A RESEARCH PROGRAM TO EXAMINE FISH BEHAVIOR IN RESPONSE TO HYDRAULIC FLOW FIELDS - DEVELOPMENT OF BIOLOGICAL DESIGN CRITERIA FOR PROPOSED WATER DIVERSIONS

by

Charles H. Hanson and Hiram W. Li
Wildlife and Fisheries Biology
University of California
Davis, California 95616

Completion Report
for

Project C-7679
Grant No. 14-34-001-7254
Office of Water Research and Technology
United States Department of the Interior

February 1978

25

SELECTED WATER RESOURCES ABSTRACTS

INPUT TRANSACTION FORM

1. *Report No.*

2.

3. *Accession No.* **W**78-12602

4. *Title* A research program to examine fish behavior in response to hydraulic flow fields - development of biological design criteria for proposed water diversions, a c Corr

5. *Report Date*

6.

8. *Performing Organization Report No.*

7. *Author(s)*

C~~harles~~ H. HANSON and H~~iram~~ W. LI

10. *Project No.* OWRT C-7679 (~~#~~7254)(1)

9. *Organization* California University, Davis,
Wildlife and Fisheries Biology.
~~University of California, Davis~~
~~Davis, California 95616~~

11. *Contract/Grant No.* ~~14-34-001-7254~~

13. *Type of Report and Period Covered*

12. *Sponsoring Organization*

15. *Supplementary Notes* Completion Report, February 1978.
23 p, 5 fig, 3 tab, 9 ref, append.

16. *Abstract*

An approach is developed for deriving intake velocity design criteria based on the interaction of bioenergetics and fish behavior in velocity gradients. Agreement between estimated energetically optimal swimming speeds and the mean of observed behaviorally selected swimming speeds for juvenile chinook salmon, bluegill, and silversides was good (r = 0.92). These results support the hypothesis that the behavioral response of fish to a hydraulic flow field is predictable in terms of an energetically optimal swimming speed for a given species and size class of fish. Physical and biological factors which influence the application of this approach to the development of design criteria which would minimize impingement losses at water intakes are discussed. Limitations of this approach and areas requiring additional research are suggested.

17a. *Descriptors*

*Water intakes, *Fish guiding, *Fish behavior, *Fish barriers, Fish physiology, Water cooling, Electric power plants, Fish attractants, Hydraulic design, Design flow, Bio-energetics, *Design criteria,

~~17b. Identifiers~~

*Water diversion, *Intake velocity, Entrainment, Impingement.

17c. *COWRR Field & Group* 08I

18. *Availability* Available from the National Technical Information Service as ~~EB~~ PB 286992

19. *Security Class. (Report)*

20. *Security Class. (Page)*

21. *No. of Pages* 25

22. *Price* A02 A01

Send To:

WATER RESOURCES SCIENTIFIC INFORMATION CENTER
U.S. DEPARTMENT OF THE INTERIOR
WASHINGTON, D.C. 20240

Abstractor Charles H. HANSON

Institution University of California, Davis, CA.

Acknowledgments

The work upon which this publication is based was supported in part by funds provided by the United States Department of the Interior as authorized under the Water Resources Research Act of 1964 as amended. The cooperation of Dan Odenweller and the California Department of Fish and Game are greatly appreciated. We would like to thank Drs. J. Cech and D. Lott of the University of California at Davis Department of Wildlife and Fisheries Biology for helpful comments and discussions throughout the project. Bill Bowman of the Optics Laboratory, U.S. Army Depot, Sacramento, California provided equipment and information essential for conducting dark phase observations. Excellent cooperation was also received from personnel of the Hydraulic Laboratory, University of California, Davis.

Individuals who contributed to the experimental investigations include: J. White, L. Decker, E. Jacobson, J. Stiles, E. Wong, J. Norton, and D. Alley. We have benefited greatly by comments and suggestions from: J. Cech, J. Skinner, L. Jensen, R. Davies, L. Brush, D. Powers, S. Oleska/Szuts, M. Wolman, J. Sonnichsen, E. Prentice, Q. Stober, C. Coutant, D. Odenweller, J. Norton, and F. Fisher.

We also thank Marjie Kirkman and her staff including K. Cooper, L. Eveland, D. McSpadden, D. Dean, and K. Steele for their efficiency and assistance throughout the study. We are grateful to Sandi Hanson for her assistance in all phases of this study.

Summary

Results of a one-year research project are presented which suggest an approach for developing biological design criteria for water intake systems based on fundamental biological and hydraulic principles. The approach for deriving intake velocity design criteria is based on the interaction of bioenergetics and fish behavior in velocity gradients. These studies, conducted under controlled laboratory conditions, were designed to assess behavioral responses of juvenile chinook salmon (*Oncorhynchus tshawytscha*), bluegill (*Lepomis macrochirus*) and Mississippi silversides (*Menidia audens*) to some of the variables encountered during entrainment or entrapment into a water intake system and to help develop solutions to the most critical problems.

An examination of behavioral and physiological mechanisms for fish exposed to a variety of velocity gradients has led to the development of a model based on energetically optimal swimming speeds and behaviorally selected swimming speeds. Results of a series of experiments using juvenile chinook salmon, bluegill, and silversides support the basic hypothesis that the behavioral response of fish to a hydraulic flow field is predictable in terms of an energetically optimal swimming speed for a given species and size class of fish. Applications of the model in understanding fish response to water intakes and the limitations of this approach in establishing intake velocity design criteria are discussed.

The proposed model has tremendous applicability and potential for making predictions of such phenomena as behavioral attraction. If fully developed this approach would provide biologically meaningful criteria as a valuable input into the siting and design of water intake systems. Although the concept of using energetic optima and selected swimming speeds as design criteria is appealing, further experimental evaluation and verification is required to relate this concept to the development of engineering designs.

The applicability of information derived from laboratory studies in making predictions of fish responses to man-made perturbations in the field is an issue of concern. Laboratory studies are limited in their simulation of field conditions and extreme care must be exercised when extrapolating predictions of fish behavior to the natural environment. However, through systematic, controlled experiments such as those described in this report a data base can be assembled which will suggest causal relationships between fish behavior and conditions experienced during entrainment or entrapment which can then be tested under field conditions. Details of special studies are summarized in the appendix.

Introduction

Population growth and the shift of our culture towards energy-intensive activities will combine to increase the demand for energy in the decades ahead. A concomittant increase in the demand for cooling-water is inevitable. To characterize the magnitude of this demand, consider that conventional 1000 MW_e fossil fuel and nuclear power plants require cooling-water at a rate of approximately 50 and 75 m^3/sec, respectively. This demand is currently being met by diverting natural surface waters which also serve as habitat for a diverse aquatic flora and fauna.

The use of natural surface waters for thermal dissipation from steam electric generating stations imposes two major potential sources of damage on aquatic organisms: thermal discharges and entrainment[1], entrapment[2], and impingement[3] at cooling-water intakes. Effects of the thermal component of power plant effluent have been extensively studied and widely publicized. However, the potentially adverse impact on aquatic organisms resulting from entrainment, entrapment, and impingement at cooling-water intake systems went largely unnoticed until the early 1970's. Expanded awareness of the magnitude of intake related problems has precipitated an intensive effort by regulatory agencies, utilities, and environmental consultants to document the problem, arrive at rational decisions regarding the consequences of these losses, and formulate acceptable solutions for minimizing adverse environmental effects.

The magnitude of entrapment-impingement losses at several power plant intakes seems significant (Table 1), but the biological importance of such losses is unknown. During recent years the trend has been to simply document the occurrence of fish loss. This, however, provides little insight into the mechanisms or factors which influence entrapment-impingement, nor is it very helpful when attempts are made to improve intake designs.

Historically, intake design criteria have been developed on a trial and error basis. It is apparent from Table 1 that this technique has resulted in limited success. Some intake designs have functioned well, however extrapolations from one site to another frequently yield unacceptable results. It is obvious that no one has understood why a particular design worked at one site and not at another. Existing criteria lack generality because studies leading to an understanding of basic mechanisms were not made.

---

[1] An organism which is drawn into a water intake as part of the volume of water which it occupies is said to be entrained.

[2] Entrapment refers to the physical blocking of larger entrained organisms by a barrier, generally some type of screen located within the intake structure.

[3] Impingement occurs when the entrapped organism is held in contact with the barrier.

4.1

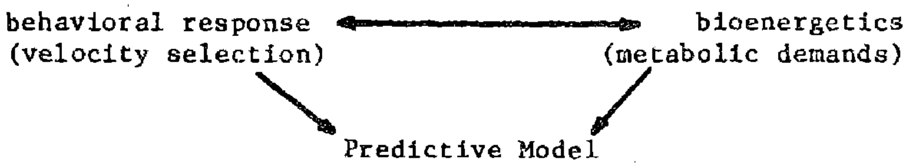
Table 1. Estimated entrapment-impingement losses at several power plant cooling-water intakes.

Plant	Location	Study Duration	# of Fish	Reference
Allen Steam Station	Lake Wylie	Oct. 1973 - Sept. 1974	898,913	Edwards *et al.* (1976)
Oconee Nuclear Station	Lake Keowee	July 1974 - May 1975	1,064,262	Edwards *et al.* (1976)
Marshall Steam Station	Lake Norman	Apr. 1974 - Mar. 1975	3,769,300	Edwards *et al.* (1976)
Buck Steam Station	Yadkin R.	July 1974 - June 1975	4,069	Edwards *et al.* (1976)
Palisades Nuclear Power Plant	Lake Michigan	July 1972 - June 1973	584,687	Edsall (1975)
Waukegan Generating Station	Lake Michigan	June 1972 - June 1973	1,200,000	Edsall (1975)
Nine Mile Point	Lake Ontario	January - December 1973	5,000,000	Edsall (1975)
Zion Plant	Lake Michigan	Sept.-Dec. 1973 Mar.-June 1974	929,000	Edsall (1975)
Quad Cities Plant	Mississippi R.	January - December 1974	10-14,000,000	Truchan (1975)
Muddy Run Pumped Storage Generating Plant	Susquehanna R.	June-July 1970	56,600,000*	Snyder (1975)

Initial attempts to improve general guidelines for developing intake design criteria were based on evaluating fish performance capabilities. Fish performance is determined by using forced swimming trials and time to fatigue for fish exposed to velocities in respirometers or stamina tunnels. In general, these fish are confined within an experimental apparatus in which velocity preferences cannot be tested. As a result of performance studies it is generally recommended that large intake areas should be provided to reduce intake velocities. That swimming capability cannot be considered independent of behavioral response is illustrated by extensive fish losses at plants with low intake velocities. Are some fishes attracted to current?

AN ALTERNATIVE APPROACH TO DEVELOPING INTAKE VELOCITY CRITERIA

Based on microhabitat theory an energetic-based model is proposed encompassing the basic hypothesis that the behavioral response of fish to a hydraulic flow field is not random but rather is predictable in terms of an energetically optimal swimming speed for a specific fish species and size class. The model is based on the conviction that: 1) entrainment, entrapment, and impingement of fish involve a number of interacting variables; and 2) only through systematic, controlled experiments can a data base be assembled that suggests design criteria for intake structures that reduce the hydraulic capture of fish to a minimum level. The probability that a fish will become entrained or entrapped by industrial or agricultural water intakes is influenced primarily by characteristics of the hydraulic flow field and various aspects of fish behavior. The research design outlined here specifically recognizes the interaction of theses variables. In light of the myriad of interacting variables, however, we have focused attention on the general conceptual framework illustrated below.



The model we propose predicts that for each species and size class of fish an optimal swimming speed exists at which each fish is most energetically efficient. The model also predicts that fish will behaviorally select their energetically optimal swimming speed when exposed to a velocity gradient.

Research Objectives

The purpose of this study was to examine behavioral responses of fish in relation to energetic expenditures of swimming in different hydraulic conditions. Although the interaction between behavior and bioenergetics in determining microhabitat selection in response to velocity gradients and migration rates has been discussed (Brett 1965; Weihs 1973; Webb 1975), the relationship between energetic optimality and behavioral selection of specific swimming speeds has not been examined experimentally. Our objective was to identify and quantify the relationship between the behavioral response of juvenile fishes to hydraulic flow fields and the swimming speed which was energetically optimal. Specific objectives of the study were: (1) to quantify behaviorally selected swimming speeds of juvenile fishes exposed to hydraulic flow gradients; (2) to define the precision of the pattern of selected swimming speed; (3) to examine the influence of various physical and biological factors on the behavioral response; and (4) to develop estimates of the optimal swimming speed based on bioenergetic (respiratory) efficiency. This type of approach may help in understanding the behavior of fishes susceptible to entrainment and entrapment by water intake systems.

We chose to study juvenile chinook salmon (Oncorhynchus tshawytscha) as a representative species from a lotic habitat and bluegill (Lepomis macrochirus) and Mississippi silversides (Menidia audens) as representatives of a lacustrine habitat. A comparative study of these three species would provide a test of our experimental methodology and would form the basis for developing a generalized model of the behavioral response of fish to hydraulic gradients.

Research Methodology

Swimming Respirometer

Oxygen consumption rates of juvenile fish swimming at various velocities were measured using a closed-cycle swimming respirometer similar to that described by Brett (1964). The respirometry system included a clear plexiglass test section 5.1 cm in diameter and 30.5 cm long fitted with perforated baffles to provide a uniform hydraulic flow pattern through the test section. Flow velocities ranged from 4 to 45 cm/sec. Illumination was provided by a 15 watt incandescent light bulb covered by an opaque diffuser directly above the respirometer test section. Water temperature within the respirometer was maintained at 15.0 ± 0.1 C.

In each experiment fish were acclimated in the respirometer for 24 hours under static conditions. Following acclimation the test velocity was started and the fish was allowed an additional 30 minutes to adjust to the water flow. Following the adjustment period the respirometer volume (2.31 ℓ) was sealed and the test begun. Dissolved oxygen and temperature measurements were made at 15 minute intervals using a YSI Dissolved Oxygen Meter (Model 54) and polargraphic probe. Oxygen consumption rate, expressed as $mgO_2/kg/hr$, was calculated using the slope of a least-squares linear regression of oxygen concentration against cummulative time during each 120 minute experiment.

The energetically optimal swimming speed for each group of test fish was determined by transforming oxygen consumption rates per unit time ($mgO_2/kg/hr$) into oxygen consumption rates per unit distance ($mgO_2/kg/km$) using the formula:

$$mgO_2/kg/km = (mgO_2/kg/hr \text{ at speed } S_1)\ (hr/km \text{ at } S_1).$$

The distance, in this case one kilometer, was chosen arbitrarily. Using this technique a relation between energetic expenditure for swimming a specific distance at a specific speed can be developed. The parabolic shape of this relationship is indicative that an energetic optimum exists for each species and size class of fish tested.

Behaviorally Selected Swimming Speed

Selected swimming speed experiments were conducted in an oval flume 15.9 m in circumference, 1.0 m wide and 0.4 m deep (Figure 1). Flow was generated from a motor-driven six-blade paddle wheel. Direct visual observations were made from glass viewing ports along the inner wall of the flume. Light intensity in the experimental system was controlled using a rheostat and eight 75-watt incandescent bulbs equally spaced around the flume circumference. Illumination at the water surface, 1 m from the light sources, was continuously variable from 14.0 to $< 1 \times 10^{-4}$ footcandles. Water temperature was maintained at 15.0 ± 0.5 C by a water cooler.

To quantify selected swimming speeds two hydraulic gradients were established within which velocities ranged from < 1 to 35 cm/sec and from < 1 to 45 cm/sec over a 3.3 m linear section of the test flume. Hydraulic gradients were formed by decreasing the cross-sectional area of the test section from 0.40 m^2 to 0.13 m^2 over a 3.3 m distance. Fish were contained within the hydraulic gradient by vexar plastic screens. Using techniques of three-dimensional mapping and correlation between fish position and water velocity within the three-dimensional matrix of the hydraulic gradient we were able to quantify the selected swimming speed for individuals or groups of fish over a range of light intensities.

Experimental Results

Energetically Optimal Swimming Speeds

The relationship between oxygen consumption ($mgO_2/kg/hr$ log scale) and swimming speed (cm/sec) derived from respirometry trials is characterized in Figure 2. Transforming oxygen consumption rates ($mgO_2/kg/hr$) by the time required to traverse a unit distance, a relationship between energetic

7.1

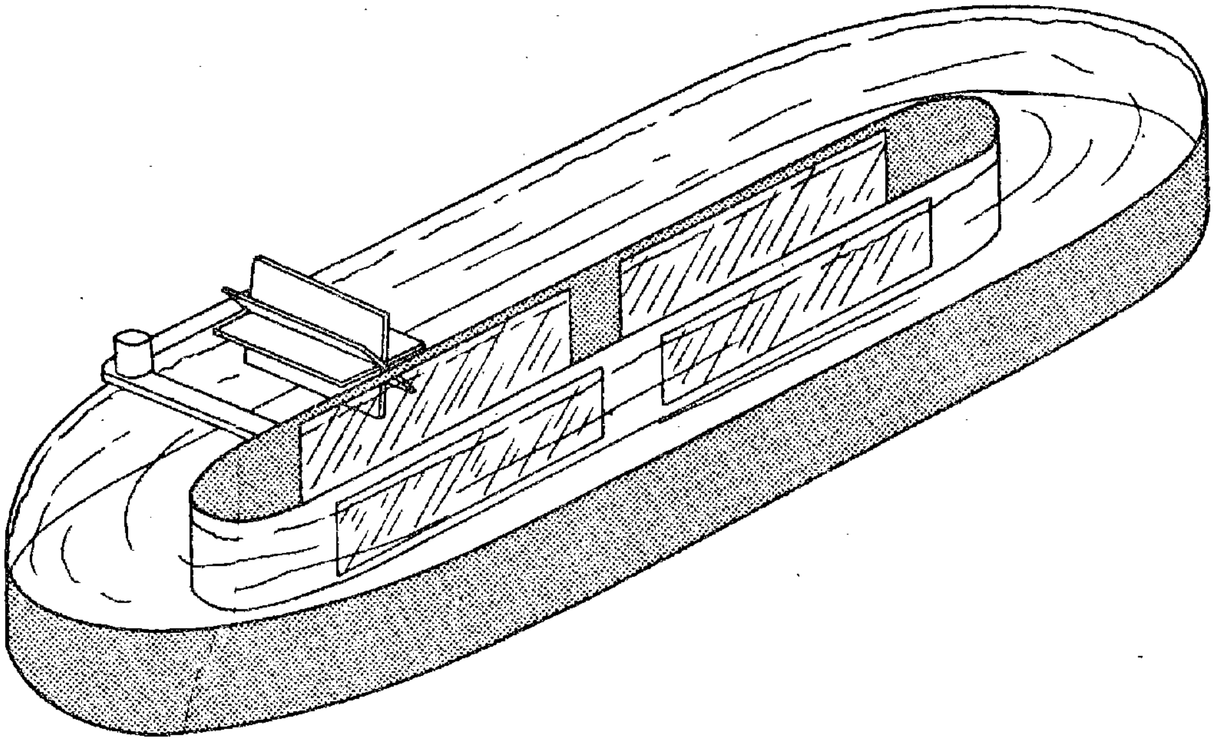


Figure 1. Diagram of the experimental flume.

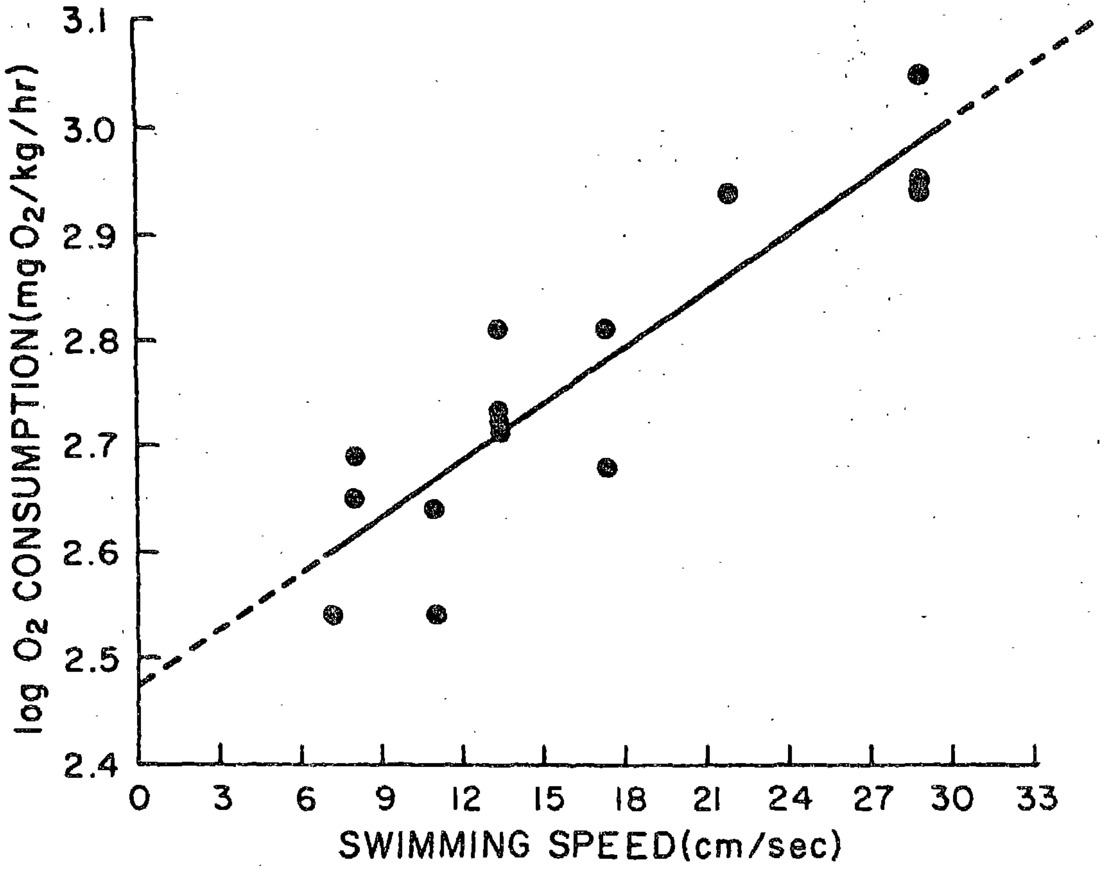


Figure 2. Relationship between oxygen consumption per unit body weight per (log scale) and swimming speed (cm/sec).

expenditure for swimming a specific distance at a specific speed as shown in Figure 3 can be developed for each species and size class of fish tested. The characteristic parabolic shape of this relationship indicates that an optimal swimming speed exists for each group examined.

A general summary of respirometry data and the estimated energetically optimal swimming speed for each test group is presented in Table 2. These estimates, however, are based on a relatively small number of replicate respirometry trials and should only be considered as an approximation of energetically optimal swimming speeds.

Behaviorally Selected Swimming Speeds

Results of three-dimensional mapping for a total of 110 juvenile fishes exposed to velocity gradients ranging from <1 to 35 cm/sec and <1 to 45 cm/sec at a light intensity of 14.0 footcandles are summarized in Table 3. Figure 4 illustrates a typical frequency histogram of selected swimming speeds for juvenile fishes exposed to a velocity gradient.

In general, bluegill selected the slowest swimming speeds, while chinook salmon consistantly selected the highest swimming speeds. Characteristics of the selected swimming speeds for each species are presented below.

Chinook Salmon (*Oncorhynchus tshawytscha*)

Juvenile chinook salmon are found in fast water: riffles and runs in rivers. A number of studies have documented that the chinook salmon prefers swifter sections of a stream in comparison to coho salmon (*O. kisutch*). Chinook salmon are also found in aggregates or schools and are less territorial than either coho salmon or steelhead trout (*Salmo gairdneri*).

Thus in the laboratory it was observed that the selected swimming speed of chinook salmon approximately 48 mm in length was approximately the same for still (21.6 cm/sec) and moving water (20.4 cm/sec). This selected speed was affected by size of the fish, group size (increasing from 13.5 cm/sec for individuals to 17 cm/sec for groups of 10 fish), and food availability. Observations of fish exposed to a velocity gradient for 50 hours suggest that juvenile chinook salmon shift towards slower velocities in the absence of food. Light or time of day seemed to have little effect on swimming velocity.

Bluegill (*Lepomis macrochirus*)

Bluegill are relatively stationary fish which hold territories in ponds, lakes, and slow and sluggish portions of streams and rivers. They are ambush

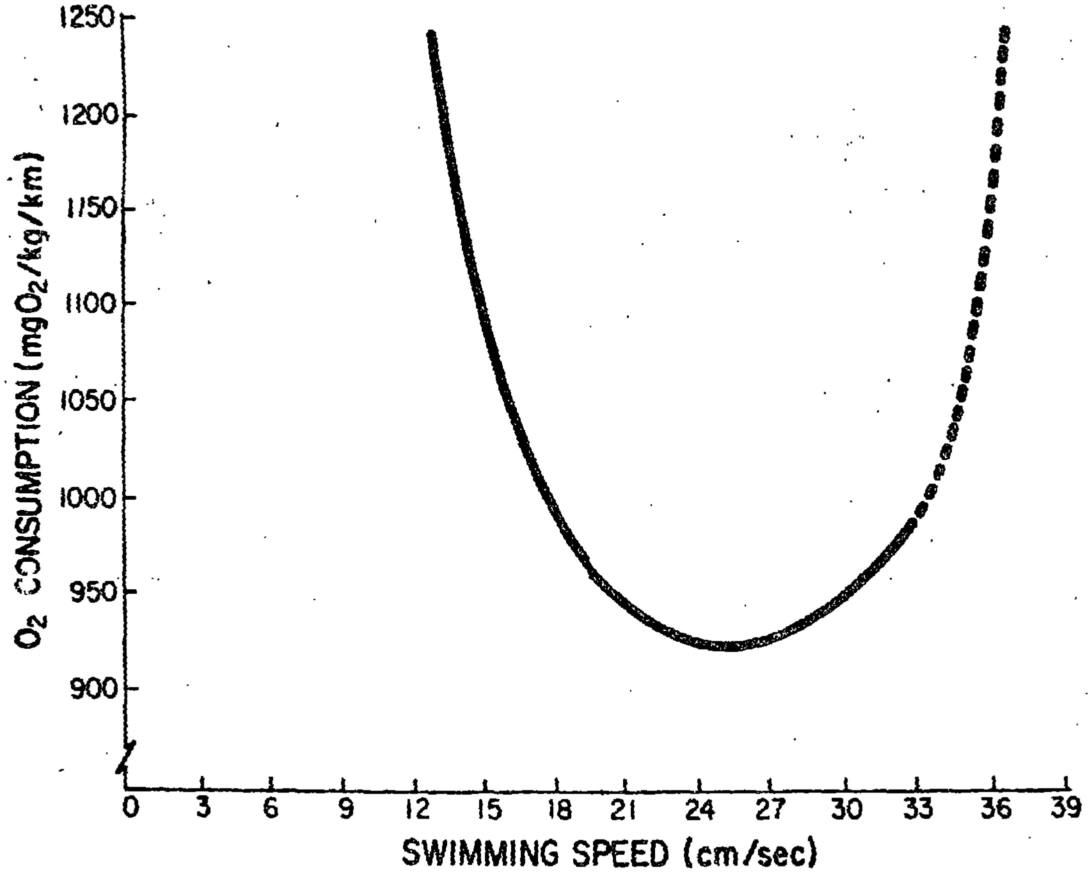


Figure 3. Relationship between oxygen consumption (mgO_2/kg/km) and swimming

Table 2. Summary of respirometry trials conducted at 15.0±0.3 C.

Species	light intensity (footcandles)	n	length (mm)		weight (g)		log mgO_2/kg/hr = a + b (velocity cm/sec)			estimated optimal swimming speed	
			$\bar{X}$	SD	$\bar{X}$	SD	a	b	r	cm/sec	L/sec
Chinook (wild)	1.7×10^1	11	37.1	2.4	0.36	0.04	3.10	0.046	0.85	9.3	2.51
Chinook (wild)	2.0×10^{-2}	8	37.2	1.3	0.42	0.10	3.11	0.051	0.54	9.0	2.42
Chinook (hatchery)	1.7×10^1	10	40.5	1.4	0.54	0.05	3.13	0.026	0.74	13.7	3.38
Chinook (hatchery)	2.0×10^{-2}	9	40.0	2.0	0.56	0.14	3.17	0.020	0.40	22.0	5.50
Chinook (wild)	1.7×10^1	13	88.6	4.2	6.94	0.48	2.50	0.009	0.89	39.0	4.40
Bluegill (wild)	1.7×10^1	11	29.9	3.0	0.40	0.09	2.85	0.061	0.90	7.1	2.37
Silversides (wild)	1.7×10^1	12	46.1	4.6	0.47	0.08	2.96	0.008	0.43	11.3	2.60

Table 3. Summary of selected swimming speed trials conducted at a light intensity of 14.0 footcandles and water temperature of 15.0 ± 0.5 C.

Species	length (mm)			hydraulic gradient (cm/sec)		selected swimming speed (cm/sec)		
	$\bar{X}$	SD	n	minimum	maximum	$\bar{X}$	SD	n
Chinook	37.4	2.0	24	< 1	34	10.9	5.5	517
Chinook	37.8	1.3	4	< 1	45	14.0	6.3	84
Chinook	37.7	1.5	3	< 1	45	10.4	6.9	53
Chinook	45.2	5.5	26	< 1	45	15.4	9.3	684
Bluegill	29.4	2.2	12	< 1	35	4.9	4.9	269
Bluegill	78.5	10.1	8	< 1	45	5.7	2.4	273
Silversides	50.7	6.9	33	< 1	35	7.7	6.5	431

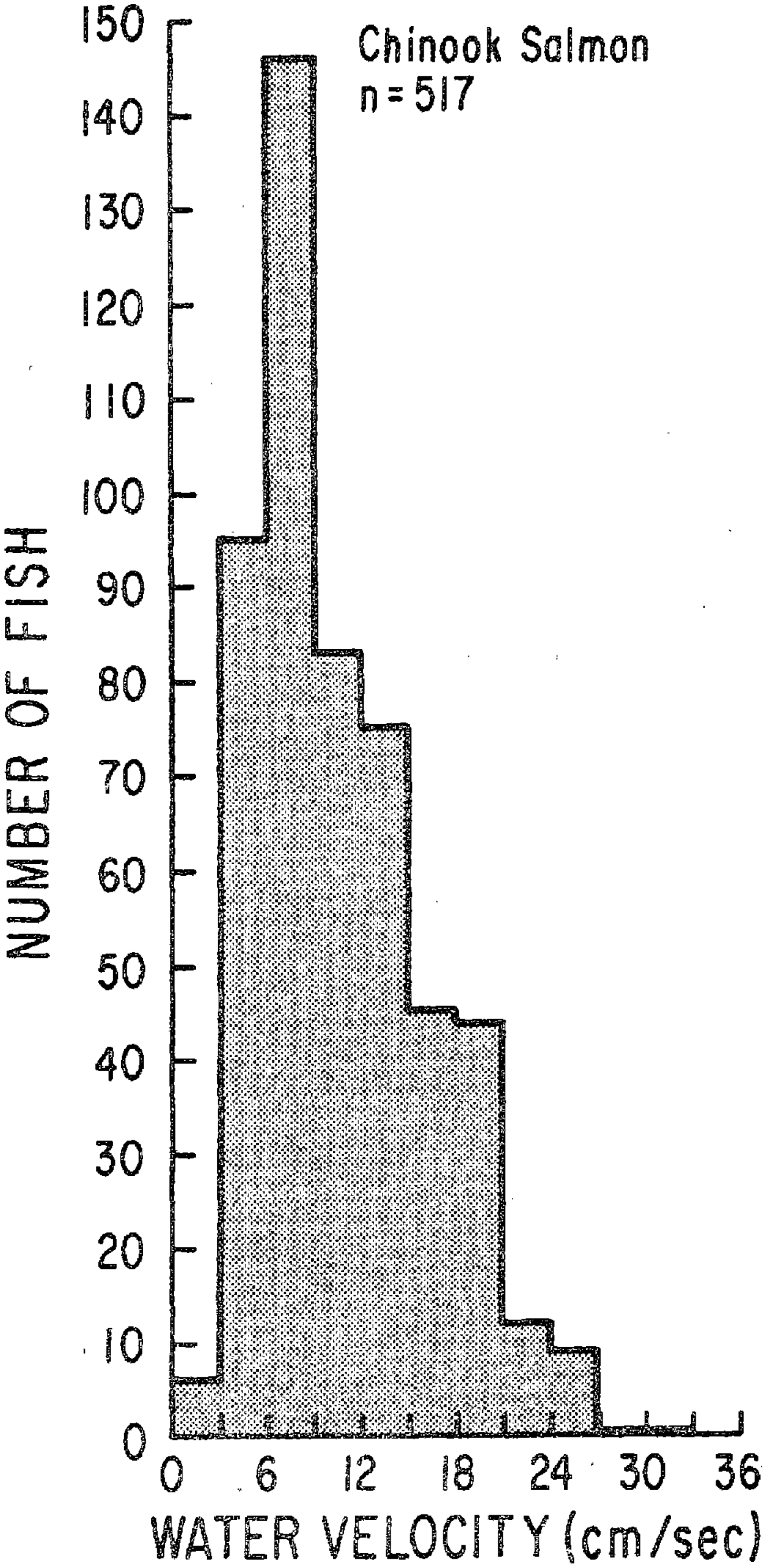


Figure 4. Distribution of selected swimming speeds for chinook salmon exposed toa velocity gradient ranging from <1 to 35 cm/sec.

or lie-and-wait predators. Thus it is not surprising to find that bluegill showed a strong tendency to select low velocities. Observations of bluegill during swimming speed selection trials suggest these fish are actively selecting areas such as the null zone created by the forward retaining screen or reduced velocity areas associated with boundary layer conditions of the tank walls and bottom. These observations suggest that bluegill are acutely sensitive to their hydraulic environment and actively avoid higher water velocities.

Bluegill exposed to a velocity gradient showed a significant positive relationship between selected swimming speed and light intensity. At a light intensity of 14.0 footcandles selected swimming speed averaged 10.7 cm/sec. As light intensity decreased to 1.9×10^{-2} footcandles (approximately bright moonlight) selected swimming speed decreased to 3.5 cm/sec.

Mississippi silverside (Menidia audens)

The silverside is found in slower streams and has been extremely successful in Clear Lake and Lake Texoma after being introduced. It is a schooling, particulate zooplanktivore which cruises in search of prey. We found that the silverside did not vary its selected swimming speed significantly during a 31 hour test period under constant light intensity (14.0 footcandles). This result, in addition to observations made during testing, have led us to conclude that once silversides select a specific swimming speed they maintain themselves at that velocity for periods of time in excess of 31 hours with no visible signs of stress or fatigue. A statistically significant positive relationship does exist, however, between the selected swimming speed of silversides and light intensity. Diel feeding studies by Elston and Bachen (1976) and Li and Wurtsbaugh (in prep.) indicate that silversides don't feed intensively during the night and, in fact, a feeding experiment showed them to be sluggish at night. Perhaps an activity rhythm and lack of visual acuity at night make silversides less responsive. No apparent relationship between the density of silversides and their selected swimming speeds was evident.

Discussion of the Findings

Past attempts to provide design criteria for water intake systems have relied on determining swimming endurance at various velocities. Research has moved beyond investigations of the stamina of fish swimming in a current of a given velocity, as this question has been addressed by numerous investigators (see Webb 1975 for a comprehensive review). Such information does not necessarily solve the impingement problem since it has been shown that fish are impinged at velocities substantially lower than those in forced swimming performance trials. Obviously many critical factors have not been studied. Information regarding the specific nature of these critical factors must be considered in designing future intakes.

The research we have described, although in an early stage of development, suggests an approach to developing biological design criteria for water intake systems based on fundamental biological and hydraulic principles. We have applied the reasoning of Brett (1965), Weihs (1973), and Webb (1975) in developing a model which integrates the concepts of energetic optimality and the behaviorally selected swimming speeds for fish. The relationship between the energetically optimal swimming speed defined by swimming energetics and the mean behaviorally selected swimming speed for juvenile bluegill, chinook salmon, and silversides is shown in Figure 5. The least-squares linear regression equation for these data was: selected swimming speed (cm/sec) = -0.77 + 1.04 (energetically optimal swimming speed in cm/sec) with a correlation coefficient of 0.92. From this regression it is apparent that behaviorally selected swimming speeds can readily be estimated using respirometry techniques. The general agreement between the predicted optimal swimming speed and behaviorally selected swimming speed supports the idea that our approach is promising.

We believe that fish loss due to entrainment and subsequent impingement at water intake systems will be minimized if structures are designed to meet the physiological and behavioral responses of fish to velocity fields. Our experimental evidence suggests that fish expend less energy when exposed to their optimal swimming speed. Thus, an intake velocity which is less stressful to a fish would enhance survival of those fish collected at the intake. Therefore, one application of these research results would be to develop biologically meaningful criteria for establishing intake velocities which do not exceed the optimal-selected swimming speed for those species to be protected. In addition, our evidence suggests that fish do select specific velocities. If this behavioral response proves to be the case these results would be applicable to establishing velocity criteria for diversion and bypass facilities commonly employed at larger intake systems.

It would be difficult, if not impossible, to establish one optimal intake velocity applicable to a mixed array of fish species and sizes. By examining a variety of fish species, however, we have documented the generality of our approach. Additional species and size classes of fish will have to be examined in order to evaluate this concept in general before making recommendations as to its applicability for establishing design criteria for a mixed species array from a wide variety of aquatic habitats. At different sites, for instance, one might design intake velocities to protect a few economically or ecologically important species at the sacrifice of others. There may even be a situation where the species which need protection have widely disparate selected velocities. Our approach will not be a panacea for all aquatic problems and certainly we should warn that an economically unimportant species may be an important food item for game or commercially valuable fishes.

It should be noted that predictions of fish behavior in hydraulic flow

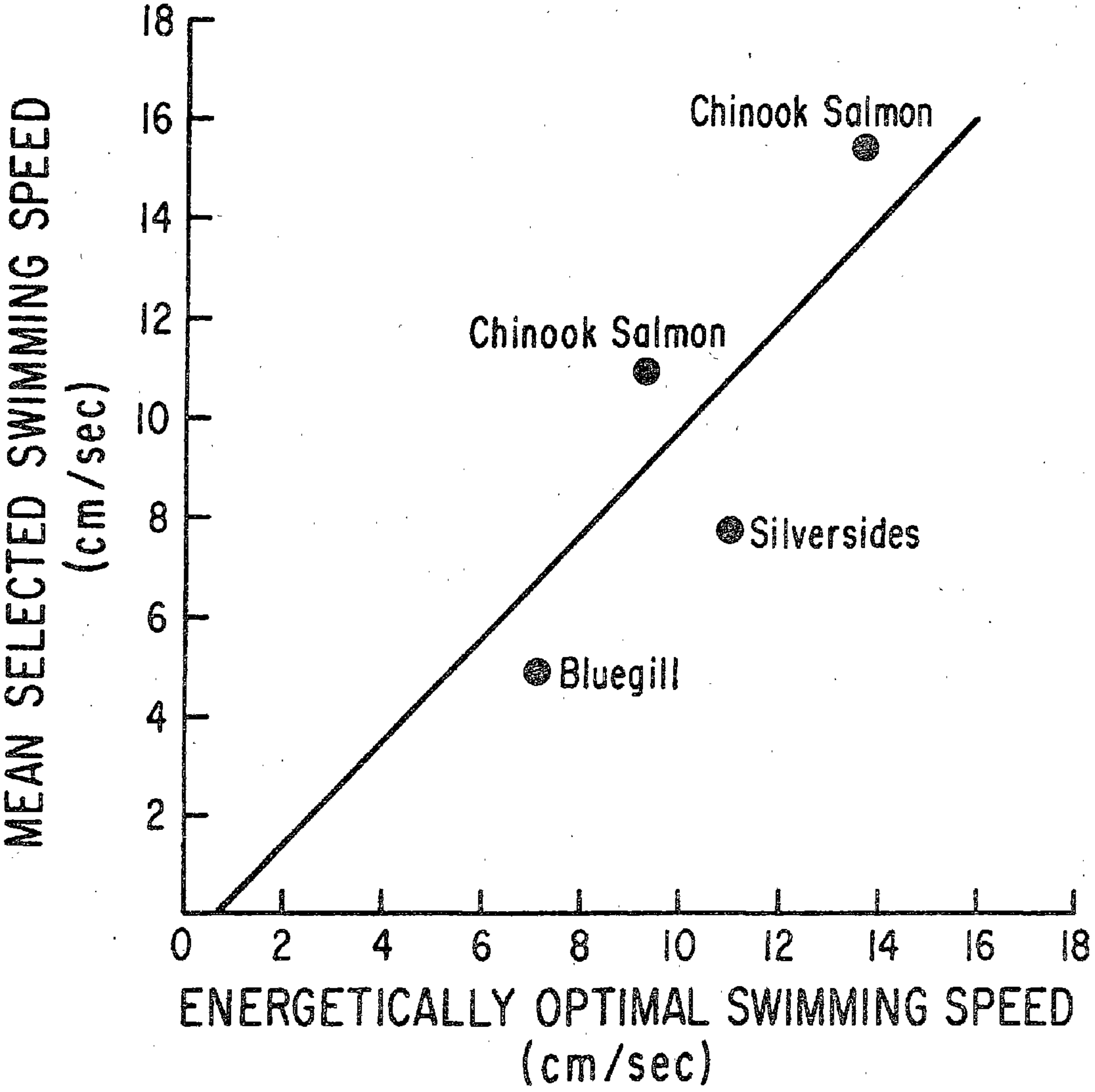


Figure 5. Comparison between the physiologically defined optimal swimming speed and the observed selected swimming speed.

fields can be developed utilizing data only from the selected swimming speed studies thus eliminating the need for oxygen consumption swimming speed experiments. Eliminating metabolic experiments would, however, eliminate two critical components necessary for developing design criteria based on these studies. First, it is through the measurement of fish metabolism (via oxygen consumption) that we are able to determine if swimming at the optimal swimming speed is, in fact, less stressful on fish than swimming at velocities above the optimal speed. As previously discussed, if we can define intake velocities which are less stressful to fish we may be able to enhance survival of those fish collected. Secondly, studies conducted on selected swimming speed for fish species and size classes in our laboratory may not be directly applicable on a site-specific basis due to differences in water temperature, critical species and size classes to be protected, etc. The experimental system required to make such site-specific determinations of selected swimming speed is large and not generally portable (i.e., hydraulic test flumes), and in addition, such studies are expensive and time consuming. We have evidence which confirms that the selected swimming speed of fish can be quickly estimated based on a knowledge of the energetically optimal swimming speed (see Figure 5). Thus site-specific studies could be carried out using a respirometer which is inexpensive to build, easily transportable, and could be used to establish design criteria using ambient water and fish species from any site under consideration.

Our choice of oxygen consumption to define the energetically optimal swimming speed was not haphazard. Aerobic respiration, which we measured using the respirometer, can be expressed in purely energetic units (e.g. calories) using known constants. The only other energetic factor is anaerobic metabolism which is of little interest since fish swimming at or below maximum sustainable speeds do not undergo anaerobic metabolism. By designing intake velocities for the optimal swimming speed of fish the incidence of anaerobic metabolism and the associated lactic acid accumulation in the blood can be minimized, thus significantly reducing the level of preimpingement stress on entrained or entrapped fishes.

Literature Cited

Brett, J. R. 1964. The respiratory metabolism and swimming performance of young sockeye salmon. J. Fish. Res. Bd. Canada 21:1183-1226.

Brett, J. R. 1965. The swimming energetics of salmon. Sci. Amer. 213: 80-85.

Edsall, T. A. 1975. Electric power generation and its influence on Great Lakes fish. Presented at Second ICMSE Conference on the Great Lakes. Argonne National Laboratory, Argonne, Ill.

Edwards, T. J., W. H. Hung, L. E. Miller, and J. J. Sevic. 1976. An evaluation of fishes at four Duke Power Company steam generating facilities. Pg. 373-380. In Thermal Ecology II (G. W. Esch and R. W. McFarlane, Eds.). ERDA Symposium Series CONF-750425.

Elston, R. and B. Bachen. 1976. Diel feeding cycle and some effects of light on feeding intensity of the Mississippi silverside, *Menidia audens*, in Clear Lake, California. Trans. Amer. Fish. Soc. 105:84-88.

Snyder, D. E. 1975. Passage of fish eggs and young through a pumped storage generating station. J. Fish. Res. Bd. Canada 32:1250-1266.

Truchan, J. G. 1975. Personal communication. In Guidelines to determine best available technology for the location, design, construction, and capacity of cooling water intake structures for minimizing adverse environmental impact. Section 316 (b) P.L. 92-500. U.S. Environmental Protection Agency. Unpubl. ms. Dec. 1975. 69 p.

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

Weihs, D. 1973. Hydromechanics of fish schooling. Nature 241:290-291.

Appendix

During the course of this research project an effort has been made to put our ideas and information before the scientific community and public through the publication of several scientific papers. Summaries of manuscripts available from the authors follow. In addition, two graduate theses (C. Hanson Ph.D. and J. White M.S.) will be available in restricted numbers when completed as a result of graduate student support furnished during the course of this project.

Entrapment and impingement of fish by power plant cooling-water intakes: an overview. Marine Fisheries Review 1977 39(10):7-17.

An overview of the recent information available on fish entrapment and impingement by power plant cooling-water intakes is presented. The types of biological problems caused by intake structures, the strengths and weaknesses of various water intake/fish protection systems, and the biological/ecological processes relevant to this problem are discussed. Factors contributing to direct and delayed mortality in screen-impinged fish are examined with emphasis on the relationship between water velocity, impingement time, and physiological stress. In considering the present state of predictive model simulations for developing impact assessments we have pointed out areas which need refinement, omissions, and limitations of our present knowledge. The biological impact of water withdrawal for power plant cooling can be minimized by consideration of intake siting and design criteria including site evaluations, cooling system design (i.e. closed-cycle cooling or once-through cooling system) and the use of guidance, diversion and fish salvage systems. We conclude that future research should focus on examining basic behavioral and physiological mechanisms associated with fish entrapment and impingement in combination with ecological processes of those populations and communities influenced by proposed and existing projects.

An alternate approach for developing intake velocity design criteria. 1977 Cal-Neva Transactions of the American Wildlife Society.

Recurring fish losses at power plant cooling-water intakes demonstrate the need for improving intake design and operation to reduce the impact on aquatic resources. An approach is proposed for deriving intake velocity criteria which focuses on the interaction of bioenergetics and fish behavior. A model based on an energetic optimum and selected swimming speed is used to predict the response of fish to hydraulic flow fields. Data on oxygen consumption rates for juvenile chinook salmon (Oncorhynchus tshawytscha) indicate maximum energetic efficiency occurs at a swimming speed of 25 cm/sec. Juvenile chinook salmon exposed to a velocity gradient behaviorally select a velocity of approximately 21 cm/sec. These results support the basic hypothesis that the behavioral response of fish to a hydraulic flow field is not random but is predictable in terms of an energetically optimal swimming speed for a given species and size class.

Physical and biological factors which influence predictions of the model are described. Applications of the model in understanding fish response to water intakes are suggested. Limitations of this approach in establishing power plant intake design criteria are also discussed.

Orientation of juvenile chinook salmon and bluegill to low water velocities under high and low light levels.

The rheotropic response of juvenile chinook salmon and bluegill to water velocities less than 2.5 cm/sec under high (1×10^3 footcandles) and low (1×10^{-4} footcandles) light levels was determined. Chinook salmon and bluegill were positively rheotropic at constant water velocities less than 2.5 cm/sec. The rheotropic response by both species was independent of light intensity. Orientation of chinook salmon and bluegill were comparable under the high light intensity. Chinook salmon, however, appear to be more positively rheotropic than bluegill under low light conditions.

Experimental investigations of the selected swimming speed of juvenile chinook salmon.

Behaviorally selected swimming speeds for juvenile chinook salmon (*Oncorhynchus tshawytscha*) in a 15.9 m test flume averaged 21.6 cm/sec (S.D. = 3.3) under static conditions and 20.4 cm/sec (S.D. = 4.5) under flowing water conditions. Swimming performance was maintained throughout a 24-hour observation period under static conditions. Selected swimming speed averaged 22.6 and 20.1 cm/sec, respectively, for 43.8 and 68.0 mm fish under static conditions and 20.7 and 19.8 cm/sec, respectively, under flowing water conditions. Selected swimming speed varied significantly over a range of light intensities; however, no statistical difference was observed at extreme light intensities tested, 11.0 and 1.3×10^{-2} footcandles. In general, selected swimming speed was independent of fish size and food availability; however, performance was directly related to group size.

Response of juvenile chinook salmon and bluegill to vertical and horizontal water withdrawals.

Spatial orientation and entrainment response of juvenile chinook salmon and bluegill exposed to vertical and horizontal water withdrawals at an approach velocity of 53 cm/sec were determined. Juvenile chinook salmon exhibited a statistically significant avoidance response to a vertical withdrawal. No significant change in spatial orientation was detected for chinook salmon exposed to a horizontal withdrawal. Significantly more chinook salmon were entrained into a horizontal withdrawal (31.7%) than a vertical withdrawal (5.0%). Similarly, 46.0% of the bluegill were entrained into a horizontal withdrawal compared to 10.0% entrained into a vertical withdrawal.

Energetically optimal swimming speeds and behaviorally selected swimming speeds of juvenile fishes: applicability for developing biological design criteria for water intake systems.

An approach is developed for deriving intake velocity design criteria based on the interaction of bioenergetics and fish behavior in veloctiy gradients. Agreement between estimated energetically optimal swimming speeds and the mean of observed behaviorally selected swimming speeds for juvenile chinook salmon, bluegill, and silversides was good ($r = 0.92$). These results support the hypothesis that the behavioral response of fish to a hydraulic flow field is predictable in terms of an energetically optimal swimming speed for a given species and size class of fish. Physical and biological factors which influence the application of this approach to the development of design criteria which would minimize impingement losses at water intakes are discussed. Limitations of this approach and areas requiring additional research are suggested.

Behavioral response of juvenile chinook salmon to trash rack bar spacing

The behavioral response of juvenile chinook salmon to vertical trash racks having interbar spacings ranging from 5.1 to 30.5 cm is reported. Experiments were conducted in a laboratory channel with a water velocity of 31.8 cm/sec under light intensities of 14.0 and 1.0×10^{-2} footcandles. Trash racks having interbar spacing less than 15 cm may act as a behavioral barrier thus increasing the susceptibility of juvenile fish to predation. The behavioral response pattern was independent of light intensity.