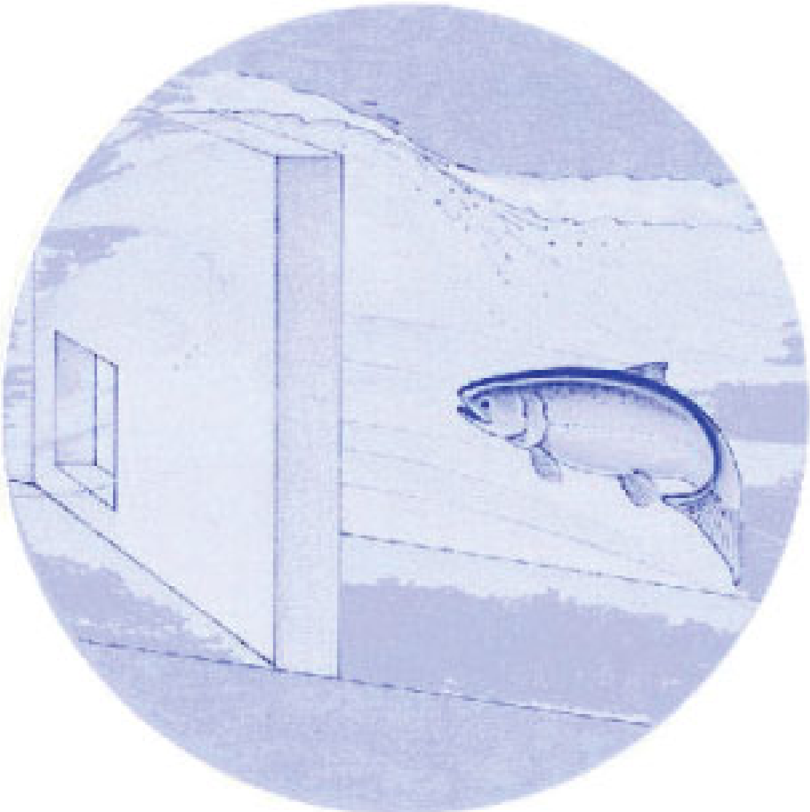
New Concepts in Fish Ladder Design: Analysis of Barriers to Upstream Fish Migration, Volume IV of IV

Investigation of the Physical and Biological Conditions Affecting Fish Passage Success at Culverts and Waterfalls

Final Report
1982 - 1984



DOE/BP-36523-1

August 1985

This Document should be cited as follows:

Powers, Patrick, John Orsborn, "New Concepts in Fish Ladder Design: Analysis of Barriers to Upstream Fish Migration, Volume IV of IV; Investigation of the Physical and Biological Conditions Affecting Fish Passage Success at Culverts and Waterfalls", 1982-1984 Final Report, Project No. 198201400, 134 electronic pages, (BPA Report DOE/BP-36523-1)

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

This report was funded by the Bonneville Power Administration (BPA), U.S. Department of Energy, as part of BPA's program to protect, mitigate, and enhance fish and wildlife affected by the development and operation of hydroelectric facilities on the Columbia River and its tributaries. The views in this report are the author's and do not necessarily represent the views of BPA.

FINAL PROJECT REPORT

Part 4 of 4

Analysis of Barriers to Upstream Fish Migration

An Investigation of the Physical and Biological Conditions Affecting Fish Passage Success at Culverts and Waterfalls

Prepared by

Patrick D. Powers
and
John F. Orsborn

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

Submitted to

Bonneville Power Administration

Part of a BPA Fisheries Project on the

DEVELOPMENT OF NEW CONCEPTS IN FISHLADDER DESIGN

Contract DE-A179-82BP36523

Project No. 82-14

Auqust, 1985

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure (cont.) Page

Figure (cont.) Page

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 Engineering
Washington 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 fi shways 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 assistinq in the enhancement and restoration of fisheries resources from the perspective of fish passage problems and their solution. Promisinq 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 drivinq 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 desiqn. 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 developinq 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. Klinqer, and Walter C. Mih.)

This volume covers the broad, though relatively short, historical basis for this project. The historical developments of certain desiqn 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], OF 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- confiquration, 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 OF 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 beinq 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 Proqram 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 qratitude to numerous active and retired aqency 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
Doug Arndt - NPD, USCE
Bill M. Bakke Director, Trout and Salmon Resource Center
Ken Bates - WDOF
Milo Bell - Consultant
Ted Bjornn - Idaho Cooperative Fishery Unit
Roger Boqden - WDOG
Bert Carneqie - ODFW
Wayne Daley - KCM
Brian Dane - Canadian Fisheries and Marine Service
Mike Dell - Grant Co. PUD
Ivan Donaldson - Retired
Edward Donahue - Fish Pro Consultants
Ray Finnigan - Canadian Fisheries and Marine Service
M. Fretwell - International Pacific Salmon Fisheries Commission
Jim Haas - ODFW
Thomas M. Humes - Consultinq Western, Ltd., Cranbrook, B.C.
John Hutchins - Anderson, Bjornstad, Kane and Jacobs
Chris Kellogg - Corrosion Controllers, Inc.
Christine Moffitt - Idaho Cooperative Fishery Unit
Bob Pearce - NMFS
Jim Riis - South Dakota Dept. of Game, Fish and Parks
Charles Ritzi - Consultant, Winthrop, Maine
Emil Slatick - NMFS
Huqh Smith - Retired
Gerry Taylor - B.C. Ministry of the Environment
Clark Thompson - Retired
Chuck Waqner - Retired
Dick Weaver - Retired
Russ Webb - WDOF

Our special acknowledgement of helpful cooperation goes to the Washinqton Department of Fisheries for the use of its hatcheries for field testing of our new fishway desiqns In particular we wish to thank Dennis Popochock for use of the Johns Creek facility.

The advice, guidance, criticism and support of our BPA contracting officer's representative, Thomas S. Vogel, were extremely important to the success of this project. His sugqestions at critical points were very beneficial.

The project personnel were:

Robert G. Aaserude
Robin Bayley
Thomas W. Bumstead
Kathy Cox
Diane Hilliard
Peter Hines
C. J. Khisty
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

ANALYSIS OF BARRIERS TO UPSTREAM FISH MIGRATION

ABSTRACT

This paper presents a detailed analysis of waterfalls and culverts as physical barriers to upstream migration by salmon and trout. Analysis techniques are based on combining barrier geometry and stream hydrology to define the existing hydraulic conditions within the barrier. These conditions then can be compared to known fish capabilities to determine fish passage success. A systematic classification system is developed which defines the geometric and hydraulic parameters for a given stream discharge. This classification system is organized in a format that can he used to catalog barriers in fisheries enhancement programs. The analysis compares hydraulic conditions and fish capabilities in detail, as the fish enters the barrier, attempts passage and exits the barrier. From this comparison the parameters which prohibit passage can be determined. Hydraulic conditions are a function of the barrier qeometry and stream hydrology, and the stream flow is constant at the time each step in analysis is performed. Therefore, the barrier geometry must be modified to alter the hydraulics to meet fish capabilities. Modifications can he accomplished by: installing instream "control" structures which deflect the flow or raise pool levels; blasting to alter or remove rock; and installing a fishway to bypass the barrier. Modifications should not be attempted until the analysis defines the excessive parameters which should be modified.

INTRODUCTION

When adult salmon and steelhead trout enter freshwater, maturing fish stop feeding and rely on energy reserves stored in body fat and protein to carry them through migration and spawning. The rate of sexual maturity is established by heredity, and cannot adjust to delay. Barriers which cause excessive delay and abnormal energy expenditures can result in mortality either during the migration or in the spawning areas. These barriers can be natural or artificial, as well as physical, chemical or thermal. Natural barriers consist mainly of waterfalls and debris jams, and artificial barriers consist mainly of dams, culverts and log jams. This study will consider only those barriers consisting of waterfalls or culverts that partially or totally obstruct salmon and trout upstream migration. In addition to existing barriers which delay or totally block upstream migration, spawninq areas which were originally accessible have become inundated by reservoirs and other instream modifications. Therefore, existing barriers must be modified to further open the "window of passage" to spawning areas.

The potential for deriving benefits from alleviatinq barriers to migration is high, but in the remote areas where these barriers usually exist, the cost of traditional fish ladders and construction methods usually outweigh the benefits to be gained. Some barriers lend themselves to simple solutions such as blasting a series of pools to assist fish passage. Rut in many cases an analysis of the geometric, geologic, hydrologic and hydraulic characteristics needs to be made so that alternative solutions can be generated and compared. Stuart (1964) suggests that the behavior of migrating salmonids can be correlated directly with the hydraulic conditions in the stream channel. This relationship is the basis for this study.

Because stream flows and site geometry control stream width, depth and velocity, the hydraulic parameters are a function of the geomorphic and hydrologic parameters. Given the geomorphic conditions at a site, considered to be constant, and the hydrologic conditions which are variable within a range of values, an analysis of the hydraulic conditions related to fish capabilities can determine the impact the barrier has on fish passage success. These relationships can be seen in the flow chart in Figure 1. The objectives of this study are to:

1. develop a classification system for waterfall and culvert barriers;
2. develop methods for analyzing harriers using site geometry, hydrology and hydraulics, and by relating the hydraulics to fish capabilities; and
3. generate "parameter specific" solutions to assist fish past barriers without the installation of a typical fishway.

It is not within the scope of this study to develop analytical methods for more complex barrier structures but to develop the conceptual basis for these methods. Complex barrier analysis would require extensive field work and/or physical model testing. It is the author's intention to use this study as a foundation to further develop analytical methods for analyzing more complex barrier systems.

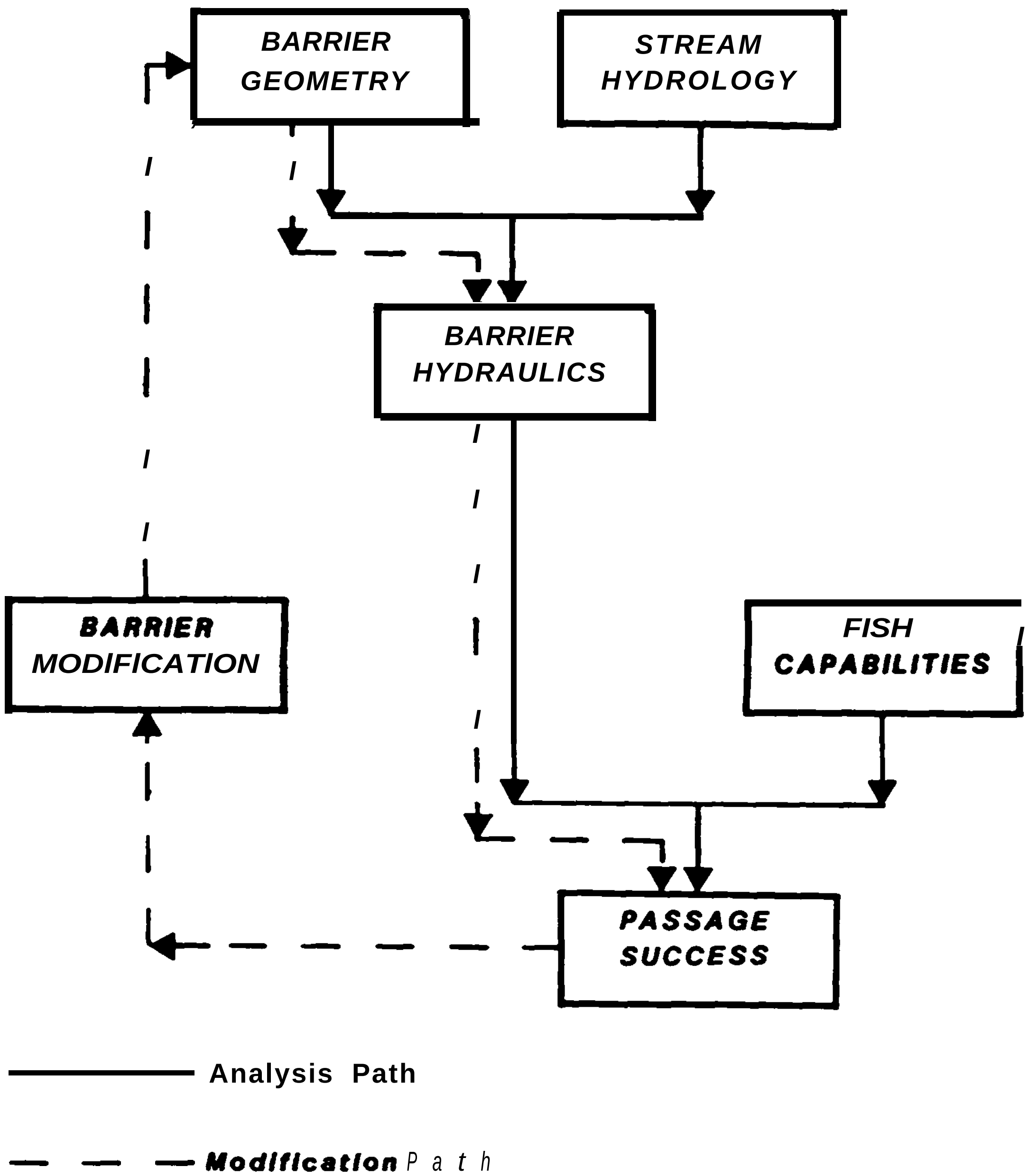


Figure 1. Flow chart analysis of a migration barrier.

Because of the wide variations in the forms of barriers, a classification system is required to facilitate the analysis and subsequent qeneration of solutions to fish passage problems. Evidence of waterfall classification in the literature points only to a system based on genetic grounds (Fairbridge, 1968). The writer is not aware of a systematic' classification system of waterfalls which correlates fish passage success. The requirements for an adequate classification system include the following:

1. site geometry,
2. hydraulic conditions, and
3. fish passage success.

Based on these three factors a classification system for waterfall and culvert barriers was developed to aide in assessing, analyzing and modifying barriers.

Natural rock barriers can be in the form of falls, chutes or cascades. Falls (Fig. 2) are characteristic of steep (commonly vertical) overflow sections where the impact of the falling water scours a deep plunge pool at the foot of the falls. Falls form elevation barriers where the difference in water surface elevation between the upstream water surface and the plunge pool, and/or the horizontal distance from the falls crest to the plunge pool exceeds the leaping capabilities of the pertinent fish species. Often the leaping efficiency of the fish is constrained by unfavorable plunge pool conditions. If the pool is shallow, the falling water will strike the bottom creating violent pool conditions, thus affecting the fishes' orientation for leaping. Even if a fish has successfully leaped a falls, it can be swept back due to high velocities and/or shallow depths above the falls crest. A cantilevered culvert outfall (Fig. 3), where the fish must leap to enter the culvert, is similar geometrically to a fall. The only difference is the nature and geometry of the bed over which the water flows.

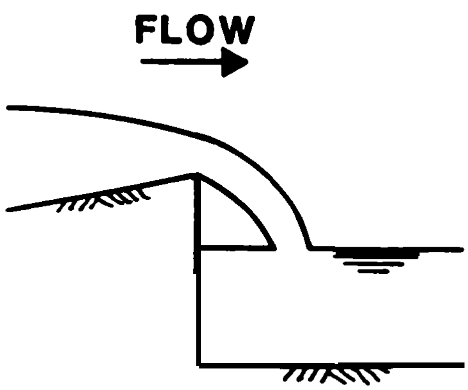


Figure 2. Profile view of a fall

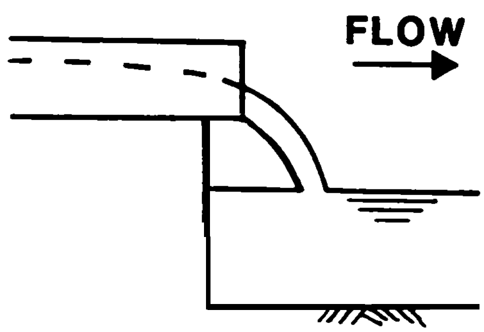


Figure 3. Profile view of a cantilevered culvert

Chutes (Fig. 4) are characterized by steep, sloping, rough open channels, offering the fish a high velocity medium in which to swim without resting areas. Chutes form velocity barriers where the water velocity near the downstream entrance to the chute exceeds the fishes' swimming speed. Often a standing wave will develop at the foot of the chute. If the downstream plunge pool is shallow, the standing wave may form too far downstream for the fish to rest before bursting into the chute. Even if the velocities down in the chute are within the fishes' swimming speed, the depth of flow and slope length could prohibit passage. Also, chutes often pass a bulked mass of water and entrained air which offers a poor medium for swimming. Stuart (1964) suggests that when flowing water entrains air, the density of the mixture will be reduced and will detract from the propulsive power of the fishes' tail and diminish the buoyancy of the fish. Air entrainment also reduces the stimulus of attraction flows. Chutes with steep slopes are very similar to culverts (Fig. 5) where the fish must swim a long slope length. The difference again is in the nature of the bed over which the water flows, and the shape of the flow area. Culverts do not offer an irregular natural boundary which can provide an occasional resting place.

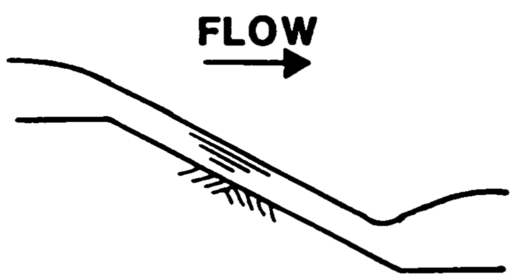


Figure 4. Profile view of a steep/ high velocity chute.

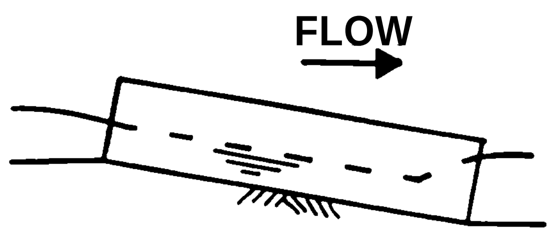


Figure 5. Profile view of a steep/ high velocity culvert.

Cascades (Fig. 6) are characterized by a reach of stream where large instream roughness elements, such as boulders and jutting rocks, obstruct and/or churn the flow into violently turbulent white water. Cascades often present fish with high velocities, excessive turbulence, and orientation difficulties which make it impossible for a fish to effectively use all its swimming power. If the rouqhness elements (or boulders) are large, they will often create periodic resting areas within the cascading reach.

Jackson (1950) noted that the sockeye salmon trying to pass Hell's Gate on the Fraser River in British Columbia almost succeeded in "eroding their noses back to their eye sockets" by contact with the bank while trying to maintain equilibrium in the turbulent water.

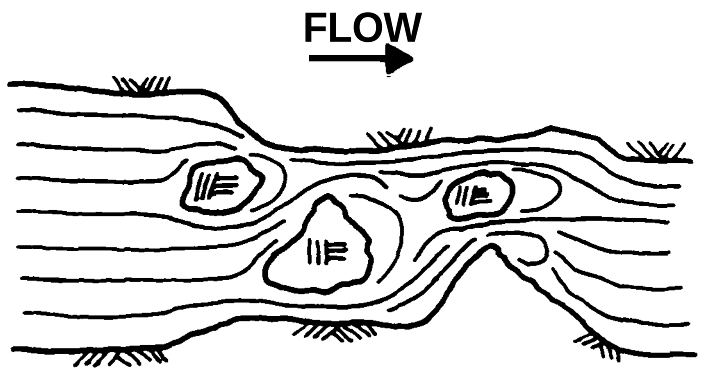


Figure 6. Plan view of a cascade.

Pioneering works in the field of analyzing waterfall barriers has been conducted mostly by fisheries biologists through methods such as field sampling by electrofishing, skin diving or just personal observation of fish passage. No significant research concerning the fluid mechanics of waterfalls has been conducted. There has been considerable work done on culverts to relate depth, velocity and discharge relationships, as reported by Dane (1978), Evans & Johnston (1980) and others. The obstruction at Hell's Gate focused a considerable amount of attention on the velocities and turbulence that sockeye salmon were facing. In that study, river velocities were measured by two methods:

1. the highest average velocities from the river discharge and the area of smallest cross section, and
2. average mid-stream surface velocities using a float.

Highest average velocities ranged from 12.9 to 17.5 fps, but Jackson (1950) noted that these computed velocities were inaccurate because of the extremely rough channels at Hell's Gate. The conclusion was that the combination of turbulence and high velocities prevented the passage of large runs of sockeye salmon. Clay (1961) suggests the following engineering field work that is required before design and construction of a fishway at a fall can be initiated:

1. topographic surveys;
2. record magnitude, direction and location of velocities;
3. locate points of turbulence, upwellings and the intensity and location of points of surge and how they relate to fish behavior; and
4. river discharge measurements.

Clay also suggests various types of fishways that can be installed at natural obstructions. He notes that because of the wide range of flows at a natural obstruction the vertical slot type of fishway should be used because it can accept a wide range of water level fluctuations while still working effectively.

Most of the design work on assisting fish past waterfalls without the installation of a fishway rests in project files. Many of these waterfalls were observed to be barriers due to shallow depths, high velocities and/or elevation drops, and were modified by blasting to try to reduce the magnitude of these constraints to passage. This study will develop detailed analysis procedures to generate "parameter specific" solutions to the "real passage problems" at barriers.

FISH CAPABILITIES

Swimming Speeds

The objective of this section is to document values for the upper limits of swimming speeds, leaping capabilities and swimming distances for adult salmon and steelhead trout, and to evaluate their performance in a format useful for analyzing barriers. In order to differentiate between water velocity, fish velocity and relative velocity of the fish to the water, the term "speed" will be used to denote the rate of motion of the fish as an object with respect to a reference plane. Relative speed will denote the difference between fish speed and the velocity of the water, that is:

$$VR = VF - VW \tag{1}$$

where VR = relative speed of the fish to the water; VF = speed of the fish; and VW = velocity of the water.

Ranqes of speeds are classified in the literature accordinq to the function, or relative speeds which fish can maintain. The classification of speeds published by Hoar and Randall (1978) which will be used in this study, is:

- sustained - normal functions without fatigue,
- prolonged - activities lasting 15 seconds to 200 minutes which result in fatigue
- burst - activities which cause fatigue in 15 seconds or less.

Ranges of speeds for these classification are shown in Table 1 from Bell (1973).

Table 1. Fish speeds of average size adult salmon and steelhead trout as reported by Bell (1973).

Specie		Fish Speed (fps)	
	Sustained[b]	Prolonged[b]	Burst
Steelhead	0-4.6	4.6-13.7	13.7-26.5
Chinook	o-3.4	3.4-10.8	10.8-22.4
Coho	o-3.4	3.4-10.6	10.6-21.5
Sockeye	0-3.2	3.2-10.2	10.2-20.6
Pink & Chum[a]	0-2.6	2.6-7.7	7.7-15.0

[a]Pink & Chum salmon values estimated from leap heights of 3 to 4 ft at waterfalls.
b Called cruising and sustained, respectively, in Bell (1973).-

Bell suggests that fish normally employ sustained speed for movement (such as migration), prolonged speed for passage through difficult areas, and burst speed for feeding or escape purposes.

For determining fish passage success over waterfalls and through culverts, some percentage of the upper limit of burst speed will be used which will depend on the physical condition of the fish. To determine actual values of these percentages, a study was conducted on coho and chum salmon swimming up a high velocity chute at Johns Creek Fish Hatchery near Shelton, Washington (see Appendix II). From this study it was concluded that most of the time the salmon were swimming at 50%, 75% and 100% of their maximum burst speeds suggested by Bell (1973), depending on the condition of the fish. These percentages will be used to define a coefficient of fish condition (C_{fc}). Values for C_{fc} are given in Table 2. with the corresponding characteristics of each. From Table 2. the actual speed that should be used for passage analysis is:

$$VF = VFB(C_{fc}) \tag{2}$$

where VFB = maximum burst speed suggested by Bell (1973) Table 1; and C_{fc} = coefficient of fish condition, Table 2.

Table 2. Coefficient of fish condition (C_{fc}). Values based on observations and data taken for coho and chum salmon at Johns Creek Fish Hatchery near Shelton, Washington, December, 1983.

Fish Condition	Coefficient(C_{fc})
Bright; fresh out of salt water or still a long distance from spawning grounds; spawning colors not yet developed	1.00
Good; in the river for a short time; spawning colors apparent but not fully developed; still migrating upstream	0.75
Poor; in the river for a long time; full spawning colors developed and fully mature; very close to spawning grounds	0.50[a]

[a] C_{fc} = 0.50, corresponds to the upper limit of prolonged speed from Table 1.

Leaping Capabilities

When fish leap at waterfalls, their motion can best be described as projectile motion (i.e. curved two-dimensional motion with constant acceleration). Neglecting air resistance, the equations for projectile motion are:

$$x = (V_0 \cos\theta)t, \text{ and}$$

$$y = (V_0 \sin\theta)t - (1/2)gt^2$$

where x = horizontal distance the projectile travels, y = vertical distance the projectile travels, V, = initial velocity of the projectile, 8 = angle from the horizontal axis the projectile is fired, t = time, and q = acceleration of gravity (32.2 ft/sec^2). Rewriting the equations for x and y in terms of the components that relate to fish leaping at a waterfall yields:

$$XL = [VF(\cos\theta L)]t \text{ and} \tag{3}$$

$$HL = [VF(\sin\theta L)]t - (1/2)gt^2 \tag{4}$$

where XL = horixontal distance or range of the leap at some time (t), HL = height of leap at some time (t), VF = fish speed, θL = angle of leap from the plunge pool, and g = acceleration of gravity acting downwards (32.2 ft/sec^2). By combining equations (3) and (4) and eliminating t from them, we obtain:

$$HL = (\tan\theta L)XL - g(XL)^2/2(VF\cos\theta L)^2 \tag{5}$$

which relates HL and XL and is the fish trajectory equation. Since VF, θL and g are constant for a given leap, equation (5) has the parabolic form of:

$$HL = b(XL) - C(XL)^2$$

Hence the trajectory of a fish is parabolic. Equation (5) is plotter! in Figures 7, 8 and 9 for six species of salmon and trout leaping at angles of HO, 60 and 40 degrees. These leaping curves will be utilized later to analyze leaping conditions at a barrier. At the highest point of the fish's leap, the vertical component of the velocity is zero, that is:

$$VF_y = VF(\sin\theta L) - gt = 0$$

Solving this equation for t gives:

$$t = VF(\sin\theta L)/g$$

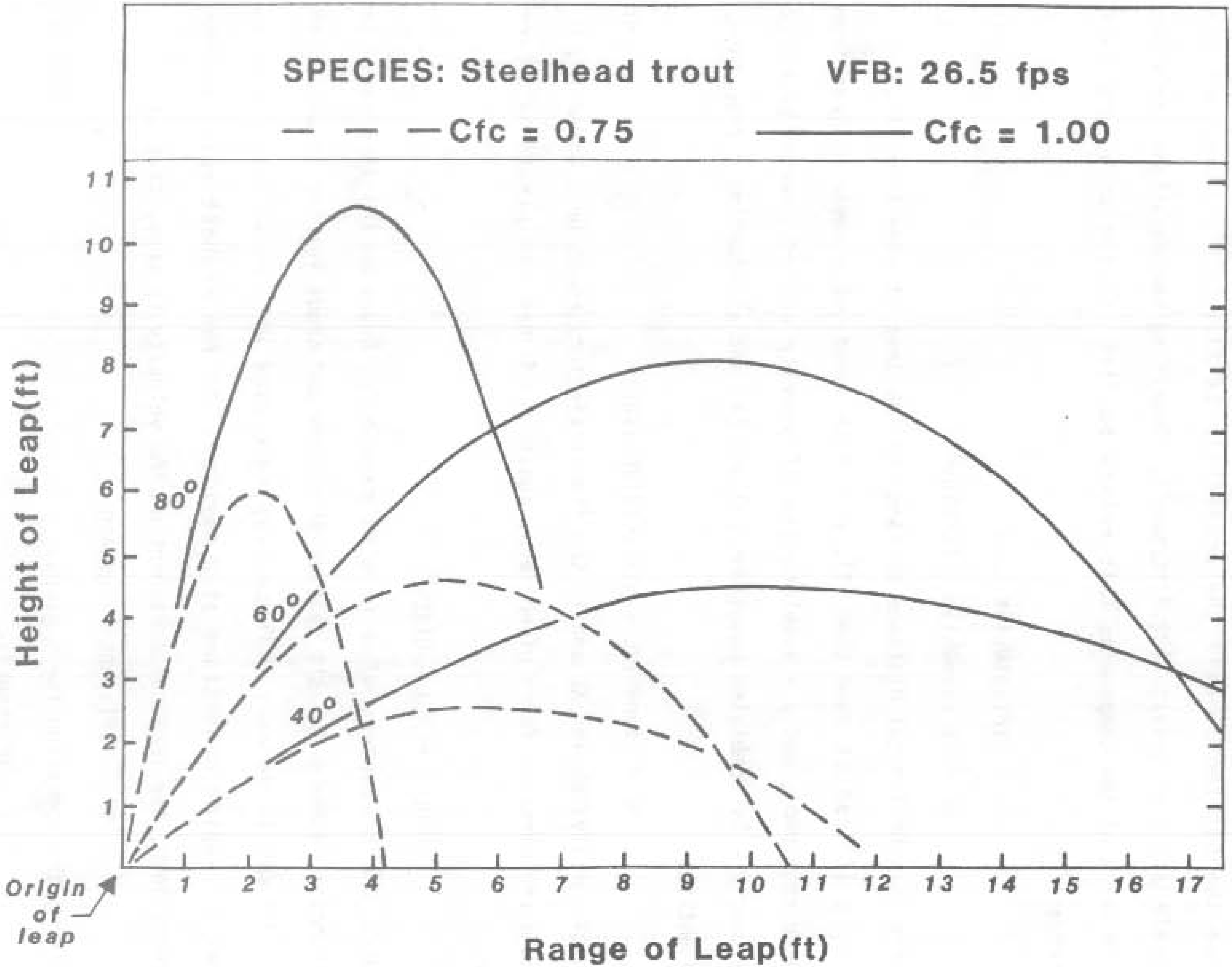


Figure 7. Leaping curves for steelhead trout.

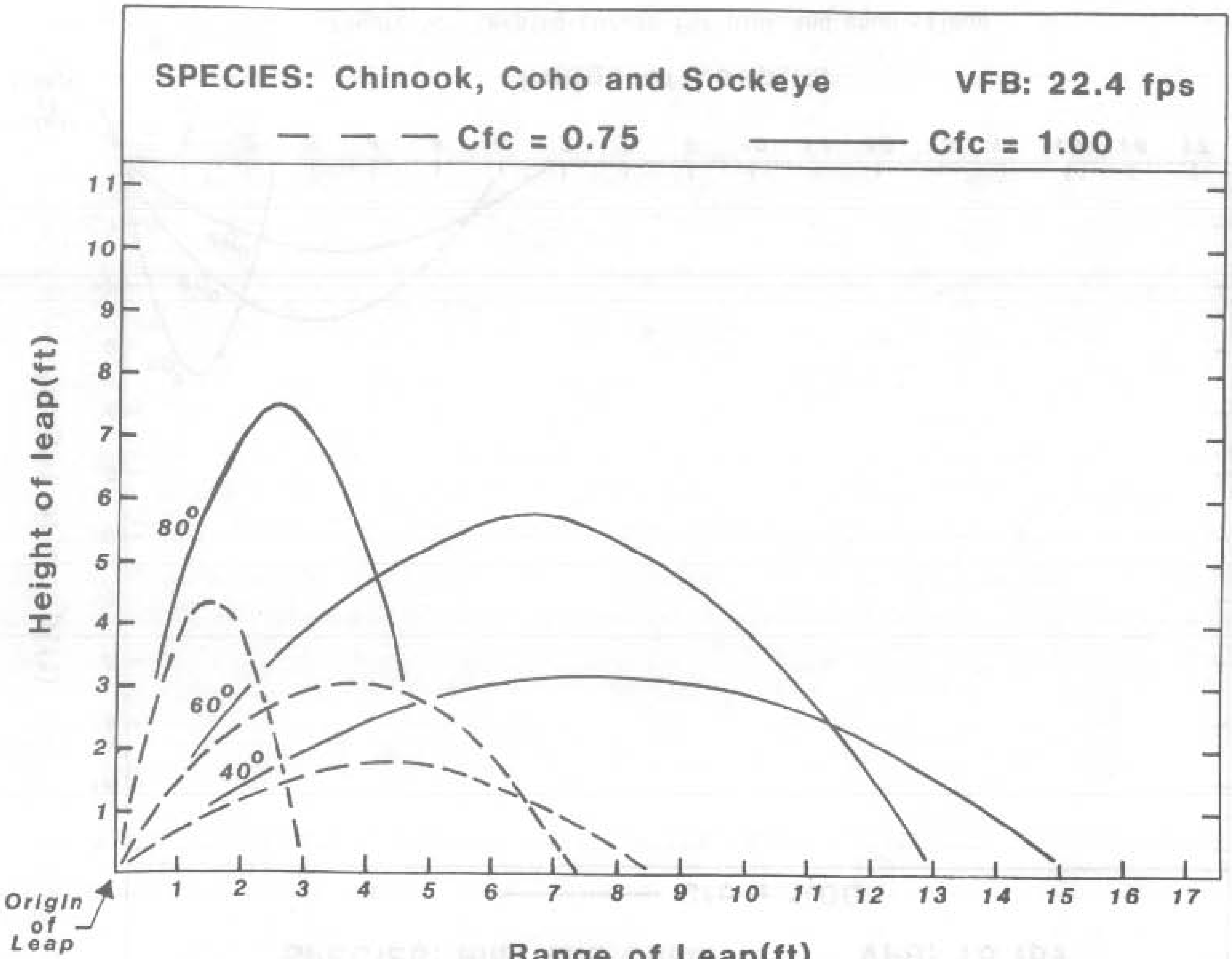


Figure 8. Leaping curves for chinook, coho and sockeye salmon.

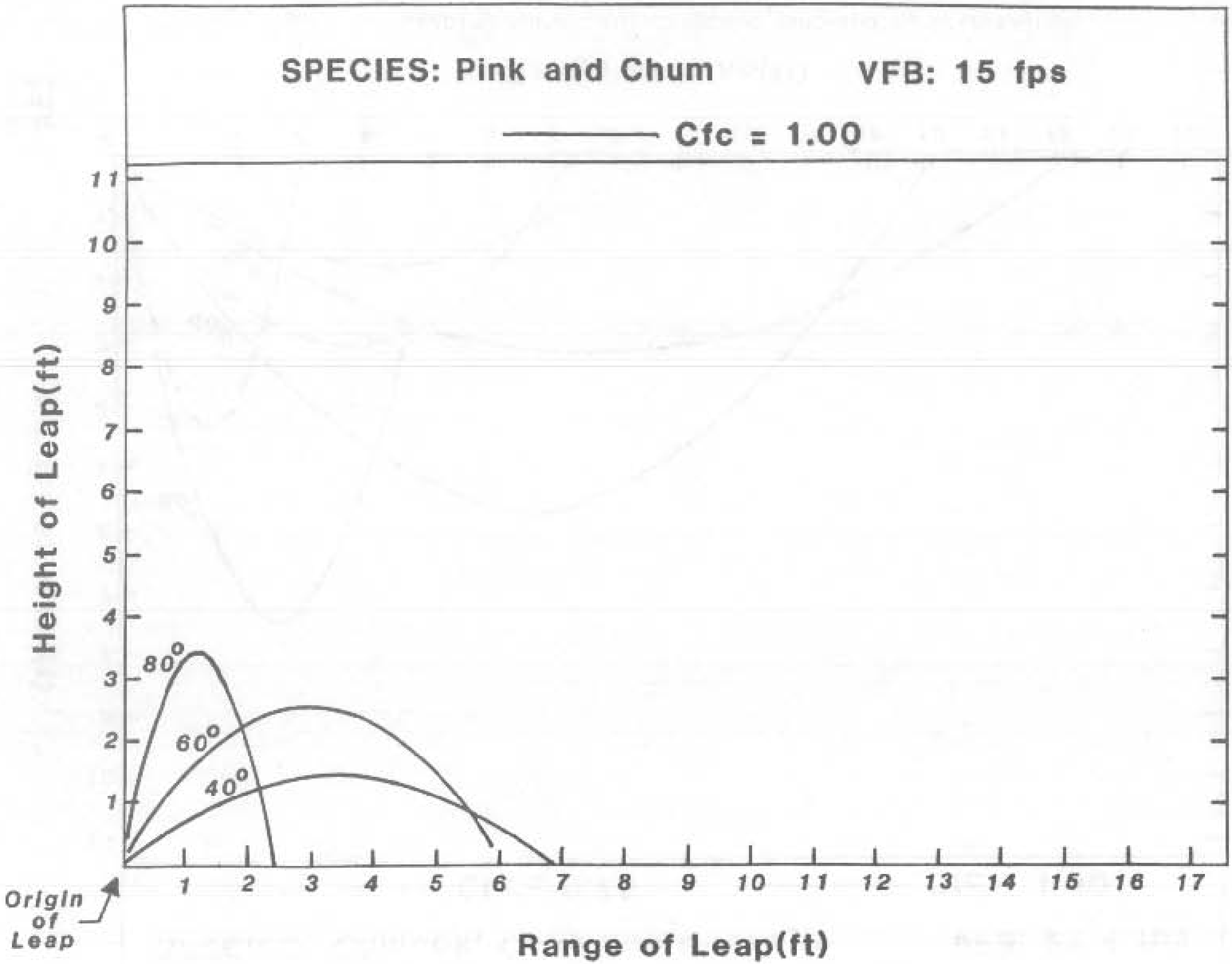


Figure 9. Leaping curves for pink and chum salmon.

Substituting this equation for t into equation (3) and (4) yields:

$$HL = (VF(\sin\theta L))^2/g - (1/2)(VF(\sin\theta L)^2)/g$$

$$HL = (VF(\sin\theta L))^2/2g \qquad (6)$$

$$XL = VF^2(\cos\theta L)(\sin\theta L/g) \qquad (7)$$

Equations (6) and (7) give the maximum height of the fish's leap and the horizontal distance traveled to the maximum height.

Bell (1973) suggests the following formula for computing velocities at which fish leave the water surface:

$$VF = (2g(HL))^{0.5}$$

Solving this equation in terms of the leap height (HL) gives the same result as equation (6), using a leaping angle of 90° to the water surface. Aaserude (1984) noted that to determine the true leaping height above the water surface, the length of the fish should be added to equation (6) because the fish uses its full propulsive power up until the point the fish's tail leaves the water, and once in the air skin drag can he neglected. Since equation (6) and (7) do not include the additive effects of fish length or an upward velocity component often found at the foot of a waterfall in the form of a standing wave (Stuart, 1964), they will be used here as conservative values from the accepted literature.

Swimming Performance

Swimming performance is a measure of the speed which a fish can maintain over a period of time (endurance). The distance a fish can swim is a function of the water velocity, fish speed and fatigue time. Bell

(1973) suggests that burst speed can be maintained-for an estimated 5 to 10 seconds. Relating this range of fatigue time to the range of burst speeds from Table 1, the swimming distances can he computed from:

$$LFS = (VF - VW)TF \qquad (8)$$

where LFS = length the fish can swim, VF = fish speed, VW = water velocity, and TF = time to fatigue. Equation (8) is plotted in Figures 10, 11 and 12 for six species of salmon and trout. An example calculation will show how these figures were derived.

Specie: steelhead

Burst Speed Range: 13.7 to 26.5 fps

Fatigue Time Range: 5 to 10 seconds

Water Velocity: 10 fps

Coefficient of Fish Condition: 0.75

$$LFS = [26.5\ (0.75) - 10]5 = 49 \text{ ft, or}$$

$$LFS = [13.7\ (0.75) - 10]10 = 3 \text{ ft.}$$

Therefore the maximum distance an adult steelhead trout can swim given the condition of the fish and a mean water velocity of 10 fps, is 49 ft. This calculation assumes the water depth to be great enough to submerge the fish and that no air is entrained in the flow. The results are in Fig. 12.

Evans and Johnston (1980) suggest that the distance the fish can swim against a given water velocity is best defined by the curves prepared by Ziemer (1961) which reflect the swimming performance of salmon, steelhead, and smaller trout (Fig. 13). This curve was developed assuming a relative fish speed (VR) of 2.0 fps. From the study reported in Appendix II, it was determined that the average relative speeds for coho and chum salmon swimming up the velocity chute were 1.9 and 2.1 fps respectively, but ranged from values of 1.0 to 3.0 fps. Because of this wide variation, it appears that calculating the maximum distance a fish can swim by simply using relative fish speed does not accurately describe the magnitude of a single passage attempt.

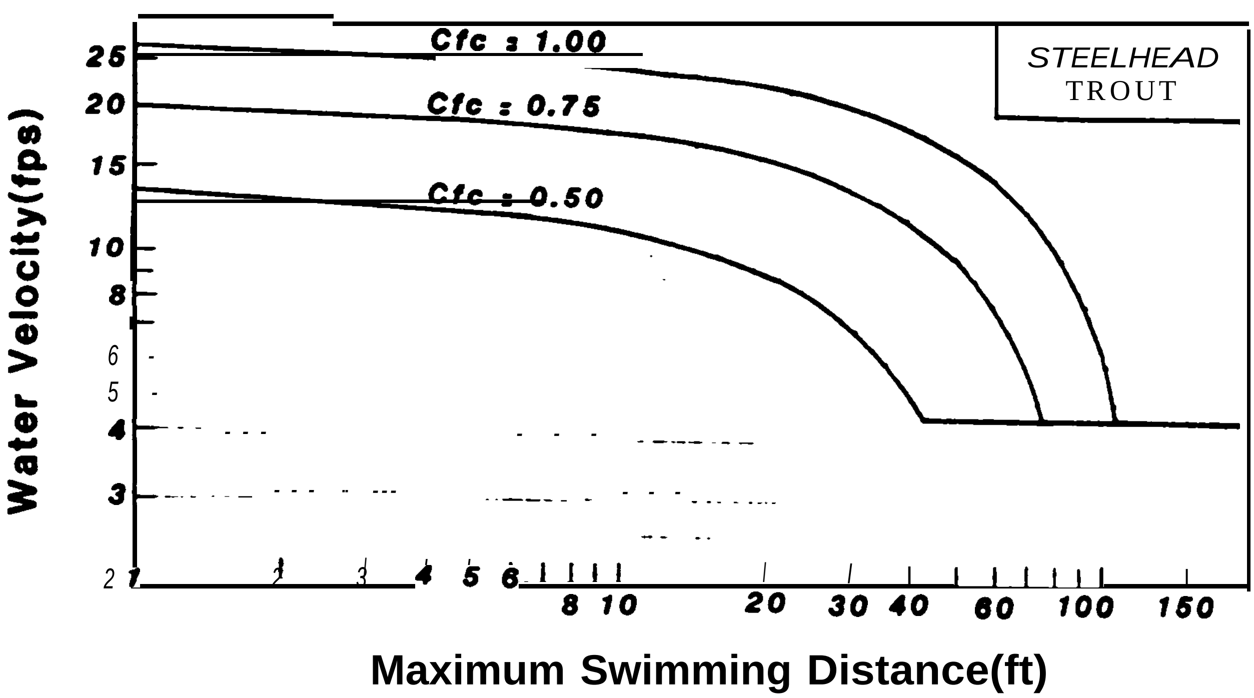


Figure 10. Maximum swimming distance for steelhead trout under three fish conditions.

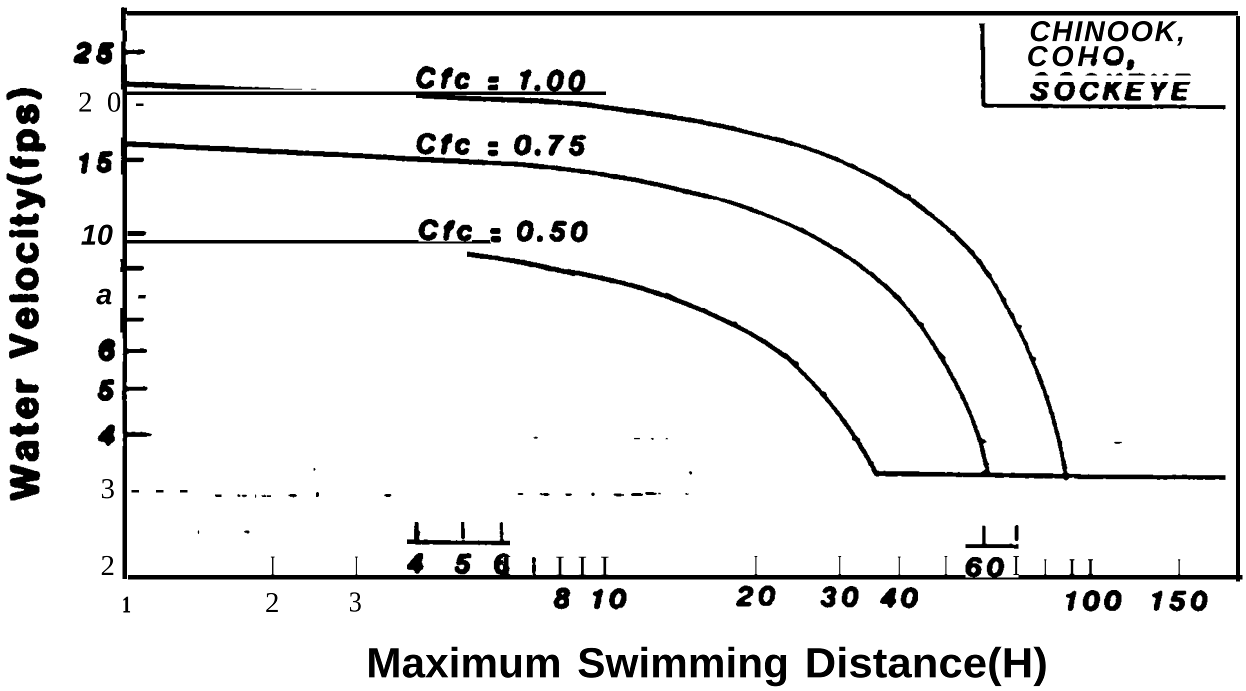


Figure 11. Maximum swimming distance for chinook, coho and sockeye salmon under three fish conditions.

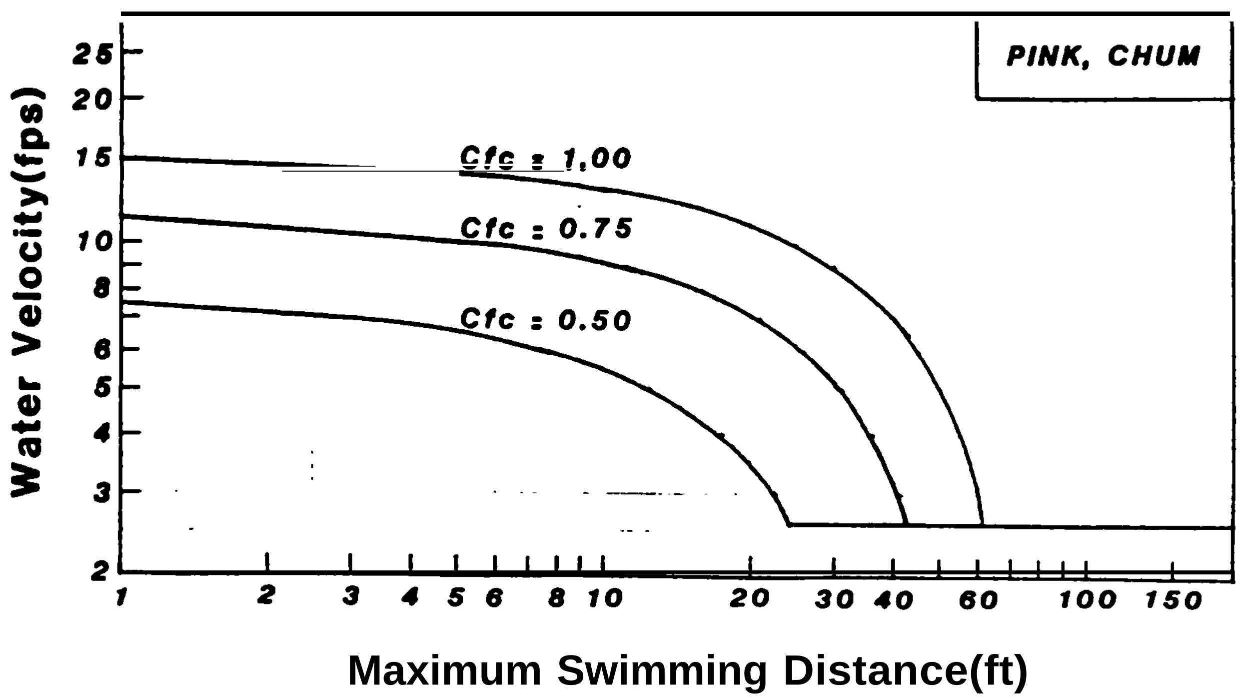


Figure 12. Maximum swimming distance for pink and chum salmon under three fish conditions.

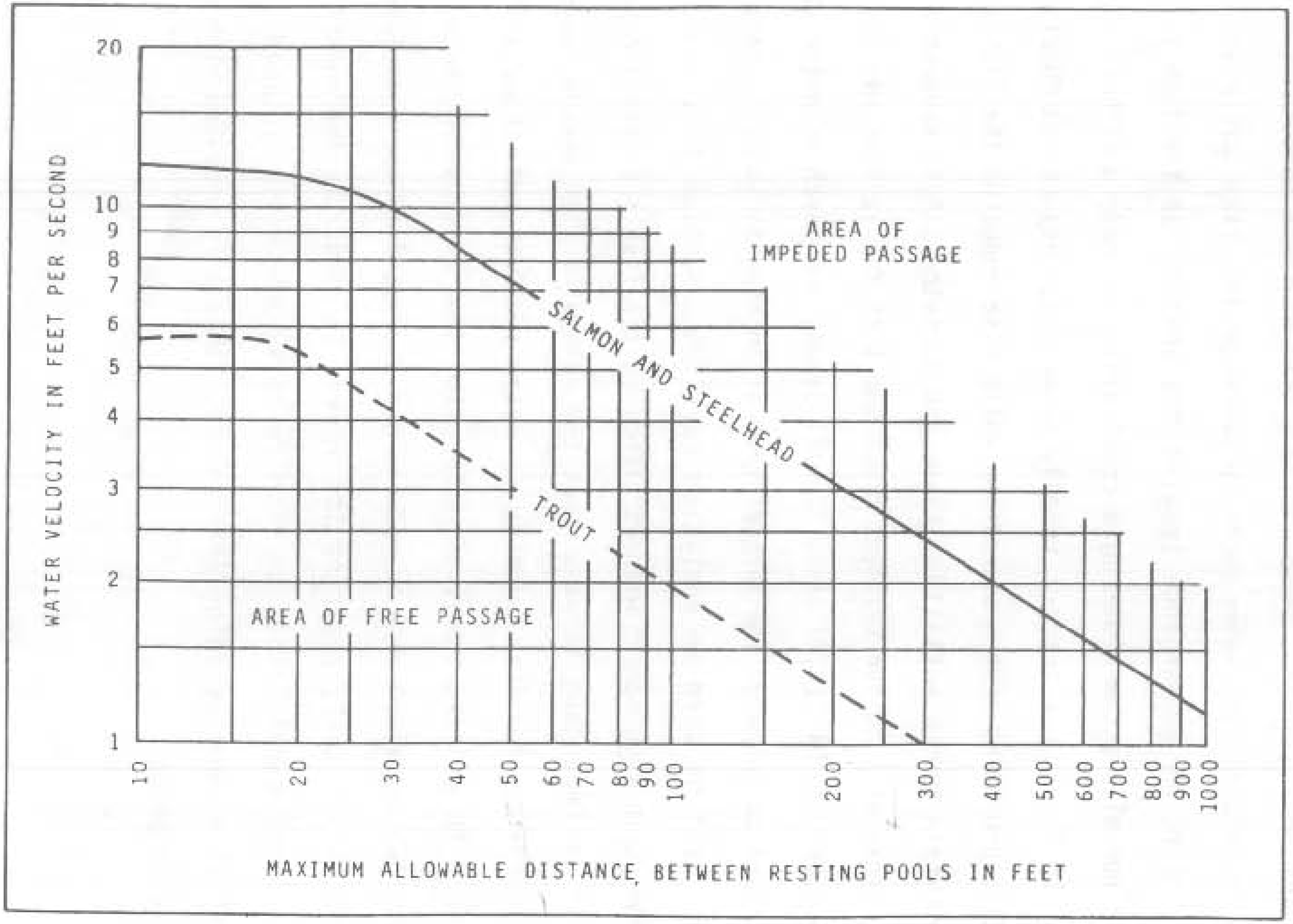


Figure 13. Swimming performance of salmon and trout from Evans and Johnston (1980). Curve developed by Ziemer, State of Alaska, Department of Fish and Game.

"Any factor interrupting or affecting the supply system (oxygen intake) as well as those affecting the propulsive system itself, affects swimming performance" (Webb, 1975). Both of these conditions exist when there is insufficient water depth to submerge the fish while it is swim- minq. Partial submergence impairs the ability of the fish to generate thrust normally accomplished by a combination of body and tail movement. Also, if its gills are not totally submerged, they cannot function effi- ciently, promoting oxygen starvation while also reducing the fish's ability to maintain burst activity. Evans and Johnston (1972) suggest a minimum water depth of 6 in for resident trout and 1 ft for salmon and steelhead. Dryden and Stein (1975) state "In all cases, the depth of water should be sufficient to submerge the largest fish attempting to pass." This limit- ation will be used in analyzing barriers, because this would be the minimum depth requirement without affecting the fish's propulsive system.

It is important to note that the values of fish speeds suggested by Bell (1973) are for fish swiming in water without entrained air (black water). In extreme cases of sufflation the density of the water/air mixture (white water) will be reduced and detract from the propulsive power of the fish's tail, reducing its speed. To summarize the equations that describe the capabilities of fish in terms of swimming speed, leaping capabilities and swimming performance, Table 3 is provided with a nomen- clature of terms.

Table 3. Fish capability equations for swimming and leaping.

Type of Motion	Equation	
Swimming	$VR = VF - VW$	(1)
	$VF = VFB(C_{fc})$	(2)
	$LFS = (VF - VW)TF$	(8)
Leaping	$HL = [VF(\sin\theta L)]^2/2g$	(6)
	$XL = VF^2(\cos\theta L)(\sin\theta L)/g$	(7)

where:

VR = relative swimming speed of the fish,

VF = fish speed,

VW = water velocity,

VFB = burst speed of fish,

C_{fc} = coefficient of fish condition,

LFS = maximum swimming distance of fish,

TF = time to fatigue,

HL = height of leap,

XL = horizontal distance of leap at fish's high point,

θL = angle of leap from water surface, and

g = acceleration of gravity (32.2 ft/sec^2).

CLASSIFICATION OF BARRIERS

To facilitate analyses and subsequent generation of solutions to fish passage problems a classification system needs to be introduced to define the parameters involved in the analysis. The objective of this chapter is to develop a systematic method for classifying barriers based on the conditions that affect fish passage success. Barrier classification sheets will be developed to enable fisheries personnel to make use of the classification system in fisheries enhancement programs, both to catalog waterfall and culvert barriers, and to design their modifications.

Evidence of classification for waterfalls in the literature was found only in terms of the site geomorphology (or origin of formation) (Fairbrige, 1968). No classification of waterfalls could be found in the literature that correlated site hydraulics or fish passage success to geometry. Pryce-Tannatt (1937) noted, "Obstructions are many and varied. It would be useless to attempt to classify them beyond distinguishing between the <u>comparatively mild</u>, the <u>definitely difficult</u>, and the <u>completely impossible</u>." Dane (1978) suggests a classification of obstructions for culvert barriers based on blockage as follows:

1. Total--impassable to all fish all of the time,
2. Partial--impassable to some fish all of the time, and
3. Temporary--impassable to all fish some of the time.

The classification system developed for this study will analyze the site geometry and hydraulics, and how they interrelate to fish passage success. Because waterfalls in nature consist of such a wide range of geologic and hydrologic combinations, a classification system for waterfalls should include several components, each of which describes waterfalls differently.

The classification system proposed here consists of four components: (1) class, (2) type, (3) magnitude and (4) discharge, extending from general to specific (Table 4). Class describes the flow patterns, number and characteristics of fish passage routes and site geometry in plan view. The class is determined by observing the characteristics in Table 4. Type describes the bed slopes, pool depths and geometry of the barrier in longitudinal profile, and therefore requires an engineering survey of the barrier site. Magnitude describes the elevation differences, water velocities and slope lengths the fish must negotiate. Because the class, type and magnitude of the barrier will vary with discharge, the fourth item for classification will be to accurately estimate or measure the discharge at the time of observation.

Also, a degree of passage difficulty rating will be applied, based on a range from 1 to 10, one being the least difficult to pass and ten the most difficult. This is a subjective comparative raating of barrier class characteristics in reference to fish passage difficulty which is independent of barrier height and velocity. The rating is based on the following assumptions:

1. The differential elevation and water velocities are within the swimming and leapinq capabilities of the species in question.

2. At higher swimming speeds (>9 fps) leaping is more energetically efficient that swimming (Blake, 1983).

3. Fish will be attracted to the area of highest momentum (flow x velocity) when migrating upstream; therefore if multiple paths arc present the fish may try to ascend the one with the highest attraction which will be created by the highest combination of drop, velocity, and discharge.

4. Turbulent flow (or white water) with surges, boils and eddies make it difficult for fish to orientate themselves and make full use of their swimming power.

Table 4. Characteristics of barrier classification components.

Classification Component	Characteristics
Class	Site geometry in plan view. Flow patterns Number of fish passage routes. Characteristics of fish passage routes.
Type	Site geometry in profile. Bed slopes Pool depths
Magnitude	Elevation drops Water velocities Slope lengths
Discharge	The flow rate at which the class, type and/or magnitude were measured.

Class

Waterfall barriers in nature are usually found in three forms; falls, chutes and cascades. From the author's field observations of many harriers, it appears that fall barriers are found either as single or multiple falls, chutes as either simple or complex, and cascades as boulder cascades or turbulent cascades. Combinations of falls and chutes will be denoted as compound barriers. These barrier classes and their characteristics are shown in Table 5 with their corresponding rating for degree of passage difficulty.

A single fall has the lowest degree of difficulty rating (DDR) because the fish has only one route to choose, and it leaps to pass. To determine the actual value of the DDR of 1 to 3, the upstream and downstream conditions must be analyzed. This will be done when barriers are classified by type. Multiple falls (falls in parallel) have a higher DDR than single falls because the fish has several routes from which to choose, and most likely will be attracted to the fall with the highest flow momentum (Stuart, 1964). Simple chutes have a slightly higher DDR than single falls because at high swimming speeds (>9 fps) leaping is more energetically efficient than swimming. Complex chutes have a higher DDR than simple chutes because the fish's propulsive power is reduced in white water. Poulder cascades have a slightly higher DDR than multiple falls because the fish have problems getting orient to leap due to the turbulent resting areas. This analysis can be continued,, comparing each barrier class based on the four original assumptions, for the degree of difficulty ratinq system.

Type

To classify barriers by type, conceptual models will he used which show the geometric and hydraulic relationships that are critical to fish passage success. Fiqures 14 and 15 show conceptual models and the notation used in profile view of a fall and chute respectively. These fiqures are not comprehensive for natural conditions, but the geometric dimensions apply and can fit any situation. Cascades are not included here because to determine the type of barrier requires measurements of bed slopes and pool depths. If these measurements could be made in a cascading reach, then a cascade would simply consist of a series of falls-and/or chutes and there would be several different types for one barrier class (i.e. several falls and/or chutes within a cascade).

Table 5. Subjective comparative rating of barrier class characteristics in reference to fish passage difficulty, independent of barrier height and velocity. Assumes passage success by strongest fish.

Class	Characteristics	Degree of Difficulty Range
Single falls	Entire stream flows through a single opening offering one path for fish passage.	1-3
Multiple falls	Flow divides through two or more channels offering the fish with several passage routes of varying difficulty.	3-5
Simple chute	Unvarying cross sections and constant bottom slope (steep), with supercritical flow at all stages	2-4
Complex chute	Varying cross sections, several changes in bed slope and/or curved alignment in plan view. White water at all stages.	4-6
Boulder cascades	Large instream boulders which constrict the flow creating large head losses from upstream to downstream sides of boulders. Intermediate resting areas in very turbulent pools.	5-7
Turbulent cascades	Large instream roughness elements or jutting rocks which churn the flow into surges, boils, eddies, and vortices. No good resting areas.	7-10
Compound	Combinations of single falls and/or simple chutes (e.g., culvert with high velocity and outfall drop)	3-7

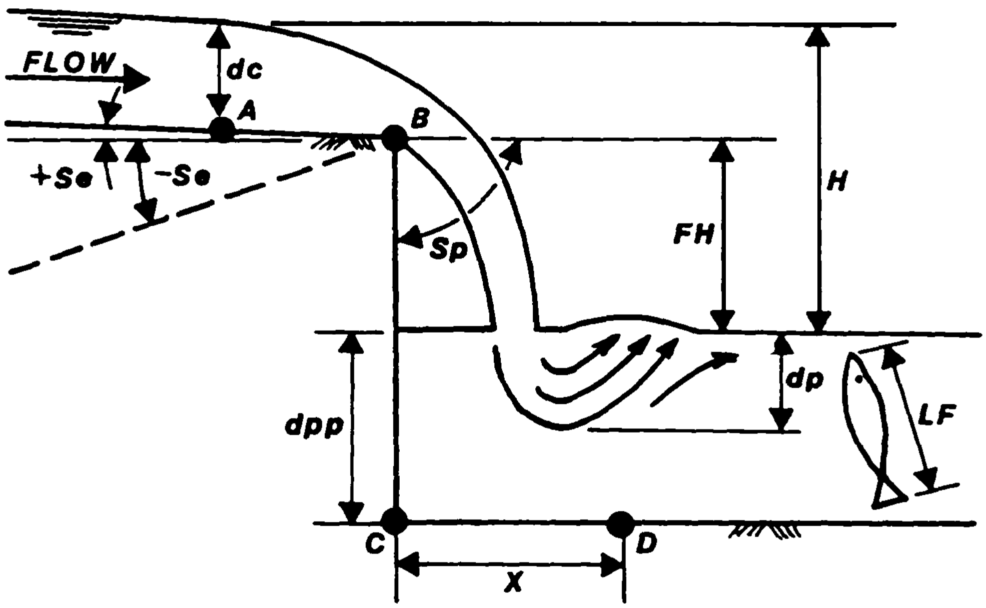


Figure 14. Conceptual model of a fall, where: A = point on fish exit bed slope where critical depth occurs; B = elevation of crest; C = furthest point upstream on bed of plunge pool; D = point just downstream of falling water (or standing wave) on bed of plunge pool; Se = fish exit slope; Sp = fish passage slope; dc = critical depth (point A); dpp = depth in the plunge pool; dp = depth the falling water plunges; X = horizontal distance from the crest (point B) to standing wave (point D); FH = fall height; H = change in water surface elevation; and LF = length of fish.

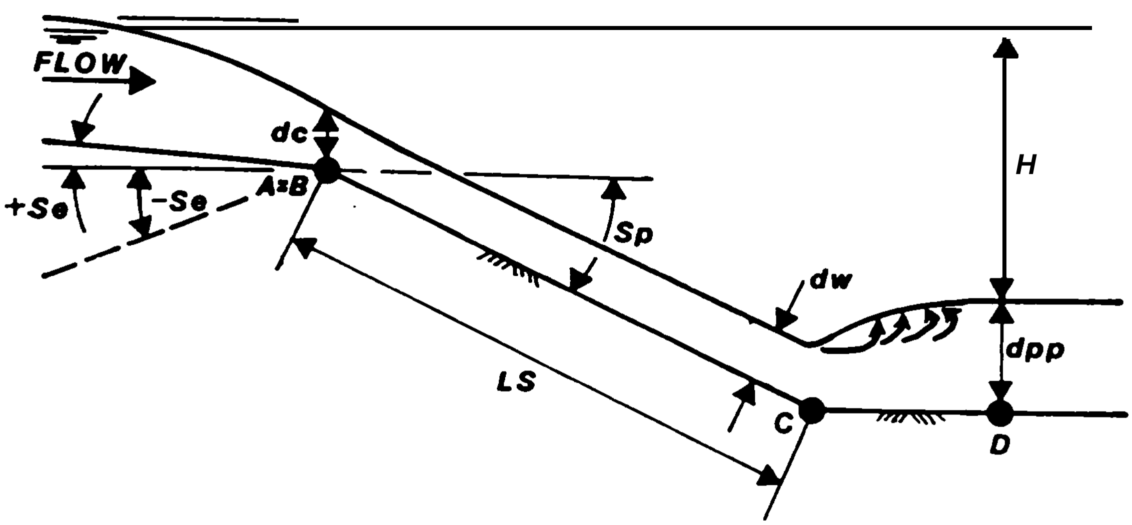


Figure 15. **Conceptual model of a chute, where: A = point on fish exit bed slope Where critical depth occurs; B = elevation of crest; C = furthest point upstream on bed of plunge pool; D = point just downstream of standing wave (or hydraulic jump) on bed of plunge pool; Se = fish exit slope; Sp = fish passage slope; LS = length of slope; dc = critical depth (point A); dw = depth of water; dpp = depth in the plunge pool; and H = change in water surface elevation.**

The conceptual models in Fiqures 14 and 15 consist of three zones: (1) the fish exit zone (point A to point B in Figure 16); (2) the fish passage zone (point R to point C in Figure 17); and (3) the fish entrance zone (point C to point D in Figure 18). The notation used to denote the barrier type is given in these figures, and follows outlininq logic from upstream to downstream. The type of barrier will be determined by measuring the exit slope, passage slope and plunge pool depth, and selectinq three characters from the notation, one each from the exit zone, passage zone and entrance zone (e.g. IIB2, would denote a chute barrier with a positive exit slope and a shallow plunge pool). From Figures 16, 17 and 18 it can be seen that there could be any of four different combinations of entrance and exit conditions for each of four passage zones; and thus 16 different types of barriers can exist according to this classification. These models are shown in Figure 19, along with the correspondinq degree of passage difficulty rating. The similarities with culvert flow and qeometry are denoted by dotted lines.

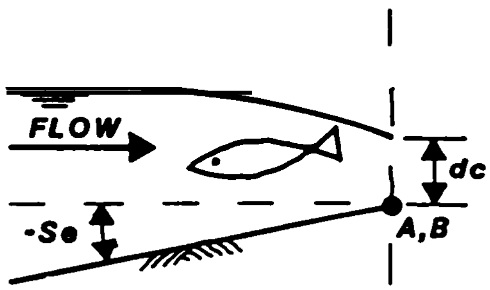
Magnitude and Discharge

To complete the classification, estimates of differential elevations, water velocities, length of slopes, etc., should be included, along with estimates of the discharge at the time of observation and migration season flows. These two components along with the barrier class and type then can be combined together to give the final barrier classification. A sample barrier classification sheet is shown in Fig. 20. This sheet can be used in the field to classify barriers and will be helpful in assessinq design modifications.

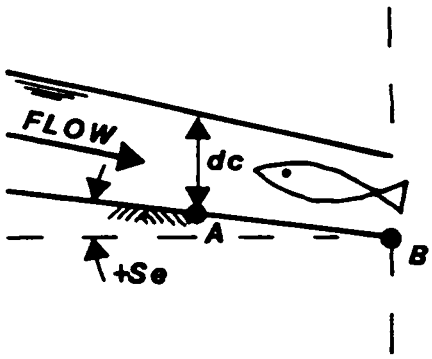
---

1 In profile, but one must consider the flow pattern in plan view because it can cause disorientation of the fish.

FISH EXIT/WATER INLET SLOPE POSITION | NOTATION



I
(Good)

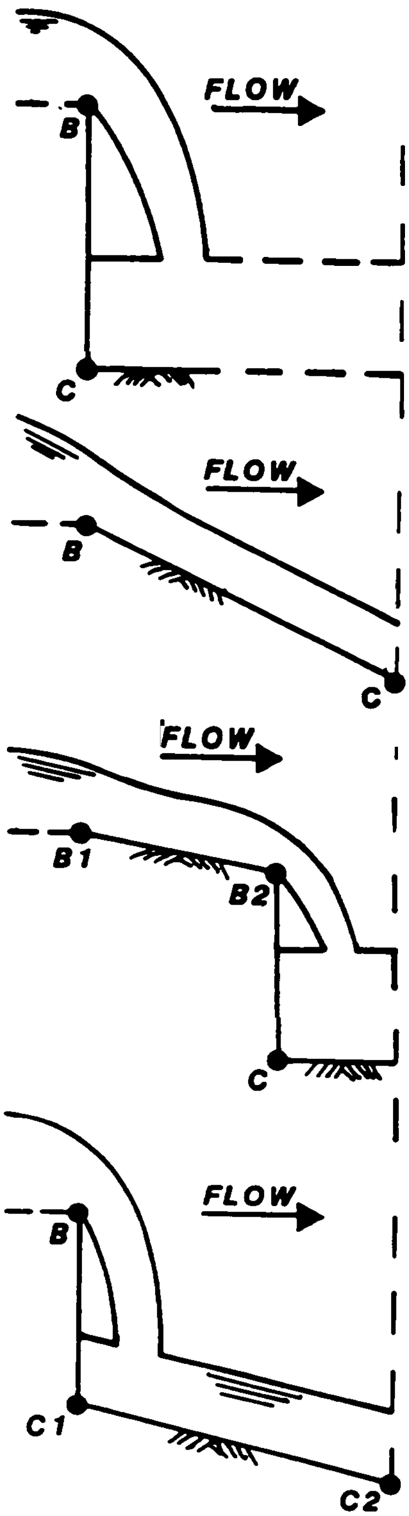


II
(Poor)

Figure 16. Fish exit zone notation, where: I = negative or nonsustaining slope at the fish exit (or water inlet). Good conditions for fish, reduced velocities, increased water depth therefore good resting areas. II = positive or sustaining slope at the fish exit (or water inlet). Poor conditions for fish, increased velocities, decreased depths and therefore poor resting areas.

FISH PASSAGE/WATER TRANSITION ZONE

NOTATION



A (fall)
(simple)

B (chute)
(simple)

C (chute/fall)
(compound)

D (fall/chute)
(compound)

Figure 17. Fish passage zone notation.

FISH ENTRANCE/WATER EXIT ZONE NOTATION

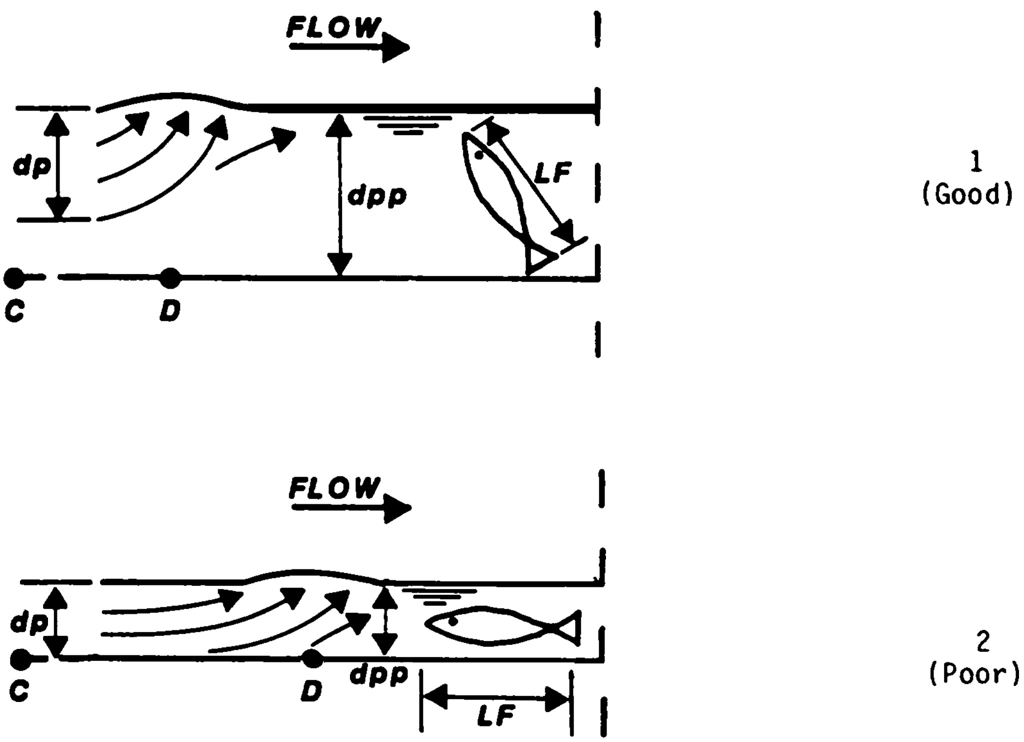
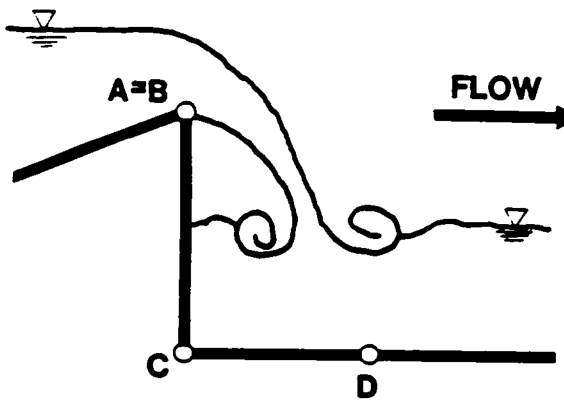
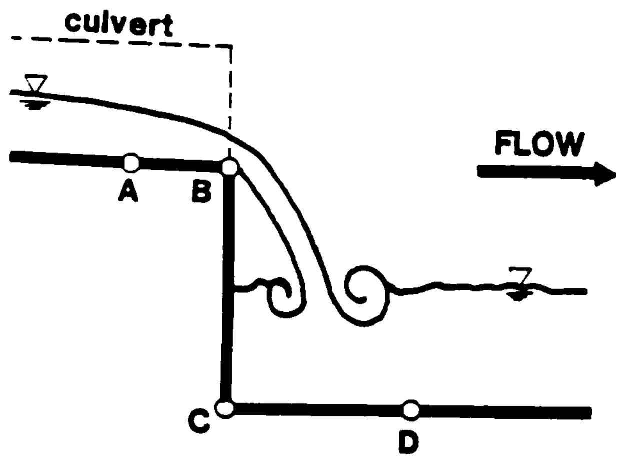


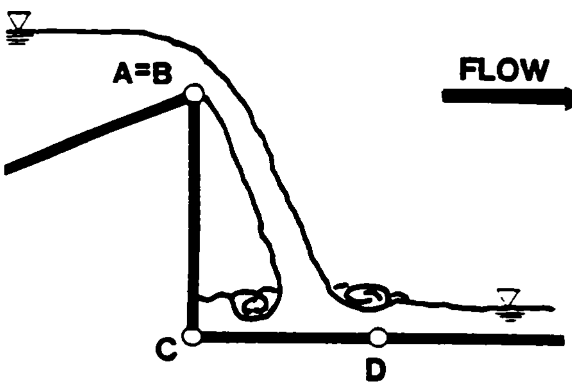
Figure 18. Fish entrance zone notation, where: 1 = deep plunge pool. Good conditions for fish, sufficient depth allows dissipation of falling water energy and standing wave to develop. Good leaping conditions. 2 = shallow plunge pool. Poor conditions for fish, falling water strikes bed of plunge pool, creates turbulence and moves standing wave downstream. Poor leaping conditions.



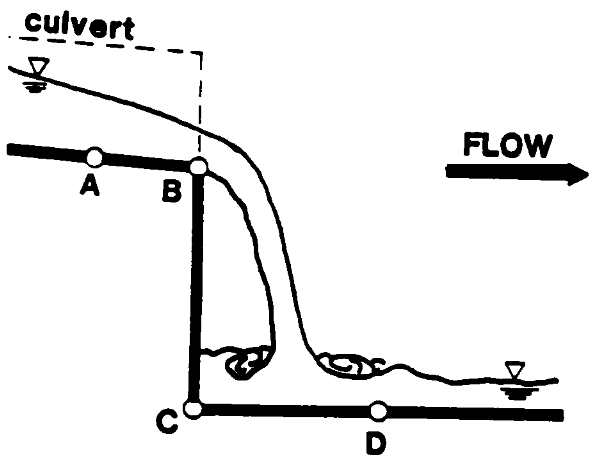
TYPE: I A 1
DEGREE OF DIFFICULTY: 1



TYPE: II A 1
DEGREE OF DIFFICULTY: 2

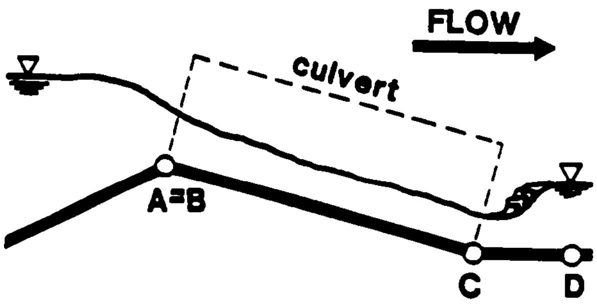


TYPE: I A 2
DEGREE OF DIFFICULTY: 2

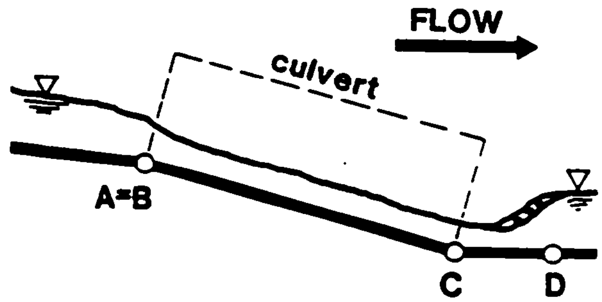


TYPE: II **A 2**
DEGREE OF DIFFICULTY: 3

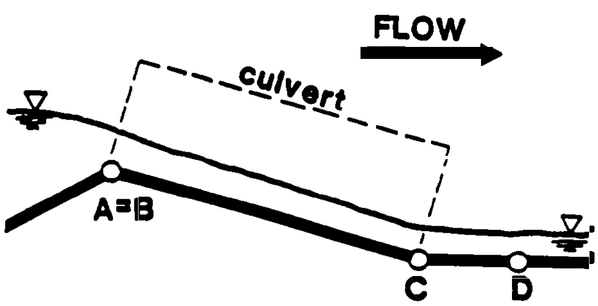
Figure 19. **Conceptual models of barrier types with the corresponding degree of difficulty rating.**



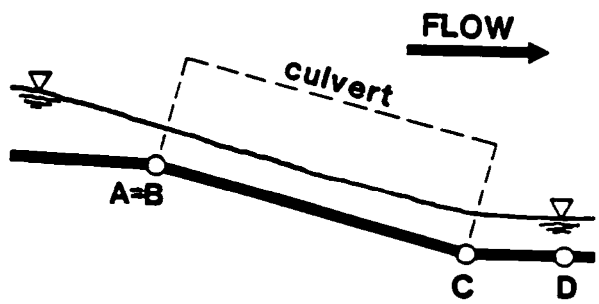
TYPE: I B 1
DEGREE OF DIFFICUTY: 2



TYPE: II B 1
DEGREE OF DIFFICULTY: 3

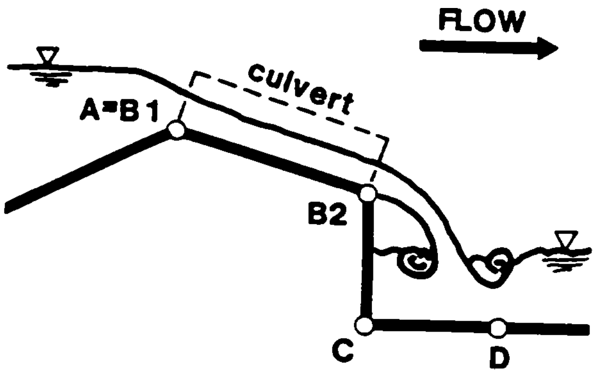


TYPE: IB2
DEGREE OF DIFFICULTY: 3

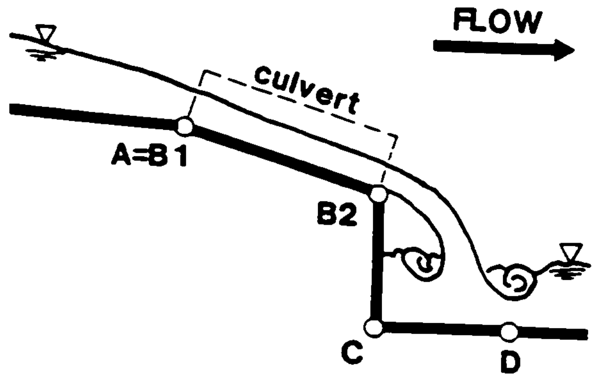


TYPE: II B 2
DEGREE OF DIFFICULTY: 4

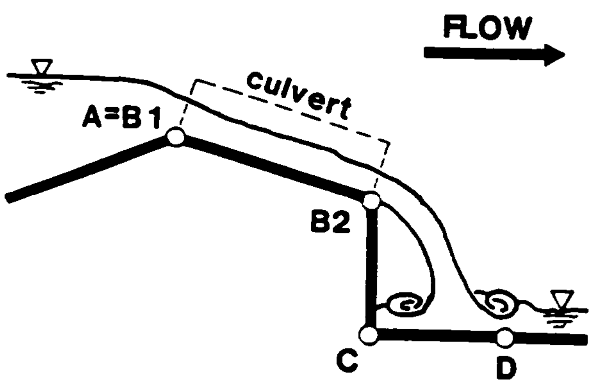
Figure 19. (Cont.)



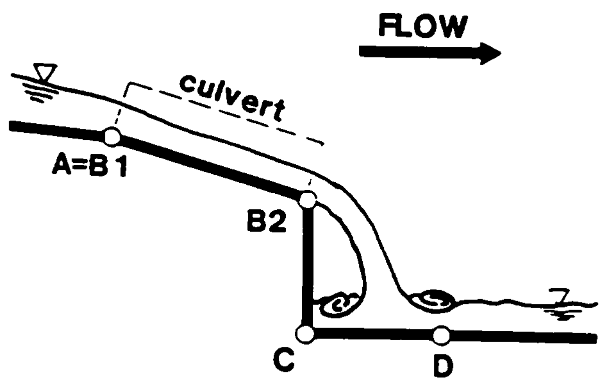
TYPE: IC1
DEGREE OF DIFFICULTY: 3



TYPE: II c 1
DEGREE OF DIFFICULTY: 4

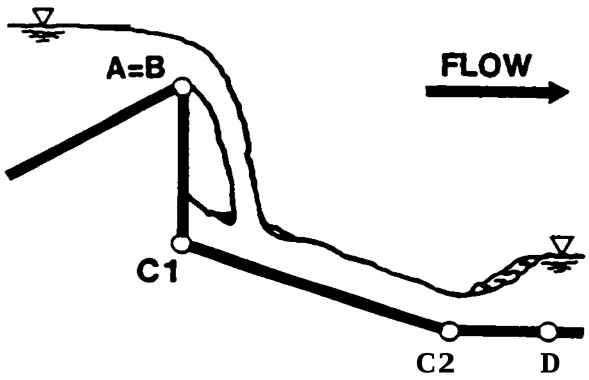


TYPE: IC2
DEGREE OF DIFFICULTY: 4

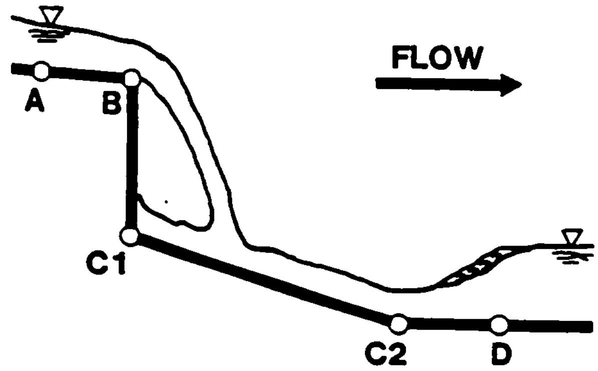


TYPE: II c 2
DEGREE OF DIFFICULTY: 5

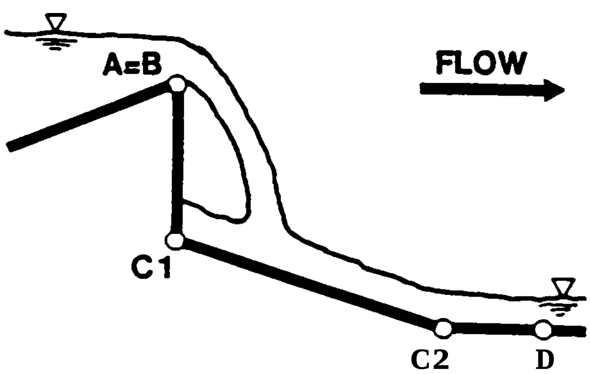
Figure 19. **(Cont.)**



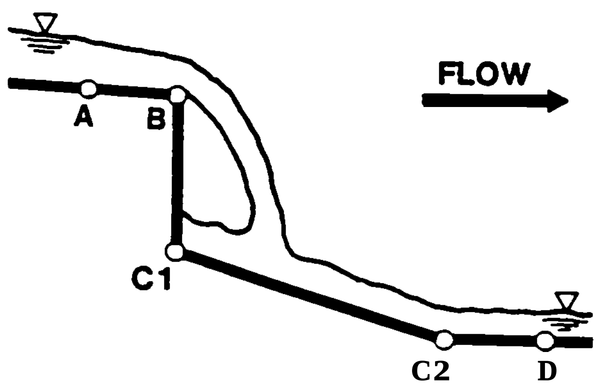
TYPE: ID1
DEGREE OF DIFFICULTY: 5



TYPE: II D 1
DEGREE OF DIFFICULTY: 6



TYPE: I D 2
DEGREE OF DIFFICULTY: 6



TYPE: II D 2
DEGREE OF DIFFICULTY: 7

Figure 19. **(Cont.)**

SITE: **DATE:**

LOCATION:

SITE SKETCH

CLASS:

TYPE:

DEGREE OF DIFFICULTY:

MAGNITUDE:

DISCHARGE:

COMMENTS:

Figure 20. Sample barrier classification sheet.

ANALYSIS OF BARRIERS

For determining fish passage success at waterfall and culvert barriers the hydraulic conditions must be evaluated and related to fish capabilities for the species in question. This chapter contains a detailed analysis of:

1. plunge pools (fish entrance zone);
2. landing conditions (fish exit zone);
3. falls (fish passage zone); and
4. chutes (fish passage zone);

and a discussion of the parameters which prohibit fish passage in cascades.

The most complicated aspect to analyze in barriers is determining how white water and turbulence affect the fish's swimming and leaping capabilities. Turbulence in "fluid mechanics" terms occurs when the viscous forces are weak relative to the inertial forces. The water particles move in irregular paths which are neither smooth nor fixed but which in the aggqregate still represent the forward motion of the entire stream. In open channel flow, turbulence is present if the Reynolds number $R = (VL)/\nu$ is large, say greater than 500 (Chow, 1959). For this study, turbulence will be used to visually describe flow patterns which are in a constant changing state of surges, boils, eddies, upwellings and vortices. Jackson (1950), noted turbulence deflects a swimming fish from its course, causing it to expend energy resisting upwellings, eddies, entrapped air and vortices, which in turn make it impossible for a fish to use its swimming power effectively. Stuart (1964) noted that the only known effect turbulence has on fish is that the reduced density of the air-water mixture reduces the propulsive power of the fish's tail.

Because of the violence in turbulent flow and the effect it has of reducing fish capabilities, it will be assumed for this study that any waterfall that is steep enough to accelerate the flow into violent turbulent white water is a total barrier to all fish species attempting to swim up the barrier. Fish can only pass if they leap and clear the area of turbulence before landing.

The analysis presented in this section is applicable to all waterfall and culvert barriers as long as the parameters needed for the analysis can he measured or estimated within ranges of practical values.

Plunge Pool Requirements

The behavior of a falling jet of water as it enters a pool depends to a great extent on the pool depth. If the pool is shallow the jet may strike the bottom and be deflected downstream. A good takeoff pool is essential if fish are to leap to any height. If the turbulent pool conditions created from the falling water impacting the shallow pool prevent a good take off, a relatively low fall may act as a total barrier. If the pool is deep enough to absorb the falling water, a standing wave will form, which assists the fish's leap, in the form of a vertical velocity component created by the pool surface (Aaserude, 1984). Air bubbles are created by the mixture of air and water as the falling water impacts the surface and entrains large quantities of air.

At falls and chutes aeration reduces the impact force of the falling water. The energy of a fall can be mostly dissipated due to transformation of aerated water into mist. At falls of medium height, but beyond the range of the fish's leaping capabilities, the impact produced by the emulsion of air and water may be reduced so that a false clue to the actual fall height is obtained by the fish. Stuart (1964) observed numerous salmon leaping over a period of several hours, constantly attaining a leap height of 4 to 5 ft, at a high impassable fall of around 30 ft; but the height attained by the fish was much less than the recorded maximum at other passable falls because of the reduced attraction flow.

Stuart (1964) suggests a ratio exists between the fall height (the vertical distance from the falls crest to the plunge pool surface) and the plunge pool depth which provides the best standing wave for leaping. He identifies this ratio as 1:1.25 (fall height/plunge pool depth). Aaserude (1984) studied standing waves and concluded that the character of the standing wave is closely related to the jet shape which strikes the plunge pool, and the depth of plunge can be estimated as S.5 (d), 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 plunge pool surface. Stuart's ratio does not consider jet shape.

From a research project the author participated in observing fish leaping over weirs at Johns Creek Fish Hatchery, near Shelton, Washington (Aaserude, 1984), it was concluded that two conditions should be satisfied to provide optimum leaping conditions in plunge pools:

1. depth of penetration of the falling water (dp) should be less than the depth in the plunge pool (dpp), and

2. depth of the plunge pool must be on the order of, or greater than, the length of the fish (LF) attempting to pass.

These two conditions assure the plunge pool will be stable with sufficient depth so the fish's orientation and propulsive power will be unimpaired. The relationships for analyzing a plunge pool are shown in Table 6.

Table 6. Relationships among plunge pool depth, depth of plunge and fish length for optimum and poor leaping conditions.

Depth and fish length relationships	Effect on fish
1. dp > dpp	Turbulent pool condition disorients fish. Standing wave reduced and moved downstream from where the falling water strikes the bed of the plunge pool.
2. dp < dpp	
a. LF > dpp	Propulsive power of fish's tail may be reduced for leaping.
b. LF < dpp	Optimum plunge pool conditions.

where: dp = depth the falling water plunges beneath the pool surface,

dpp = depth in the plunge pool measured at the point of plunge, and

LF = length of the fish attempting to pass.

Landing Conditions

When fish leap at waterfalls, often the landing conditions near the crest are such that the fish may be swept back by high velocities, or unable to propel themselves in water depths less than their body depths, where they are not totally submerged. Stuart (1964) notes that when fish leap towards the crest of a waterfall, they are geared for immediate propulsion when they land. The slightest delay in reaction would cause the fish to lose ground and be swept back over the waterfall. He also observed fish landing near the crest, relaxing their swimming effort immediately if they began to lose ground, and then were swept backwards. Even if fish are successfully passing a given waterfall, improvements of the landing conditions can reduce stress on the fish and further open the "window of passage".

If the velocity and depth of flow near the crest cannot be measured for a range of stream flows, an analysis near the crest of a fall or chute can be made by locating the point of critical depth and measuring the channel cross section at that point. Critical depth in open channel flow is that depth for which the specific energy (sum of depth and velocity head) is a minimum, and the Froude number Fr = $V/(gL)^{1/2}$, is equal to unity. Critical depth is also a "stream control," which determines a depth-discharge relationship. If the fish exit bed slope (S_e) is negative (increases in elevation in the direction of flow) critical depth will occur at the crest for a fall or chute. If the exit slope is positive (decreases in elevation in the direction of flow) critical depth will occur at the crest for a chute, but will occur some distance upstream of the crest for a fall. If critical depth does not occur at the crest, the following steps will locate the point where critical depth occurs:

1. measure the mean depth of flow some distance upstream of the crest,

2. calculate the equivalent pool elevation from

   pool elevation = bed elevation + measured depth of flow + hydraulic depth/Z, where: hydraulic depth = cross sectional area divided by the top width,

3. measure the pool elevation some distance upstream of the crest where the water is quiet,
4. if the pool elevation (measured) = pool elevation (calculated) the critical depth occurs at the point where the depth of flow was measured, and
5. if the pool elevation (measured) > pool elevation (calculated), move farther upstream and return to step 1.

This analysis is required because of the effect of the approach velocity. As Se increases from zero to some positive value the approach velocity will increase and critical depth will occur further upstream. If the fish exit slope is steep and thus flowing at supercritical flow, critical depth will not be reached and the landing condition should he analyzed as a velocity chute.

It can be shown mathematically (Henderson, 1966) that critical depth occurs in any channel shape when:

$$Q^2/g = A^3/W \tag{9}$$

where Q = total stream discharge in cfs, W = surface width of the waterway in ft, g = acceleration of gravity in ft/sec^2, and A = flow area of the cross section. Since most natural channels are of irregular shape and can be composed of several distinct subsections, the solution of equation (9) for rectangular and triangular sections will -allow computation of the discharge as a function of the critical depth for any irregular channel shape. For rectangular shapes:

$$Q = (A^3g/W)^{0.5},$$

but $A = W(d_c)$ where d_c = critical depth in ft, so substitution yields:

$$Q = (W)(g)^{0.5}(d_c)^{1.5},$$

and using $g = 32.2\ ft/sec^2$ yields:

$$Q = 5.7(W)(d_c)^{1.5} \qquad (10)$$

For triangular shapes the substitution is:

$$A = W(d_c)/2$$

which yields the following equation for triangular shapes:

$$Q = 2W(d_c)^{1.5}$$

Rut substituting $W = d_c/S$ where S = slope of one side of a triangle in percent yields:

$$Q = [2(dc)^{2.5}]/S \qquad (11)$$

Once the discharge has been solved as a function of the critical depth, substitution of a range of migration flows will give the critical depths, which can then be compared to the fish depth (df) to determine if the fish will be totally submerged. Also, the mean velocities can be calculated from:

$$V_C = Q/A, \qquad (12)$$

where V_C = mean velocity at critical depth, Q = stream discharge, and A = cross sectional flow area.

Optimum leaping conditions exist when the water velocity near the crest is less than or equal to the sustained swimming speed (VFS) for the species in question, and the depth of flow is greater than the fish depth.

At sustained speed, fish can function normally without fatigue (Hoar and Randall, 1978), and therefore are able to swim whatever distance is required before locating a resting area. If the water velocity is greater than the sustained swimming speed, the landing conditions should he analyzed as a chute because the distance the fish can swim will decrease as the water velocity increases above the sustained speed.

The relationships for analyzing the landing conditions at the crest of a fall or chute are shown in Table 7. An example calculation will show how this analysis can be used.

Table 7. Relationships between fish depth, critical depth, mean velocity and sustained swimming speed for optimum landing conditions.

Velocity, depth relationships	Effect on fish
1. $d_f > d_c$	Propulsive power of fish will be reduced
2. $d_f < d_c$	
a. $V_c > VFS$	Landing conditions should be analyzed as a chute
b. $V_c < VFS$	Optimum landing conditions

Where: df = depth of fish,

d_c = critical depth calculated from a range of migration flows (equation 9) if d_c occurs close enough to crest for fish to reach, or

= depth near the crest where fish may land if the critical depth occurs too far upstream for the fish to reach,

V_c = mean velocity at critical depth if critical depth occurs close enough to crest for fish to reach, or

= mean velocity near the crest where fish may land if the critical depth occurs too far upstream for the fish to reach, and

VFS = sustained swimming speed for the species in question from Table 1.

Example: Given the irregular channel shape in fig. 21, determine the discharge (0) in cfs as a function of the critical depth (dc) assuming critical depth occurs at the crest, and calculate the critical depth that will occur at migration flows of 5, 20 and 50 cfs, and the correspondig mean velocities from equation 12. Using Table 7, determine the effects on an adult steelhead trout with a maximum fish depth (df) of 0.5 ft.

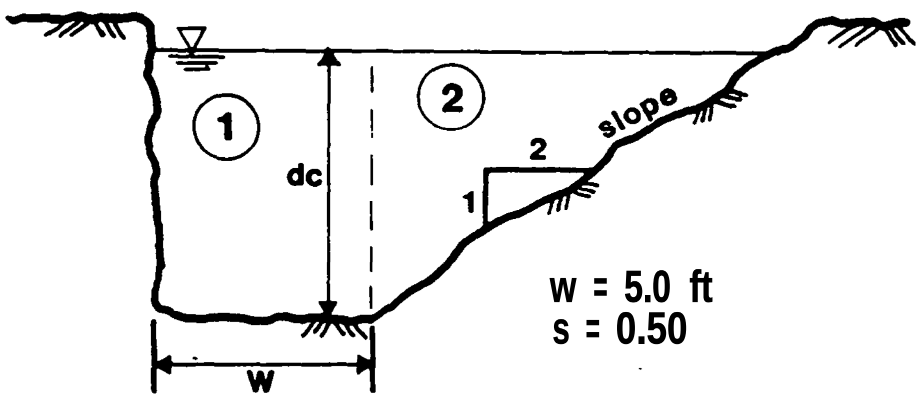


Figure 21. Irregular crest shape used for landing condition analysis example.

The channel shape in Fig. 21, can best be represented by the combination of a rectangle (section 1) and a triangle (section 2). Therefore:

$$Q_{total} = Q_1 + Q_2$$

where: $Q1 = 5.7(W)\, d_c^{1.5}$, from equation (10), and $Q_2 = [2(d_c)^{2.5}]/S$ from equation (11).Substituting, W = 5 ft and S = 0.50 yields:

$$Q_1 = 28.5(d_c)^{1.5} \text{ and } Q2 = 4(d_c)^{2.5}.$$

Therefore, the discharge as a function of critical depth is:

$$Q = 28.5(d_c)^{1.5} + 4(d_c)^{2.5}.$$

Substituting Q = 5, 20 and 50 cfs, and solving for d, and V_c gives:

Q (cfs)	d_c (ft)	V_c (fps)
5	0.30	3.1
20	0.74	4.7
50	1.30	6.1

From Table 1, the sustained swimming speed for steelhead is, VFS = 4.6 fps. Usinq Table 7, the effects on fish are:

1. At 5 cfs; $d_f > d_c$ and
2. At 50 cfs; $V_c >$ VFS.

The only discharge which provides good landing conditions from Table 7 is 20 cfs. At the other two flow rates, passage will not be blocked, but a higher passage success rate may be obtainable if these conditions were not present.

This example assumes the fish lands at critical depth, and therefore is not applicable if critical depth occurs some distance upstream of the crest. In that case the fish would land in higher velocities and shallower depths between critical depth and the depth at the falls crest.

In summary, for analyzing landing conditions near the falls crest, the following factors must be considered:

1. The depth of flow where the fish lands must be equal to or greater than the depth of the fish.
2. The velocity where the fish lands should be within the range of the sustained swimming speed for the species in question.
3. The velocity and depth should be analyzed under a range of fish migration flows.

Analysis of Falls

The most obvious obstruction at falls is when the change in water surface elevation between pools (14) exceeds the leaping height (HL) of the species in question. For Pacific salmon and steelhead trout, the highest calculated height of leap from level pool using equation (6) and $\theta L = 90°$ is 10.9 ft (steelhead). Therefore, falls where the change in water surface elevation is in excess of 11 ft can be considered for all practical purposes a total barrier to all species of Pacific salmon and steelhead trout. Evans and Johnstone (1980) suggest for natural bedrock waterfalls that if the vertical drop is more than 6 feet, it should he considered to he a barrier for salmon and steelhead without further study.

Often, though, the actual distance the fish must leap is greater than the vertical drop between pools. Unless the water is falling vertically, some horizontal component of the leap (XL) will be required for successful passage. If the horizontal distance the fish must leap cannot he measured, and the geometry of the falls is such that the water breaks off the crest and is unobstructed until it strikes the plunge pool, then this distance can be calculated. The calculation requires knowledge of the velocity of the water and the angle of trajectory at the crest (Fig. 22). An example of where this analysis would apply is at a cantilevered culvert outlet. Using the equations for projectile motion, developed in the fish capability section, the horizontal distance the water travels before striking the Plunge pool can be calculated from:

$$XP = VW_C[\cos(\theta W_C)]t \qquad (13)$$

where XP = horizontal distance from the crest to the point of the falling water, VW_c = velocity of the water as it leaves the crest, θW_c = angle at which the water leaves the crest at in relation to the horizontal, and t = time. To use equation (13), measurements of VW_c and θW_c are required before t can be calculated from:

$$H = [VW_c(\sin\theta W_c)]t - (1/2)gt^2 \tag{14}$$

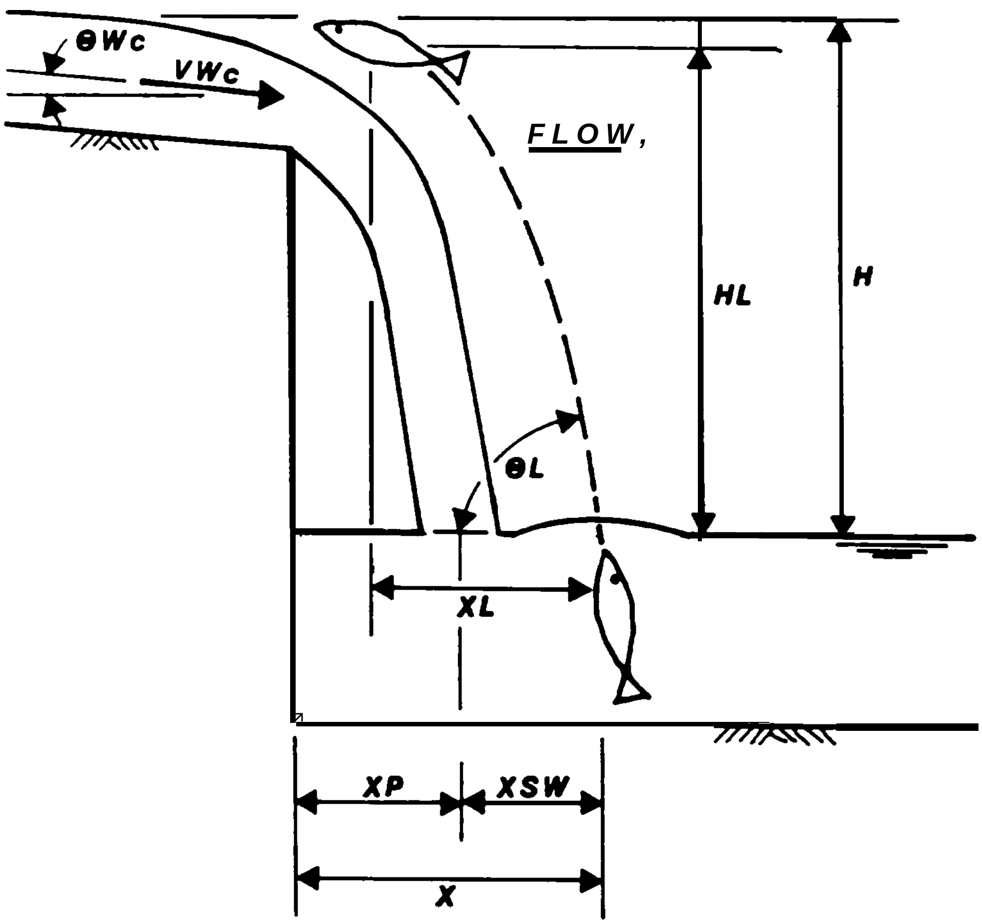


Figure 22. Leaping analysis parameters.

where H = change in water surface elevation (measured), and g = acceleration of gravity (32.2 ft/sec^2). If the approach flow is from a negative or nonsustaining slope (rises in the direction of flow) then $\theta W_c \leq 0$, and equation (14) can be solved as a function of t, or:

$$t = [2(H)/g]^{0.5},$$
$$\text{and } XP = VW_c[2(H)/g]^{0.5} \qquad (15)$$

If the approach flow is from a positive or sustaining slope (elevation decreases in the direction of flow) then $\theta W_c > 0$, t must be found by using the quadratic equation, and then substitute t into equation (13) to solve for XP. Once XP has been determined, adding the distance from the point where the falling water strikes the plunge pool to the standing wave (the point just downstream of the falling water from which fish most likely leap) gives X.

This analysis shows that even if the height the fish can leap (HL) is greater than the change in water surface elevation (H), and X is greater than XL, then a leaping fish will not reach the crest at the top of its leap. It will either fall short of the crest on its way down or reach the crest as it continues upstream on its descending parabolic path. These conditions are shown in Figure 23 for a steelhead trout. If the water surface profile of a barrier is superimposed on the fish leaping curves (Figure 23), the possibilities for a successful leap at a given leaping angle can be analyzed. The wide solid line shown is a falls barrier on Eldorado Creek in Idaho (Figure 24). The distances H and X were measured at the site. It can be seen from Figure 23 that a leaping angle of 60 degrees would allow passage. 80 and 40 degrees fall short of the crest by about 6 ft.

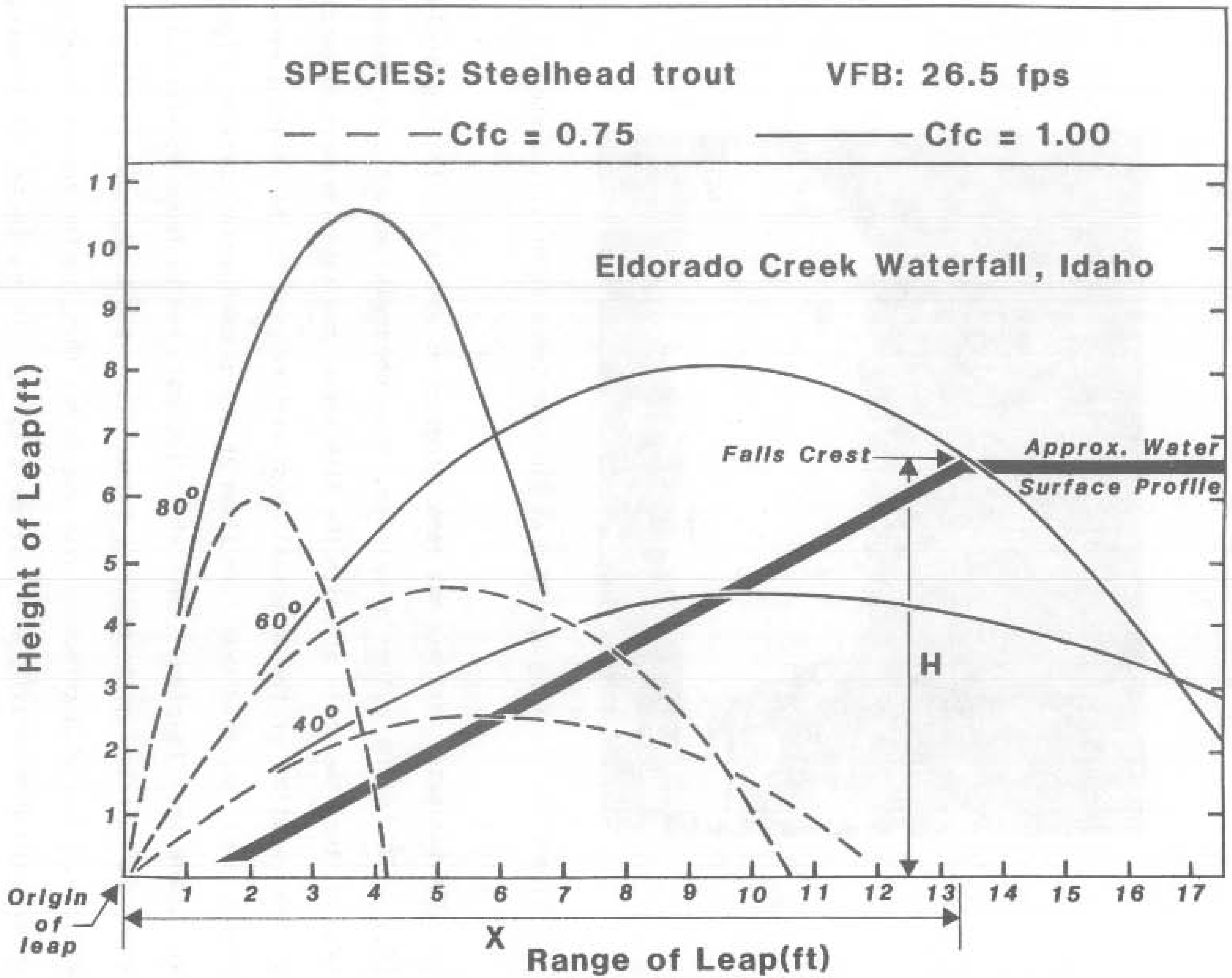


Figure 23. Eldorado Creek waterfall superimposed on steelhead leaping curves.

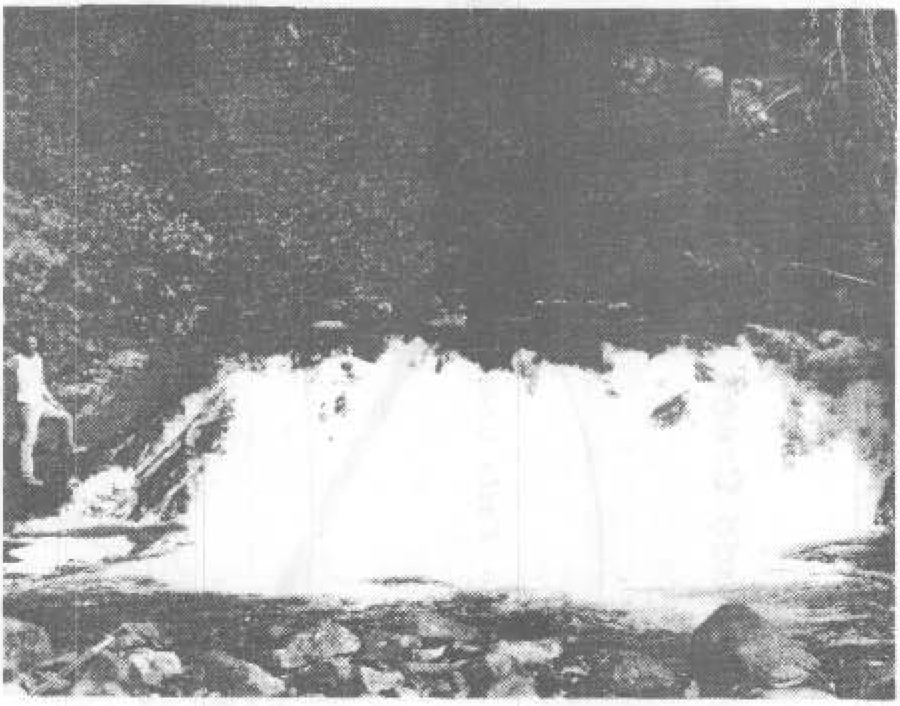


Figure 24. Looking upstream at Eldorado Creek Waterfall, Idaho.

One parameter that has not been discussed as yet is the leaping angle (θL). It is the author's opinion, from observations of coho salmon leaping, that the angle at which the fish leaves the standing wave depends on the location of the waterfall crest with respect to the standing wave. Stuart (1964) observed that fish aimed at sharp boundaries between light and shade when leaping. This sharp boundary can be found at waterfalls where the contrast at the boundary between water and background is clearly visible. This also coincides with the theory that leaping ceases abruptly at dusk and under heavily overcast conditions. To estimate the leaping angle, looking again at Figure 23, for a water surface slope of 29°, the optimum leaping angle was 60°. Since the fish is sighting the crest from some horizontal distance of 12.3 ft and a vertical distance of 6.7 ft the angle is some function of X and H. For this example in Figure 23, solving for H as a function of X gives:

$$H/X = \tan \theta_L = \tan 60° = 1.73$$

where H = change in water surface elevation, X = horizontal distance from the point where the fish will leap (or standing wave) to the crest, and θ_L = leaping angle. Holding X constant and solving for H gives:

$$H = X(1.73) = 12.3(1.73) = 21.3 \text{ ft}$$

Since the measured value of H was 6.7 ft, this value is approximately 3 times larger than the measured H. This is because the fish does not leap on a straight line, its path is parabolic and therefore to reach the crest the optimum leaping angle, θ_L, should be:

$$\theta_L = \tan^{-1} [3(H/X)] \tag{16}$$

This is the leaping angle equation.

Table 8 describes the two conditions that must be analyzed to determine whether or not a fall is a barrier, assuming the plunge pool and landing conditions are not adverse.

Table 8. Conditions for analyzing a fall assuming-plunge pool requirements and landing conditions are satisfied.

Water Surface Drop and Leaping Capability Relationships	Form of Barrier
1. H>HL	elevation barrier
2. H<HL	
a. X>XL (Superimpose water surface profile on fish leaping curves, Figures 7, 8 and 9)	passable or horizontal distance barrier
b. X<XL	passable

Where: H = change in water surface elevation (measured),

HL = height the fish can leap from Equation (6),

X = horizontal distance from the crest to the standing wave, and

XL = horizontal distance of the fish's leap at the highest point of the leap from equation (7).

Analysis of Chutes

In natural streams uniform flow is rare. However, the uniform-flow condition is frequently assumed in the computation of flow in natural streams. The results obtained are approximate and general, but offer a relatively simple and satisfactory solution for analyzing the velocities fish must swim against. Laminar uniform flow rarely occurs in natural channels, so turbulent uniform flow should be used for all velocity calculations in chutes.

From the definition of chutes, the flow must be supercritical down the chute (Froude number is greater than unity). At the start of the chute the flow will pass through critical depth and then into a transition zone of varied flow for some distance before uniform flow is established. If the chute length is shorter than the transition length required to reach normal depth, uniform flow cannot be attained. The length of the transition zone depends on the discharge and on the physical conditions of the channel, such as entrance condition, shape, slope and roughness.

For hydraulic computations the mean velocity of a turbulent uniform flow in chutes can be expressed by Mannings equation

$$v = (1.49/n)(R)^{0.67}(S_p)^{0.5} \tag{17}$$

where V = mean velocity of flow in fps, n = empirical roughness coefficient, R = hydraulic radius in ft, and Sp = passage slope (or bed slope). Outlet velocities in chutes computed by assuming uniform flow will give conservative estimates of velocity, because as the fish approach the transition zone the mean water velocity will be reduced. In culverts, the water surface profiles can be calculated because of the unvarying cross section, constant bed slope and uniform roughness throughout. From equation (17) it can he seen that the mean velocity varies as the slope to the 0.5 power, hydraulic radius to the 0.67 power and roughness to the -1.0 power. Since the mean velocity is highly dependent on n, it is important that the proper value of n be used. Chow (1959),suggests the following values for Manning's n, shown in Table 9. A problem arises when one value of n is selected, because n changes as the depth of flow changes as well as the slope, discharge and cross-sectional shape. This is shown in Appendix II. Three tests were run with identical bottom and side roughness, and n increased as the slope and depth of flow increased.

Table 9. Manning's n value for corrugated metal pipe and bed rock (from Chow, 1959).

Surface Material	Manning's n	
Culverts (C.M.P.)	0.024	
Red Rock		
smooth	min-0.025	max-0.040
jagged	. min-0.035	max-0.050

The hydraulic radius is calculated by dividing the flow area by the wetted perimeter. If the cross-section cannot be measured, a method can be applied to estimate the hydraulic radius that gives values with errors less than 5%. This method was suggested by Renard and Laursen (1975), but the author has expanded the method. It is used to estimate the hydraulic radius for rectangular and symmetrical triangular shaped channels, or combinations of such basic geometric shapes. For rectangular channels where the average stream width divided by the average depth is greater than 35, the hydraulic radius can be estimated by the average depth of flow. If the average width divided by the average depth is between 10 and 35, the hydraulic radius can be estimated by 0.9 times the average depth. If the averaqe width divided by the average depth is less than or equal to 10, the hydraulic radius can be estimated by the following equation

$$R = \bar{d}[0.524 \log(\bar{w}/\bar{d}) + 0.35] \tag{18}$$

where: R = hydraulic radius, a = average depth in a rectangular channel, and w = average width in a rectangular shaped channel. For symmetrical trianqular shaped channels where the average stream width divided by the maximun depth in the center of the stream is greater than or equal to 7, the hydraulic radius can be estimated by 0.5 times the thalweg depth (maximum depth). If the average width divided by the thalweg depth is between 3 and 6, the hydraulic radius can be estimated by 0.45 times the maximum depth. If the average width divided by the maximum depth is less than or equal to 3, the hydraulic radius can be estimated by

$$R= d_t[0.36 \log (\bar{w}/d_t) + 0.23] \quad (19)$$

where: d_t = depth at the thalweg; and w = average stream width for the triangular channel section. These conditions are summarized in Table 10.

Table 10. Hydraulic radius as a function of the width and depth for rectangular and triangular shaped channels.

Channel Shape	Width : Depth Ratio $\bar{w}/\bar{d}$ (rectangle) $\bar{w}/d_t$ (triangle)	Hydraulic Radius (feet)
	≥ 35	$\bar{d}(1.0)$
Rectangular	$10<\bar{w}/\bar{d}<35$	. $\bar{d}(0.9)$
	<10	$\bar{d}[0.524 \log(\bar{w}/\bar{d}) + 0.35]$
	≥ 7	$d_t(0.5)$
Symmetrical Triangle	$3<\bar{w}/d_t<6$	$d_t(0.45)$
	≤ 3	$d_t[0.36 \log (\bar{w}/d_t) + 0.23]$

An example will show how this information can be used to estimate the mean flow velocity in a chute.

Example: Determine the velocity at the bottom of a chute the fish must face given that the bed material is jagged rock, the channel shape is rectangular with an average width of 20 ft, and average depth at the bottom of chute is 1 ft. The bed slope is 0.4.

For jagged rock, n = 0.035 to 0.050.

For a rectangular channel shape and $\bar{w}/\bar{d}$ = 20, R = 0.9 ($\bar{d}$), or R = 0.9(1) = 0.9 ft.

Therefore, assuming uniform flow (because of the steep slope and a short transition from critical depth near the crest), the velocity can be estimated using equation (17):

$$v = (1.49/n)R^{0.67}S^{0.5}$$

using n = 0.035, yields:

$$V = (1.49/0.035)(0.9)^{0.67}(0.4)^{0.5}$$

$$\underline{V = 25.1 \text{ fps}}$$

using n = 0.050, yields:

$$V = (1.49/0.050)(0.9)^{0.67}(0.4)^{0.5}$$

$$\underline{v = 17.6 \text{ fps}}$$

Therefore, depending on the roughness, the velocity at the bottom of the chute will vary between 17.6 and 25.1 fps.

The actual velocity the fish must swim against can be reduced from the mean velocity if the water depth is great enough so the fish can swim near the boundary layer at velocities less than the mean.

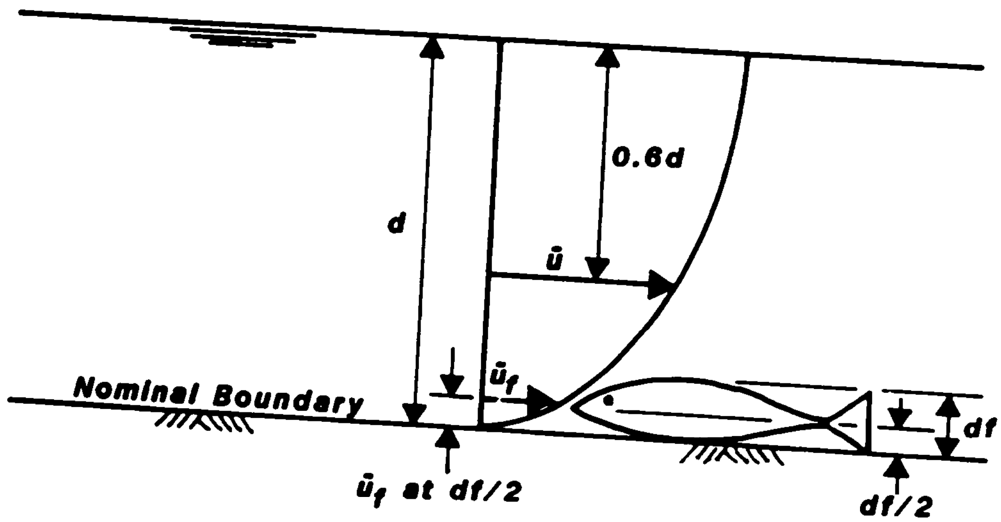


Figure 25. Fish swimming in reduced velocities near stream bed.

The velocity variation with depth in conduits is logarithmic, and the velocity at 0.6 of the depth below the water surface is very nearly equal to the mean velocity in a vertical section (Linsley and Franzini, 1979). The velocity reduction is most pronounced nearer the boundary where the local velocities may be irregular when vortices are being shed behind large roughness elements. Daily and Harlenan (1973), suggest the following formula for calculating the mean velocity in the case of a rough wall:

$$\bar{u}/u_{\star} = 5.6 \log (y/k) + 6.1 \qquad (20)$$

where: $\bar{u}$ = temporal mean velocity, $u_{\star}$ = shear velocity, y = mean depth of flow at which u is calculated and k = height of dominant bed material. The shear velocity $(u_{\star})$ can be calculated from (Henderson, 1966)

$$u_{\star} = (gRS_f)^{0.5}$$

where g = acceleration of gravity, R = hydraulic-radius and S_f = friction slope. Assuming uniform flow conditions exist, the friction slope is parallel to the bed slope as the resistance to the flow is balanced by the gravity forces.

An example of how the velocity in the boundary layer varies from the mean velocity of flow as depth increases along the centerline in a corrugated metal pipe will be shown (Table 11).

Table 11. Fish swimming in a culvert at velocities less than the mean velocity of flow.

Depth of flow (d), ft	Mean Velocity at 0.6 (d), fps	Mean velocity at y = 0.3 ft, fps (half fish depth)	Velocity Reduction
1	8.2	7.5	9%
2	13.3	10.0	25%
3	16.9	11.6	31%
4	19.5	12.6	35%
5	20.6	12.8	38%

Assumptions:
1. Culvert diameter (D) = 6 feet.
2. Height of corrugations (k) = 2 inches (Standard dimension, American Iron and Steel Inst., 1971).
3. Uniform flow occurs at a culvert bed slope of 5%.
4. Fish depth (df) = 0.6 feet, therefore to calculate the mean velocity the fish will swim against use y = $(d_f)/2$ = 0.3 feet, using Eq. (20).

This table shows that as the depth of water increases the velocity the fish must swim against near the culvert bottom (compared to the mean velocity) decreases. For smaller fish the gain will be more significant, but local eddies may disorient them. Equation (20) can be rearranged in terms of the minimum mean velocity the fish could swim against at the bed of a chute as:

$$\bar{u}_f = (5.6 \log (df/2)/k + 6.1)(gRS_f)^{1/2} \qquad (21)$$

where: $\bar{u}_f$ = minimum mean velocity the fish could swim against near the bed of a chute, df = depth of fish, g = acceleration of gravity, R = hydraulic radius and Sf = friction slope or bed slope for uniform flow conditions.

Velocities in natural rock chutes are seldom simple to analyze, because of the wide variations in channel shape and bed roughness. When flow occurs on a steep rock chute, large amounts of air may be carried below the water surface in the highly turbulent flow. This entrained air reduces the density of the fluid, resulting in an increase in volume called bulking. Although not strictly applicable, the Manning equation is often used to design channels on steep slopes and the cross-sections thus determined are increased by an arbitrary bulking allowance to provide for air entrainment. Hall (1943) has presented empirical data for smooth concrete chutes which permit use of a modified value of n in the Manning equation to allow for the effect of air entrainment.

If the channel shape can be surveyed and a cross section determined, applying the continuity equation:

$$Q = AV \qquad (22)$$

can yield estimates of the average water velocity-where: Q = flow rate in the measured cross section, A = cross-sectional area of channel, and V = mean velocity of flow. This method was used at Hell's Gate on the Fraser River in British Columbia to estimate the velocities sockeye salmon were facing as they attempted to negotiate the obstruction. The flow patterns at Hell's Gate could be described as a constantly changing state of turbulence, where the water surges, boils and entraps huge volumes of air. Because of these flow patterns and the extremely rough channels, Jackson (1950) noted that the average velocities computed this way are inaccurate. Using equation (22), if the cross-section is measured at some point in the chute, a staqe-discharge relationship can be developed so as the discharge increases or decreases, the mean flow-through velocity can be estimated.

When analyzing a chute, the depth of flow should be greater than the depth of the fish, or the fish will not be able to make full use of its propulsive power. In a study conducted at Johns Creek Fish Hatchery near Shelton, Washington by the author (Appendix II), chum and coho salmon were observed swimming up a velocity chute. At a depth of 0.13 ft, a 0% passage success rate was recorded for both species. When the depth was increased to 0.66 ft, a passage success rate of 100% was recorded for chum salmon at a water velocity only slightly less than the first test. The maximum depth of chum salmon was 0.65 ft. The results of these two tests show the importance of the depth of flow for the fish to achieve successful passage. Table 12 describes the two conditions that must be analyzed to determine whether or not a chute is a barrier assuming the plunge pool requirements, landing conditions and depth of flow are sufficient.

Table 12. Conditions for analyzing a chute assuming plunge pool requlrements, landing conditions and depth of flow are sufficient.

Water velocity, fish speed, slope length and fish performance relationships	Form of Barrier
1. VW > VF	velocity barrier
2. VW < VF	
a. LS > LFS	distance/velocity barrier
b. LS < LFS	passable

where: VW = velocity of water (measured or calculated),

VF = fish speed from equation (2),

LS = lenqth of slope (measured), and

LFS= distance the fish can swim from Figures 10, 11 or 12.

Cascade Barriers

A cascade was described in the introduction as a reach of stream with large boulders or jutting rocks that obstruct the flow. This obstruction usually results in a narrower stream width, sharp changes in flow boundaries, and consequently high velocities and violent conditions. If the bed slope over the reach is steep enough to accelerate the flow, white water and turbulence will consume most of the channel and offer little or no resting areas for the migrating fish. If the reach is not too steep, the obstructions in the stream can create good resting areas as the fish work their way through the cascade.

Cascades are usually located in areas with steep topography (canyons) and are very difficult to survey because of the high velocities, deep pools and turbulence. Cascades usually persist as either boulder cascades or turbulent cascades. Boulder cascades consist of boulders in the stream that are large enough to provide resting areas for the fish in their wakes. To analyze a boulder cascade, application of the four following steps can be helpful:

1. measure the total drop in water surface over the entire reach,
2. determine the number of paths and/or steps per path the fish must pass within the reach,
3. estimate the water surface drop and/or velocity the fish must negotiate to successfully pass each step in each path, and
4. locate resting areas between each step (on each path) where the fish may rest before attempting to pass the next step.

Often the flow between obstructions (boulders) can act like flow down a short chute. Douma (1943) noted that for short chutes, the velocity may be determined by:

$$V_{sc} = (2gH)^{0.5} \tag{23}$$

where V_{sc} = velocity down a short chute, g = acceleration of gravity, and H = total vertical drop between two pools. Using this analysis, if any step within the reach has velocities or elevation drops in excess of the fish's capabilities, or resting areas are not present between each step, the cascade would be a barrier to fish.

Turbulent cascades present the fish with a variety of difficulties, but usually the excessive velocities and excessive turbulence is enough to obstruct passage. These two conditions were studied extensively at the Hell's Gate obstruction (Jackson, 1950). Velocities were measured by methods described earlier, but the turbulence could not be measured in any manner that could be related to passage success. Turbulence in cascades serves to deflect a swimming fish from its course, causing it to expend energy to resist up-wellings, eddies, entrained air and vortices. Most of the fish's energy is utilized simply to maintain position and direction at the foot of a high velocity obstacle (Jackson, 1950).

To analyze a turbulent cascade, application of the three following steps can be helpful:

1. time floats through the cascade to get an approximate surface velocity (floats may be delayed in eddies);
2. observe possible resting areas and zones of reduced turbulence and velocity near the banks and behind obstacles; and
3. locate points of extreme upwellings and surges in the cascade which might deflect a fish from its swimming path.

If the surface velocities are excessive, there may be a path for the fish to pass along the stream bank, away from the excessive velocities and upwellings in the main channel..

In summary, this section has presented a detailed analysis of four components which affect fish passage at waterfalls and culverts:

1. plunge pools;
2. landing conditions near waterfall crest;
3. falls; and
4. chutes.

A discussion of the parameters involved in each component, followed by a table summarizing the important conditions to analyze have been presented. Also, a discussion of hydraulic/fish capabilities in cascades is introduced with steps to follow which will aid in determining the effect on fish passage success.

SITE ANALYSIS AND SOLUTIONS

The generation of solutions to fish passage problems at barriers is dependent on the parts of the analysis performed. If the barrier is total, the analysis will reveal the parameters which exceed fish capabilities. The geometric conditions can be altered to reduce the excessive parameters and assist fish passage. Evans and Johnston (1980), suggest the following corrections for natural bedrock waterfall barriers:

1. Dam the plunge pool below the falls.
2. Blast a plunge pool below the falls.
3. Blasts series of pools through the falls.
4. Provide a fish ladder over the falls.

According to Evans and Johnston (1980), the plunge pool should be raised so the depth is 1.5 to 2 times deeper than the barrier is high. They also suggest that blasting a series of pools through the falls is only practical for bedrock falls under 10 feet in height.

These correction methods have been employed successfully by the U.S. Forest Service and State Agencies in Washington (Schoettler[2], 1953), Oregon and Alaska. To build vertical-slot fishways at remote barrier sites on British Columbia rivers, engineers working for the Salmonid Enhancement Program (SEP) have perfected blasting techniques that allow natural rock to be used as the floor and sides of the fishway (Salmonid, 1983). This

---

[2] Schoettler, R.J., Improvement of Minor Falls, Federal Project No. 852-W-SI-10, Dept. of Fisheries, State of Washington, 1953.

innovation, along with the use of precast concrete panels flown in by helicopter, has resulted in substantial cost savings. Kerr, et al. (1980) suggest techniques to remove or bypass obstructions:

1. A steel bar can be used to hand pry and roll rocks for selective placement.
2. Larqe rocks and boulders may be removed and/or relocated utilizing slings with block and tackle.
3. Large boulders may be reduced to a size that can he readily removed, using a portable gas-powered rock drill or with explosives.

Removal of an obstruction during egg incubation could cause serious mortality by silting the downstream spawning bed.

Of the few project reports published, no information was found on the pre-construction or analysis phases except the mention of the height of the barrier.

The objective of this section is to evaluate "parameter specific" solutions with varying degrees of construction difficulty. For example, if the height of a harrier is determined to not be excessive, but the fish cannot reach the crest, then one of three things (or a combination) may he happening:

1. The plunge pool hydraulic characteristics are such that the propulsive power and the orientation of the fish's leap are affected (Table 6); and/or
2. The horizontal distance (or range) which a fish leaps is excessive compared to the actual horizontal distance the fish must leap to reach the crest; and/or

3. Flow over the waterfall is diagonal, or concentrated on one side, thus providing the fish with a false directional stimulus.

Analyzing these components will suggest the excessive parameter(s), that must be reduced. Without this analysis the height of the falls may have been reduced when it was not excessive to fish passing in the first place. In-depth analysis of this type will often reduce site construction' costs and assure correction of the real passage problems.

The solutions to waterfall and culvert barrier physical problems are directly dependent on the analysis. If the velocity in a rock chute or culvert is excessive (Table 12), then the velocity and/or the length must be reduced. Assuming that Mannings equation (17) is exact, the components that would reduce the velocity in descending order of effectiveness are:

1. increase the roughness coefficient(n);
2. decrease the hydraulic radius; or
3. decrease the slope.

Adding baffles to culverts essentially increases the roughness and decreases the hydraulic radius. If the depth of flow at the crest of a falls is shallow, then to increase the depth requires one of three hydraulic changes:

1. increase the discharge,
2. decrease the crest width, or
3. decrease the velocity.

These solutions can be incorporated at the crest of a waterfall barrier by using instream control structures such as gabion baskets, rock weirs and small retaining walls as flow deflectors to concentrate the flow. in order to create an adverse slope, one would need to blast a pool above the crest. Each structure placed instream must be carefully analyzed hydraulically to assure proper functioning as the forces in the stream channel change with discharge, ice and debris.

To show how this analysis/solution approach to barriers can be used, two sites were chosen in Western Washington and analyzed for the discharge recorded during the site visits. It is important to note that these examples address changes in parameters which were determined to be excessive from the analysis. When these parameters are changed, the analysis must be repeated, because the hydraulics of the entire barrier system may have changed.

Red Cabin Creek - Analysis

Red Cabin Creek is a small tributary that flows into the Skagit River near Lyman, Washington. The barrier on the creek is a culvert located in the SE 1/4 of Section 3, Township 35 North and Range 6 East. The culvert runs underneath Camp 17 Road about 3 miles from Hamilton, Washington. The creek is used by chinook and pink salmon for spawning and contains good coho spawning and rearing habitat. The culvert barrier is 35 river miles from saltwater. The outlet of the culvert is shown in Figure 26. Note the 2 ft wide wooden scour apron.

> Culvert Description: Starting at the water inlet, the circular culvert is concrete lined with some patches of corrugated metal on the bottom. This continues until about the last 30 ft which is steel pipe. There is a debris jam about 2 feet high in the middle of the culvert which should be removed.

Culvert Dimensions: Diameter = 6.0 ft

Length = 150 ft

Slope = 4.4%

Hydraulic Analysis: Velocities in the culvert must be determined so that the distance the fish can swim can be compared to the culvert length.

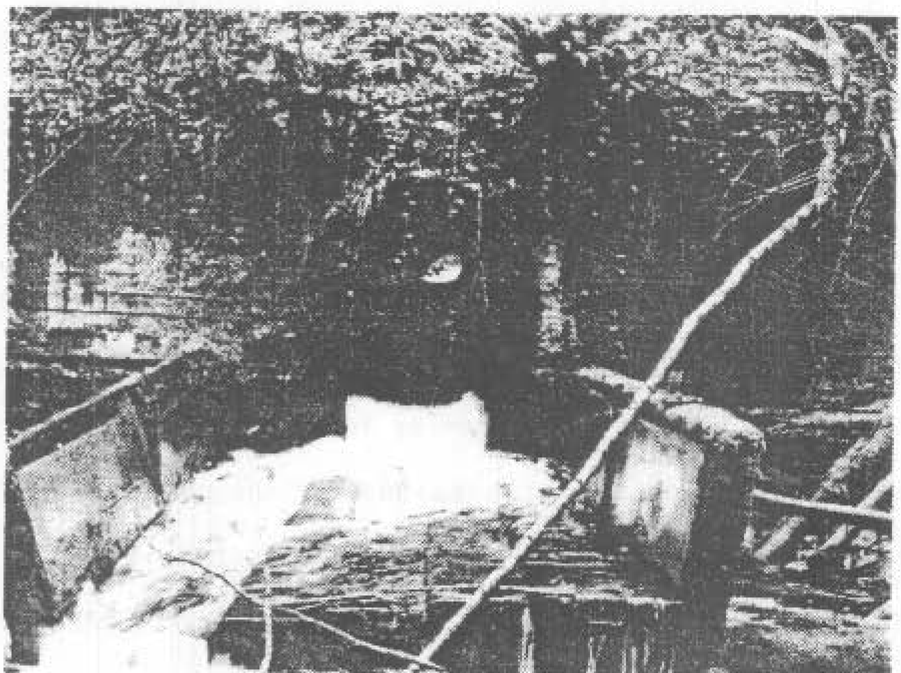


Figure 26. Looking upstream at Red Cabin Creek culvert outlet.

Using **equation** (17)

$$V = (1.49/n)R^{0.67}S^{0.5}$$

where V = average velocity of flow in fps, n = roughness coefficient (0.012 for smooth steel surface, Chow, 1959), S = bed slope (measured at 4.4%) (for assumed normal flow depth), and R = area of flow/wetted perimeter in ft. For circular culverts the flow area can be calculated by:

$$A_f = (\pi/180)\cos^{-1}[(r-d)/r]r^2 - [r^2-(r-d)^2]^{0.5}(r-d)$$

where A_f = area of flow, r = radius of culvert, and d = depth of flow (or uniform depth). At the culvert outlet, the flow can he assumed to be uniform, and this depth was measured at 0.55 ft on December 8, 1983.

The wetted perimeter of the flow area can be calculated by:

$$Yp = (2\pi/180)\cos^{-1}[(r-d)/r]r$$

where W_p = the wetted perimeter, r = radius of culvert, and d = depth of flow. Solving for A_f and W_p yields:

$$A_f = 1.29 \text{ ft}^2 \text{ and } W_p = 3.69 \text{ ft}$$

Substituting these into equation (17) yields:

$$v = (1.49/.012)x((1.29/3.69)^{0.67}(.044)^{0.5}$$

$$\underline{V = 12.9 \text{ fps}}$$

Multiplying this velocity by the flow area, equation (22) yields a discharge of:

$$0 = VA_f = (12.9)(1.29) = \underline{16.6 \text{ cfs}} \text{ (on 12/8/83)}$$

The distance the fish can swim is a function of the fish condition, water velocity and depth of flow. For average sized adult chinook, coho and pink salmon, a depth of 0.55 ft is probably a minimum, and will therefore not reduce the swimming capabilities. Since i?ed Cabin Creek is a short tributary, with the barrier located near the spawning grounds, a coefficient of fish condition (Cfc) of 0.75 will be used (description is given in fish capability section). Using Figures 11 and 12, a water velocity of 12.9 fps, and C_{fc} = 0.75, yields the following distances the fish can swim:

Specie	Maximum Swimming Distance
Chinook	16 ft
Coho	16 ft
Pink	Impassable

Because the culvert is 150 ft long, the fish will not be able to negotiate the culvert swimming against the mean velocity. Also, the shallow depth forces the fish to swim against the mean flow velocity.

The measured outfall height at the end of the culvert was 2.3 ft, but because of the high exit velocity, there was some horizontal component to the falling jet. This distance can be calculated from equation (13):

$$XP = VW_c[\cos(\theta W_c)]t,$$

where t can he determined from the equation (14):

$$H = [VW_c(\sin\theta W_c)]t - (1/2)gt^2,$$

where H = 2.3 ft (measured), VW_c = 12.9 fps, and θW_c = 2.5°.

Substituting in these values yields:

$$2.3 = 0.56(t) + 16.1(t^2),$$

and solving for t yields:

$$t = 0.36 \text{ seconds}.$$

Substituting this into equation (13) gives:

$$XP = (12.9 \cos 2.5°)0.36 = 4.6 \text{ ft}.$$

Because of the wooden scour apron, the distance to the standing wave could not he observed. Therefore, this distance, XSW (Fig. 22) will be assumed equal to 1 ft. with the apron removed. This gives a X value of:

$X = XP + XSW = 4.6 + 1.0 = 5.6$ ft

Now X and H can be substituted into the leaping angle equation (16):

$$\theta L = \tan^{-1} 3(H/X),$$

where H = 2.3 ft (measured), and X = 5.6 ft (calculated). Therefore:

$$\theta L = \tan^{-1} 3(2.3/5.6) = 51°$$

Superimposing H and X on Figures 8 and 9 shows coho and chinook will land right at the crest, and pink salmon about 1 ft short of the crest, at a leaping angle of 60 degrees (dotted lines Figures 27 and 28). This angle corresponds well with the calculated leaping angle of 51°. Because of the high velocities at the culvert outlet, the fish will not be able to land successfully and swim through. Therefore, the outfall drop is considered a horizontal distance (or range) barrier with adverse landing conditions.

This analysis has shown that at a discharge of 16.6 cfs, Red Cabin Creek culvert is a velocity - length barrier and a leaping range barrier. Classification for this barrier is shown in Figure 29.

Red Cabin Creek - Solutions

To negotiate the culvert length of 150 ft, the velocities would need to be less than or equal to 3.4 fps for chinook and coho, and 2.6 fps for pink salmon. In the corrugated metal pipe section with increased roughness coefficient, the velocity would only be reduced to 6.4 fps. Dane (1978) recommends for culverts greater than 80 ft in length, the average velocity should not exceed 2.9 fps for adult salmon, and that the culvert slope should not exceed 0.5%, unless appropriate compensation is made by the addition of baffles within the culvert. The design on culvert baffles can be found in McKinley and Webb (1956), Engel (1974) and Watts (1974). The addition of baffles essentially increases the value of the roughness

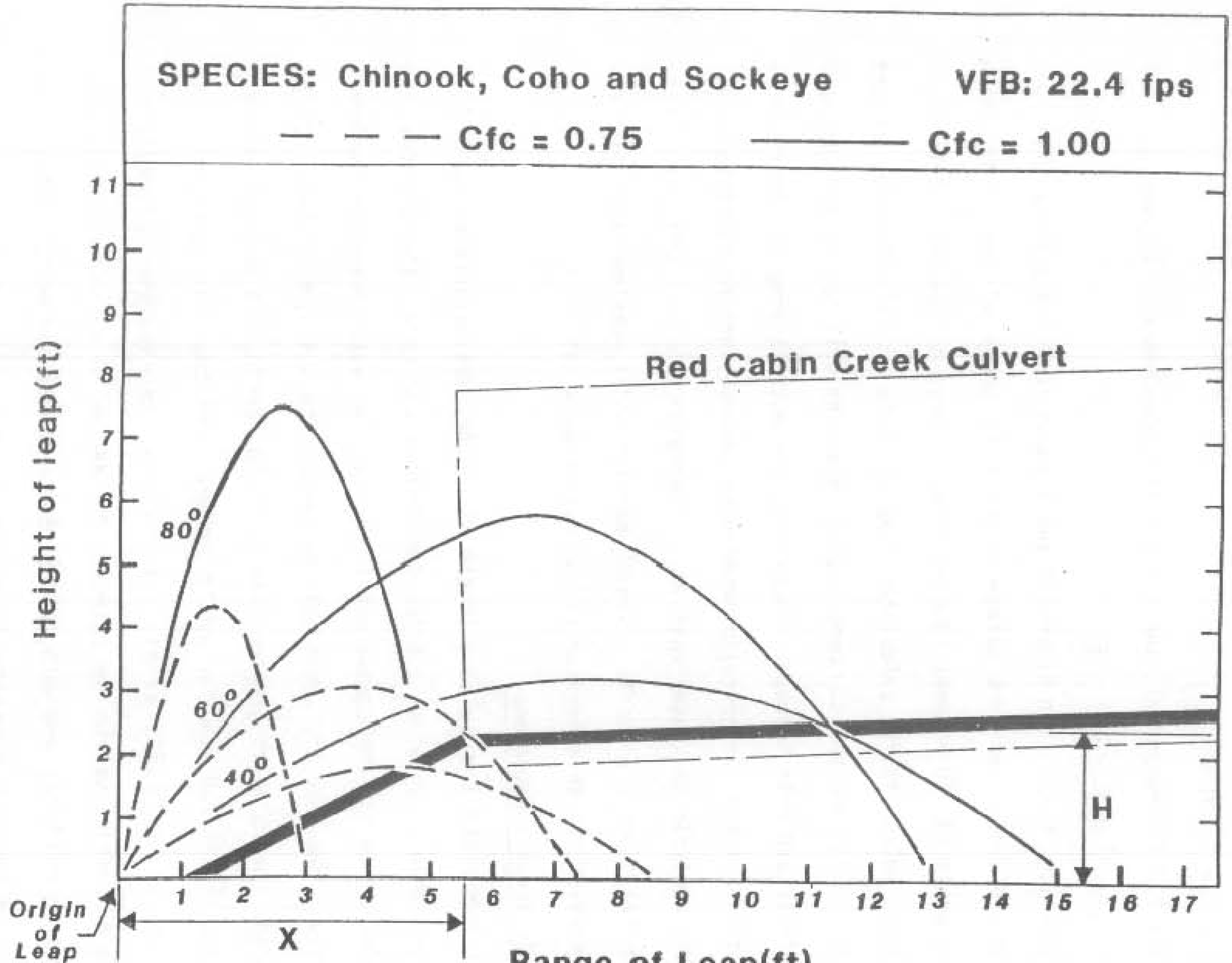


Figure 27. Red Cabin Creek culvert outlet superimposed on chinook and coho salmon leaping curves.

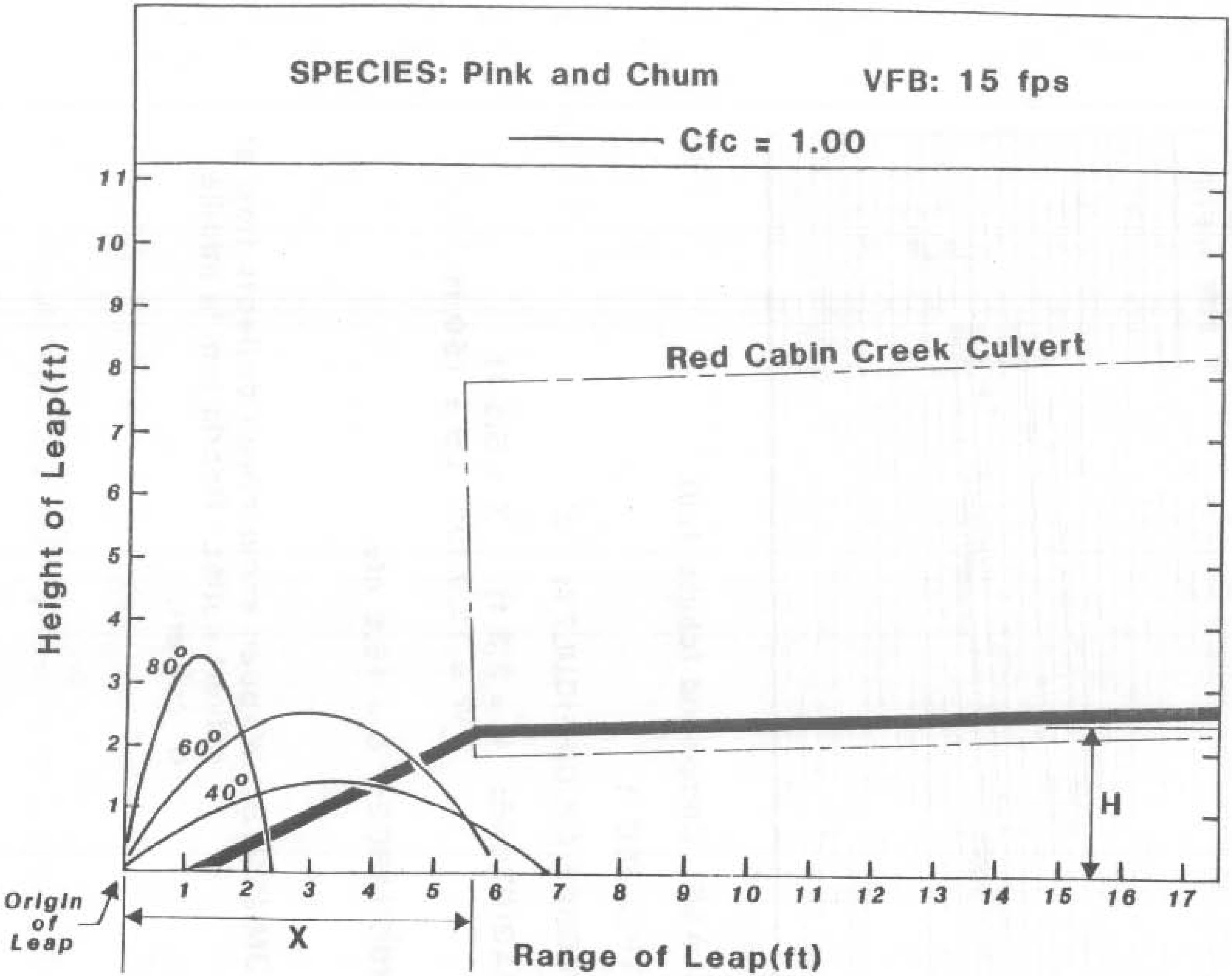
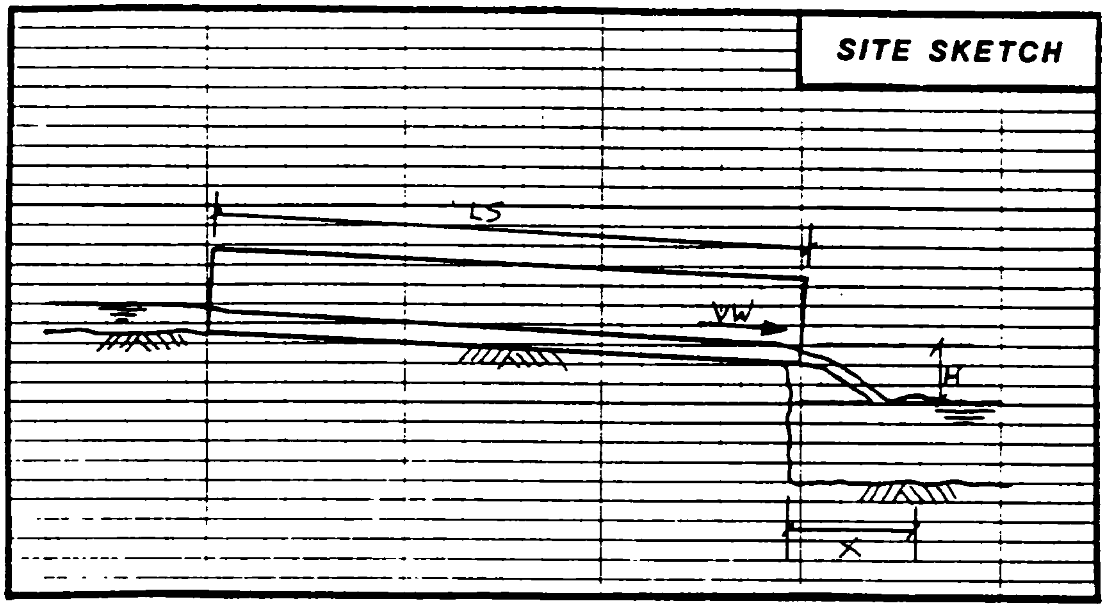


Figure 28. Red Cabin Creek culvert outlet superimposed on pink salmon leaping curves.

SITE: Red Cabin Creek Culvert DATE: 12/8/84

LOCATION: SE 1/4 of Section 3, T35N, R6E



CLASS: Compound (chute/fall)

TYPE: II C 1

DEGREE OF DIFFICULTY: 4

MAGNITUDE: H = 2.3 ft X = 5.6 ft
VW = 12.9 fps LS = 150 ft

DISCHARGE: Q = 16.6 cfs

COMMENTS: Wooden scour apron deflects flow at culvert outlet. Debris jam in middle of culvert.

Figure 29. Classification of Red Cabin Creel: culvert.

coefficient, therefore decreasing the velocity and increasing the depth of flow, creating a pool and weir fishway at lower flows. This could be accomplished simply by placing roughness elements on the culvert bottom, but would not provide resting places as baffles do. Since the slope cannot be changed, the parameters that could be varied to decrease the velocity to 2.6 or 3.4 fps in equation (17) is the roughness coefficient, assuming Manning's equation is exact, and the hydraulic radius. To achieve these velocities, the roughness coefficient should equal:

Water Velocity	n(roughness coefficient
2.6 fps	0.059
3.4 fps	0.045

In Chow (1959) these roughness coefficients correspond to a natural steam channel with cobbles or large boulders. The actual size of the roughness elements could best be determined by a model study so that velocity measurements could be made over a range of discharges and roughness element heights and arranqements.

At the culvert outlet, because the velocity is excessive, the fish could leap into the culvert and then be swept back. Therefore assume here that the velocity in the culvert is reduced in some manner to a value suggested earlier for passage to be achieved. An average of 2.6 and 3.4 fps, will he used OF 3.0 fps. From equation (13) this reduces XP to 1.1 ft, and X to 2.1 ft, adding 1 ft for the distance to the standing wave. Calculating the leaping angle for the new outlet geometry gives:

$$0L = \tan^{-1} 3(2.3/2.1) = 73°$$

Superimposing the outfall geometry again on Figures 8 and 9 shows that coho, chinook and pink salmon can successfully enter the culvert at a leaping angle of about 60°, shown as dotted lines in Figures 30 and 31.

Again, this angle is close to the calculated leaping angle of 73°. Therefore, decreasing the velocity in the culvert to 3 fps will allow the fish to successfully swim the culvert length of 150 ft and reduce the horizontal leaping distance. Table 13 is a summary of the problems and suggested solutions for Red Cabin Creek culvert.

Table 13. Red Cabin Creek problems and solutions.

Problems	Solutions
Wooden scour apron prevents fish from entering culvert.	Remove apron.
Horizontal leaping distance is excessive, caused by high velocities at crest of 12.9 fps.	Decreasing velocity to 3 fps at the crest would reduce the horizontal leaping distance and allow successful passage.
Velocity in the culvert is excessive for a culvert lenath of 150 ft.	Add baffles OF some type of roughness elements to decrease the velocity. Check culvert capacity to pass flood flows.
Debris jam in middle of culvert prevents fish passage.	Remove debris

Chuckanut Creek Waterfall - Analysis

Chuckanut Creek is located just south of Bellingham, Washington; it flows along the Old Samish Highway and discharges into Chuckanut Bay. The barrier in Question, figure 32, is located at river mile 1.8, in the middle of the western 1/2 of Section 17, Township 37 Noth, Range 3 East. The creek. be the barrier is used by chum Salmor in the lower part below the harrier and coho and steelhead spawn in the creek above the barrier.

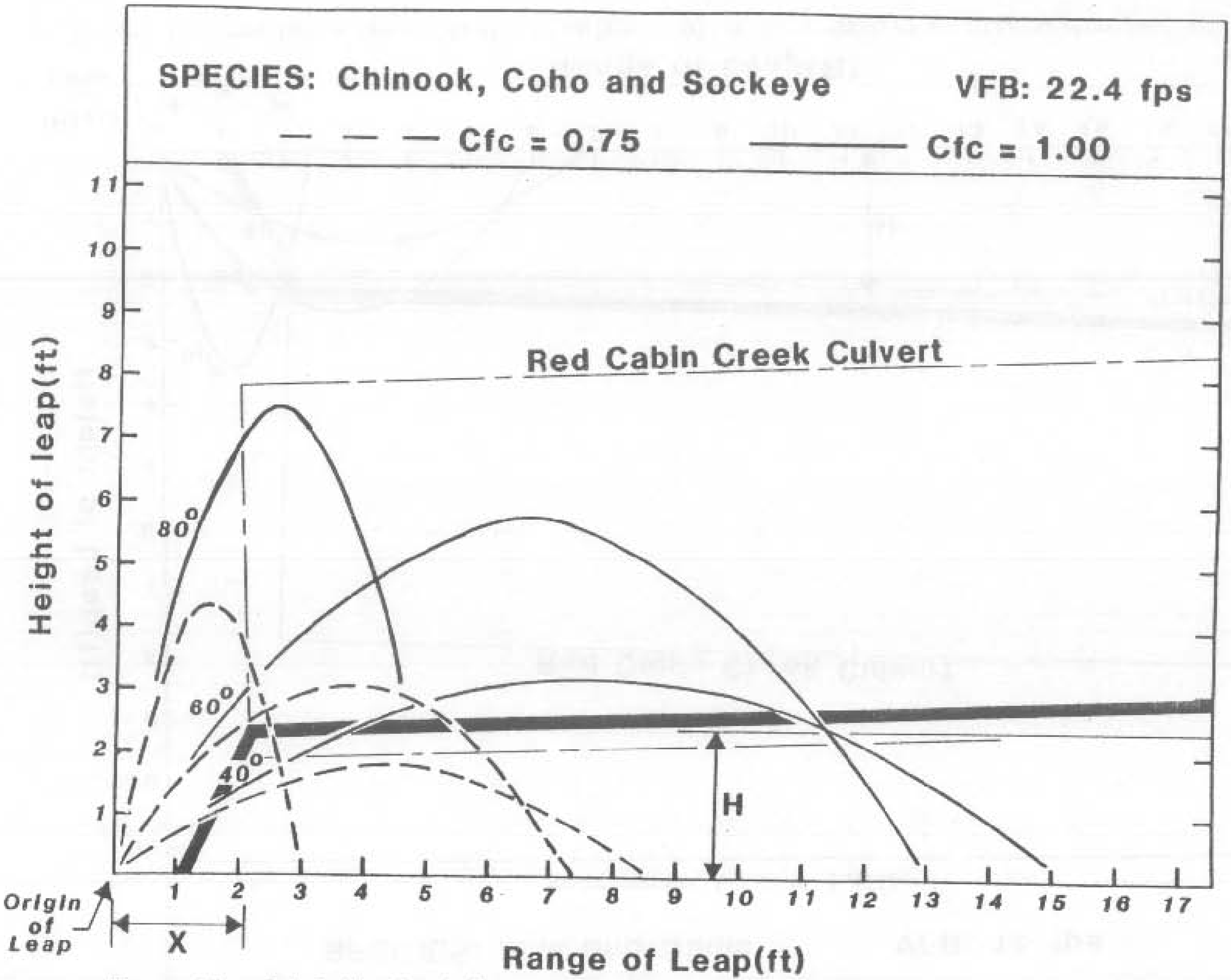


Figure 30. Red Cabin Creek "revised" culvert outlet superimposed on chinook and coho salmon leaping curves.

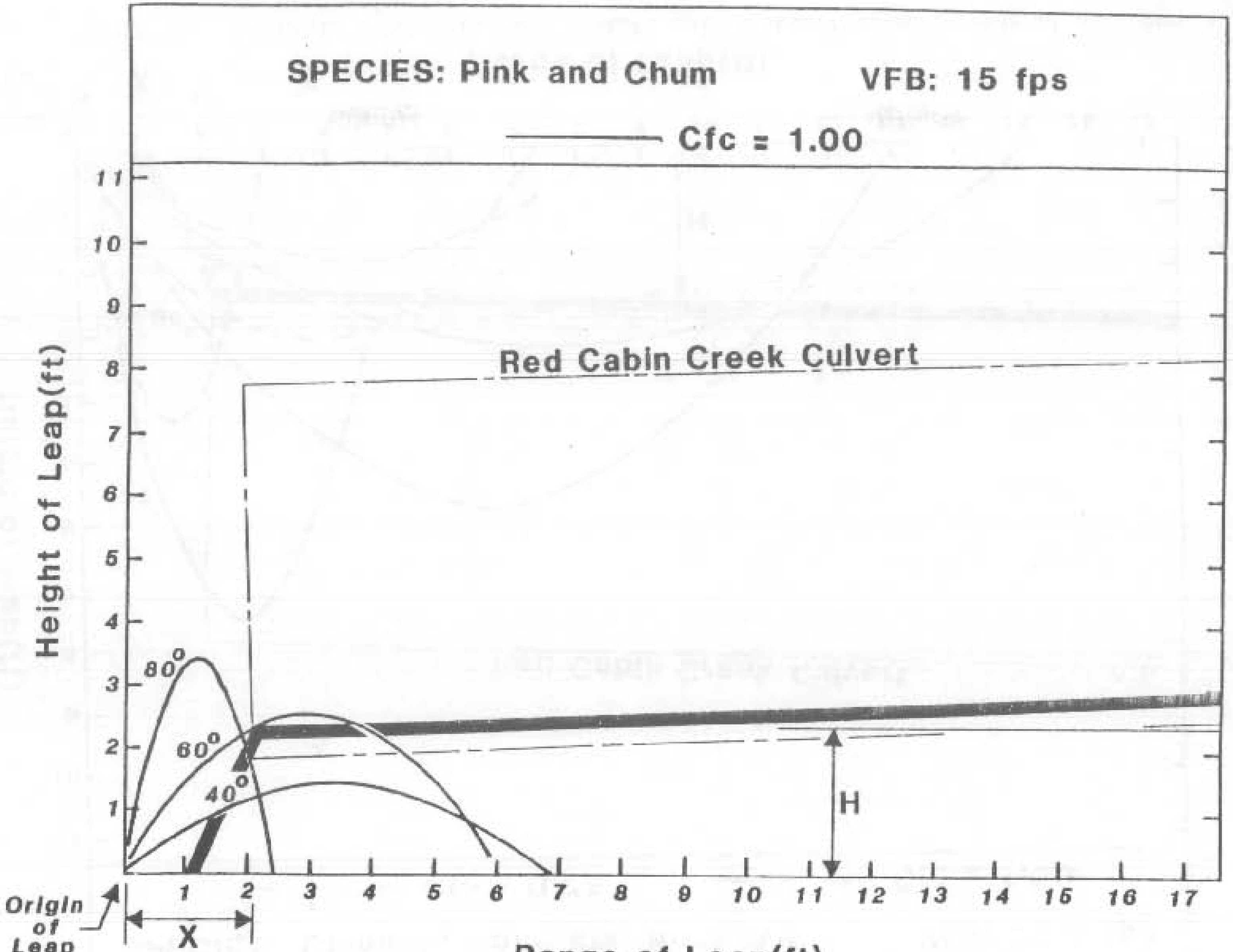


Figure 31. Red Cabin Creek "Revised" culvert outlet superimposed on pink salmon leaping curves.

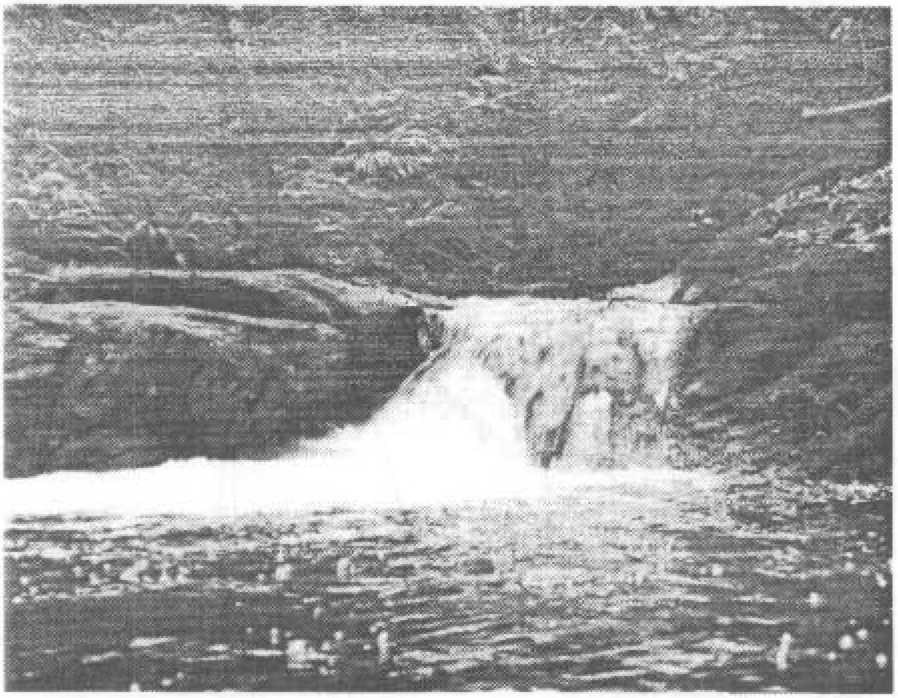


Figure 32. Looking upstream at Chuckanut Creek waterfall.

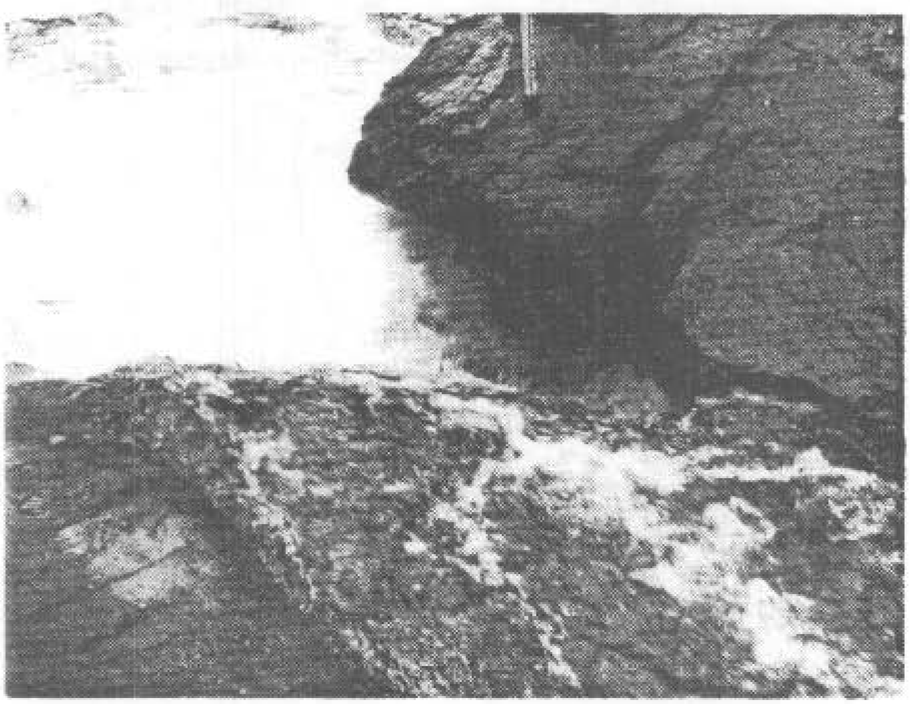


Figure 33. Plan view of obstructing rock near Chuckanut Creek waterfall crest.

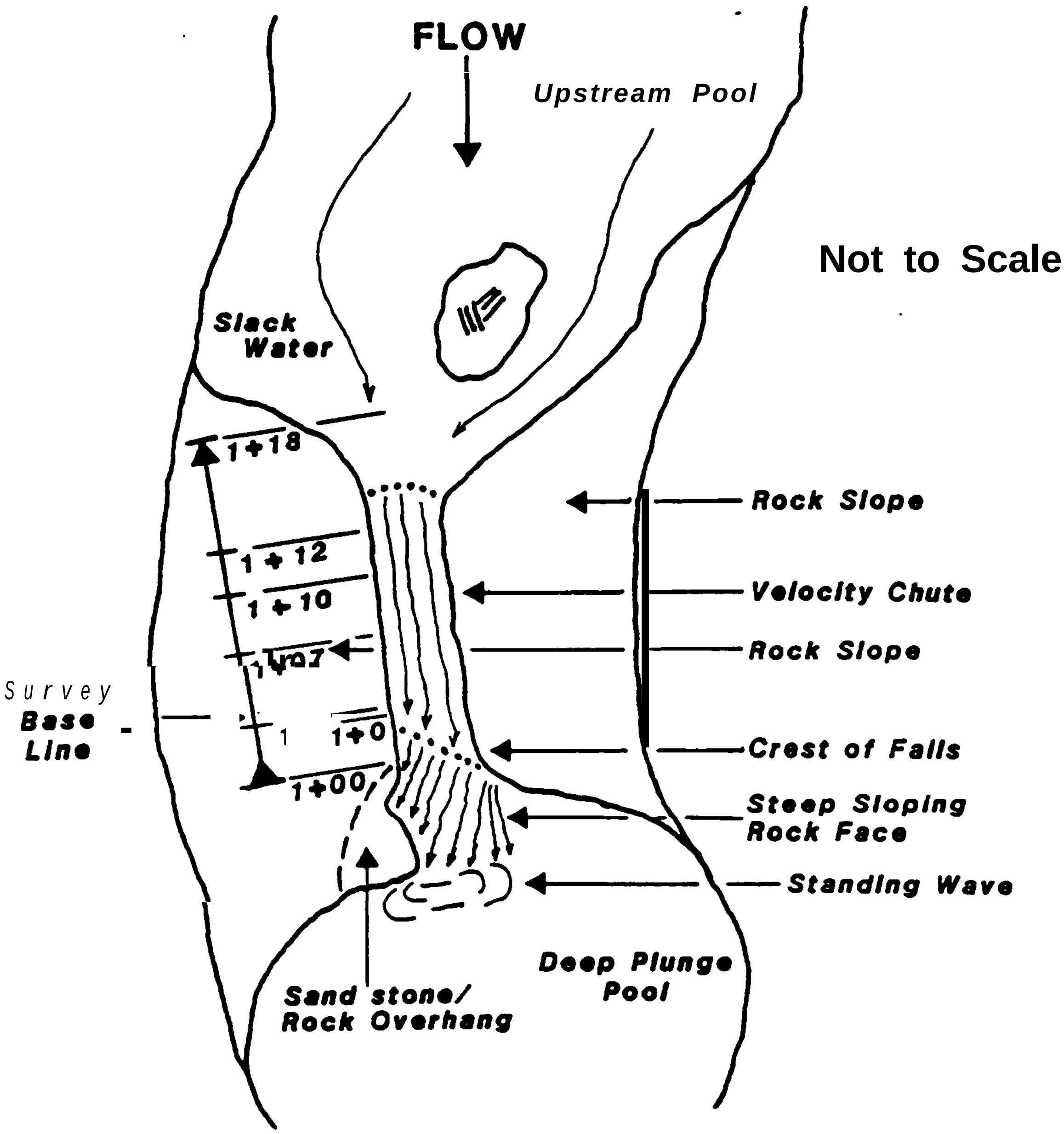


Figure 34. Plan view sketch of Chuckanut Creek waterfall.

Waterfall Description: In the upstream section the harrier begins with a short, narrow rock chute (triangular Cross section) which terminates in a 2 to 3 it drop. At the drop there is 3 rock/sandstone overhang which say obstruct passage to the upper chute of the barrier, Figure 33. The main openinq for passage appears to present a very shallow depths near the crest. This waterfall does not appear to he an elevation or velocity barrier, but because of the rock overhang it may present orientation problems. Steelhead have been observed by Dept. of Fisheries personnel to successfully pass the barrier, hut have also been observed falling back after landing near the crest.

Hydraulic Analysis: To analyze the hydraulics at Chuckanut Falls, an engineering survey was conducted on 12/8/83 to determine the chute cross sections and significant topographic points throughout the barrier site. A survey base line was established (Figure 34) and measurements of channel cross-sections taken. Using station 1+07 as a representative cross-section (Figure 35) for the chute, the velocities can be calculated using equation (17) with the following values: bed slope (assume uniform flow) = 7.7- (measured), flow area (measured from Figure 35) = 1.5 ft^2, wetted parameter (from Figure 35) = 3.9 ft, and roughness coefficient (jaqqed rock 0.035 to 0.050, Table 9). Substituting these values into equation (17) yields for the average velocity at station 1+07:

$$V = (1.49/0.035)(1.5/3.9)^{0.67}(0.077)^{0.5} = \underline{6.2\ fps,}\ \text{and}$$

$$V = (1/49/0.050)(1.5/3.0)^{0.67}(0.077)^{0.5} = \underline{4.4\ fps}.$$

Multiplying the average velocity by the flow area, equation (22) yields a discharge of:

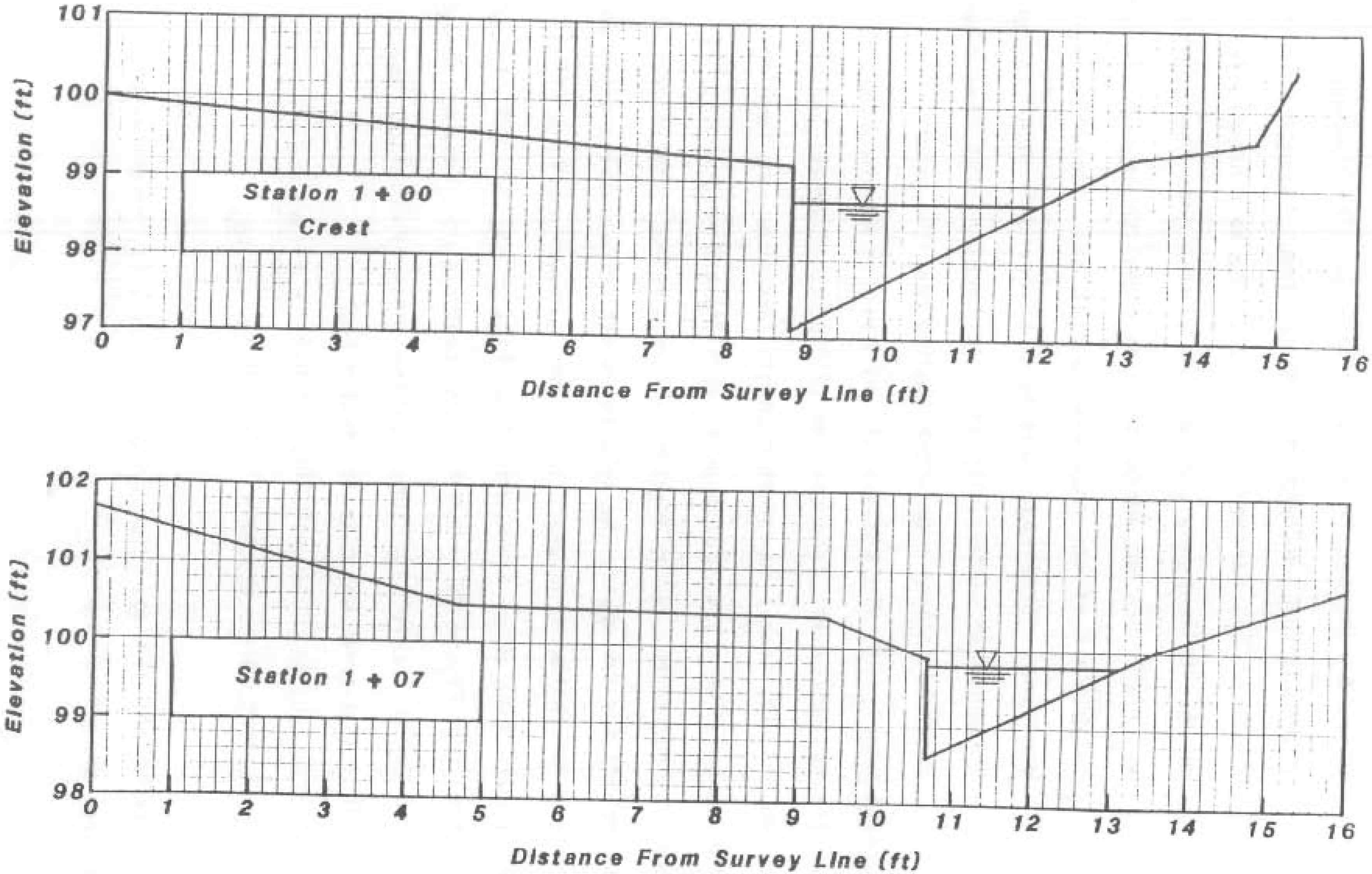


Figure 35. Cross sectional areas of stations 1+00 and 1+07 at Chuckanut Creek waterfall looking upstream.

Q(n=0.035) = VA = 6.2(1.5) = 9.3 cfs and

Q(n=0.050) = VA = 4.4(1.5) = 6.6 cfs.

Therefore at station 1+07, the average velocity the fish must face assuming a discharge of 8.0 cfs is 5.3 fps. A similar analysis was applied to station 1+00 (Figure 35, the crest), and an average velocity of 3.1 fps was calculated. The velocity decreases near the crest because of the increased flow area from station 1+07 to 1+00.

The barrier is located only 1.8 river miles from the salt water, so a coefficient of fish condition, Cfc, of 1.0 will be used. The distance the fish can swim for the average velocity calculated (5.3 fps) is given by Figures 10, 11 and 12 as:

Specie	Maximum Swimming Distance
Steelhead	105 ft
Coho	80 ft
Chum	48 ft

Since the chute is only 12 ft in length, if the fish can get into the chute they will easily pass the barrier.

The upper chute terminates in an overfall where the water breaks off the crest (which is angled to the flow) and strikes the plunge pool. The change in water surface elevation from the crest to the plunge pool was measured at 2.7 ft. Because of the overhanging rock on the right side of the fall (left looking upstream in Figure 32) the fish are forced to leap at the right side (looking upstream), where the water breaks off the crest and flows down a short chute (7.5 ft long) at a measured depth of 0.1 ft. Because of the shallow depth it is not possible for the fish to swim up this chute, and therefore they must leap to pass.

The distance X was measured to be 8 ft. Using equation (16), and the measured H and X values of 2.7 ft and 8.0 ft respectively gives a leaping angle of:

$\theta L = \tan^{-1} 3(H/X) = 45^\circ$

Superimposing H and X on the fish leaping curves (Figures 7, 8, 9) shows the following:

1. Steelhead and coho can successfully pass at leaping angles of 60 and 40 degrees (Figures 36 and 37).
2. Chum salmon will fall short of the crest by about 4 ft at leaping angles of 60 and 40 degrees (Figure 38).

The calculated leaping angle of 45° will extend to the point of maximum leaping distance for this falls geometry. The fish that successfully leap will probably land in very shallow water and higher velocities because of disorientation caused by the overhanging rock.

The plunge pool depth was measured at 5.5 ft, and therefore provides a good leaping situation. Under the present conditions, Chuckanut Creek falls appears to be an elevation and orientation barrier at low flows (8 cfs) to chum salmon, but not to steelhead and coho, except for the overhanging rock obstructing the path to the upper chute. Classification of this barrier is shown in Figure 39.

Chuckanut Creek - Solutions

A very good low flow channel is present above the falls, upstream from the falls crest. Referring to Figure 33, if the overhanging rock was removed, the fish would have a "straight-shot" into the upper chute. Also, they would be attracted to leap at the area of highest flow momentum because of the deep channel on the left side (looking upstream). This would also allow the fish to get further upstream before they attempt their leap, and decrease the horizontal leaping distance (X). Even at high flow, the majority of the flow would he concentrated in the deeper low flow channel.

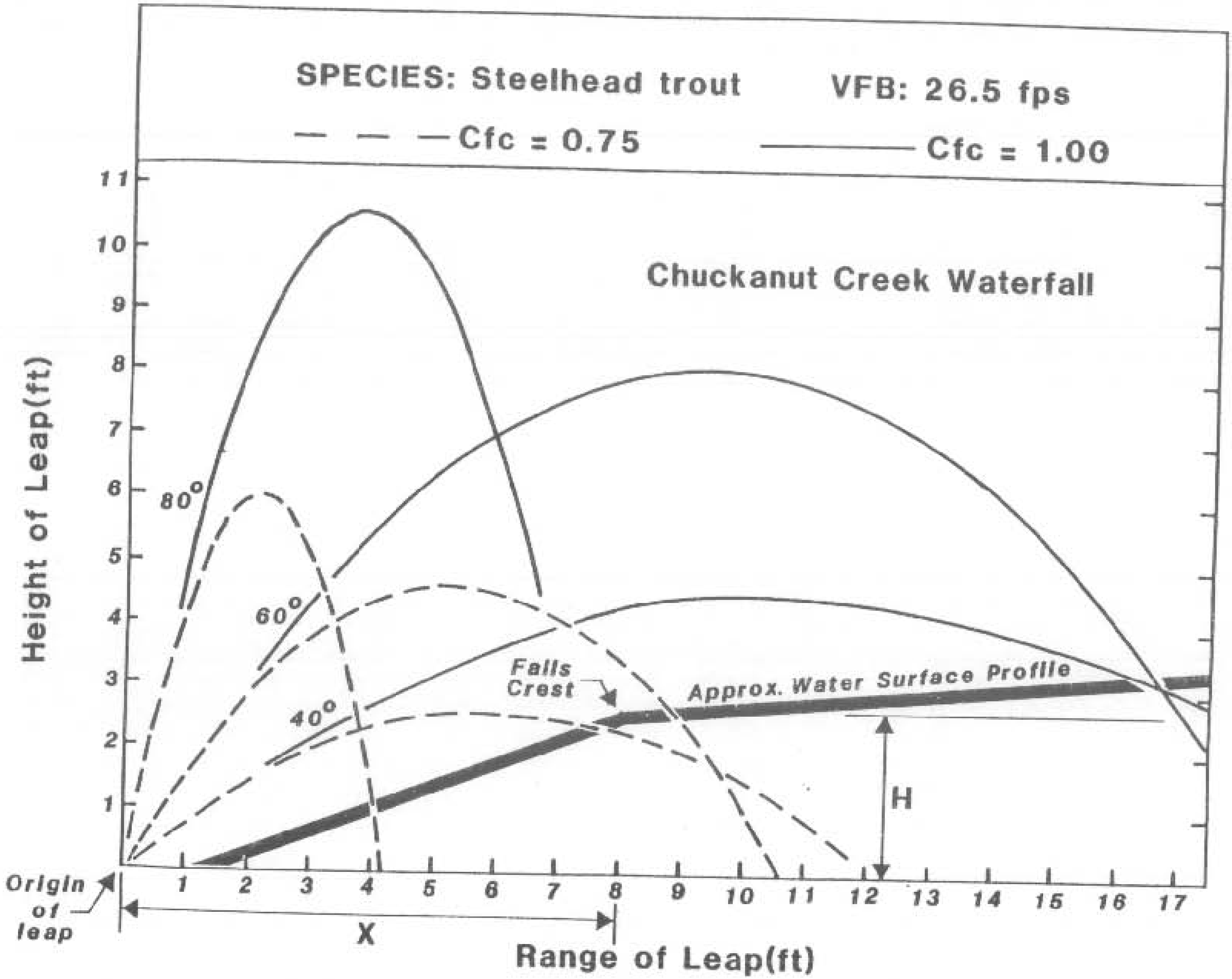


Figure 36. Chuckanut Creek fall superimposed on steelhead leaping curves.

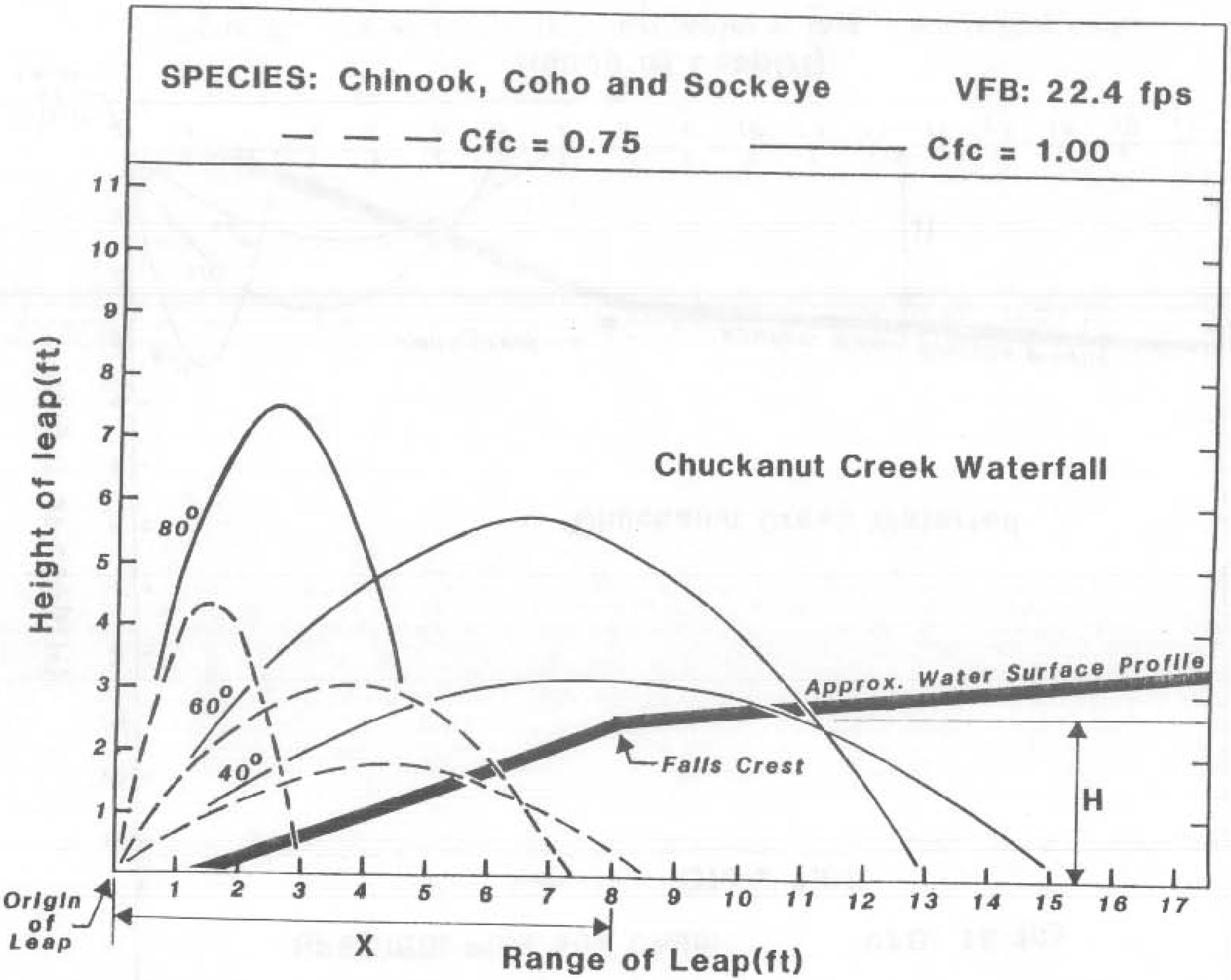


Figure 37. Chuckanut Creek fall superimposed on coho salmon leaping curves.

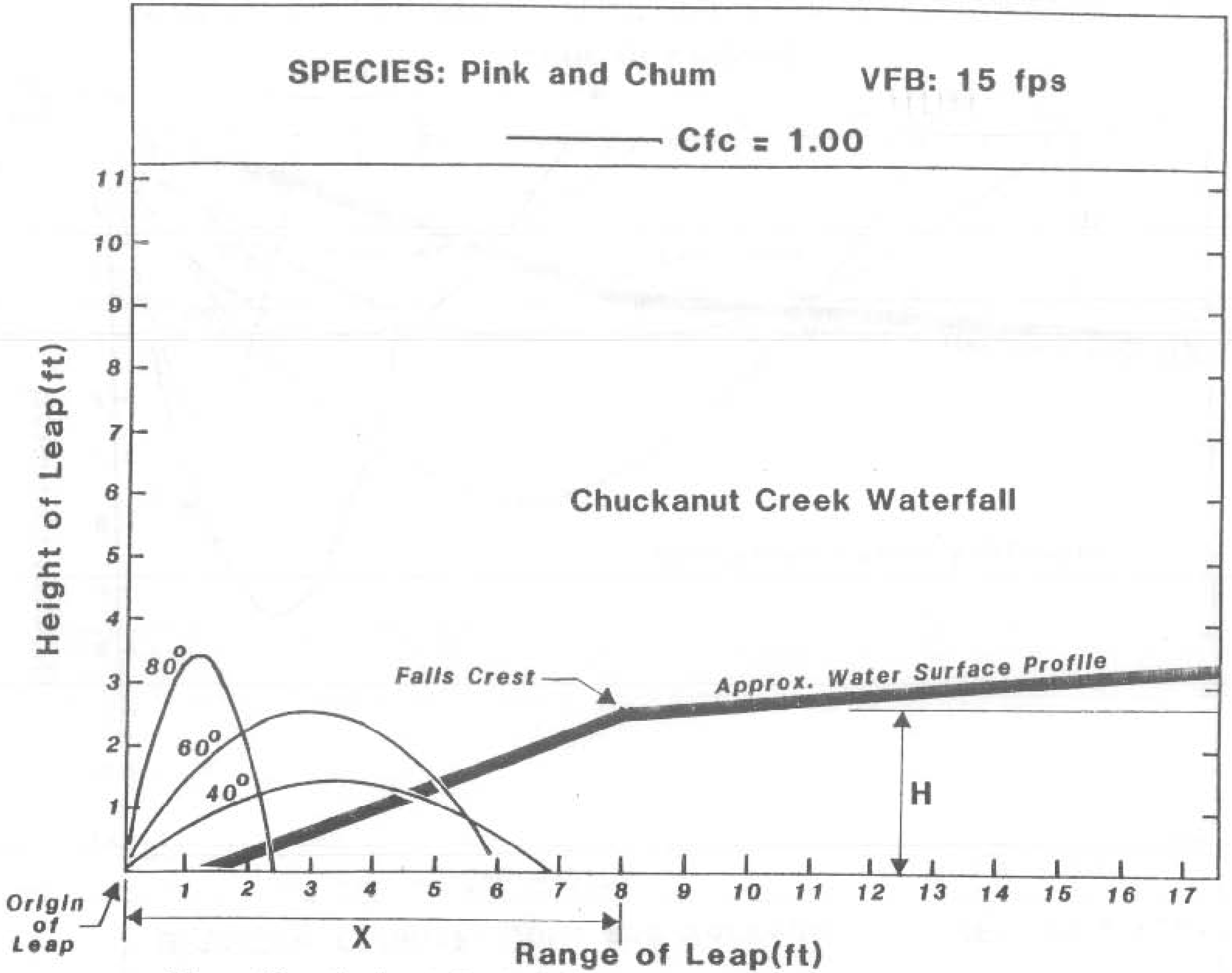
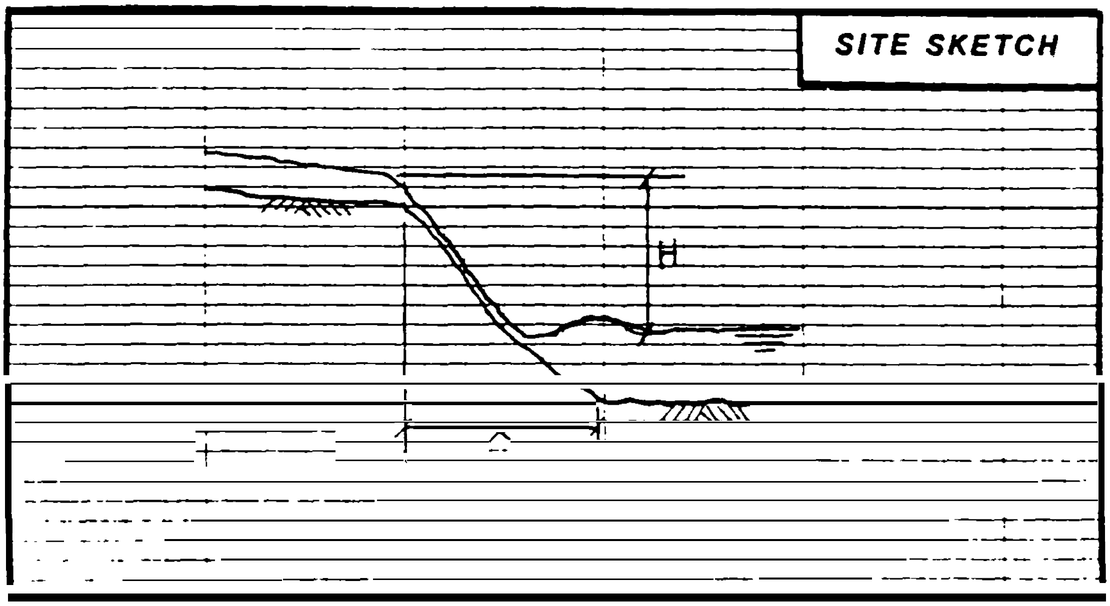


Figure 38. Chuckanut Creek fall superimposed on chum salmon leaping curves.

SITE: Chuckanut Creek Waterfall DATE: 12/8/84

LOCATION: Middle of the Western 1/2 of Section 17, T37N, R3E



CLASS: Single Fall

TYPE: II A 1

DEGREE OF DIFFICULTY: 2

MAGNITUDE: H = 2.7 ft
X = 8.0 ft

DISCHARGE: Q = 8 cfs

COMMENTS: Rock overhang at crest may obstruct orientation for leaping.

Figure 39. Classification of Chuckanut Creek waterfall.

CONCLUSIONS

The guidelines for analyzing a waterfall or culvert barrier in this report are relatively simple. With the expertise of a fisheries biologist and a hydraulic engineer these guidelines can be used effectively to resolve the dilemmas of fish passage problems at barriers. The following is a list of significant conclusions developed:

1. Unstable plunge pools disorient and reduce the fish's leap trajectory and height respectively.

2. Velocities and depths can be estimated for any irregular shaped falls crest as a function of the discharge at critical depth from:

$$Q^2/g = A^3/W$$

where Q = stream discharge, g = acceleration of gravity, A = cross sectional flow area and W = top stream width.

3. Water surface profiles at barriers can be superimposed on fish leaping curves to analyze passage success. The optimum leaping angle can be estimated by:

$$\theta L = \tan^{-1} 3(H/X)$$

where H = the difference in water surface elevations, and X = horizontal distance from the standing wave to the crest of the falls or chute.

4. For rectangular and triangular shaped channels the hydraulic radius can be estimated as a function of the average width and depth with errors less than 5%; this allows the mean velocity to be calculated.

5. For depths greater than 1 feet in corrugated metal pipe culverts, fish can swim in reduced velocities near the boundary where the velocitv opposing the fish is less than the mean velocity by as much as 30 .

6. Stage-discharge relationships,when compared wit'! migration season flows, will define hydraulic conditions at the harriers which the fish must negotiate.

SUGGESTIONS FOR FURTHER STUDY

Concepts for analyzing harriers to upstream fish migration have been presented in this paper. As each section was written, more and more ideas about methods for analyzing barriers were unveiled. The urge to go back and include these new ideas was eventually offset by the necessity to complete the study. Further study of the following areas will increase the accuracy of analyzing and finding solutions to fish passage problems.

1. Plunge pool: guidelines should be developed to accurately determine the plunge pool depth for the given barrier geometry and hydraulics which create optimum leaping conditions.
2. Fish speeds in an air-water mixture: there should be some reduction in the fish's burst speed in a air-water mixture because of the reduced water density. Calculations need to be made using fish locomotion equations (Blake, 1984) to determine the reduction of the propulsive power of the fish's tail in a medium with reduced density. Corresponding leaping heights and trajectories can then be calculated.
3. Leap success ratios: as the height of barrier increases, the number of attempts required for a successful pass should increase. This could he studied in a hatchery fishway, where the leap success ratio (successful 1eaps:leap attempts) is recorded for a range of water surface drops.
4. Migration distance from ocean to barrier reducinq fish capabilities: a survey could be taken to record the river miles to a barrier, height of barrier and species which pass or are blocked.

5. Aerial photography: the design of low-level, balloon mounted photoqraphic equipment could he used. These photograph can greatly reduce site survey tine and provide excellent visualization when used with ground survey controls and at different stages of stream flow.

REFERENCES

Aaserude R. G. 1984 New concepts in fishway design. M.S. Thesis, Dept. Civil and Environmental Engineering, Washington State University

Bell, Milo C. 1973. Fisheries handbook of engineering requirements and biological criteria. Fisheries-Engr. Res. Prog. Corps of Engrs. N. Pac. Div. Portland, Oregon.

Blake, R. W. 1983. Fish locomotion. Cambridge University Press, Cambridge.

Chow, V. T. 1959. Open-channel hydraulics. McGraw-Hill Book Company.

Clay, C.H. 1961. Design of fishways and other fish facilities. The Dept. of Fisheries of Canada. Ottawa. 301 p.

Daily, J. W. and Harleman, D. 1966. Fluid dynamics. Addison-Wesley Pub. Co., Inc., Reading, MA.

Dane, B. G. 1978. A review and resolution of fish passage problems at culvert sites in British Columbia. Fish. and Marine Service. Tech. Rpt. 810.

Douma, J. H. 1943. Open channel flow at high velocities. Trans. Amer. Soc. Civ. Engrs., No. 205, 1462-1473.

Dryden, R. L. and Stein, J. M. 1975. Guidelines for the protection of the fish resources of the Northwest Territories during highway construction and operation. Dept. of the Environment, Fish and Marine Service. Tech. Rt. No. CEN/T-7 5-1.

Evans, Willis A., and Beryl Johnston. 1980. Fish migration and fish passage. USDA Forest Service, EM-7100-12 Washinqton, D.C., 63 p. plus appendices.

Fairbridge R. W. 1968. The encyclopedia of geomorpholoqy. Encyclopedia of Earth Sciences Series. Vol. III. Waterfalls by D. C. Ford. Peinhold Book Corp. New York. pp. 1219-1220.

Hall, L. S. 1943. Open channel flow at high velocities. Trans. Amer. Soc. Civ. Enars. No. 2205, 1393-1434.

Hoar, W. S. and D. J. Randall (Eds.). 1978. Fish physiology. Volume VII. Locomotion. Academic Press New York. (Selected chapters on locomotion, swimming capacity, and hydrodynamics by Lindsey, Beamish and Webb.

Jackson, R.I. 1950. Variations in flow patterns at Hell's Sate and their relationships to the migration of sockeye salmon. Int. Pac. Salmon Fish. Comm. Bulletin III Part II.

Kerr Cons, et al. 1980. Stream enhancement guide. Prepared for Prov. of British Columbia. Ministry of the Environment. Vancouver, B.C. 82 p.

McKinley, W. R. and Webb, R. D. 1966. A proposed correction of migratory fish problems at box culverts. Washington Dept. of Fisheries Fish. Res. Papers. 1(4):33-45.

Orsborn, J. F. 1982. Low-cost fish passage facilities at five waterfalls. Stikine and Ketchikan Areas, Tongass National Forest, Alaska.

Pryce-Tannatt, T.E. 1938. Fish passes. Buckland Lectures, 1937. Edward Arnold and Co., London.

Renard, K. G. and Laursen, E. M. 1975. Dynamic behavior model of ephemeral stream. J.Hyd. Div., ASCE, 101 (HY5):511-528.

Salmonid. 1983. Dept.of Fish. and Oceans. Vancouver, B.C. Vo. VIII. No. 4.

Stuart, T. A. 1964. The leaping behavior of salmon and trout at falls and obstructions. Dept. of Agri. and Fish. for Scotland, Freshwater and Salmon Fish. Res. (Edinburgh: Her Majesty's Stationery Office). 28, 46 p.

Watts, F. J. 1974. Design of culvert fishways. Water Resources Research Inst., Univ. of Idaho, Moscow, ID 62 p.

Webb, P. W. 1975. Hydrodynamics and energetics of fish propulsion. Bull. Fish. Res. Bd. Can. 190:159 p.

Ziemer, G. L. 1961. Fish transport in waterways. Alaska Dept. of Fish and Game.

APPENDIX I

NOTATION

NOTATION

Elevation (H)

H	in water surface elevation
t!L	Height of the fishes leap

Distances (L and X)

LS	Length of slope
X	Horizontal distance from the crest to standinq wave
XP	Horizontal distance from the crest to point where falling water plunges
XSW	Horizontal distance from point where falling water plunges to standing wave
LF	Length of fish
LFS	Length the fish can swim

Velocities (V)

VW	Velocity of water
VF	Fish speed
VFB	Burst speed of fish
VFP	Prolonged speed of fish
VFS	Sustained speed of fish
ii	Temporal mean velocity
$\bar{u}_f$	Temporal mean velocity at which the fish swim
u_*	Shear velocity
VR	Relative speed of the fish to the water
VW_c	Velocity of water at falls crest

Depths (d)

d_w	Depth of water
d_c	Critical depth
d_{pp}	Depth in the plunge pool

d_p	Depth of plunge by waterfall jet
d_f	Depth of fish

Slopes (S)

S_e	Fish exit (water inlet) slope
S_p	Fish passage (water transition) slope

Others

C_{fc}	Coefficient of fish condition
θW_c	Angle in degrees from horizontal at which the velocity leaves the crest
θL	Angle in degrees from the horizontal at which the fish leaps
R	Hydraulic radius
g	Acceleration of gravity
n	Manning's emperical roughness coefficient
W	Width

APPENDIX II

AN ANALYSIS OF COHO AND CHUM SALMON SWIMMING UP A VELOCITY CHUTE

AN ANALYSIS OF COHO AND CHUM SALMON SWIMMING UP A VELOCITY CHUTE

Waterfalls and culverts sometimes form velocity barriers to the upstream migration of adult salmon and steelhead trout. Often, the swimming capabilities of the species in question will determine the success of passage. Other factors which effect the success of passage are: depth of flow, distance the fish must swim, and violent turbulence (unstable flow patterns). In order to analyze how these factors effect fish passage, a "velocity chute" study was conducted at Johns Creek Fish Hatchery near Shelton, Washington. This study was done in conjunction with the Bonneville Power Administration (BPA) Fisheries Project 82-14, "New Concepts in Fish Ladder Design." At the conclusion of the study, it became apparent that a velocity chute could be used as an efficient and economical method of passing fish. With a fishway pool length of 12 ft (3.66 ml and a chute length of 8 ft. (2.44 m) chum salmon (Onchorhynchus keta) were observed passing a change in water surface elevation of 1.8 ft (0.55 m1 with a passage success rate of 100%.

Experimental Facilities

The chute was installed in the existing fishway bulkhead slots. It was constructed with 3/4 inch plywood at a length of 8 ft (2.44 ml. In test +l the chute width was 2 ft (0.61 m) with a wall height of 1 ft (0.30 m). After completion of test #1, the width was decreased to 1.25 ft. (0.38 m) and the wall height was increased to 1.5 ft (0.46 m) in order to obtain a greater depth of flow (test #2). At the inlet (crest) the chute was supported by two hinges, which allowed adjustment of the slope. Near the fish entrance it was supported by adjustable vertical and horizontal support rods (Fig. 1).

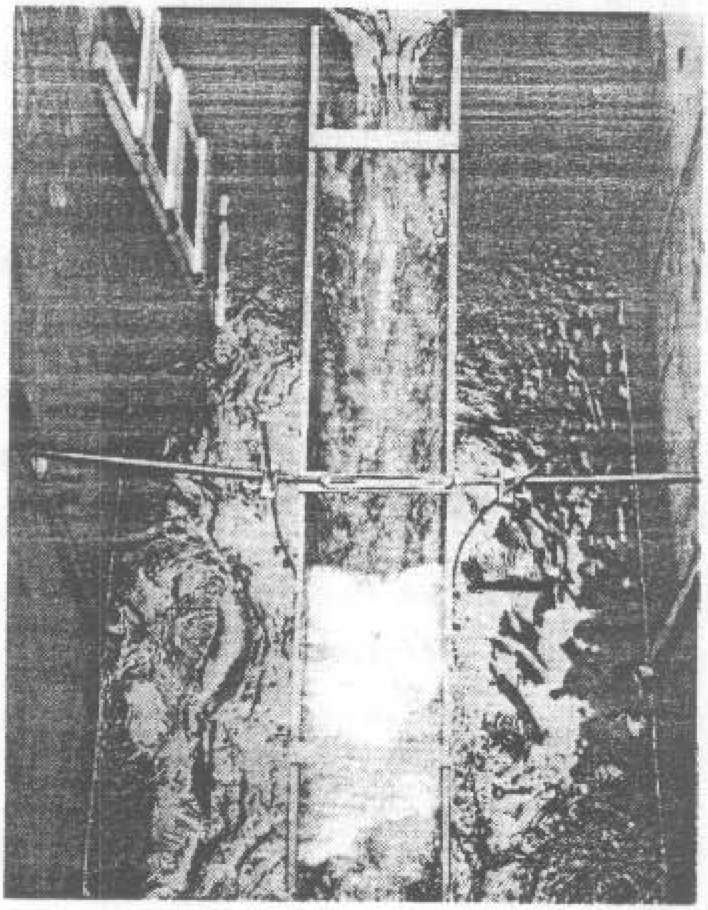


Figure 1. Plan view of the 8 ft long and 1.25 ft wide velocity chute test apparatus installed in the Johns Creek Fishway.

Chute Hydraulics

The approach velocity from the upstream pool was negligible, and critical depth (Froude No. = 1) always occurred at the chute water entrance or crest. The three zones of flow observed during testing were: 1) transition zone; 2) uniform flow zone; and 3) hydraulic jump/standing wave zone. In the transition zone, the flow was passing through critical (at the crest) to uniform depth approximately 2 ft (0.61 m) down the slope from the crest. The depth is greater in the transition zone than in the uniform flow zone and when the fish approached the transition zone they "burst" through it into the upstream pool because of the decreased flow velocity. The uniform flow zone began at approximately 2 ft (0.61 m) from the crest and remained at constant depth until it dissipated into the downstream pool. At this point, a hydraulic jump developed which increased in intensity as the chute velocity increased.

The addition of roughness elements on the floor of the chute had the effect of increasing the depth and decreasing the velocity for a given slope. The spacing between the roughness elements was filled with circulating water containing stable eddies, creating a pseudo wall. Chow (1959) classifies this as "quasi-smooth flow." Quasi-smooth flow has a higher friction factor than flow over a true smooth surface because the eddies in the grooves consume a certain amount of energy. These hydraulic conditions were observed in a plexiglass model of the chute in Albrook Hydraulics Laboratory at Washington State University. The model was also used to verify field measurements of velocity and discharge.

Study Objective

The objectives of this field study were to observe and record the following:

1. The response of coho and chum salmon to outflow conditions at the downstream end of the chute:
   a. leaping;
   b. swimming; and
   c. attraction conditions.

2. Water depths which affect passage:

   a. minimum depth;

   b. depth where swimming is unimpaired; and

   c. effect of roughness elements on water depth/fish passage.

3. Swimming speeds of coho and chum salmon:

   a. relative velocity of fish with respect to water (fish speed),

   b. relative velocity of fish with respect to chute, and

   c. passage time.

<u>Results</u>

Test No. 1; Chute Width = 2.0 ft (0.61 m)

In this test observations were made of the chute hydraulics and fish movements. The majority of fish tested were adult coho salmon (*Onchorhynchus kitsutch*) which were in poor physical condition, displaying full spawning colors and averaging about 2 ft (0.61 m) in length. The few chum salmon tested also displayed full spawning colors and averaged 30 in (76.2 cm) in length. The maximum depths of the fish bodies were: coho 0.4-0.5 ft (0.12-0.15 m) and chum 0.65 ft (1.65 cm).

An immediate problem developed because the depth of flow at 0.2 to 0.3 ft (0.06 to 0.09 m) was too shallow. The smaller coho could pass but the larger chum could not. Average velocities in the chute ranged from 5 to 8.3 fps (1.74-2.9 m/s) which is in the range of the upper prolonged speed of 10.6 fps (3.23 m/s) for coho salmon suggested by Bell (1973).

The fish response to different types of hydraulic jumps (or standing waves) was observed. The Froude number for all tests was in the 1.2 to 4.1 range. Chow (1959) suggests for this range the jump type is just beginning to oscillate as was observed. Stuart (1964) describes these water surface oscillations as points from where fish are often seen leaping. The fish that passed were observed to be holding in the standing wave, then bursting into the uniform flow zone (Fig. 2), and proceeding at a constant speed until the transition zone was reached. Coho salmon that reached the transition zone always swam successfully into the upper pool. Unsuccessful fish were usually slow starters who, after several attempts, were observed leaping out of the standing wave.

Test No. 2; chute width = 1.25 ft (0.38 m)

The coho tested were in worse condition than in test #1 but a fresh run of chum salmon entered Johns Creek only a few days before the testing started. Fish sizes were the same as Test No. 1. The channel width was decreased to 1.25 ft (0.38 m) and roughness elements were added to the chute floor. The height of the roughness elements was 1.5 in (3.8 cm), spaced at a distance of 3 in (7.6 cm) and 6 in (15.2 cm) in separate removable false floors. The data obtained from these tests are summarized in Table 1.

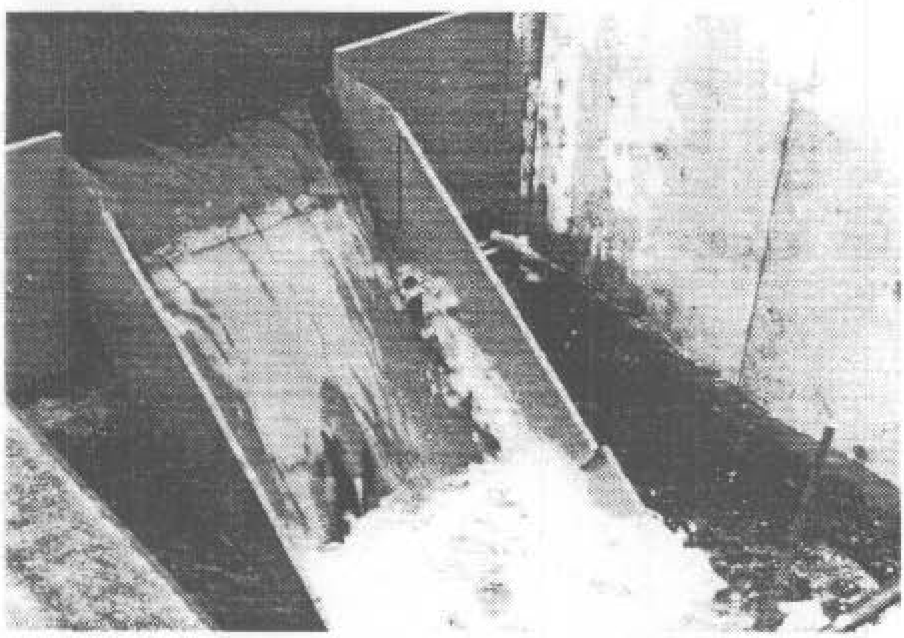


Figure 2. Coho salmon bursting out of hydraulic jump into uniform flow zone.

Table 1. Velocity chute test #2 data.

Test No.	Uniform Depth From Floor (ft)	Uniform Depth Above Roughness El. (ft)	Uniform Velocity (fps)	Length Slope (ft) (Slope) (%)	Passage Success (%)	Flow (cfs)
2a[a]	0.13	---	8.3	5.5	0(coho)	1.1
				(26)	0(chum)	
2b[b]	0.41	0.28	5.2	7.5	95(coho)	2.3
				(15)	92(chum)	
2c[c]	0.51	0.38	5.0	8.0	64(coho)	2.9
				(19)	89(chum)	
2d[c]	0.66	0.54	6.8	7.0	78(coho)	5.0
				(27)	100(chum)	
2e[c]	0.56	0.44	6.7	7.0	No coho	4.1
				(36)	23(chum)	

Notes: a - roughness elements not used, floor consisted of plywood (n=0.021).

b - Roughness elements with 3 inch longitudinal spacing (n=0.044).

c - Roughness elements with 6 inch longitudinal spacing (n=0.055, 0.053 and 0.059 for tests 2c, 2d and 2e respectively).

In test 2a, roughness elements were not used, and the depth of flow was 0.13 ft (0.04 m) with an average velocity of 8.3 fps (2.53 m/s). The success passage was 0X for coho and chum, so this depth was a barrier. Once the roughness elements were added to the floor the depth increased to 0.4 ft (.12 m) - 0.6 ft (0.18 m) range which was adequate for fish passage. This is the depth from the floor to the water surface. Dane (1978) suggests a minimum depth of 0.75 ft (0.23 m) for Pacific Salmon, and Dryden and Stein (1975), suggest that "in all cases, the depth of water in a culvert should be sufficient to submerge the largest fish to use the structure." This field study has shown how partial submergence impairs the ability of the fish to generate thrust.

Fish Movements

As noted in Test #1 results, fish were observed holding in the hydraulic jump where the velocity is decreased and then bursting into the uniform flow zone as shown in Figure 3. Once into the uniform flow zone (zone of highest velocity) the fish always moved laterally to the chute side wall and continued through the uniform flow zone along the wall (Fig. 4). Near the wall boundary the water velocity was decreased as much as 60% of the centerline velocity, because of the shearing resistance created. When fish approached the transition zone and the velocity decreased, they moved out into the middle of the chute (Fig. 5) and burst through the crest into the upper pool. Some of the unsuccessful or slower fish were observed crossing back and forth laterally in the chute searching for a zone of lower velocity.

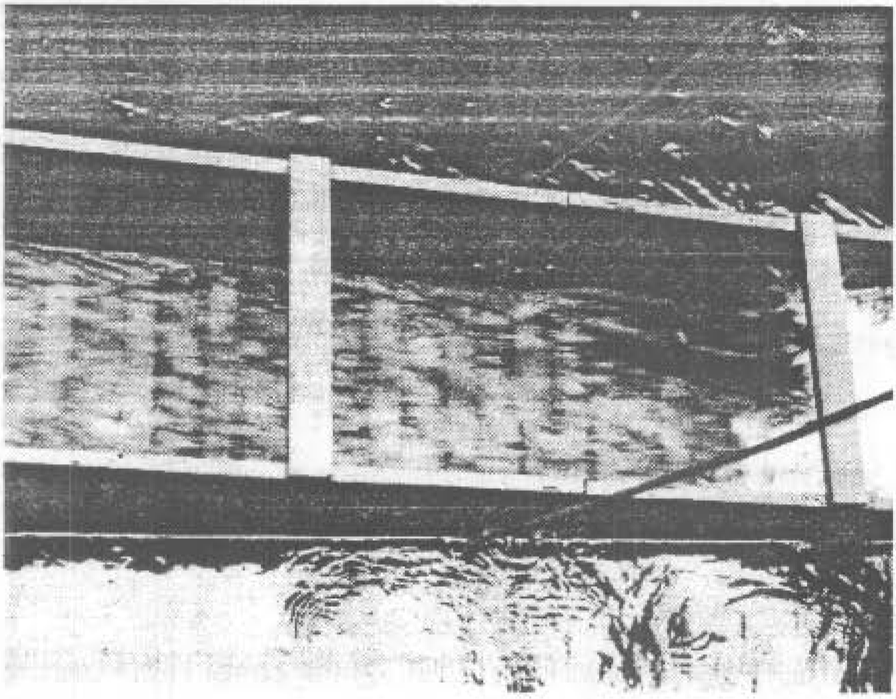


Figure 3. Chum salmon bursting out of hydraulic jump after several seconds of holding in the jump.

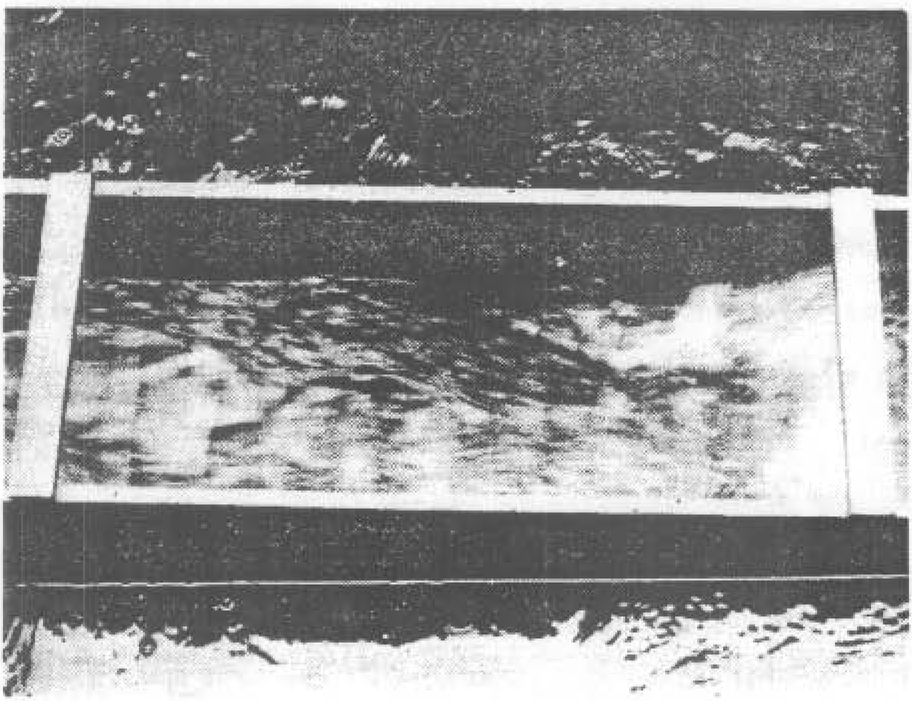


Figure 4. Chum salmon swimming up chute taking advantage of reduced velocities in boundary layer.

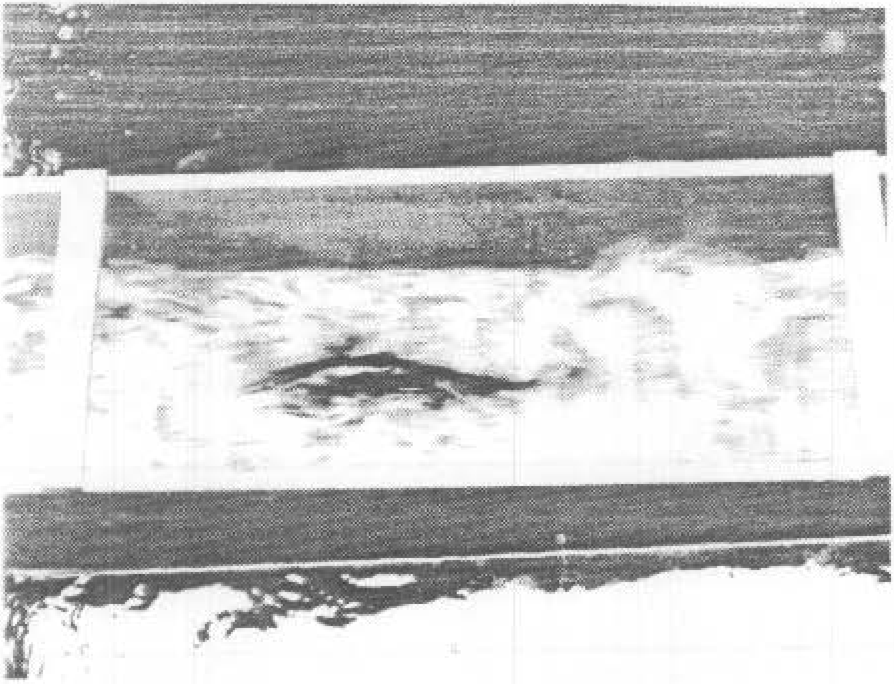


Figure 5. Chum salmon approaching transition zone moving laterally into middle of chute.

Analysis of Fish Speeds

Tests Results

The time required to successfully pass the chute was recorded with a stop watch. Knowing the distance that the fish swam to reach the crest, the velocity of the fish with respect to the chute can be calculated. When the water velocity is determined the actual swimming speed of the fish can be calculated. This calculation assumes constant velocity down the chute which is not exactly true because of the transition zone near the crest. But as noted earlier, uniform depth was reached within 2 ft (0.61 m) of the water inlet. As the slope was increased in subsequent tests the flow approached uniform depth in an even shorter distance.

A calculation of fish speeds for test #2b is shown below

Length of Slope(LS) = 7.5 ft.

Water Velocity (VW) = 5.2 fps

Passage Times (PT) in seconds:

Test #2b:

	coho	chum
maximum	4.7	5.5
average	3.5	4.0
minimum	2.0	2.3

Fish Velocity (fps) = (LS)/(PT) + VW

Species	Fish Velocity (fps)		
	Maximum	Average	Minimum
Coho	8.9	7.3	6.8
Chum	8.5	7.1	6.6

Velocities for the other tests are summarized in Table 2.

Table 2. Maximum, average and minimum swimming speeds of coho and chum salmon passing the velocity chute.

Test No.	Species	Fish Velocity (fps) Minimum	Average	Maximum
2b	Coho	6.8	7.3	8.9
	Chum	6.6	7.1	8.5
2c	Coho	6.0	6.5	7.6
	Chum	6.0	6.4	7.1
2d	Coho	9.1	9.5	10.7
	Chum	8.6	8.8	8.9
2e	Chum	8.8	9.1	10.0

Discussion

Swimming speeds of fish are usually reported in three categories: sustained, prolonged and burst. Burst speed is defined as causing fatigue in 5 to 10 seconds (Bell, 1973). From observations and fatigue times recorded, the fish passing the chute were assumed to be using burst activities. Bell (1973) suggests a burst speed range of 10.6 to 21.5 fps (3.2 to 6.5 m/s) for coho salmon. The maximum swimming speed (or burst speed) recorded in these tests for coho salmon was lg.7 fps (3.26 m/s), definitely on the lower range of Bell's suggested speeds. But as noted earlier, these coho were in very poor physical condition. Therefore, the maximum speed of 10.7 fps (3.26 m/s), which is 50% of the maximum burst sneed suggested by Bell (1975), is probably the upper range of burst speed for a coho salmon near its spawning time.

Burst speeds of chum salmon have not been recorded in the literature, but they are generally thought to be a weaker fish in comparison to coho. Observations1 of chum salmon leaping 3 and 4 ft (0.91 and 1.2 m) suggest a burst speed of about 15 fps (4.6 m/s) to achieve these heights. The maximum swimming speed recorded for chum salmon was 10.0 fps (3.05 m/s) or 67% of the maximum burst speed of 15 fps (4.6 m/s). The chum tested were in good shape, but their spawning colors and teeth were fully developed.

This information can he helpful in analyzing waterfalls and culverts as barriers to upstream fish migration. The speed of the fish can be based on some percentage of the maximum burst speed suggested by Bell (1973), depending on the condition of the species in question. This will be termed the "coefficient of fish condition" (C_{fc}). Table 3 gives a range of C_{fc} and the corresponding fish conditions based on observations made of coho and chum salmon in Johns Creek.

Table 3. Coefficient of fish condition (C_{fc}); values based on observations and data taken for coho and chum salmon at Johns Creek Fish hatchery near Shelton, Washington.

Fish Condition	C_{fc}
Bright, fresh out of the ocean or still a long distance from spawning grounds, no spawning colors yet developed.	1.00
Good, in the river for a short time, spawning colors apparent but not fully developed, still migrating upstream.	0.75
Poor, in the river for a long time, full spawning colors developed and fully mature, very close to spawning grounds.	0.50

Relative Fish Velocity

Another concept tested in this study was that of the relative velocity at which fish swim with respect to the chute. Studies on fish passing through culverts have assumed this "fish passage velocity" to be 2 fps (0.61 m/s) in relation to the culvert (Dane, 1978). This is an important parameter for passage analysis because, given the water velocity, one can determine the speed the fish must swim to pass. Values obtained in this study were average4 over four runs and are given in Table 4.

Table 4. Relative velocity of chum and coho salmon with respect to chute.

Species	Relative Fish Velocity (fps)
Coho	2.1
Chum	1.9

Feasibility for Fish Passage

All tests were conducted with a pool length of 12 ft (3.66 m) and the change in water surface elevations (H) were measured for each test. The water surface drop was not a variable in this study because the velocity down the chute is independent of the change in water surface elevations, as can he seen by Manning's equation:

$$V = (1.49/n)\ R^{2/3}\ S^{1/2}$$

The change in water surface elevation (H) was varied to obtain the same chute length at a steeper slope. When the values of H are compared with the passage success rates and fishway slope, the feasibility of using slightly roughened chutes for fish passage becomes obvious (Table 5). Currently fishway designers suggest a maximum water surface drop of 1.0 ft (0.305 m) for coho salmon, 0.75 ft (0.23 m) for chum salmon, and a maximum fishway slope of 1 on 8. In test 2d, with a water surface drop of 1.85 ft (0.567 m) and a fishway slope of 1 on 6.5 a 100% passage success rate was recorded for chum salmon. This was achieved by adding only roughness elements 1.5 x 1.5 in (3.81 x 3.81 cm) at 6 in (15.2 cm) clear spacing to the floor of the chute.

Table 5. Change in water surface drop, percent successful passage and fishway slope for chum salmon testing at Johns Creek Fish Hatchery near Shelton, Washington.

Test No.	H (ft)	Chute Slope (%)	% Passage (Chum)	Overall Fishway Slope Including Pool Length
2b	1.03	15	92	1/11.7
2c	1.80	19	89	1/6.7
2d	1.85	27	100	1/6.5
2e	2.52	36	23	1/4.8

Conclusions

This study showed how an 8 ft (2.44 m) wooden rectangular chute can be used to estimate the swimming capabilities of coho and chum salmon and to determine the feasibility of using chutes in series to pass fish. Some of the findings can be summarized:

1. When passing the chute, coho salmon only leaped after several unsuccessful attempts at swimming. Chum salmon always swam to pass.
2. Minimum suggested depths for passage are: coho 0.4 ft (0.12 m) and chum 0.5 ft (0.15 m). Depth of water where fish are unimpaired should be equal to the maximum depth of the fish body.

3. The maximum speed obtained for coho and chum salmon are 10.7 and 10 fps (3.26 and 3.05 m/s), respectively.

4. Coho salmon were swimming at a level of 50% of their maximum burst speed and chum salmon at 67%.

5. The average relative velocities of the fish with respect to the chute were coho 2.1 fps (0.64 m/s) and chum 1.9 fps (0.58 m/s).

6. The use of a velocity chute 1.25 ft (0.38 m) wide by 1.5 ft (0.46 m) high with roughness elements can be used to pass salmon with a high passage success rate and water surface drops of up to 2 ft (0.61 m) with a pool length of 12 ft (3.66 m). The pool length is the dimension from one chute inlet to the next,

Suggestions for Future Testing

To measure the response of fish to a certain parameter, all others must he held constant. For example, in test #2 the velocity was increased by increasing the slope of the chute, but because the depth was not held constant it was hard to determine whether the depth of flow or the increased velocity was affecting the passage success rate. This could be solved by keeping the depth of flow always greater than OF equal to the maximum depth of the fish at the midsection. Other suggestions for further testing might address the following:

1. At what slope does the velocity increase creating a velocity barrier, by species, assuming the depth is sufficient?

2. What is the fish response at a velocity barrier; does leaping commence or do the fish continue to try to swim up the chute?

3. At one velocity where the passage success is low, try three different sizes of roughness elements and observe behavior.

4. As the velocity increases, does the relative velocity of the fish with respect to the chute increase cr remain constant?

LITERATURE CITED IN APPENDIX II

Bell, M. C. 1973. Fisheries Handbook of Engineering Requirements and Biological Criteria. Fisheries Engineering Research Program. U. S. Army Engineering Division. North Pacific Corps of Engineers. Portland, Oregon.

Chow, V. T. 1959. Open Channel Hydraulics. McGraw Hill Book Company. New York.

Dane, B. G. 1978. A review and resolution of fish passage problems at culvert sites in British Columbia. Fisheries and Marine Service Technical Report No. 810. Vancouver, BC.

Dryden, R. L. and Stein, J. M. 1975. Guidelines for the protection of the fish resources of the Northwest Territories during highway construction and operation. Dept. of the Environment. Fisheries and Marine Service. Technical Report Series No. CEN/T-75-1.

Stuart, T. A. 1962. The leaping behavior of salmon and trout at falls and obstructions. Freshwater and Salmon Fisheries Research Paper 28, Department of Agriculture and Fisheries. Her Majesty's Stationery Office. Edinburg, Scotland.