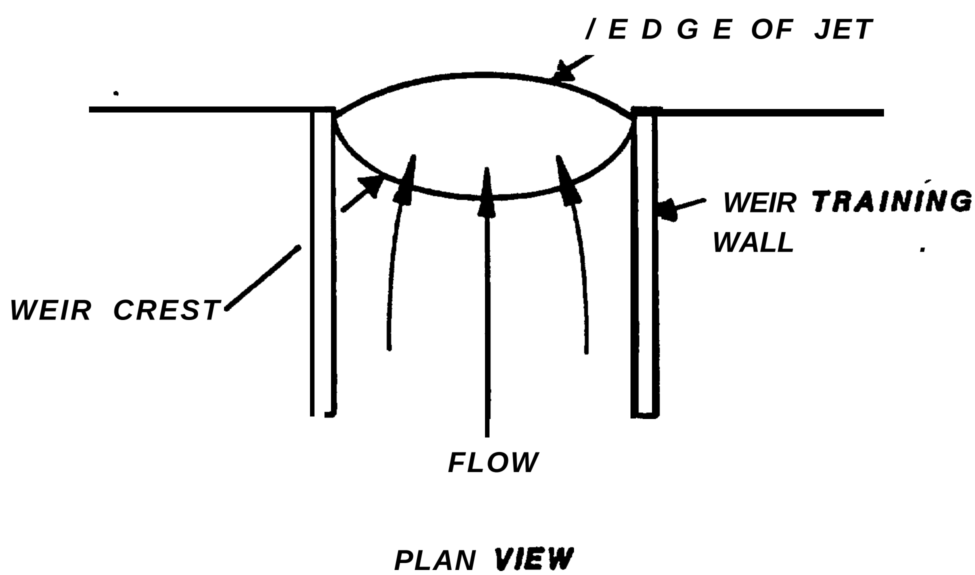
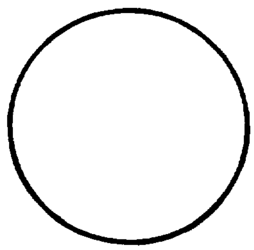
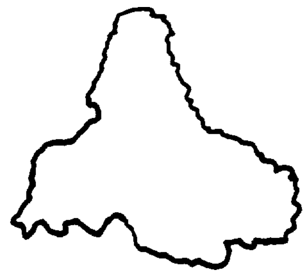


Figure 38.--Plan view of the approach flowlines to the weir with training walls. Elimination of the side flow prevents roostertail formation. A cohesive jet form results.



MINIMUM PERMETER FOR GIVEN JET CROSS SECTIONAL AREA

Figure 39 --A circular jet cross-section is theoretically the most cohesive and concentrated jet form. It entrains the least volume of air per unit discharge and penetrates deep into the recieving pool.



IRREGULAR SHAPE INCREASES PERIMETER FOR SAME JET CROSS SECTIONAL AREA

Figure 4 .--Irregular jet cross-section presents a more dispersed distribution of momentum to the receiving pool. It characteristically entrains more air and penetrates less deeply than cohesive jet forms.

Figure 41 --Side view showing the characteristic deep penetration of cohesive jet forms

Figure 42 --Side view showing the characteristic shallow penetration of irregular jet forms.

Upward velocities ranging from 1.0 to 2.0 fps were measured in the standing waves of characteristically shallow penetrating jet forms. The deeper penetrating jet forms generated upward velocity components ranging from 0.7 to 1.6 fps with average values of approximately 1.1fps.

The standing waves of the irregular jet forms were measured to be higher, and more stable than those of the more cohesive jet forms. Stability 'refers to the height and position of the standing wave. In more cohesive jet forms, the standing waves were observed to pulse in height and were relatively mobile as to position. This was less the case with the more irregular jet forms. The approximate size range of the air bubbles in the standing wave, as estimated visually through the plexiglass sidewall, was 10-50 millimeters.

Overflow Weir Effects

A summary of the combinations of the total discharge (Q), main weir discharge (QWW), and the overflow weir discharge (QOW) that were tested appears in Table 7. The objective was to qualitatively assess the relative influence of the overflow jets (Figure 24) versus the main weir jets on the pool flow patterns.

The characteristic sheet flow of the overflow jets was dissipated quickly in the receiving pool, as evidenced by the entrained air bubbles which defined the limited reach of the plunge plume (Figure 43). It was thus concluded that the overflow jets constituted a weak hydraulic subsystem. They offered an effective method of wasting water in a manner unobtrusive to the overall pool hydraulics. For this reason, it was also concluded that the overflow jets would not be competitive with the more concentrated flow momentum of the main weir jet for fish attraction.

Table 7. Summary of the combinations of the total discharge (Q), central weir discharge (QWW), and the overflow weir discharge (QOW) that were tested in the overflow weir effects study

Q (cfs)	QWW (cfs)	QOW (cfs)	QWW/QOW
0.82	0.75	0.07	11.0
0.99	0.46	0.53	0.87
1.57	1.15	0.42	2.7
2.38	1.38	1.00	1.38

Data from tests performed August 1 and 2, 1983, Albrook Hydraulic Laboratory, Washington State University.

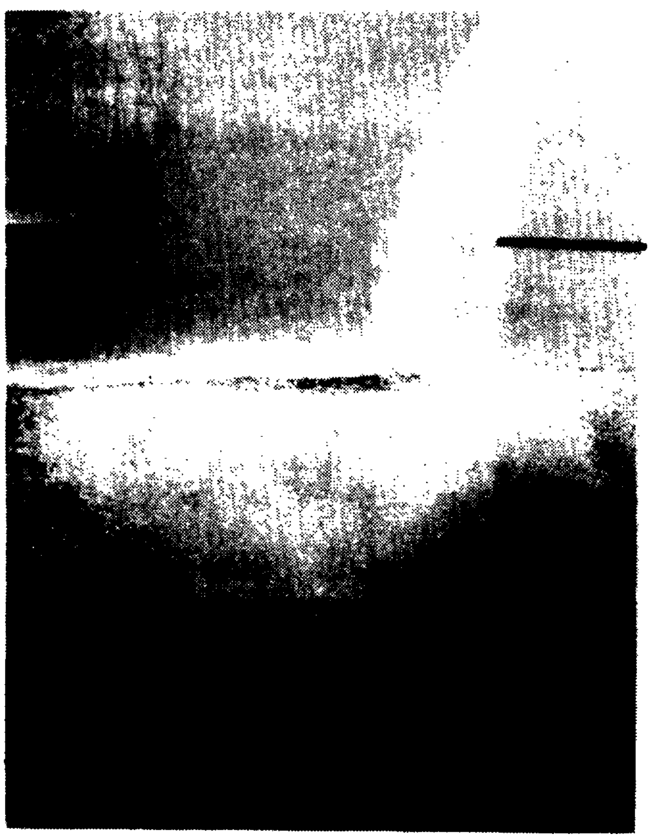


Figure 43.--Side view of overflow plunge plume. Note the limited penetration of the air-bubble plume into the receiving pool.

Baffle Orientation Study

A summary of the baffle orientation study appears in Table 8. The flow characteristics that the baffles influenced directly were the presence of upwelling or return eddies in the pool downstream of the baffles (Figures 44 and 45). For each location (XB) of the baffles, there was a particular orientation angle (θ) which divided the flow such that neither pronounced upwelling nor return eddies occurred. The angle which produced this neutral pool condition was considered the optimal orientation angle corresponding with the given location (XB).

Table 8. Summary of the baffle orientation study.

Distance from weir bulkhead (XB) to baffle point of attachment on chamber sidewall (ft.)	Baffle angle with chamber sidewall (θ) (degrees)	Upwelling along chamber sidewall downstream of baffle	Eddy along chamber sidewall downstream of baffle	Angle θ corresponding to distance XB which produces nearly neutral (no strong upwelling or return eddies) pool conditions downstream of baffle along chamber sidewall (degrees)
6.6	50	Yes (weak)	Yes (weak)	50
7.1	45	Yes (weak)	Yes (weak)	45
7.6	40	Yes	No	
7.6	45	No	Yes	42.5
8.1	35	Yes	No	
8.1	40	No	Yes (weak)	37.5
8.6	30	Yes	No	
8.6	35	No	Yes (weak)	32.5

From tests performed July 11 to August 2, 1983, Albrook Hydraulic Laboratory, Washington State University.

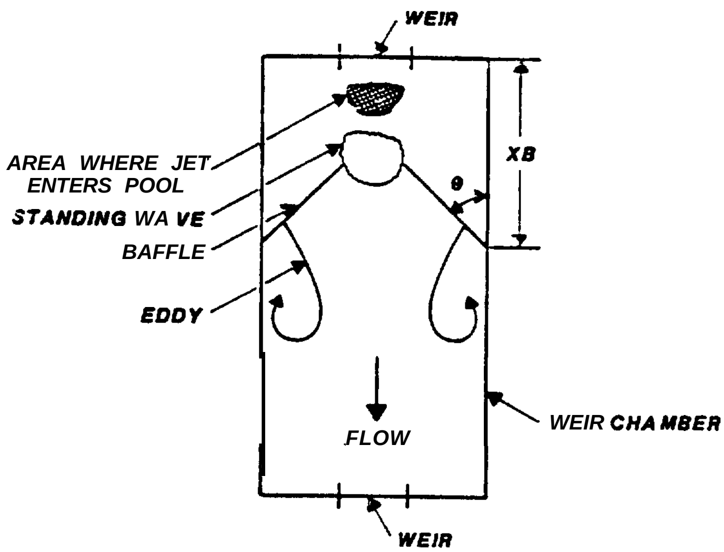


Figure 44.--Plan view of model fishway cell showing the characteristic eddies which occurred downstream of the baffles when the baffle angle θ was more than the optimal orientation angle (tank size is 8 x 15 feet).

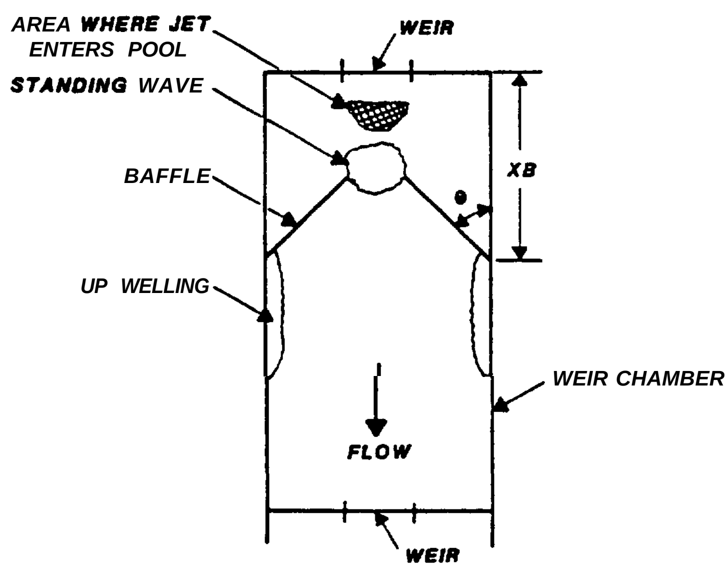


Figure 45.--Plan view of model fishway cell showing the characteristic upwelling which occurred when the baffle angle θ was less than the optimal orientation angle.

From the table it is clear that a trend exists. The further downstream (increasing XB) the baffles were located, the less the optimal orientation angle became. A plot of these baffle settings (XB and θ) reveals that the planes of the baffles, if extended towards the jet, intersect approximately just downstream of the lead edge of the jet as it enters the pool (Figure 46). This observation can serve as a guideline for preliminary baffle location in future designs.

In selecting the one best baffle setting (XB and θ), the use of the baffles as a fish guide was considered. With the objective of guiding the fish expediently and directly to the standing wave, the baffle setting of XB = 7.1 feet and $\theta = 45°$ was selected. At this setting the baffles have the desired relative position with respect to the standing wave.

Standing wave heights (SWH) and vertical velocities (VSWY) were measured to determine if the baffles influenced the standing wave flow circulation. Two conclusions were reached from this analysis. The first conclusion was that the measured values of SWH were poor indicators of VSWY. This was because much of the standing wave height was attributed to air being vented at the surface. It was not a direct function of velocity head being converted to potential head.

The second conclusion was that although the baffles do not enhance the standing wave at any particular setting, they do have the potential to weaken the standing wave circulation. This occurred at the larger values of θ, where increased volumes of water were detained in the pool upstream of the baffles, creating strong upwelling at the sides of the pool. The surface currents emanating from the upwelling on each side of the standing

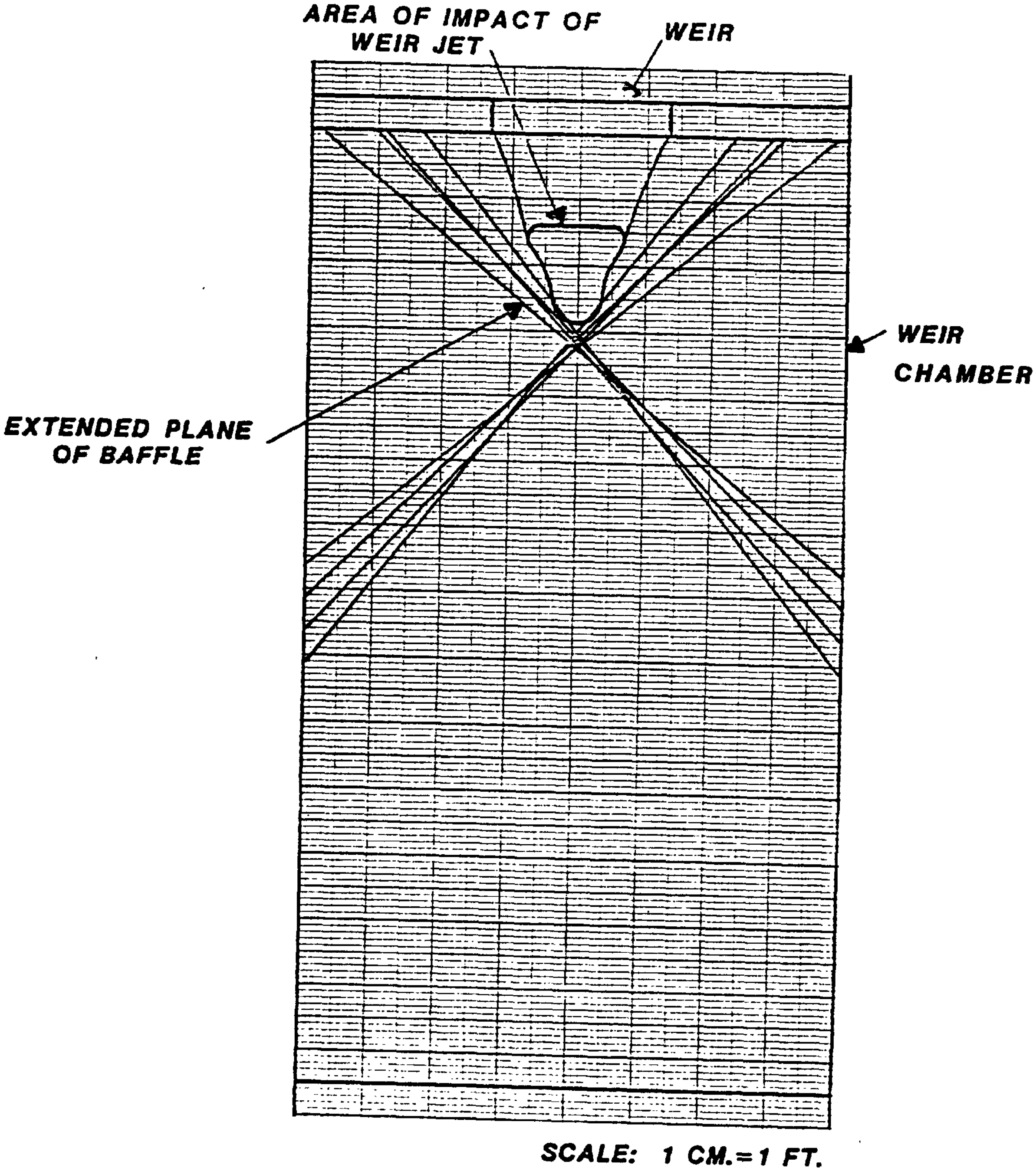


Figure 46.--Plan view of fishway cell with planes of optimal baffle settings extended. Note common intersection zone immediately downstream of jet entrance into receiving pool.

wave was of sufficient strength to shear the standing wave between them (Figure 47).

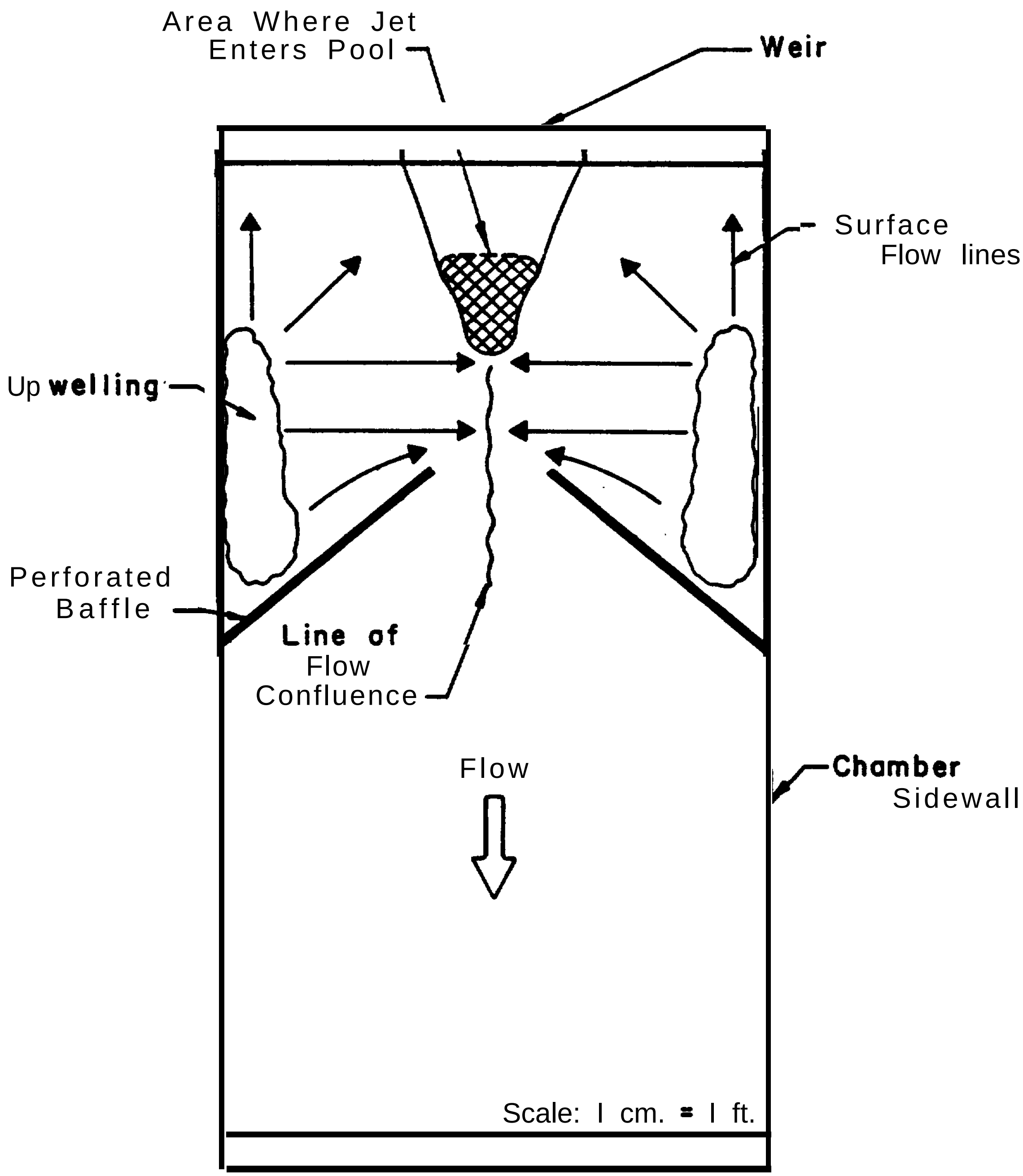
In the best appearing standing waves VSWY ranged from 0.5 to 1.5 fps with an average value of approximately 1.1 fps.

Pulsing of the standing waves was observed for all baffle settings. It was noted while making Secchi disk measurements that readings were less for high standing wave cycles than for the lower standing wave cycles.

Secchi disk measurements proved futile for comparative analysis of water visibility or air concentration. The values obtained were similar for all the tests and no significant differences were detected. The dynamic nature of the pool hydraulics made measurements difficult. The range of mean readings vertically into the standing wave was 0.5 to 0.8 feet. Through the horizontal plane, one foot below the water surface and adjacent to the standing wave, the range was 1.9 to 2.6 feet. Measurements downstream were less meaningful. Most of the air had vented to the surface so these readings were primarily an indicator of water transparency. The vertical reading was limited by the pool depth (3.44 feet) in all but a few cases. The horizontal visual measurements ranged from 4.0 to 5.3 feet.

Measurements of flow velocity indicated that virtually the entire pool downstream of the baffles was satisfactory resting area for fish. Velocity measurements ranged from approximately 0 to 2.0 fps, with local higher velocities near the bottom center of the pool just downstream of the baffles (Figures 48 and 49).

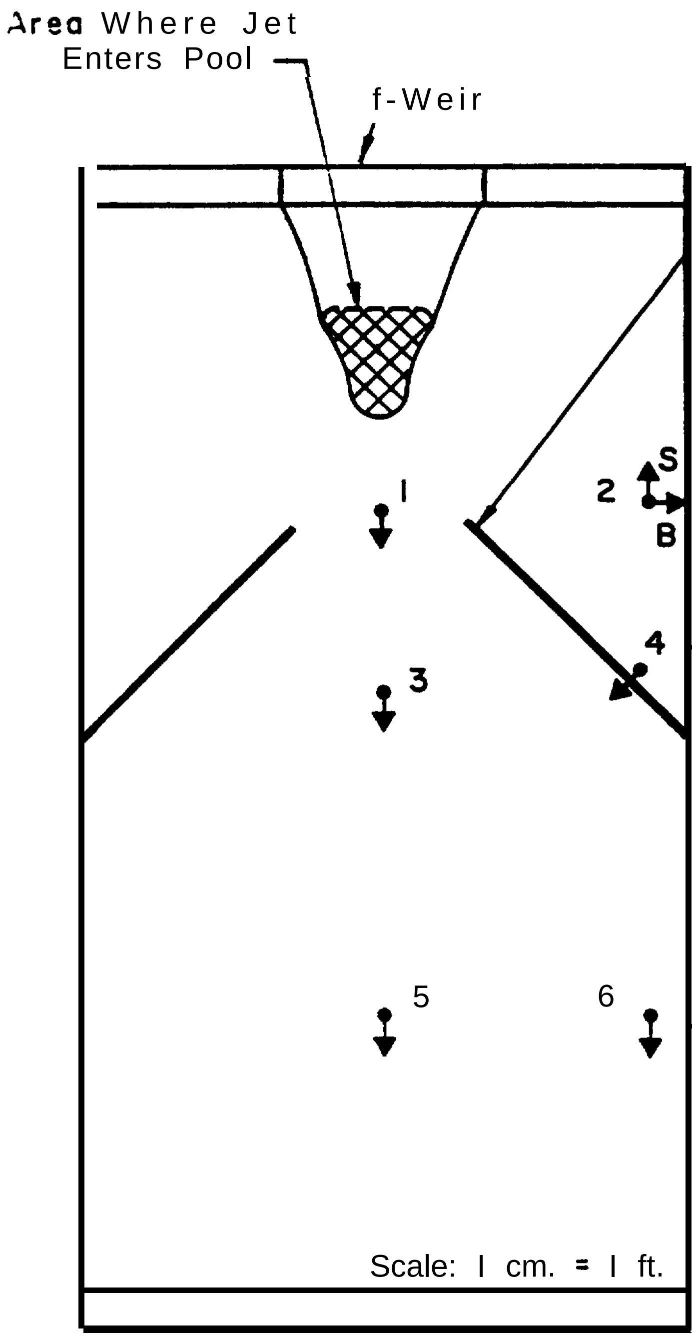
In an effort to view the flow patterns from a fishes perspective, a diving mask was donned and the observer entered the test chamber. Flow patterns wereobserved of the optimal baffle setting and also the no baffle



Arrows indicate direction of flow.

PLAN VIEW

Figure 47.--Plan view of flow pattern when baffles are set at an angle larger than optimal. Note how surface flow from upwelling converges to shear standing wave in center.



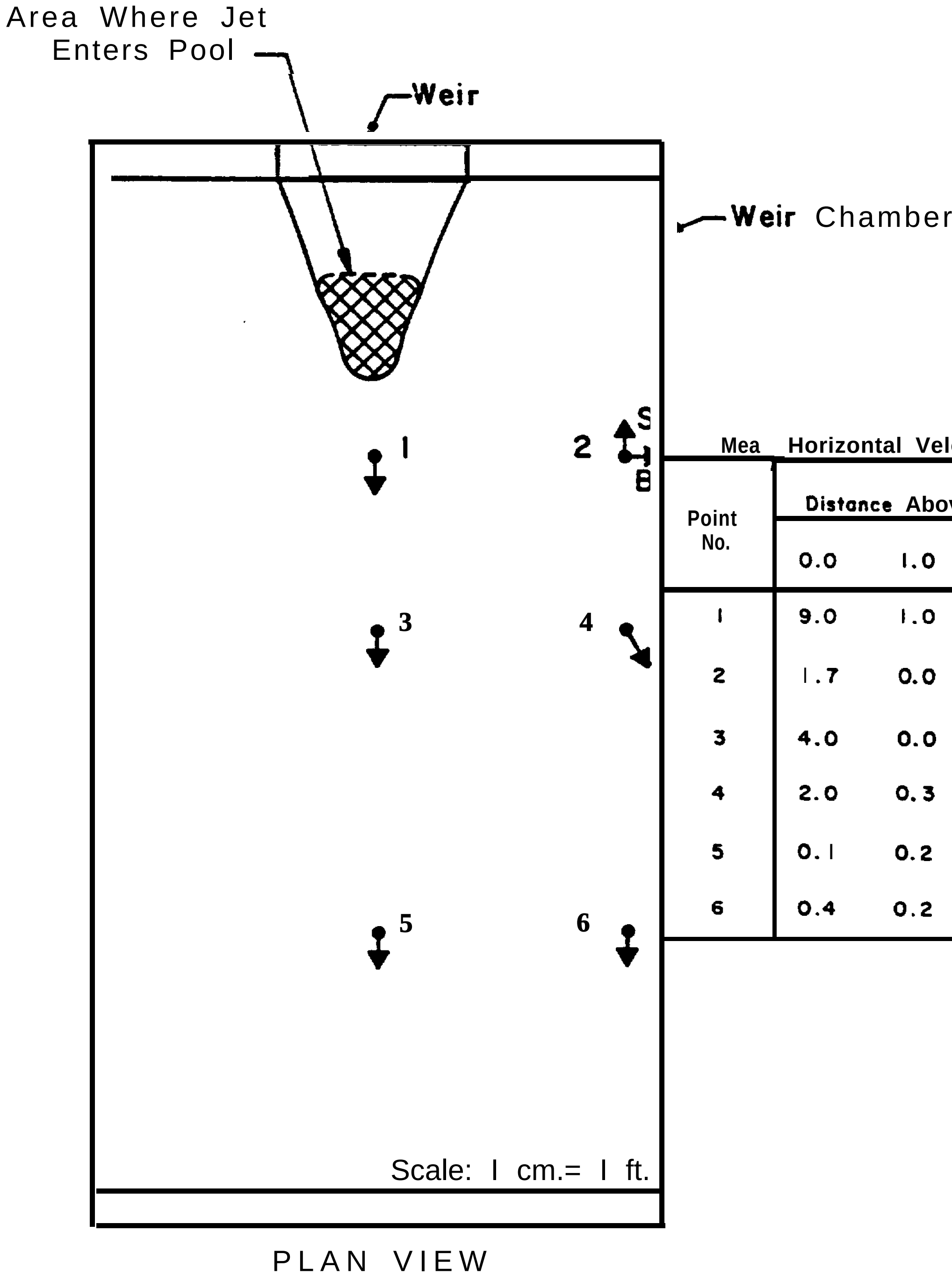
PLAN VIEW

Point NO.	Mean Horizontal Velocities (fps) — Distance Above Bottom (ft) 0.0	1.0	1.7	3.4
I	5.9	3.0	0.5	0.0
2	2.7	-	-	0.7
3	5.0	0.0	0.0	0.9
4				I.9[1]
5	0.2	0.5	0.3	0.4
6	0.4	0.5	0.5	0.3

[1] Point No. 4 was measured in a 3 inch diameter baffle hole at the surface.

Pool was 3.4 ft deep.
S = surface of pool.
B = bottom of pool.
Arrows indicate direction of flow.

Figure 48.--Mean horizontal velocities for the trial with XB = 7.1 feet and θ = 45 degrees.



Point No.	Mea Horizontal Velocities (fps)			
	Distance Above Bottom (ft)			
	0.0	1.0	1.7	3.4
1	9.0	1.0	0.0	0.0
2	1.7	0.0	0.0	–
3	4.0	0.0	0.0	0.4
4	2.0	0.3	0.0	0.0
5	0.1	0.2	0.2	0.3
6	0.4	0.2	0.0	1.2

PLAN VIEW

S = surface of pool.
B = bottom of pool.
Pool was 3.4 ft. deep.
Arrows indicate direction of flow.

Figure 49.--Mean horizontal velocities for the trial without baffles.

baffle codition (Figures 50, 51, 52, and 53). Without baffles, the visibility was poor due to entrained air, the flow patterns appeared wild, and the overall impression to the diver was one of disorientation. With baffles, visibility was good moving upstream to the standing wave. The flow path was relatively simple and uniform, and the baffles served to funnel the diver directly to the standing wave.

Standing Wave Study with a Nozzle

Summaries of the results of nozzle angles of 45 and 70 degrees and a depth of 1.4 feet appear in Tables 9 and 10, respectively. The results obtained for a depth of 1.2 feet were not significantly different.

The vertical velocities measured in standing waves when air was entrained (nozzle above water surface) were significantly higher than those for the submerged jet (height of nozzle = 0). In fact, when the jet was submerged, the standing wave as described by Stuart (1962) was not present (Figures 54 and 55). It was thus concluded that the principal mechanism of the standing wave is the buoyancy of entrained air.

Standing Wave Enhancement Study

A standing wave enhancement device (SWED) was constructed and floor-mounted in a position to direct the plunging get towards the surface (Figures 56, 57, 58, and 59). Tests were conducted using a semicircular weir (32-inch diameter), oriented 45 degrees from vertical, downstream, about a horizontal axis perpendicular to the flow. Weir training walls with 4-inch diameter rounded entrances were attached adjacent to the weir opening at skew and lean angles of 5 and 10 degrees, respectively. The discharge was 3.6 cfs and the tailwater depth was constant at 3.44 feet.

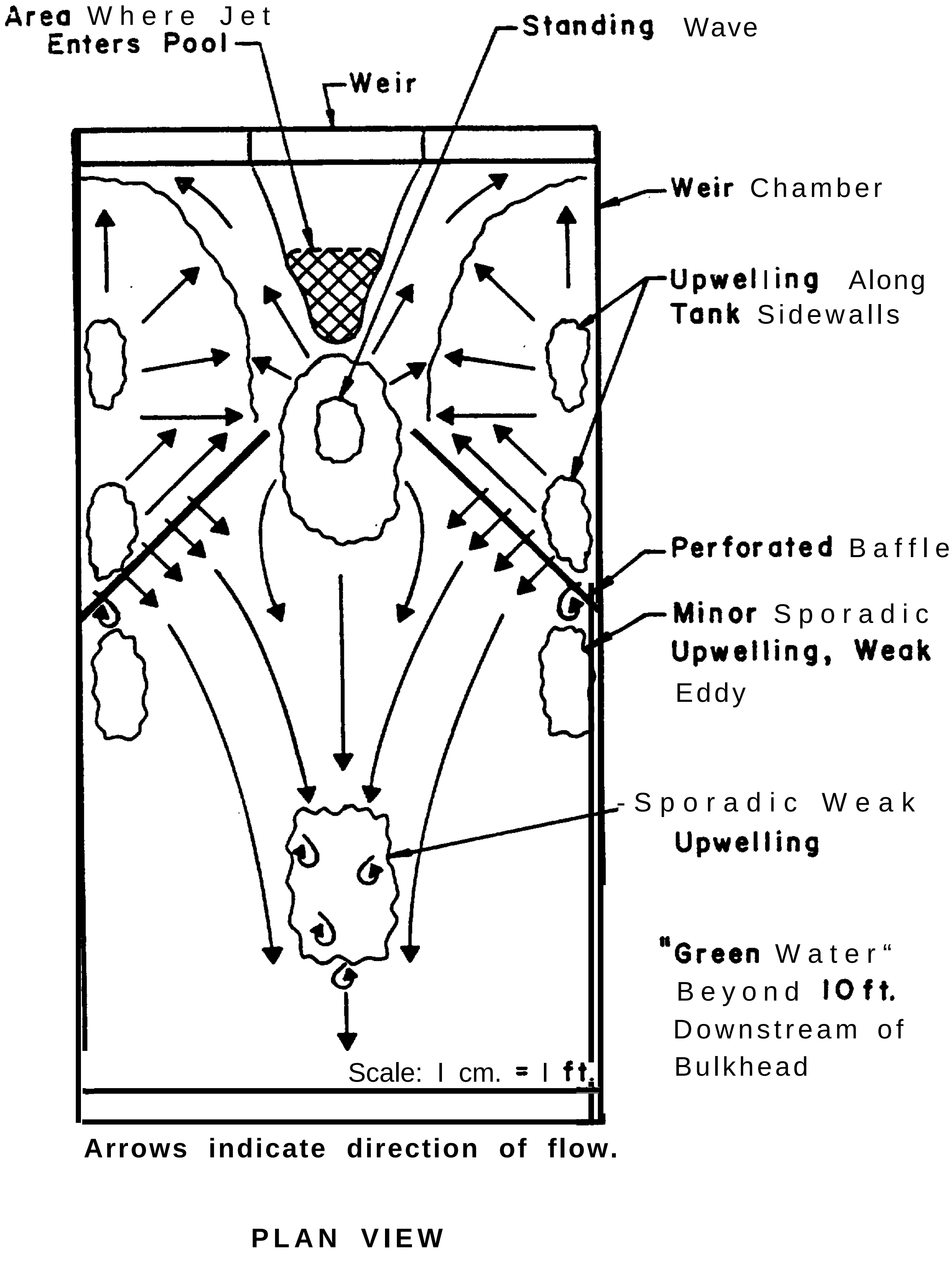


Figure 50.--Plan view of the surface flow patterns for the trial with XB = 7.1 feet and θ = 45 degrees.

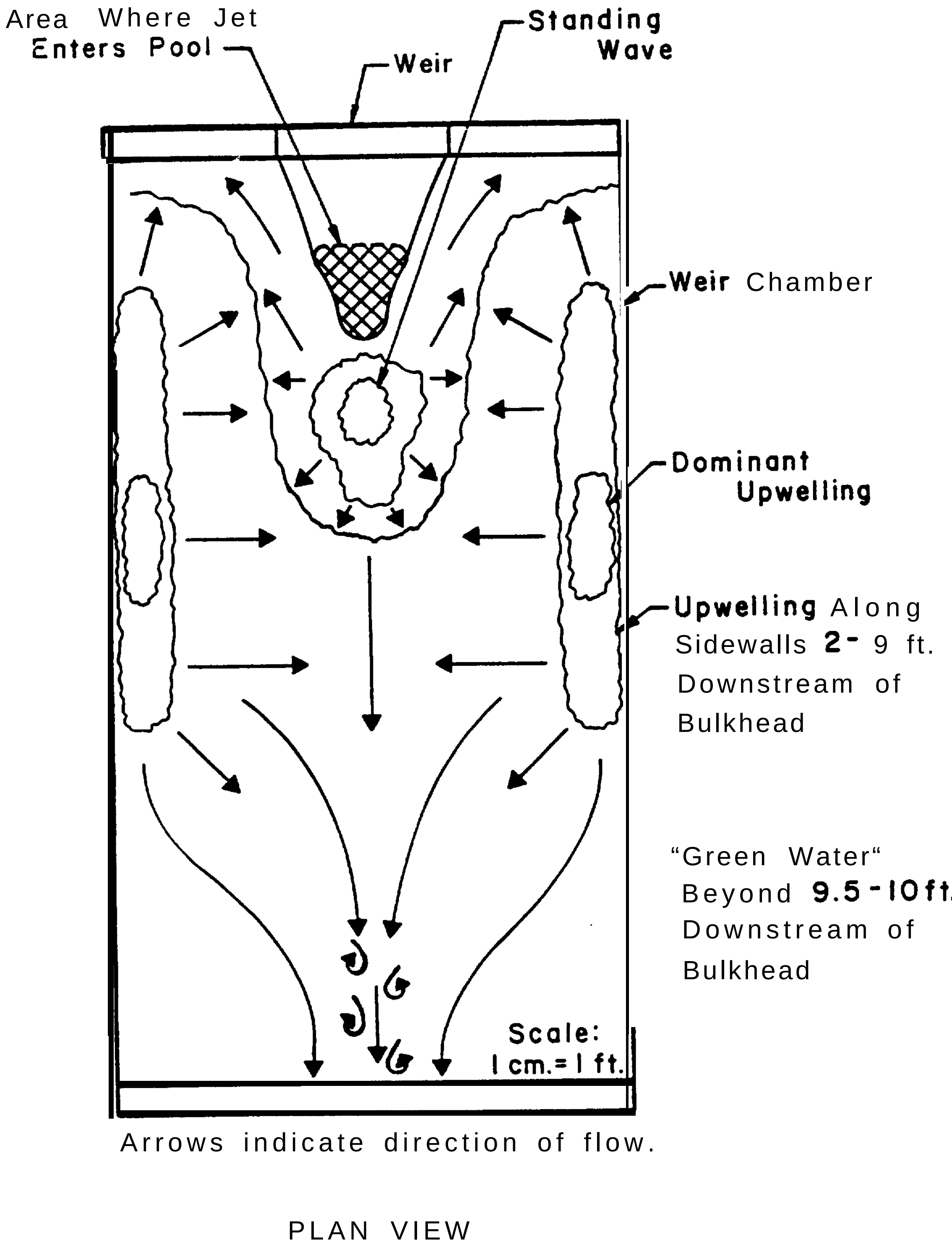


Figure 51.--Plan view of the surface flow patterns for the trial without baffles.

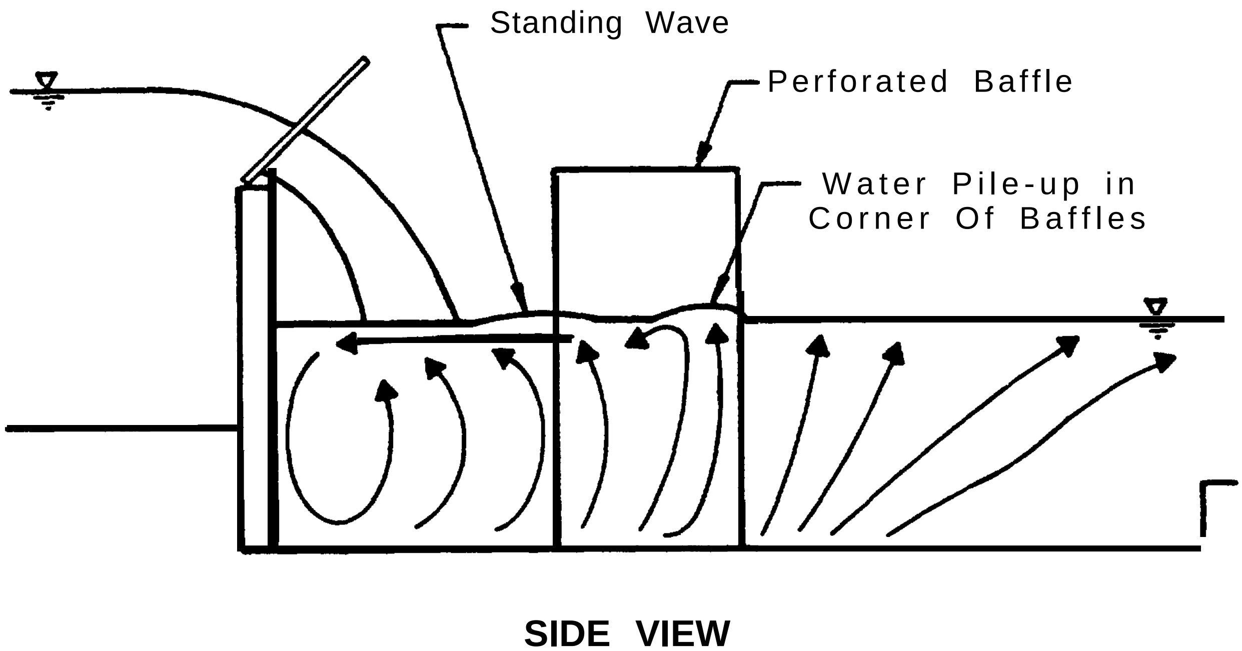


Figure 52.--Side view of the flow patterns for the trial with X6 = 7.1 feet and θ = 45 degrees.

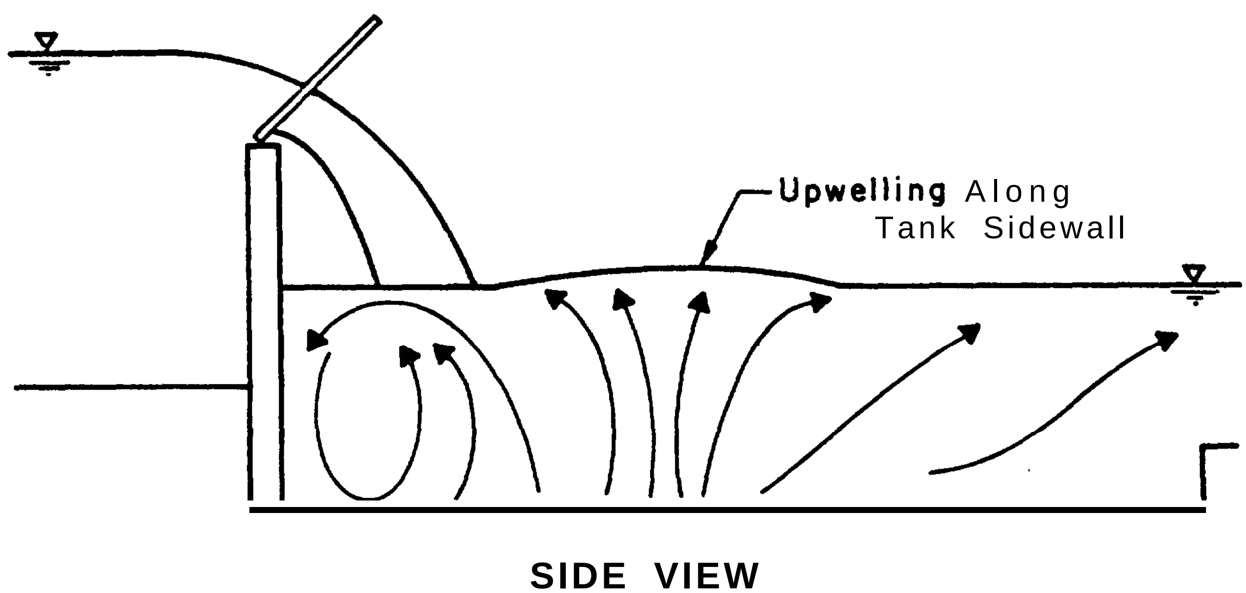


Figure 53.--Side view of the flow patterns for the trial without baffles.

Table 9.--Summary of the Standing Wave Study for a 45 degrees and a pool depth of 1.4 feet.

Tank Width (ft)	Height of Nozzle (ft)	Initial Jet Velocity (fps)	Maximum VSWY[1] (fps)	Maximum VHS[2] (fps)
1.00	0.00	4.1	0.15[3]	0.35
1.0	0.35	4.1	0.35	0.10
0.77	0.00	4.3	0.20[3]	0.45
0.77	0.35	4.2	0.40	0.35
0.52	0.00	4.8	0.15[3]	0.60
0.52	0.35	4.0	0.40	0.45
0.27	0.00	4.6	0.80[3]	0.70
0.27	0.35	4.5	0.60	0.00

Data from tests performed February 26, 1984, Albrook Hydraulic Laboratory, Washington State University.
[1]VSWY = vertical velocity component of standing wave flow circulation.
[2]VHS = horizontal surface velocity measured adjacent to the jet.
[3]Boundary velocity at endwall of tank, not measured in a true standing wave.

Table 10.--Summary of the Standing Wave Study for a nozzle angle of 70 degrees and a pool depth of 1.4 feet.

Tank Width (ft)	Height of Nozzle (HN) (ft)	Initial Jet Velocity (fps)	Maximum VSWY[1] (fps)	Maximum VHS[2] (fps)
1.00	0.0	4.2	0.09	0.05
1.00	0.3	2.8	0.80	0.08
0.77	0.0	4.5	0.05	0.10
0.77	0.3	4.5	0.45	0.40
0.52	0.0	4.6	0.05	0.15
0.52	0.3	4.6	0.50	0.20
0.27	0.0	4.6	0.40[3]	0.40
0.27	0.3	4.6	0.80	0.00

Data from tests performed February 26, 1984, Albrook Hydraulic Laboratory, Washington State University.
[1]VSWY = vertical velocity component of standing wave flow circulation.
[2]VHS = horizontal surface velocity measured adjacent to the jet.
[3]Boundary velocity at endwall of tank, not measured in a true standing wave.

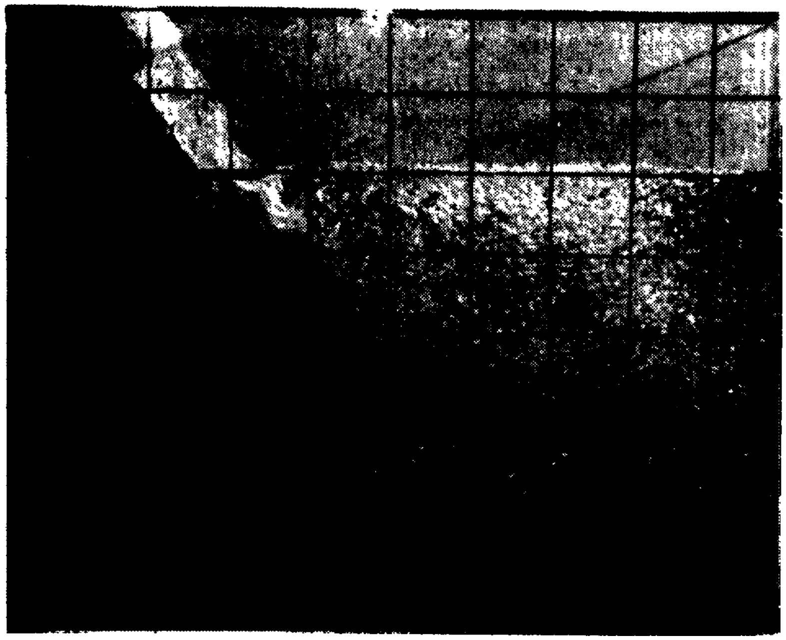


Figure 54.--Side view of the observation tank showing the standing wave for a nozzle angle of 45 degrees, depth of 1.4 feet, and width of 1.0 feet.

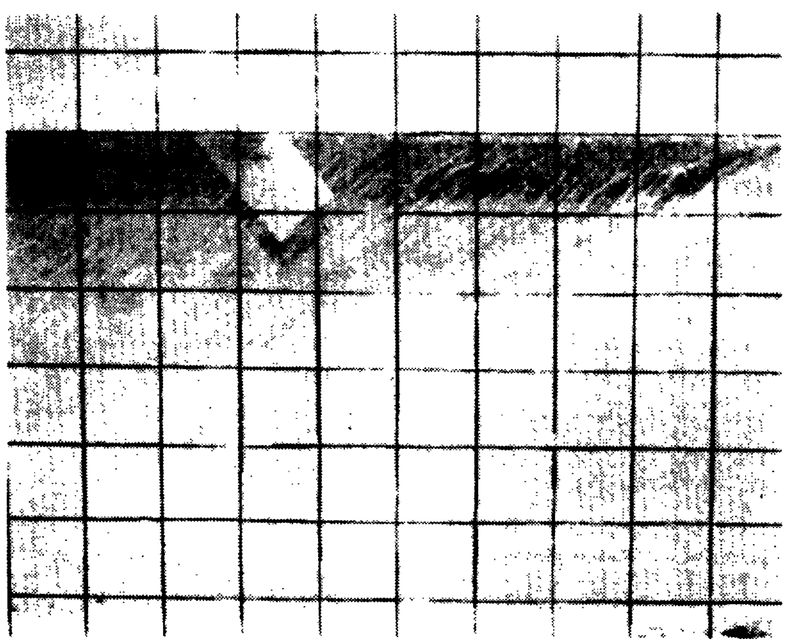


Figure 55.--Side view of the observation tank showing the absence of the standing wave when the nozzle is submerged. Nozzle angle is 45 degrees, depth 1.4 feet, and width 1.0 feet.

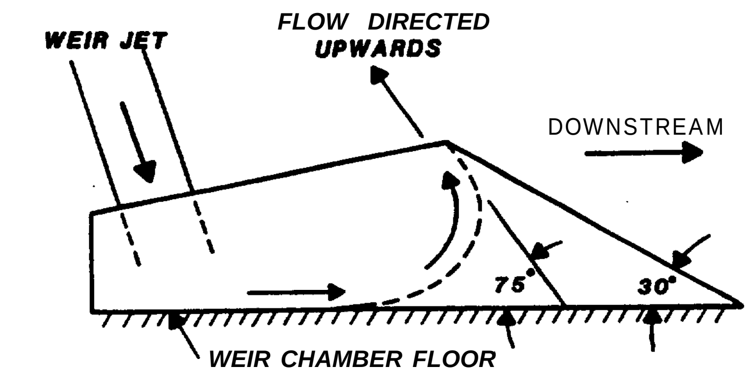


Figure 56.--Side view of floor-mounted standing wave enhancement device showing path of directed jet.

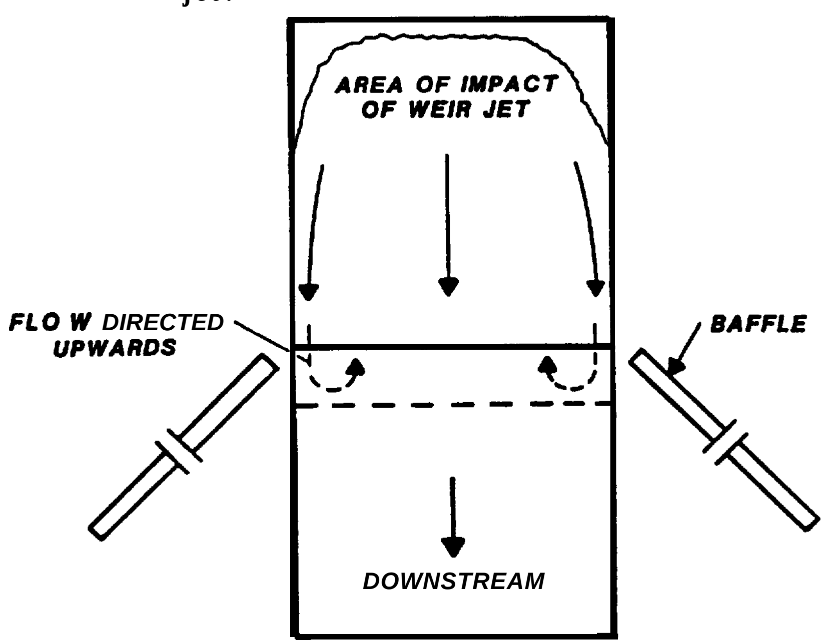


Figure 57.--Plan view of floor-mounted standing wave enhancement device showing impact area of jet and relative position of baffles.

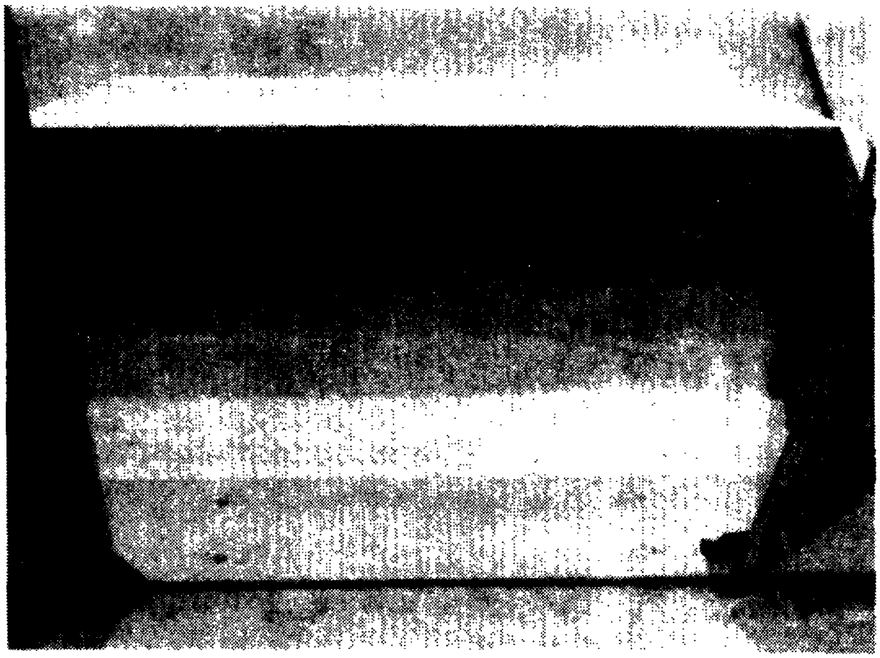


Figure .58.--Front view of initial standing wave enhancement device design looking downstream.

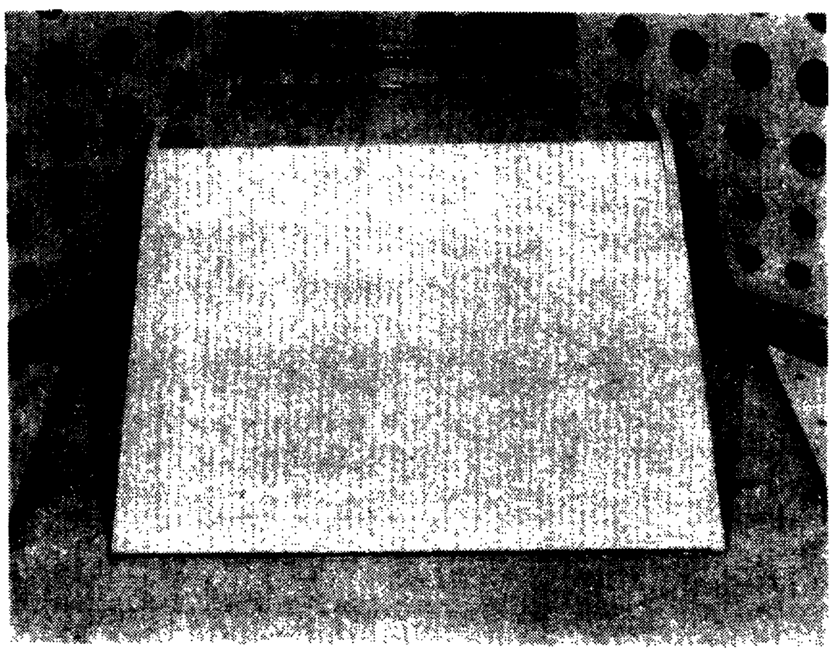


Figure 59.--Back view of initial standing wave enhancement device design looking upstream.

The results of the initial design were encouraging, but also suggested refinements. A second design was developed and constructed (Figures 60 and 61).

Testing of the second device revealed that it was possible to enhance the standing wave. In combination with baffles, a standing wave was produced with a VSWY of 5.5 fps (Figures 62 and 63). The SWED was located (XFB) 4.3 feet downstream, as measured from the weir bulkhead to the upper edge of the SWED flow turning vane.

An additional benefit from the SWED was a general improvement in the pool hydraulics. The SWED effectively contained and directed the entire jet plume to the surface in the form of the standing wave. It amounted to an intense local hydraulic condition with the surrounding waters remaining relatively quiet.

Additional testing revealed a couple of problems with the SWED. The first was that the operational flow range of the SWED was limited (up to 4.5 cfs) by movement of the weir jet downstream with increasing discharge. This caused increasing interference with the upward direction of the SWED jet, until eventually the action was reversed and a standing wave formed at the surface upstream of where the jet entered the pool (Figure 64). It was demonstrated in the laboratory that this situation could be corrected with the addition of a jet deflecting vane mounted just below the surface of the pool (Figure 65). The effective operational range of the SWED was thus extended to 6.0 cfs. The practical concern of fish striking the deflecting vane precluded further consideration of this solution, however.

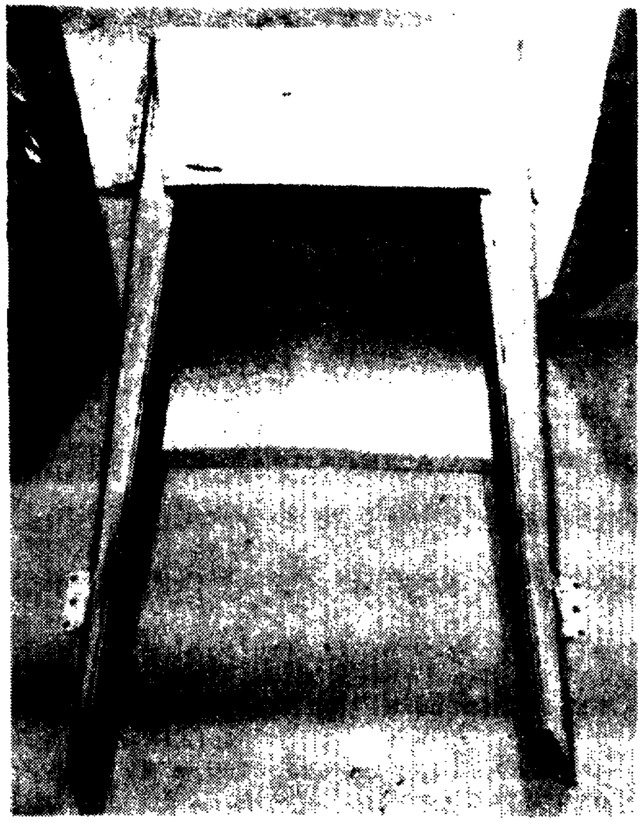


Figure 60.--Front view of the improved standing wave enhancement device design looking downstream.

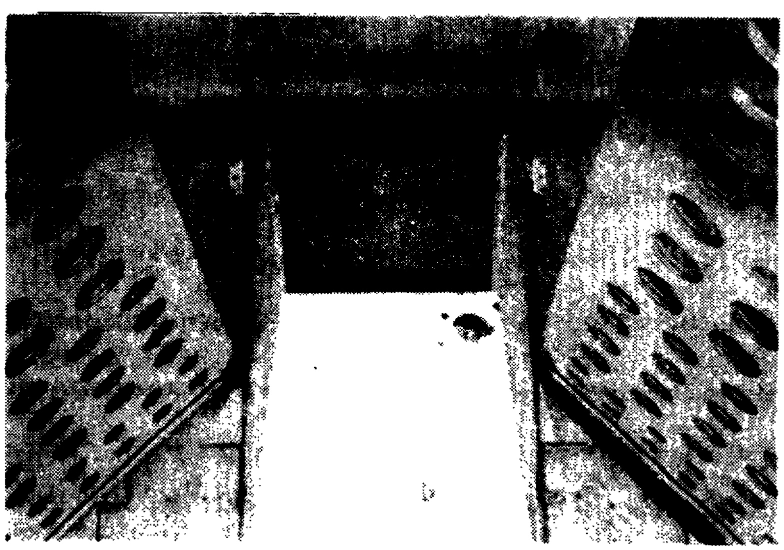


Figure 61.--Top view of the improved standing wave enhancement device design looking upstream.

Figure 62.--The enhanced standing wave developed using the standing wave enhancement device.

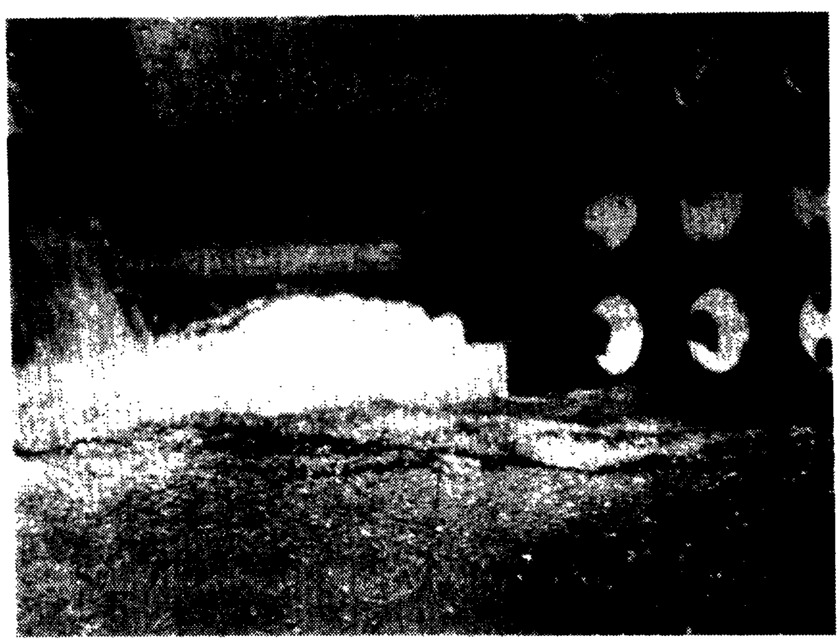


Figure 63.--Side view of the enhanced standing wave developed using the standing wave enhancement device. Note its position relative to the baffles.

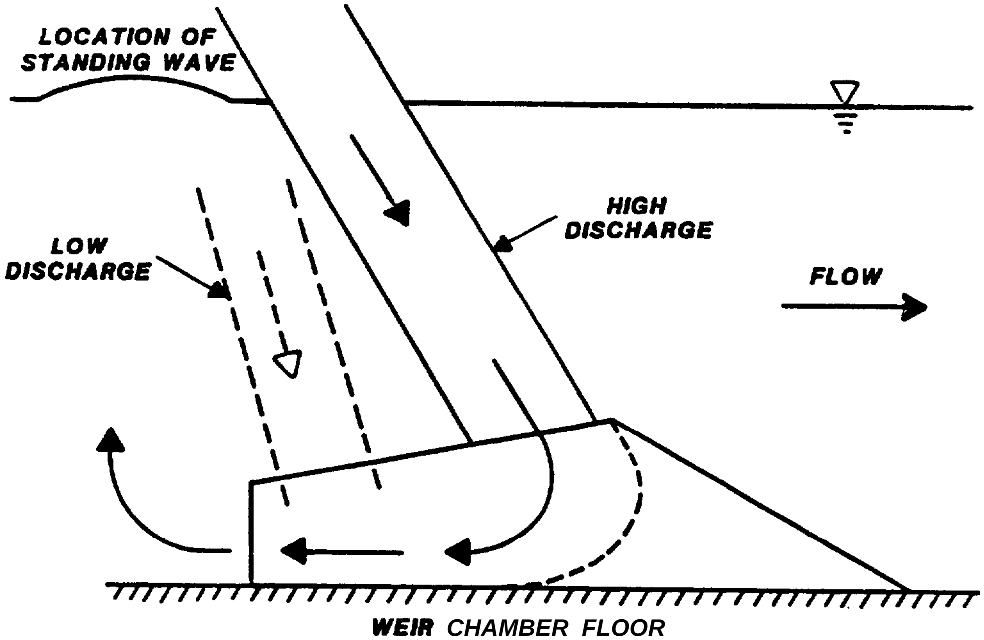


Figure 64.--Side view of standing wave enhancement device showing reversal of flow direction with increased discharge.

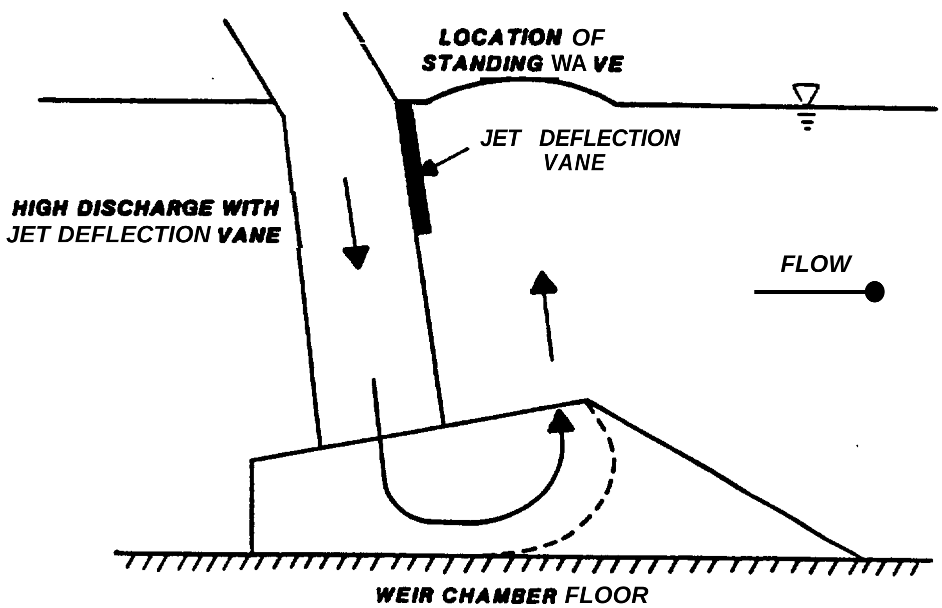


Figure 65.--Side view showing how jet deflection vane corrects the flow direction in the standing wave enhancement device at a high discharge.

Another problem associated with the SWED was related to the strength of the enhanced standing wave. Surface waves in the pool, which originated from the enhanced standing wave, were reflected off the tank sidewalls and returned to reduce the stability of the standing wave.

Discussion

Standing Wave Mechanics

The jet theory discussed in Chapter 3 provides an adequate explanation for the air entraining characteristics of different jet shapes. The fact that jets described as irregular in shape (smaller hydraulic radius [R]) entrained more air and penetrated less deeply into the receiving pool than more cohesive (larger R) jet shapes was predictable. The theory also provides insight into why the more irregular jet forms were observed to produce 'higher and more stable standing waves.

In the standing wave study it was shown that the mechanism for standing wave formation was entrained air. In the baffle orientation study it was shown that the measured standing wave heights were not indicative of vertical velocity components, but were a function of air being vented at the pool surface. It follows that if one jet form was entraining more air than one of another form,it would be expected to have a higher measured standing wave height.

As for stability, the jet penetration distance is partially a function of the amount of air entrainment. Recall that the buoyant force of entrained air was shown to dissipate jet centerline velocities (Anderson, 1968). Thus the air-bubble plumes of irregular jet forms would be expected to have higher air concentrations than more cohesive jet forms for two reasons: (1) greater air entrainment at the jet/pool interface, and (2) less spatial dispersement. It is reasonable to presume that the higher air concentrations of such bubble plumes would vent air to the surface more regularly (i.e., better standing wave height stability) than less concentrated air-bubble plumes. In short, high air concentration bubble plumes constitute a more homogeneous hydraulic condition.

The position of the standing wave would also be expected to be more stable for the higher air concentration plumes. One reason already mentioned is that they are simply less spatially dispersed. Perhaps more important, however, is that the large volume of air bubbles in the shallow plume presents a strong collective flow condition that dominates surrounding flow patterns. The position of the standing wave would thus be less susceptible to influence from extraneous transient flow patterns, such as surface waves reflected off the tank sidewalls.

It seems intuitive that similar reasoning could be used to explain why higher vertical velocities in the standing wave were measured in the shallower air-bubble plumes than in the deeper ones. Higher concentrations of air-bubbles represent a greater buoyant force which would induce greater vertical flows. This may be true, but the velocity of the induced flow is intrinsically related to the terminal velocity of the air-bubbles. The terminal velocity of the air-bubbles is in turn related to their size (Figure 66). Thus, an increased concentration of air-bubbles does not necessarily indicate increased air-bubble size and corresponding increased vertical velocities. Consideration must be given to bubble dynamics and the subject flow field.

The mean bubble size in flowing water is determined primarily by the shearing stresses within the fluid (Falvey, 1981). The processes which

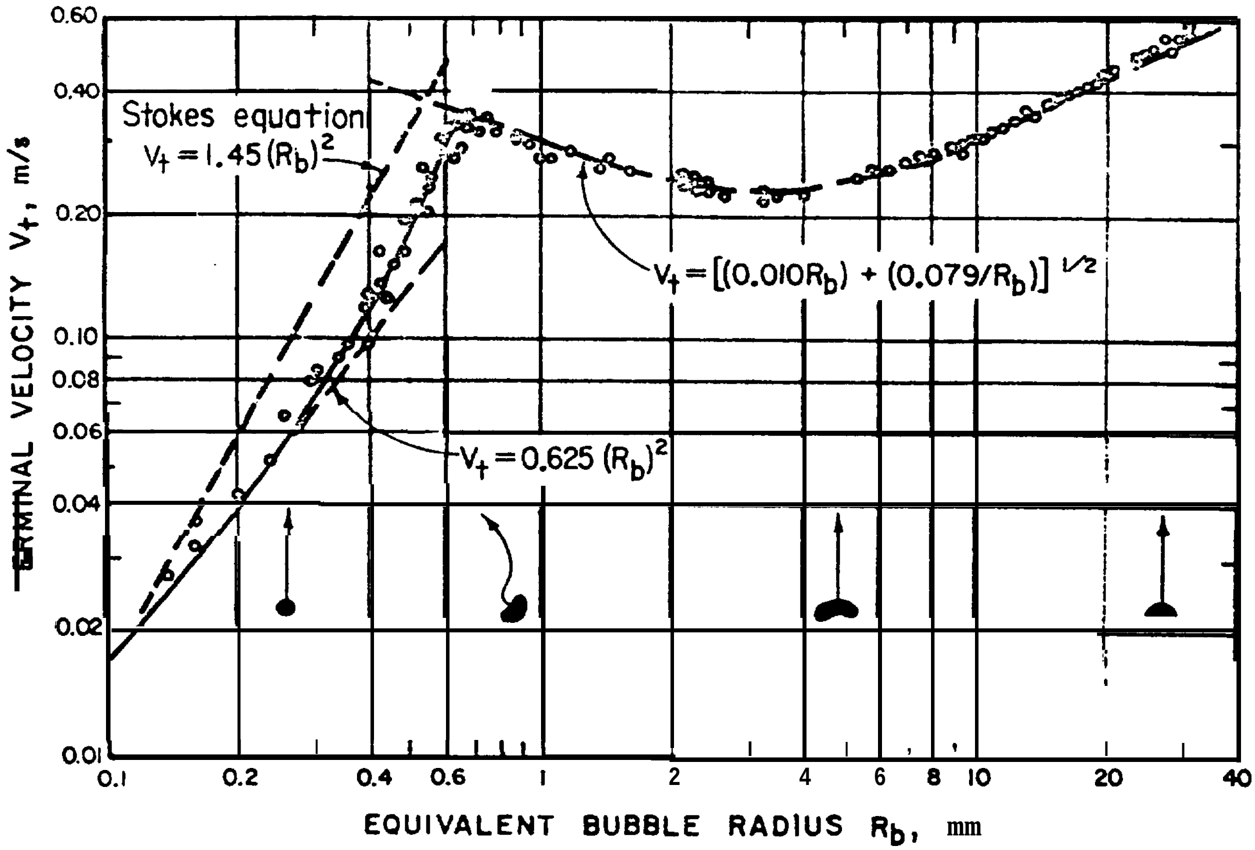


Figure 66.--Terminal velocity of air-bubbles in filtered or distilled water as a function of bubble size (after Haberman and Morton, 1953).

occur are dynamic and can be described as follows. The first process is termed agglomeration and involves the coalescence of smaller bubbles into larger bubbles as they come into contact in the flow field. This action can be visualized as bubbles come together, thus growing larger, as they float towards the surface. The second process, termed fracture, occurs as larger bubbles are torn into smaller bubbles by the turbulence of the flow field. Both processes occur simultaneously and given time and space a critical bubble size will be reached which represents a balance between surface tension forces and fluid stresses.

Higher air concentration plumes would have a greater tendency towards agglomeration than the lower air concentration plumes. Agglomeration causes the formation of larger bubbles and corresponding larger measured velocities of the induced vertical flow. It should be noted that the terminal velocities of the air bubbles observed (10-50 mm in diameter) in the plumes in the laboratory are very close to the measured vertical velocities of the standing wave.

Fishway Design Applications

With this understanding of standing wave (i.e., air-bubble plume) mechanics and free jet theory, fishway design principles can be developed in a new light. The fisheries applications will be considered first. They fall into three general categories: (1) hydraulic stimuli, (2) aeration, and (3) hydraulic aid.

Stuart (1962) concluded that "the maximum energy of fall, designed for the optimum stimulus for leaping, must be dissipated as nearly as possible below the point of entry in order that the uplift will be available to the fish." From free jet theory, the application would be to provide a jet with a small hydraulic radius (dispersed form). This could be accomplished with provision of the appropriate weir shape and orientation. There are a couple of other concerns that merit caution, however. The first is fish orientation and attraction. It has been demonstrated that salmonids orient themselves into the stronger flow currents (Thompson, 1970) and show preference for the higher velocities when presented with a choice (Weaver, 1963). The rapid reduction of jet centerline velocities may present orientation difficulties or encourage lingering because the fish will not be able to sense a strong directional flow velocity filament downstream in the pool.

The second concern is with aeration. Because there is not agreement in the literature about the effects of aeration on fish behavior, it should be noted that the dispersed jet forms do entrain more air. Practical considerations include reduced visibility, and in extreme cases, the reduced effectiveness of the fishes tail for propulsion in the rarefied air/water mixture.

That the standing wave, as described by Stuart (1962), has the potential to aid fish in their leaps, was verified by our laboratory testing. Vertical velocities as high as 2.0 fps were measured in the air-bubble plumes. A more typical value was 1.6 fps. The possibility of a fish taking advantage of this upward current is plausible on two accounts. Firstly, they have demonstrated an affinity for standing waves as take-off points in their leaps (Stuart, 1962). Secondly, the distance required for a fish to attain burst velocity is short, on the order of one body length (Paulik and DeLacy, 1957). Gray (1966) describes such leaps as "standing" jumps. This is important, because the extent of the upward current of these plumes is limited. If a fish was required to get a "running start" prior to leaping, as was once thought, it is doubtful that the upward boost could be developed to its full advantage. It would represent a fleeting hydraulic condition to the fish which required considerable time and distance to gain velocity. Summaries of the heights and energetic requirements of fish leaping from a standing wave appear in Tables 11 and 12, respectively.

Table 11.--Leap heights calculated from burst velocities for several species of salmonids.

Species	Burst Velocity (fps)	Leap Height from a Still Pool[1] (ft)	Leap Height from a Standing Wave [1,2] (ft)
Salmon		3.4	
Chum	10.6	3.8	3.8
Pink	11.3	9.3	4.3
Sockeye	20.6	10.0	10.3
Coho	21.5		11.1
Chinook	22.4	10.1	11.2
Trout			
Steelhead	26.5	13.9	15.2
Cutthroat	13.5	4.0	4.7

Burst velocities primarily from Bell (1973), Beamish (1978) and Dimeo (1977). Leap heights calculated using procedures described in Chapter 2.
[1]A leaping trajectory of 75 degrees was assumed.
[2]Assumes the complete utilization of a 1.6 fps vertical flow velocity by the fish.

Table 12.--Energy requirements for a four-pound ascending fish.

Energy Requirements	Elevation Difference Ah (ft)			
	1	2	4	6
Swim through ports (ft-lbs)[1]	7.2	14.4	28.9	43.3
Swim up a ramp 1:1 (ft-lbs)[1]	1.6	6.1	23.5	38.6
Leaping from a still pool[1,2] (ft-lbs)	5.3	10.7	21.3	32.0
Leaping from a standing wave[3] (ft-lbs)	3.4	7.9	17.3	27.0
Leaping from an enhanced standing wave[4] (ft-lbs)	0.5	2.8	9.2	16.6

[1]After Mih, W.C. 1983. A conceptual, analytical model from the energy requirements of ascending fish. Albrook Hydraulic Laboratory, Washington State University, unpublished.
[2]A leaping trajectory of 60 degrees was assumed.
[3]Assumes the complete utilization of a 1.6 fps vertical flow velocity by the fish.
[4]Assumes the complete utilization of a 5.5 fps vertical flow velocity from the SWED by the fish.

Free Jet Entrainment and Pool Depth

It is interesting that Stuart (1962) suggests that a ratio exists between the fall height and pool depth that provides the best standing wave for leaping. He identifies this ratio as a depth equal to 1.25 times the fall height, where the fall height is the distance from the weir crest to the pool surface. He states further that "if the pool was too shallow the force of the downward jet caused the current to splay outwards along the base; if too deep, the force was dissipated some distance from the base."

It is clear from free jet theory that Stuart's suggested ratio of 1.25:1 has no basis for general application. This was confirmed in the laboratory where it was demonstrated that the character of the standing wave was more closely related to jet shape. Horn-ma (1953) conducted experiments on free jets from a circular nozzle and, as a result, suggested the following equations to describe the centerline velocity dissipation.

$$Re < 25{,}000 \qquad \frac{V_m}{V_o} = 1.24\ e^{-0.109Y/d}$$

$$Re > 30{,}000 \qquad \frac{V_m}{V_o} = 1.24\ e^{-0.137Y/d}$$

where

V_m = jet centerline velocity at distance (Y) below water surface,

V_o = water velocity near pool surface,

Y = distance below water surface,

d = computed jet diameter at entrance to the pool.

Again, the jet diameter is shown to be important. Anderson (1968), in his study of free jets, related centerline velocity reduction to air concentration. He described four zones, each with different deceleration laws. His equations for a circular jet and a maximum air concentration of 8 percent are:

Zone	Dimensionless Distance	Equation
1	$\frac{Y}{D}$ from 0 to 2.7	$\frac{V_m}{V_o} = 1$
2	$\frac{Y}{D}$ from 2.7 to 5.0	$\frac{V_m}{V_o} = \frac{1.40}{(Y/D)^{1/3}}$
3	$\frac{Y}{D}$ from 5.0 to 20	$\frac{V_m}{V_o} = \frac{3.3}{(Y/D)^{6/7}}$
4	$\frac{Y}{D} > 20$	$\frac{V_m}{V_o} = \frac{100}{(Y/D)^2}$

where D = nozzle diameter. It is the fourth zone that is particularly interesting. After attainment of a 20-diameter depth, Anderson (1968) observed a rapid decrease in centerline velocities due to the increased effect of the buoyancy of the air bubbles. This is the zone where the air-bubble plume would appear to rise towards the surface. The equation is thus related to the position of the standing wave.

Before this equation can be applied to the jets of our study, an estimation of the air concentration along the jet centerline must be made. To do this, it is first necessary to estimate air entrainment. Ervine and Elsawy (1975) developed an empirical equation to predict air entrainment for a rectangular jet falling into an open pool.

$$\frac{Q_a}{Q_w} = 0.26 \frac{b_n}{p_n} \left(\frac{H_f}{d_n}\right)^{0.446} \left(1 - \frac{V_m}{V_i}\right)$$

where

Q_a = volume flow of air,

Q_w = volume flow of water,

b_n = nappe width,

d_n = nappe thickness,

H_f = fall height of a waterjet,

P_n = nappe perimeter,

V_i = nappe velocity at impact,

V_m = minimum velocity required to entrain air = 1.1 m/s (3.6 fps).

Although the jet shape of the semicircular weir oriented at 45 degrees was more triangular than rectangular, an approximate magnitude of the volume of air entrained should be obtained using the equation for a comparable fall height (3.7 ft) and a rectangular jet of comparable cross-sectional area. This yields a ratio of Qa/Qw equal to 0.16. Realizing that a triangular jet shape has a smaller hydraulic radius than a rectangle, and that the jet studied was an irregular triangle, it is reasonable to round up this ratio to 0.2.

Babb et al. (1974), in a study using a vertical circular jet, reported a ratio of Qa/Qw equal to 0.35. They were using a jet with a velocity of 7 m/s (23 fps) discharging from a 1.27 cm (0.5 in) diameter nozzle elevated 8.2 cm (3.2 in) above the pool surface. The higher ratio they obtained can be explained by the small size of their jet. Geometrically it can be shown that the hydraulic radius of a circular jet increases with increasing jet diameter. The ratio of Qa/Qw would thus be an inverse function of jet diameter. Since the diameter of the jet they used was much smaller than the equivalent jet diameter of this study, their ratio of 0.35 is considered unrepresentative. It is concluded that the ratio of 0.20 obtained from the previous relationship is more reasonable.

Air concentration can be estimated with the following equation.

$$[Air] = Qw\ (Qa/Qw)\ T/Volume$$

where

Volume = portion of pool volume containing air,

T = detention time of air in the pool.

For this study air concentration is estimated as:

$$[Air] = 7.4\ cfs\ (0.20)(3\ seconds)/(3.44')(3')(5') = 9\%$$

where

3 seconds = estimate of detention time based on a bubble rising from the pool bottom to the surface at 1.1 fps,

3.44 ft = pool depth,

3 ft = length of pool with heavy air concentration,

5 ft = width of pool with heavy air concentration.

The value obtained is an average value. The air concentration at the jet centerline would be greater. For this reason, the dissipation of jet centerline velocities would occur at a greater rate than would be predicted by Anderson's equations for an 8 percent air concentration.

In the laboratory it was observed that the air-bubble plumes began rising to the surface at depths comparable to Y/d of approximately 8.5, where d is defined as the diameter of the circle that can be superimposed completely within the boundaries of the jet cross-section at the pool surface. The rationale for defining the diameter in this manner is that although it excludes flow momentum that must be dissipated, this is compensated for by the additional air entrained by the longer jet perimeter.

The laboratory results invalidate Anderson's deceleration laws for application to our study situation. The zone defined at Y/d > 8.5 in our study is clearly the fourth zone defined by Anderson as occurring at Y/D > 20. A sensitivity analysis using different values for d indicated that the study definition of d was not the total reason for the discrepancy. The ratio of 8.5 was also obtained in the standing wave study with a circular jet. The discrepancy is more likely attributed to differences in air concentration which were probably substantially greater than 8 percent locally along the jet centerline.

Horn-ma's equations are not directly a function of air concentration. Laboratory data validates their applicability. It is still a difficult proposition, though, to use them to design for standing wave location. It can be reasoned that the objective is to provide sufficient depth (Y) so that the air bubbles begin their ascent before the jet strikes the pool bottom and carries the bubbles downstream. This would circumvent the problem of the standing wave being located too far downstream for leaping fish. But to apply the equation rationally, it is necessary to know the local centerline velocity (Vm) at which the bubbles begin their rise. This in turn would depend on bubble size and rise velocity.

Although a satisfactory explanation is not offered for the phenomenon, it is interesting that a common ratio of Y/d = 8.5 was obtained for the position of the bottom of the air-bubble plume for data from both the standing wave study and the preliminary weir tests.[2] When the ratio was applied to the baffle orientation study, similar agreement was obtained, even though the jet struck the floor and was deflected downstream. It was

2 Data from Hilliard, N.D. 1983. Weir optimization: A new concept in fishladder design. Washington State University, unpublished.

observed that air-bubbles were released downstream a distance along the flowpath equal to approximately 8.5d. Perhaps the vigorous mixing which occurs in these plumes, the rapid rate of velocity dissipation, and the dominance of jet geometry as a factor, reduces the sensitivity of the plume penetration distance to entrance velocities. Recall that air entrainment does increase with velocity. Since increased air concentrations accelerate the rate of centerline velocity dissipation, it makes sense that the effects of increased initial jet velocity would be at least partially offset by the additional air entrainment. It is also possible that the plume penetration distance is simply not sensitive to the limited range of velocities that normally occur in fishway weir jets. If this is the case, it may be possible to develop a relationship, such as $Y = 8.5\ d$, to be used as a guideline for fishway pool depth design because velocity could be treated as a constant. Additional research is needed to further define the interaction of these parameters.

Energy Dissipation

Another value that appears frequently in fishway design is the recomnendation of dissipating no more than 4 ft-lb/set per cubic foot of pool volume (Bell, 1973). This recommendation applies only to specific existing designs, and is used for establishing an upper limit for fishway discharge. As a relative measure of the utility of perforated baffles in fishway design, it is interesting to compare the spatial energy dissipation achieved in this study with and without baffles. Without baffles the energy dissipation was:

$$ED = Q\gamma(\Delta WSE)/\text{pool volume}$$
$$= 7.4 \text{ cfs } (62.4 \text{ lbs/ft}^3)(3.7 \text{ ft})/(15 \text{ ft})(3.44 \text{ ft})(8 \text{ ft})$$
$$= 4.1 \text{ ft-lb/sec per cubic foot of pool volume.}$$

where

ED = energy dissipated (ft-lb/sec-ft^3) per unit pool volume,

γ = specific weight of water,

ΔWSE = change in pool surface elevation.

At this level of energy dissipation, the pool hydraulics, particularly in the upstream 11 feet of the pool where most of the energy dissipation occurred, did not meet the study criteria. With baffles, the pool hydraulics met all the study criteria, and it was apparent that the pool length could be shortened from 15 to 10 feet. The level of energy dissipation was:

$$ED = 7.4 \text{ cfs } (62.4 \text{ lbs/ft}^3)(3.7 \text{ ft})/(10 \text{ ft})(3.44 \text{ ft})(8 \text{ ft})$$
$$= 6.2 \text{ ft-lb/sec per cubic foot of pool volume}$$

It is apparent that perforated baffles, when applied properly, have the potential to increase fishway design efficiency considerably.

Pool Width

The design of pool width is traditionally based on space requirements for fish or is adapted from existing fishway designs with proven hydraulics (U.S. Dept. of Interior, 1960; Bell, 1973). Bell (1973) notes that fishway capacity is normally not a design problem, because the hydraulic criteria usually control. In the standing wave study, the data (height of nozzle > 0) suggests that a relationship exists between the magnitude of the vertical standing wave velocity component (VSWY) and the width of the pool (Tables 9 and 10). This was more evident for the nozzle angle of

70 degrees than for the nozzle angle of 45 degrees. It was noted that VSWY was larger for 70 degrees than 45 degrees for all tank widths. This was probably because the air-bubble plume was less dispersed horizontally, thus promoting agglomeration of air-bubbles, and increased rise velocities.

Looking at the data for the nozzle angle of 70 degrees in Table 10 , it was observed that VSWY was a maximum for widths of 0.27 feet and 1.00 feet. The intermediate widths had smaller measured components of VSWY. It was also observed that the intermediate widths had larger horizontal velocities (VHS) at the pool surface. These velocities are indicative of the vigor of the return eddy manifested at the pool surface. It was expected that the velocities measured in the return eddy would become larger as the pool widths decreased, because of flow continuity. The return eddies are a physical response to maintain hydraulic continuity by replacing the flow entrained by the jet. Since the flow entrainment was expected to remain the same with decreasing pool width, it was expected that return eddy velocities would thus increase. The reason this did not occur is probably due to the dominant strength of the air bubble plume at the smaller tank widths. Anderson (1968) determined from photographs that the angle of flare of the air-bubble plume from the apex at the pool surface was 21.8 degrees. Recall that the distance to the bottom of the air-bubble plume occurred approximately at 8.5 d, where d was the jet diameter at the pool surface. To develop an understanding of the approximate magnitude of the width of the plume, it is interesting to analyze the plume cross-section at $Y = 7d$. The plume is analyzed at this depth instead of at $Y = 8.5d$, because $Y = 8.5d$ denotes the bottom of the plume, where it has lost much of its characteristic shape. Using trigonometric relationships, the diameter and area of the plume can be calculated at 7d.

$$d_7 = d_o + 14d_o \tan 21.8/2$$

where

d_7 = plume diameter at $y = 7d_o$,

d_o = initial jet diameter (2 inches).

$$d_7 = 2 + 14(2) \tan 10.9$$
$$= 7.4 \text{ inches} = 0.62 \text{ feet}$$
$$A7 = \pi(d_7)^2/4$$
$$= 42.9 \text{ inches}^2 = 0.3 \text{ feet}^2$$

where

A7 = area of the plume at 7d.

From the magnitude of the diameter of the plume, it is apparent that the smaller widths of the standing wave study actually constricted the plume. The constriction for the 0.27 foot tank width was sufficient to concentrate the air-bubbles to the extent that their upward flow completely sheared the surface return eddy, hence VHS = 0. As the width of the tank was increased, there was a zone where neither flow circulation pattern dominated the other. In this zone, the return eddy was able to flow around the standing wave circulation, but it apparently influenced the upward flow, because measured values of VSWY were lower. This zone can be termed the zone of interference. As the tank width was increased further, the measured value of VSWY increased to the same magnitude as for the smallest tank width. The measured values of VHS correspondingly decreased. This suggests that sufficient cross-sectional area was provided in the tank so that the velocity of the return eddy was of insufficient magnitude to interfere with the standing wave circulation.

Additional research is needed to further define the interaction of these flow patterns. One would anticipate that jet velocity would be an important factor, in addition to channel and jet geometry. It was interesting, however, that Bumstead,[3] in a study of standing waves, weir width and channel width, concluded that if the weir opening was approximately 1/4 the channel width, the best standing wave resulted. The weir jet diameter at the pool surface was undoubtedly less than the weir opening because of acceleration of the nappe. It was quite possibly on the order of 1/6 the channel width. This was the same ratio that provided the maximum VSWY for the nozzle angle of 70 degrees (Table 10).

Standing Wave Enhancement

The standing wave enhancement device (SWED) study was interesting because of the tremendous potential of the device. To illustrate the potential bioenergetic advantages of the device, a comparison of the energy requirements of a fish leaping from a still pool, a standing wave, and an enhanced standing wave, appears in Table 12.

The device was also observed to improve the overall pool hydraulics. The only problem was that surface waves emanating from the enhanced standing wave were reflected off the tank sidewalls and were observed to destabilize the enhanced standing wave. This was remedied with the placement of additional perforated baffling parallel to the flow as shown in Figure 67. This fishway cell configuration is the prototype design for field testing.

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3 Bumstead, T.W. Research Associate, Washington State University, unpublished data, 1983.

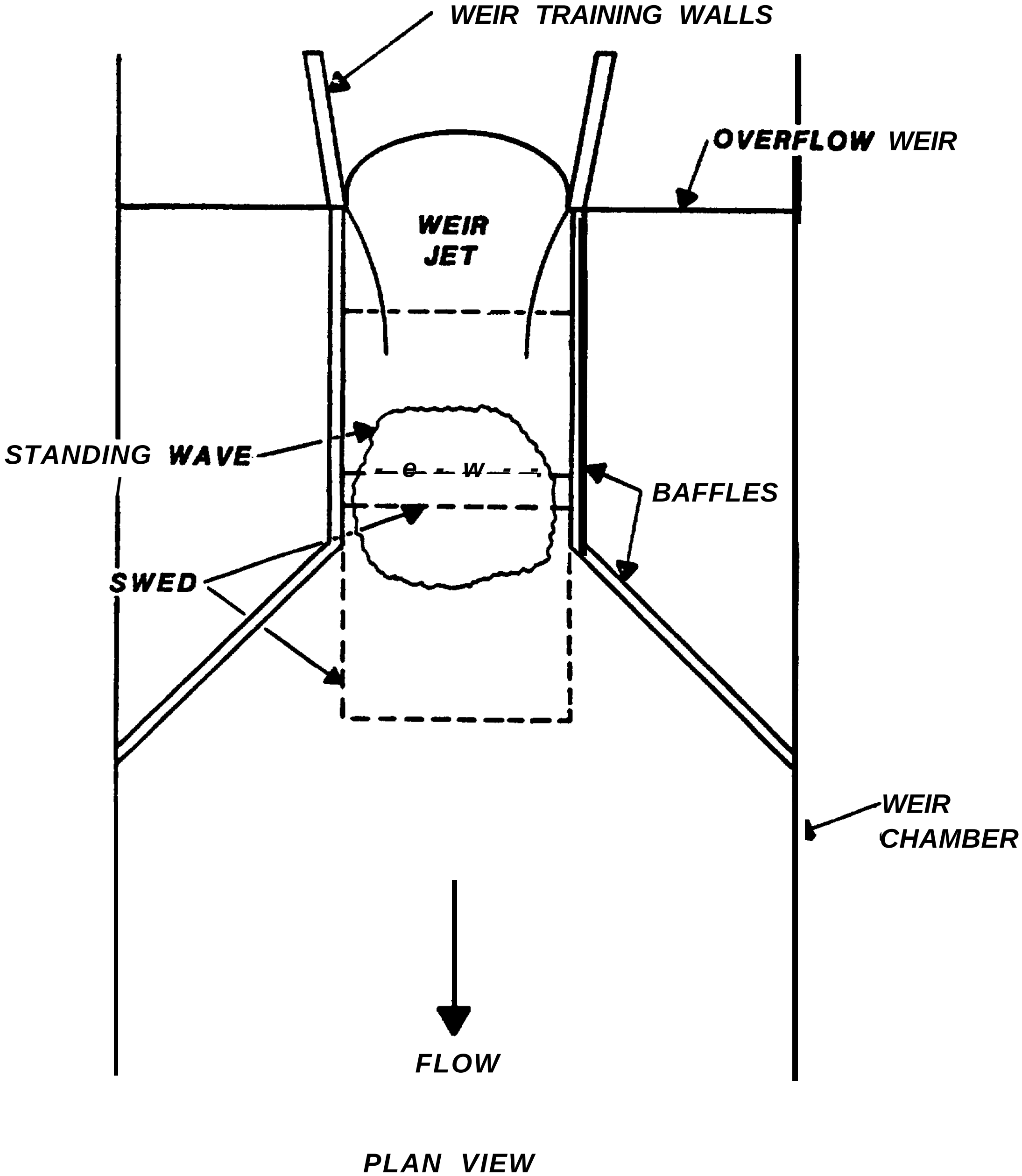

Figure 67.--Prototype fishway chamber design developed in the laboratory for field testing.

RESULTS AND DISCUSSION OF JOHNS CREEK FIELD TESTS

Results

Four field trips were made to the Johns Creek test facility during the fall of 1983. The objective was to determine fish response to the new fishladder components and configurations that had been developed in the laboratory. Johns Creek offered runs of coho and chum salmon for this purpose.

Field Trip of October 7-9, 1983

A summary of the tests performed appears in Table 13.

Test No. 1--Observations

1. Coho and chum salmon were present, few were moving.
2. Coho and chum salmon were capable of negotiating the 1.1 foot change in water surface elevation.
3. Coho salmon passed by swimming through the jet with apparent ease.
4. Chum salmon had difficulty locating the jet in the pool without baffles. They leaped in the upstream corners of the pool, often hitting their heads on the overhanging overflow weir.
5. The 16-inch diameter semicircular weir used appeared to provide too small of an opening for effective fish passage.
6. The baffles aided the fish in their orientation towards the jet.

Test No. Z--Observations

1. Baffles definitely aided the fish in their orientation towards the jet. Fewer errant leaps were observed with baffles present.
2. No avoidance reaction by fish to the standing wave enhancement device was observed.
3. The standing wave enhancement device was positioned too far downstream for the fish to take advantage of the enhanced standing wave.
4. Chum and coho salmon were capable of negotiating the 1.9 foot change in water surface elevation.
5. The overhanging weir baseplate appeared to hinder fish passage. Both churn and coho salmon were observed hitting their heads on the overhang while leaping.

Table 13.--Summary of Johns Creek field tests performed on October 7-9, 1983.

Test No.	Weir and Pool No.	Q (cfs)	WSE (ft)	Weir Description	Baffles	SWED	Pool Length (ft)
1	1	3.5	1.1	Semicircle, D=16" rotated 45° DS	No	No	12
	2		1.1	Semicircle, D=16" rotated 45° DS	Yes	No	12
2	1	3.2	1.6	Semicircle, D=24" rotated 45° DS	Yes	Yes	12
	2		1.9	Semicircle, D=20" rotated 45° DS	Yes	No	12
	3		1.8	Semicircle, D=20" rotated 45° DS	No	NO	12
3	-	5	1.3	Semicircle, D=20" rotated 45° DS	No	No	6

DS = downstream, SWED = standing wave enhancement device

6. Orientation of fish movement upstream is influenced by flow currents and solid boundaries. Smaller fish appeared to be influenced by flow currents more than larger fish. Chum salmon appeared to be influenced primarily by solid boundaries.
7. The larger weir (24-inch diameter) provided better fish passage than the smaller weir (20-inch diameter) by virtue of its larger opening.
8. Velocities were too low in the downstream portions of the pools to stimulate fish movement.
9. The 12-foot pool length provided too much resting area. This encouraged lingering in the pools.
10. The weir jet produced a standing wave which was too far downstream for leaping fish to use effectively.
11. An 8-foot pool length would have provided suitable hydraulic conditions.
12. Fish were observed leaping at areas of extraneous upwelling.
13. Fish were observed leaping in the upstream corners of the baffles at their points of attachment to the weir bulkhead.
14. Overflow jets were noisier than the main weir jet at fall heights of 1.5 feet or less.
15. Some fish were observed trying to pass upstream via the overflow jets.

Test No. 3--Observations

1. Many fish were moving.
2. The flow patterns in the 6-foot pools appeared wild.

3. The 1.3-foot change in water surface elevation, coupled with the 6-foot pool length, provided approach flow conditions to the downstream jet which affected the jet shape. Disturbed jet shapes entrained more air than jets that had less turbulent approach conditions.

4. The rate of fish movement was higher when the pool lengths were shortened from 12 feet to 6 feet.

5. Chum and coho salmon were able to negotiate the 1.3 foot change in water surface elevation.

Field Trip of October 21-23, 1983

A summary of the tests performed appear in Table 14.

A summary of the fish passage data appears in Table 15. Baffles were found to improve the leaping success for coho salmon at a significance level of 0.05 (Table 16).

Test No. 1--Observations

1. Chum salmon were in full spawning colors and in fair to good condition. Average size was estimated at 10 pounds.

2. Coho salmon were in good condition. Some fish were dark, but most were silvery or showed signs of slight coloration (red). There was a preponderance of jacks present. The larger fish were estimated at 5-6 pounds.

3. Coho and chum salmon were capable of negotiating the 3-foot change in water surface elevation.

4. Successful passage was achieved primarily by leaping. Few fish successfully swam up the jet.

Table 14.--Summary of Johns Creek field tests performed on October 21-23, 1983.

Test No.	Weir and Pool No.	Q (cfs)	WSE (ft)	Weir Description	Baffles	SWED	Pool Length (ft)
1		3	3.0	Semicircle, D=20" rotated 45° DS	Yes	No	12
2	-	3	2.0	Semicircle, D=20" rotated 45° DS	Yes	No	12
3	1	3	2.1	Semicircle, D=20"[1] rotated 20° US	Yes	No	12
	2	3	2.3	Rectangular, 18.5" walls[2]	Yes	No	12
4	1	3	2.1	Semicircle, D=20"[1] rotated 20° US	No	No	12
	2	3	2.3	Rectangular, 18.5" wide, training walls[2]	No	No	12

[1]Semicircular weir opening was flared at 45 degrees to a 30-inch top width.
[2]Training walls had skew and lean angles of 0 degrees.
DS = downstream, US = upstream.

Table 15.--Summary of fish passage data for Johns Creek field tests performed on October 21-23, 1983.

Test No.	Weir and Pool No.	Species	Total Leaps (N)	Successful Leaps (n)	Leap Success Ratio (%)	Passage Rate (Fish/Hr)
3	1	Coho	91	39	43	77
		Chum	24	5	21	10
		Coho	86	36	42	72
		Chum	6	2	33	4
	2	Coho	137	52	38	104
		Chum	20	1	5	2
		Coho	76	28	37	56
		Chum	33	1	3	2
4	1	Coho	103	31	30	62
	2	Coho	126	29	23	58
	Existing Fishway	Coho	37	23	62	92
		Chum	11	7	64	28

Data were taken for periods of approximately 30 minutes, except for the existing fishway cell which was counted for 15 minutes. Replicate data were taken for test no. 3. The discharge and ΔWSE for the existing fishway were 3 cfs and 0.75 ft, respectively.

Table 16.--Summary of the statistical analysis to test for significance at the 0.05 level of the difference in leaping success for coho salmon with and without baffles[a].

Weir and Pool No.	With Baffles			Without Baffles			Z	Significant?
	n_1	x_1	P_1	n_2	x_2	P_2		
1	177	75	0.42	103	31	0.30	2.0	Yes
2	213	80	0.38	126	29	0.23	2.77	Yes

[a]Data from Johns Creek field tests numbers 3 and 4, October 21-23, 1983. Analytical procedure for tests of hypotheses on two proportions as described by Hines and Montgomery (1980) was used.

5. Although chum salmon were capable of negotiating the 3-foot overfall, their leap success ratio was low.

Test No. 2--Observations

1. The weir plate that was rotated upstream provided a jet that fell closer to the weir bulkhead than weir plates rotated downstream. This prevented fish from moving upstream (underneath) of the jet. It also moved the standing wave closer to the weir bulkhead.
2. Rotating the weir plate upstream eliminated the problem of fish banging their heads on an overhang while leaping.
3. Baffles improved leaping success by three mechanisms: (a) guiding fish to the best spot for leaping, (b) containment of upwelling to the standing wave, and (c) the physical deflection of fish through the weir notch (when the baffles extended above the pool surface to the height of the upstream weir plate). All three mechanisms function by reducing the number of errant leaps.

4. Baffles should have an opening for fish to escape should they leap behind them.

5. Perforated baffles should be constructed with holes no larger than 2 inches in diameter. Larger holes are capable of "gill netting" fish.

Field Trip of November 17-21, 1983

A summary of the tests performed appears in Table 17.

Table 17.--Summary of Johns Creek field tests performed on November 17-21, 1983.

Test No.	Weir and Pool No.	Q (cfs)	WSE (ft)	Weir Description	Baffles	SWED	Pool Length (ft)
1	1	3	1.2	Semicircle, D=20" rotated 20° US	Yes	No	6
	2	3	1.1	Semicircle, D=20" rotated 20° US	Yes	No	6
2	1	3	1.7	Semicircle, D=20" rotated 20° US	Yes	No	6
	2	3	0.9	Semicircle, D=20" rotated 20° US	Yes	No	6
3	1	3	1.3	Semicircle, D=20" rotated 20° US	Yes	Yes	6
	2	3	1.8	Semicircle, D=20" rotated 20° US	Yes	No	12

The semicircular weir opening was flared at a tangent of 45 degrees to a 30-inch top width; US = upstream.

Test No. 1--Observations

1. The 6-foot pool length provided adequate pool volume for energy dissipation for the pool differential of 1.2 feet and the discharge of 3 cfs.
2. The jet of the second pool was distorted in shape because of the level of turbulence in the approach flow from the first pool.
3. Unsuccessful leaps were generally the result of orientation difficulties for both coho and chum salmon.
4. The jet was laterally expanded in shape.
5. Chum salmon were in full spawning colors and fair condition. They were not very active in their movement up the fishway.
6. Coho salmon were in full spawning colors and fair condition.

Test No. 2--Observations

1. The 6-foot pool length provided insufficient pool volume for energy dissipation for the pool differential of 1.7 feet and discharge of 3 cfs.
2. The water was more turbid than usual. as a result of persistent rainfall.
3. Orientation difficulties were the principal cause of unsuccessful leaps. This was evidenced by a high number of errant leaps.
4. The jet of the second pool was distorted in shape by the turbulent approach flow.

Test No. 3--Observations

1. The standing wave enhancement device performance was encouraging when it was positioned properly. Two coho salmon made outstanding leaps from the enhanced standing wave.
2. The laterally expanded jet produced by the weir was ineffective in conjunction with the standing wave enhancement device. The momentum of the jet was largely dissipated in the pool before it reached the standing wave enhancement device.
3. Increasing the pool length from 6 to 12 feet reduced the number of errant leaps by improving the pool hydraulics.

Field Trip of December 8-12, 1983

The principal result of this field trip was to confirm that anadromous fish performance capabilities deteriorate with time in the river. There were few coho salmon present. Those present were in a state of advanced sexual maturity and were generally in poor condition. The chum salmon that were present were in fair condition, but few were moving through the fishway.

Discussion

Fish Behavior

As a result of the field test program, much was clarified concerning fish behavior, at least for the stocks studied (Figure 68). Fish were observed to "nose out" of the water prior to leaping, probably to visually orient themselves to the obstacle as suggested by Stuart (1962) (Figure 69). Gray's (1968) description of a salmons leap as a "standing"

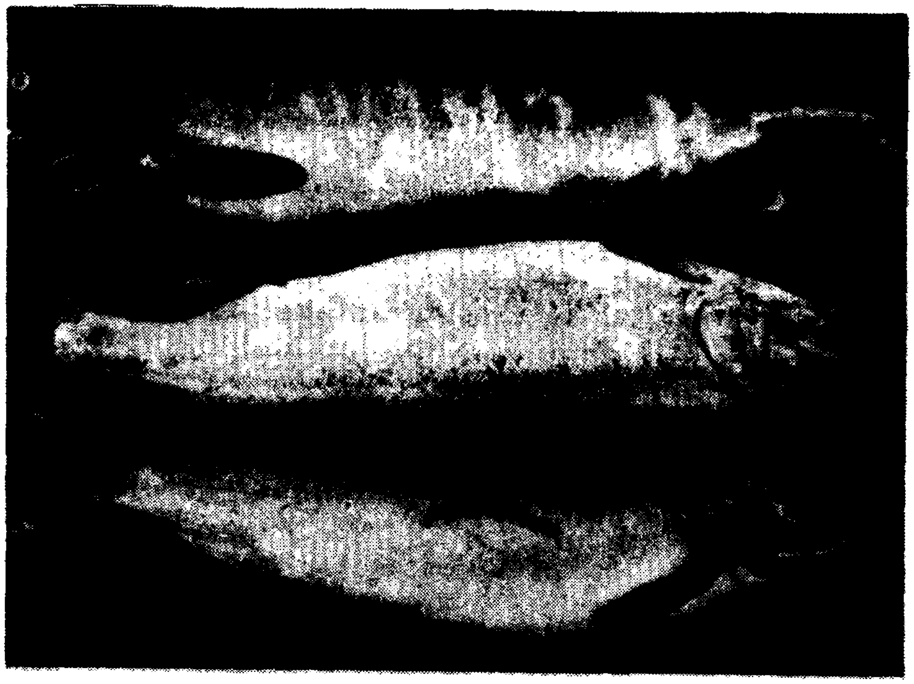

Figure 68.--Johns Creek offered runs of chum (top) and coho (lower two specimens) salmon for field testing.

Figure 69.--Coho salmon orienting itself visually to weir prior to leaping.

jump was also accurate. In no instance was a fish observed to get a running start prior to leaping.

As for Stuart's (1962) postulate of the stimulus for fish movement preparatory to leaping being the force of the impact of falling water, the results were less supportive. There were times when fish were present and no activity was observed, as well as times when the fish were extremely active. No discernible pattern or trend was observed. The impression was that the fish moved simply whenever they felt like moving, no matter what the time of day.

It was noticed that the level of activity could sometimes be increased by increasing the flow. Whether the fish were reacting to escape the increased turbulence in the pools or were stimulated to move by the increased flow was uncertain. The latter was suspected because this activity was observed in 12-foot long pools where ample resting area was present even at the higher discharges.

Stuart (1962) reported that a threshold stimulus existed that was the minimum to incite movement in fish. This threshold stimulus varied directly with the size of the fish. Although this phenomenon was not observed, it was concluded that if a threshold stimulus for fish movement did exist, it must be a small value for coho and chum salmon. Both species were observed leaping at veritable trickles of water on occasion. Again, there were also times when a relative flood would not incite movement.

Although fish were observed to leap from the standing wave in our study, they did not demonstrate the same proclivity for this behavior as they did in Stuart's study. Stuart (1962) noted that "the fish, without exception, all leapt from the same small area on the hump." In our study they frequently leapt from the standing wave, but many times they did not.

This was particularly true for chum salmon, which were predominately influenced in their movement by solid boundaries. Without baffles guiding the chum salmon to the standing wave, they would often follow the sidewalls to the upstream corner of the fishway cell and leap ineffectually at the overflow weirs (Figure 70). Coho salmon would also occasionally exhibit this behavior, but much less frequently. They were clearly much more masterful leapers than chum salmon and usually initiated their leaps within the vicinity of the standing wave. Whether this was because they sensed the upwelling flow of the standing wave, or coincidental because the standing wave naturally occurred at the appropriate location to initiate a leap, was uncertain. It was apparent, though, that an intelligent fish passage strategy was to design the fishway so that the standing wave occurred at a position coincidental with where the fish would naturally initiate a leap. This position, in turn, could be influenced by the placement of baffles.

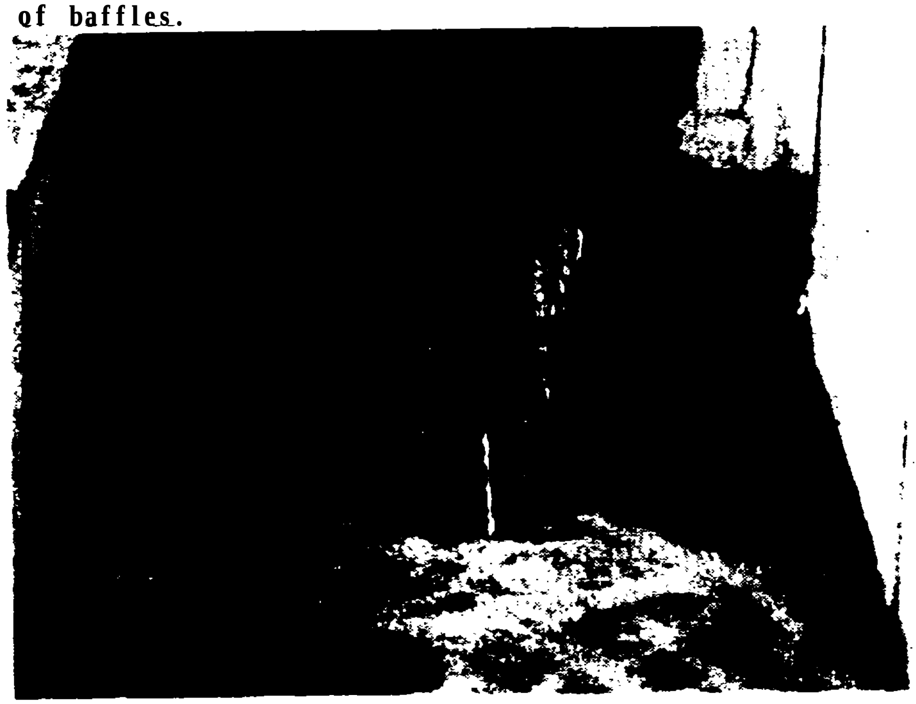

Figure 70.--A coho salmon successfully negotiates the weir while a chum salmon leaps ineffectually in the corner of the fishway cell.

Both coho and chum salmon were observed leaping at areas of upwelling extraneous to the standing wave. This lended credence to the concept that fish were stimulated to leap when presented with this characteristic hydraulic condition. It was also observed that the smaller resident trout that were present appeared to initiate their leaps from the standing wave with greater regularity than either of the larger anadromous species. Perhaps the upwelling flow of the standing wave presented a more influential flow condition to their smaller mass. This would represent a scale effect for fish size. It should be noted that much of Stuart's (1962) work was based on laboratory tests with salmon parr (6-15 cm). The scale effect of testing with such small fish possibly explains why he reported the fish leaping without exception from the hump. Although this behavior was observed with the larger coho and chum salmon of our study, frequent deviation from this behavior was also observed. It was not possible to conclude decisively that the standing wave was a significant hydraulic condition for leaping.

Standing Wave Enhancement Device

Although testing of the standing wave enhancement device (SWED) was limited, the results were encouraging (Figure 71). One of the concerns was that fish may avoid the enhanced standing wave due to its intensity. This was observed not to be the case. Both coho and chum salmon were observed sighting and leaping from the wave. There were two hydraulic problems associated with the SWED, however. It was demonstrated that the SWED was incompatible with certain jet forms. In particular, the SWED requires a jet that will penetrate deep into the pool. This precludes use of the weir plate that was oriented 20 degrees upstream from vertical into the flow.

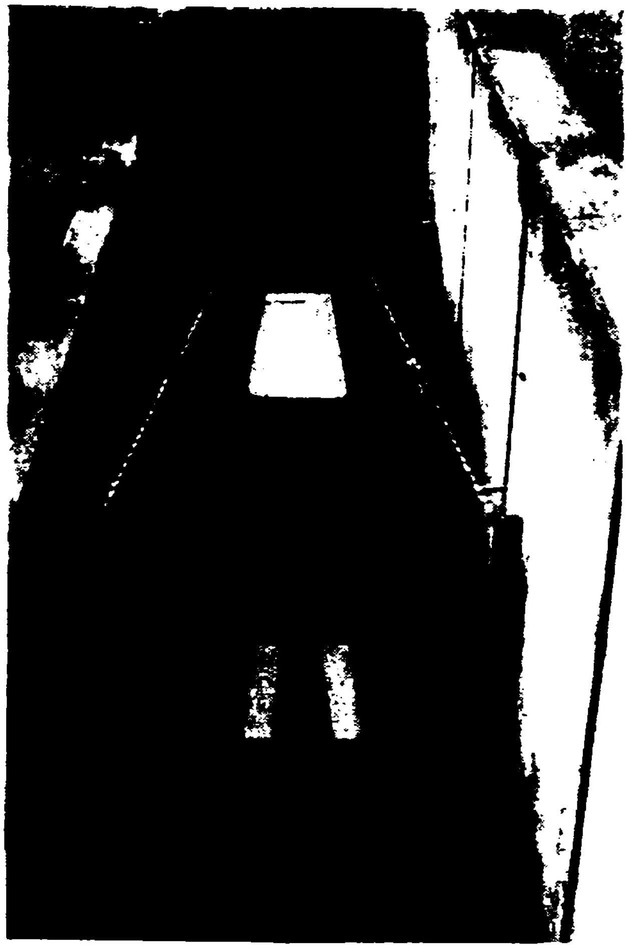

Figure 71.--Two types of standing wave enhancement devices (SUED) tested in conjunction with two types of baffles and two types of weirs. The SUED in the foreground was designed to permit part of the jet to penetrate to the downstream portion of the fishway pool for fish attraction.

This weir Plate orientation produced a characteristically shallow penetrating jet. The other problem with the SUED was that it was sensitive to position. If it was located too far upstream it would not function hydraulically. If it was located too far downstream, the enhanced standing wave was then positioned too far downstream for fish to leap successfully. Additional research is required to further define the operational parameters (discharge and location) of the SHED.

Baffles

The utility of baffles in weir and pool fishway design was observed and shown statistically to be significant (Table 16). They functioned well as hydraulic energy dissipators, fish guides, and fish deflectors. They not only improved fish passage efficiency, but allowed the shortening of fishway chambers. Several configurations were tried in the field test program and the following conclusions were reached: (1) the baffles should be as high as the upstream weir plate (Figure 72); (2) perforated baffles should be constructed with holes 2 inches or less in diameter; (3) access openings should be provided out from behind the baffles, preferably along the pool bottom; (4) baffles should be positioned to direct the fish to the standing wave; (5) the configuration developed in the laboratory test program worked effectively;- and (6) simpler configurations may work as well. Preliminary testing of slotted baffles indicated that they may be more effective energy dissipators than perforated baffles.

Weir Design

Practical considerations was the lesson taught by the field test program concerning weir design. It was apparent that the size and

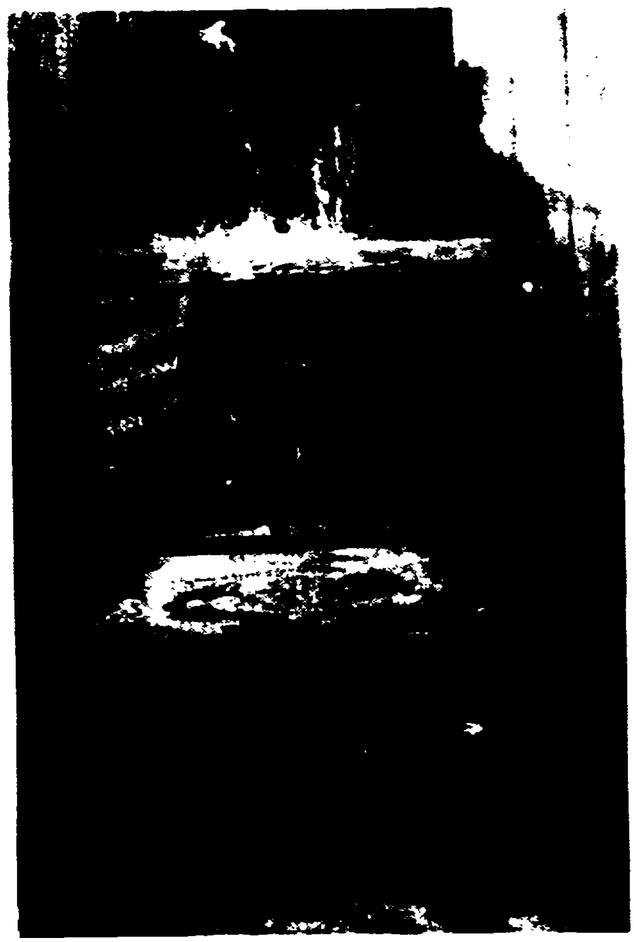

Figure 72.--Baffles should be as high as the weir plate as shown in the center of the photo. A coho salmon leaps successfully in the background. In the foreground, a weir of the incumbent fishway is shown.

orientation of the weir opening was as important to successful fish passage, if not more so, than the hydraulic characteristics of the weir. Stuart (1962) recommended a minimum weir opening of 24 inches for adult salmon and trout. From our observations, this seems to be a reasonable guideline. In general, the larger the weir opening provided, the better. It was also apparent that the orientation of the weir plate to the flow was important. This was evidenced by the difficulty that fish had with the weir plate that was oriented at 45 degrees to the vertical in the downstream direction. If their leaps were askew such that contact was made with the weir surface, they were abruptly deflected back. The overhang of the overflow weir created even a more difficult situation for fish. It was particularly a source of frustration for chum salmon. They would continuously work their way upstream under the overhangs and repeatedly beat their heads on them in their attempts to leap upstream (Figure 73). Baffles provided part of the solution by directing them away from the overhang and towards the weir opening (Figure 74). The rest of the solution was provided by orienting the weir plate upstream, 20 degrees from vertical. This orientation was more compatible with the lqaping trajectory of fish (Figure 75). Leaps that missed the weir opening and struck the weir plate were afforded a glancing blow which sometimes deflected them upstream. Although this weir orientation provided some practical advantages to leaping fish, as was discussed previously, it was incompatible with the standing wave enhancement device. It was also observed that the laterally expanded jet shape it produced was compatible with fish which try to swim up the jet (Figure 76). Additional research is needed to consolidate the hydraulic and practical aspects of weir design.

Figure 73.--Even when baffles were used, chum salmon would occasionally work their way upstream under the weir overhang and bang their heads in their attempts to leap upstream (left center of the photo). A coho salmon successfully negotiates the weir (upper left).

Figure 74.--Although baffles successful in gu salmon to the we they would occas askew and land b baffles.

Figure 75.--Chum salmon shown leaping successfully at the weir plate oriented 20 degrees from vertical in the upstream direction. Note the baffles submerged slightly beneath the pool surface.

Figure 76.--A coho salmon
up the jet pr
plate oriente
vertical in t
tion.

Fish Capabilities

One of the objectives of our study was to provide hydraulic conditions which allowed fish to pass through a weir and pool fishway at a steeper rate of ascent. This translates into shorter pools with larger differentials in successive pool elevations. It was easy to demonstrate that shorter pools could be developed by incorporating baffles into the design. Laboratory studies provided the necessary evidence. The demonstration that larger pool differential elevations (steps) could be incorporated into fishladder design was considerably more difficult. It necessarily involved an interpretation of fish capabilities.

The question of step size is fundamental to fishladder design. Everhart and Youngs (1981) suggest that the maximum drop in water surface between pools should be about 0.30 meters (1.0 ft.). The reason cited is "to provide for as rapid and easy a migration as possible." They acknowledge that fish are capable of leaping higher. The key words are rapid and easy.

This ideology is in harmony with Clay's (1961) objective of allowing fish to ascend "without undue stress." The recurrent theme is the facility of passage. The task remains, however, to develop a means to define what constitutes facility of passage.

It is likely that facility of passage was traditionally defined empirically. After many observations of fish moving through fishladders, step sizes were probably selected because the fish passage conditions looked good. Such decisions may have been tempered with the desire to pass the weaker fish. It is even possible that an engineering factor of safety was included. Whatever the decision process actually was is uncertain, but it is doubtful that much science was applied. The result is that many fishways were probably designed based on criteria that underestimated fish capabilities.

From the field test program it was apparent, after trying to compare leap success ratios of fish for different step sizes, that a probabilistic model could Se developed to match fish capability with step size. The objective of the model was to determine the fishladder step size which provided a fish of average leaping capabilities (species specific) the greatest probability of negotiating the ladder without an unsuccessful leap. The premise was that this step size best matched the natural leaping capability of the fish and could be used in fishladder design.

The development of the model relied on the fact that statistically, fish leaps can be considered Bernoulli trials that have a binomial distribution (Hines and Montgomery, 1980) given by p(x), where

$$p(x) = \binom{n}{x} p^x (1-p)^{n-x} \qquad x = 0,1,2,\ldots,n$$
$$= 0 \qquad \text{otherwise}$$

and

n = number of leaps,

x = number of successful leaps,

p = leap success ratio.

This relationship is used to calculate the probability of x successful leaps in n total leaps. For the special case where $x = n$, the relationship simplifies to:

$$p(x) = p^x$$

This simplified formula is used to determine the probability of a fish negotiating a fishladder with x number of steps without a leaping failure. If data for determining leap success ratios for different step sizes were available, one could determine the probabilities of unhindered passage for several step sizes for comparison purposes. The step size with the greatest probability for unhindered passage would be chosen as the best.

On closer inspection of the simplified formula, it can be shown that the exponent, x, can be equated to the total elevation gain of the fishladder by the step size.

$$x = \Delta H/\Delta h$$

where

ΔH = total elevation gain of the fishladder,

Δh = fishladder step size.

Thus

$$p(x) = p^{(\Delta H/\Delta h)}$$

Although this formula is applicable to all fishladders, it is useful to normalize the relationship by recognizing the maximum leap height capability of a species of fish as the fundamental maximum elevation differential unit of a fishladder. Then

$$Pn = p^{(HL/\Delta h)}$$

where

Pn = normalized probability for step size Δh,

HL = maximum leap height of the study species.

The utility of normalizing the formula is that it allows the development of standard curves of normalized probability versus step size. Although there were insufficient data to develop a curve for coho or chum salmon in our study, the data did suggest the likely form of these curves (Figure 77).

To demonstrate how this methodology can be used to match fishladder step size with fish leaping capability, a comparison is made using the leap success ratios obtained in this study for coho salmon for step sizes of

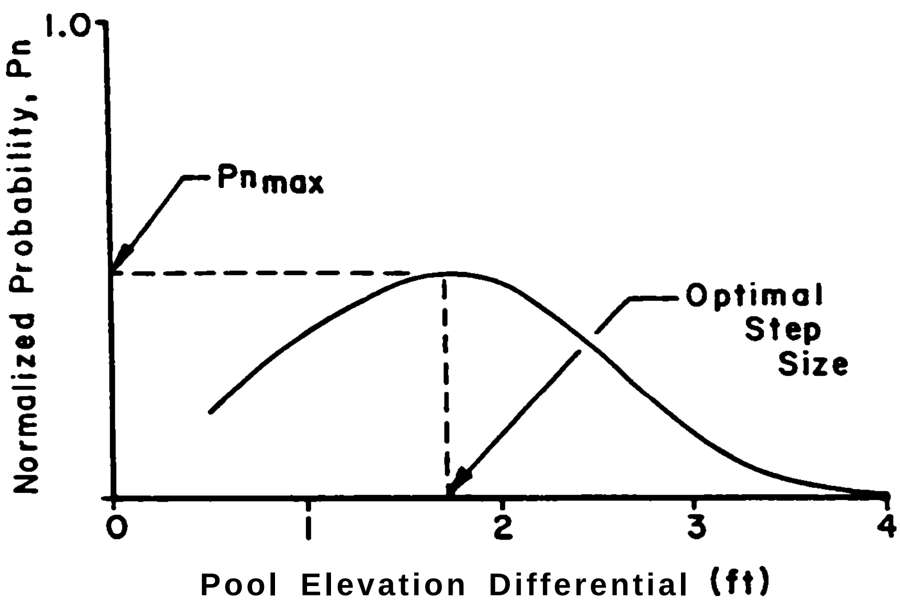

Figure 77.--Likely shape of the plot of normalized probability versus fishladder step size for coho salmon, as suggested by the data from this study.

0.75 and 2.1 feet (Table 15). Note that in this case, since only two step sizes are being compared, 2.1 feet is HL.

$$Pn = 0.62^{(2.1/0.75)}$$

$$= 0.26$$

$$P_{max} = 0.42$$

For this example the 2.1-foot step size provides a better match with the capability of the coho salmon than does the 0.75-foot step size.

To visualize the concept, it is helpful to consider the analogy of a man ascending a staircase. If the steps are too small, the man is uncomfortable and may stumble. Likewise, if the steps are too large, the same uncomfortable feeling and stumbling may result. There exists an optimum step size that best matches the natural capability for the man. This is also true for the fish.

A logical criticism of this methodology is that a leaping failure at, say, a 3-foot overfall, cannot be equated to a leaping failure at a lesser overfall. On the surface this appears to be true. However, it is suggested that the increased incidence of trauma from fish leaping errantly and striking weirs and bulkheads, and the increased energy expenditure of approach for additional leaps, compensates for the higher energy expenditure of leaping failures at higher overfalls.

To illustrate these premises, consider the coho salmon passing through a fishladder with a 12-foot total elevation gain. Assume that the leap success ratios for 0.75 and 2.0 foot step sizes are 0.62 and 0.42, respectively. The total number of steps in the fishladder can be calculated.

For 0.75-foot step sizes:

$$\text{No. of steps} = 12/0.75 = 16$$

For 2.0-foot step sizes:

$$\text{No. of steps} = 12/2.0 = 6$$

The expected number of leaps (n) required to ascend each of these ladders can be determined from probability theory for the binomial distribution.

$$n = E(x)/p$$

where

$E(x)$ = the expected number of successful leaps.

For the 0.75 foot step sizes:

$$n = 16/0.62 = 25.8 \text{ leaps}$$

For the 2.0 foot step sizes:

$$n = 6/0.42 = 14.3 \text{ leaps}$$

The expected number of unsuccessful leaps can be obtained by subtracting the successful leaps from the expected number of leaps required.

For the 0.75 foot step sizes:

No. of unsuccessful leaps = 25.8 - 16 = 9.8 leaps

For the 2.0 foot step sizes:

No. of unsuccessful leaps = 14.3 - 6 = 8.3 leaps

This shows that coho salmon are required to make, on the average, 11.5 additional leaps, and 1.5 additional errant leaps, for the fishladder with 0.75 foot step sizes than for the fishladder with 2.0 foot step sizes. This is despite the fact that coho salmon leap with a greater success ratio for the 0.75-foot step size. The increased number of leaps constitute a significant increase in the exposure to injury during leaping, and additional time and energy for approach and sighting prior to leaping. This is the justification for selecting the step size which maximizes the probability of ascent without a leaping failure as the best for the fish.

As was mentioned previously, insufficient data were gathered in our study to develop these curves for coho and chum salmon at Johns Creek. It was demonstrated, however, that this approach was both rational and practical. Replicate data sets taken in test number 3 of the October 21-23, 1983, field trip indicated that results were reproducible. This voided the concern that variability in leaping behavior would affect the data. The only real problem was one of planning. Field personnel must be present and prepared to collect this data when fish are present and active. Data collected during different periods of the run could serve to show the change in fish capabilities with time in the river. It is anticipated that further research in this area will provide more refined estimates of fish capability.

For now, the traditional empirical method of fish capability assessment must be relied upon. From our study, pool steps of 1.25 feet and

2.0 feet seemed reasonable for chum and coho salmon, respectively. Although these steps appear modest in light of the leaping capabilities of these species, they do reflect a significant increase over traditional practice. In economic terms, adaptation of these standards could possibly reduce the cost of a fishway by one half. At a time when the fisheries resource is at historically low levels, it offers the opportunity to stretch the resource dollar further.

CONCLUSIONS

The results of laboratory experimentation guided the development of a new fishway configuration based on the concept that fish can be stimulated to leap. Field tests to assess the performance of the new fishway provided insight into fish response which served to further refine the design. From these studies the following conclusions were reached.

1. The physical mechanism governing the formation of the standing wave, as described by Stuart (1962), is the buoyancy of entrained air bubbles.
2. The magnitude of the vertical velocity in the standing wave is a function of air bubble size. A typical value is 1.5 fps.
3. Standing waves can assist leaping fish.
4. Perforated or slotted baffles improve fishway pool hydraulics by dissipating energy and directing flow.
5. Baffles improve fish passage by guiding fish.
6. It is possible to enhance the standing wave with a device which directs the plunging jet back towards the surface. Vertical velocities of 5.5 fps were measured in enhanced standing waves.
7. The required depth of the fishway pool is a function of jet entrance velocity and geometry. However, since the range of velocities that occur in fishladder weir jets is limited, our data suggest that jet geometry is the dominant factor influencing fishway pool depth requirements.

8. A minimum weir opening of 24 inches at the water surface for salmon and trout is adequate. Generally, the larger the weir opening provided, the better.

9. Fish do often leap from the standing wave. Whether they do because they are stimulated to or that it is coincidental that standing waves occur where fish would naturally initiate a leap is uncertain.

10. A methodology was developed to match fish capabilities with fishway pool elevation differentials.

11. Fish capabilities are often underestimated in the design of fishway pool step sizes. From this study, pool steps of 1.25 feet and 2.0 feet seem reasonable for chum and coho salmon, respectively.

SUGGESTIONS FOR FURTHER STUDY

The broad scope of our study presented limitations which precluded the in-depth treatment of several topics which were worthy of closer inspection. For this reason, at times it seemed that we were unveiling more questions than we were answering. It is suggested that further study of the following areas will increase the understanding and development of fishway design principles.

1. Free jet entrainment.--Practical guidelines for the design of fishway pool geometry can be derived from the definition of descriptive equations for the entrainment of jets of variable size, shape, and velocity.
2. Weir design.--Definition of jet shape versus fall height for variable weir shapes, orientations, and sizes can be used in conjunction with free jet theory to develop design curves for fishway pool geometry.
3. Standing Wave Enhancement Device.--Additional laboratory and field testing is required to define operational parameters and fish response.
4. Fish capabilities.--Additional data are required to develop curves matching fish capabilities to fishway pool elevation differentials for the various species of anadromous fish.

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APPENDIX

LABORATORY APPARATUS AND METHODS

Preliminary Weir Tests

Main Weir Selection[1]

Apparatus

The test apparatus was a flume 4 feet wide, 6 feet high, and 30 feet long (Figure 27). Water was supplied to the flume through a 20-inch diameter steel pipe by an American-Marsh HLM pump, size 8, rated at 6.1 cfs. The flow into the flume was regulated by wasting excess water through a bypass pipe.

The weir bulkhead was located 5.42 feet downstream from the pipe inlet. It measured 4.67 feet high. Cantilevered 0.75 feet from the top of the bulkhead in the downstream direction was a plywood plate. Attached vertically to the downstream end of the plywood cantilever were plywood endwalls that stood 1.25 feet high at either side of the weir opening. The weir opening was centered in the plywood cantilever and measured 0.75 feet by 0.75 feet (Figure 78).

A plywood baseplate, for supporting the 16-gauge steel weir plates, bordered the weir opening and was attached to the bulkhead by a 2-foot long

[1] Diane Hilliard was the principal researcher on this study component. The work was the basis for her senior paper, "Weir Optimization: A New Concept in Fishladder Design," Washington State University, May 26, 1983, unpublished.

Figure 78.--Detail of the weir assembly used in the main weir selection study.

hinge. This allowed rotation of the weir plates about a horizontal axis perpendicular to the flow. Weir plates were supported at various angles to the flow by plywood side plates.

Two stilling wells were used to monitor the level of the head and tail water in the flume. The headwater level was monitored 1.5 feet upstream of the weir. The tailwater level was monitored 14.0 feet downstream from the weir.

A point gage wired to illuminate a light when contact was made with the water surface was used to measure the standing wave height.

To reference the position of the standing wave, a scale marked in half-inch increments was affixed to the top of the flume, and the origin of the scale was referenced to the weir bulkhead. A steel T-section, which supported the point gauge, spanned the flume perpendicular to the side-walls. By positioning the point gauge over the standing wave, and recording the distance to the bar downstream from the bulkhead, the standing wave location was referenced.

A standard 90-degree 'J-notch weir was used to calibrate the stage/discharge relationships for the weirs. The calibration weir was located 3 feet downstream from the tailwater stilling well. A port with a sluice gate mechanism was installed through the tailwater bulkhead to adjust the level of the tailwater.

Methods

The independent variables in the study were:

Weir Geometry. --Four weir shapes were tested: (1) hexagonal with one-on-one sideslopes, (2) semicircular, (3) trapezoidal with four-on-one side slopes, and (4) a 68-degree V-notch (Figure 20). The maximum horizontal opening dimension for each weir was 0.75 feet.

Weir Angle. --The weirs were tested at several orientation angles measured from a horizontal plane and rotated upwards about a horizontal axis perpendicular to the flow. The angles tested were 18, 33, 45, 90, and 135 degrees (Figure 21).

Discharge. --The discharge was varied between 1.0 and 2.0 cubic feet per second (cfs).

Tailwatet Depth. --The depth downstream of the weir was varied from approximately 0.9 to 3.3 feet in 0.8 foot increments.

The procedure was systematic, and began by activating the pump and regulating the flow into the flume with the bypass valve until approximately 1.0 feet of depth flowed through the test weir. The sluice gate in the tailwater bulkhead was then closed, and the tailwater pool was allowed to fill to equilibrium.

Measurements of the headwater elevation (HWE) and tailwater elevation (TWE) were made using the upstream and downstream stilling basins. The heads on both the test (HWW) and calibration (HTW) weirs were then calculated using known (level surveyed) spatial relationships between the weir crest elevations and the stilling basin scales. The discharge (Q) was calculated with the following equation for the standard 90-degree calibration weir.

$$Q = 2.5(HTW)^{2.5}$$

The position of the highest portion of the standing wave was determined visually and the point gauge was centered above it. The point gauge was then lowered until the first flicker of light was observed. This measurement was recorded as the maximum point gauge reading (PGR 1). The point gauge was then lowered further until the light stayed on continuously. This was recorded as the minimum point gauge reading (PGR 2). The distance (X) of the point gauge from the upstream bulkhead was recorded also.

The diameter of the jet cross-section parallel to the flow direction and just prior to entering the tailwater pool was measured visually with a Z-inch grid through the glass sidewall of the flume. In addition, observations regarding the jet shape and general tailwater pool flow patterns were recorded on a comment sheet, and photographs were taken.

The head and tailwater elevations were checked to verify the initial readings.

The above procedure was repeated for three additional tailwater settings. For each repetition the tailwater was lowered approximately 0.8 feet.

The discharge was then lowered by opening the bypass valve and wasting additional flow. The above procedure (inclusive of tailwater variations) was then repeated. The discharge was reduced for two additional repetitions. The amount of the reduction in discharge was predicated on the judgement of the observer. The function was to test each weir over flows ranging from weir-full to a small fraction thereof (four discharges).

The weir shape was then changed, and the above procedure (inclusive of tailwater and discharge variations) repeated until each of the four shapes had been tested.

Finally, the weir orientation angle was changed. The above procedure (inclusive of tailwater, discharge, and weir shape variations) was repeated for each of the five vertical angles tested.

Weir Training Wall Effects*

Apparatus

The laboratory facilities were identical to those of the main weir selection study with the following exceptions.

A 12-inch diameter semicircular weir was used for the test weir. The weir opening was centered in the top edge of a 4-foot by 4-foot by 3/4-inch plywood plate. The plywood plate was then affixed to the top of the

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Valerie Monsey, a civil engineering senior student, was responsible for the dominant portion of the laboratory testing in this study component and the overflow tests in the next section.

bulkhead at a vertical angle of 45 degrees (Figure 79). The point of attachinent of the plywood plate to the bulkhead was such that the dimension From the upstream top edge of the bulkhead to the upper edge of the inclined plywood plate measured 1.7 feet. This position provided sufficient space for the nappe of the jet to spring clear of the bulkhead in its trajectory downstream.

Adjacent to the weir opening, on both sides, were attached training walls (Figures 22, and 23). The training walls were constructed of 3/4-inch plywood with the dimensions of an isosceles right triangle with 2-foot sides. They were attached with hinges along the bases of the training walls to allow rotation away from the weir centerline.

A multiple dye stream injection assembly was used to study the tailwater pool flow patterns (Figure 80).

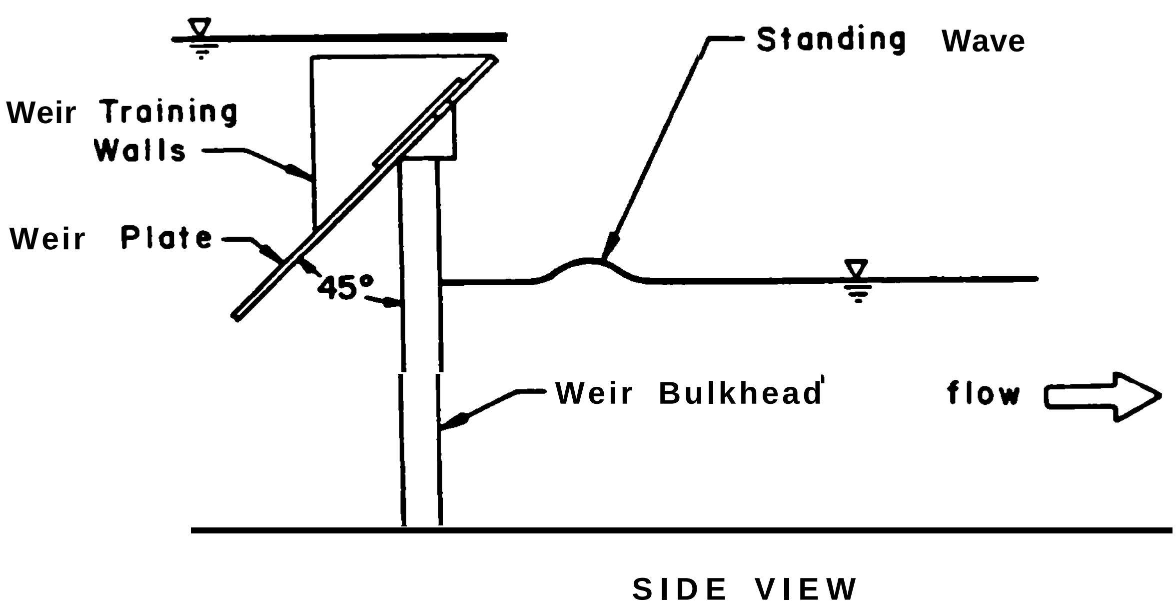

Figure 79.--Side view of the test facility used in the weir training wall effects study.

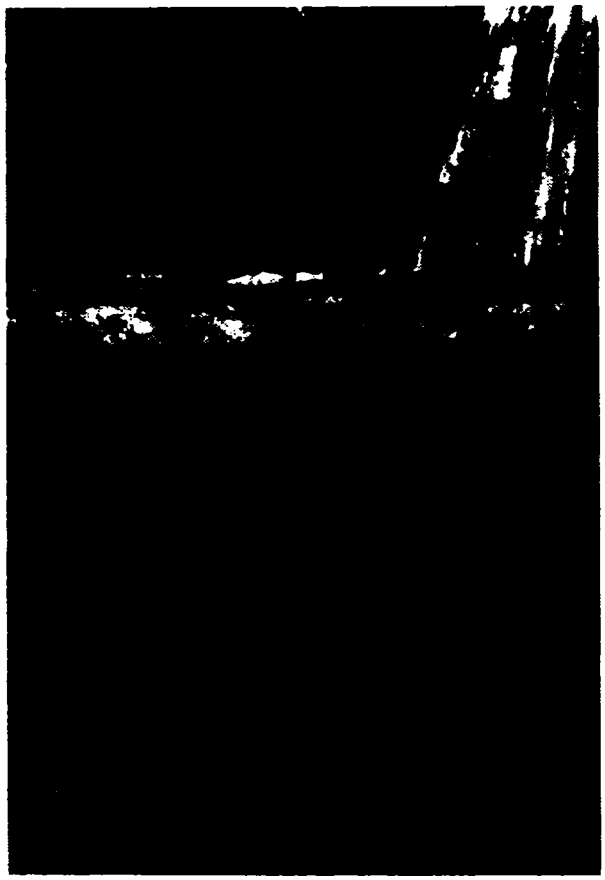

Figure 80.--Dye injection apparatus.

Methods

The independent variables in the study were:

Training Wall Skew Angle.--Defined as the rotation of the training wall hypotenuse away from the weir centerline about the downstream point of the training wall (Figure 28).

Training Wall Lean Angle.--Defined as the rotation away from the weir centerline about the bottom edge (hypotenuse) of the training wall (Figure 29).

Discharge.--The discharge was varied between approximately 0.2 and 1.0 cfs in increments for each test series.

The tailwater depth was held constant at 3.0 feet. This depth was established as 1.25 times the distance from the weir crest to the tailwater surface as suggested by Stuart (1962).

The procedure was systematic and began with the training walls set at skew and lean angles of 0 degrees. The pump was then activated, the tailwater pool allowed to fill to equilibriuim, and the water surface elevations, discharge, standing wave height and position, were determined by the same procedures used in the main weir selection study.

The entrance position of the jet into the tailwater pool was referenced by measuring the distance dormstream from the test weir bulkhead to the closest and furthest jet surfaces. The jet shape, standing wave, and general pool flow patterns were then described and photographed. Blue dye was introduced into the pool at several depths simultaneously to aid in flow visualization.

The above procedure was repeated for up to three additional discharges, predicated on the judgement of the observer.

The lean angle was then changed and the above procedure repeated. This methodology was continued for additional lean angles. Then the skew angle was changed and the entire process was repeated. This continued until skew angles of 0, 5, 10, and 20 degrees were tested.

The last test was done without training walls. This test served as a basis for comparison and analysis of the training wall effects on flow patterns.

Overflow Weir Effects

Apparatus

The laboratory facilities were identical to those of the weir training wall effects study with two exceptions.

Overflow weirs, constructed out of 16-gauge sheet steel measuring 1.5 feet by 1.5 feet, were positioned adjacent to either side of the semicircular test weir opening. They were attached to the 45-degree sloping plywood base plate such that their positions relative to the test weir opening could be adjusted by sliding the metal plates up or down the sloping surface. In this manner, the relative discharge between the test weir and overflow weirs could be varied.

No weir training walls were attached adjacent to the semicircular weir opening.

Methods

The independent variables in the study were:

Total Discharge.- The total discharge (Q) through the flume was varied.

Relative Discharge.- The relative discharge between the semicircular weir (QWW) and the overflow weirs (QOW) was varied.

The tailwater depth was held constant at 3.0 feet.

The procedure began by setting the overflow weir plates in a position such that some overflow would occur before the semicircular weir was full. The pump was then activated, the tailwater pool allowed to fill to equilibrium, and the water surface elevations, total discharge, standing wave height and position, were determined by the same procedures used in the main weir selection study.

Critical depth (Y_c) was assumed to occur directly above the overflow crest. It was measured with a hand held scale. The discharge of the overflow weirs was calculated with the following equation.

$$QOW = LOW(g(Y_c)^3)^{1/2}$$

where LOW = length of overflow weirs (3.0 feet).

The semicircular weir discharge (QWW) was calculated by the following relation.

$$QWW = Q-QOW$$

The jet shapes, standing wave, and general pool flow patterns were then described and photographed.

The above procedure was repeated for three additional-discharge combinations.