#58

(31)

TECHNICAL NOTE
B26
AUGUST 1978

A STUDY ON THE PROTECTION OF FISH LARVAE AT WATER INTAKES USING WEDGE-WIRE SCREENING

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AR-391

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ABSTRACT

Protection of fish in the vicinity of power plant cooling water intakes has become a major environmental concern over the past several years. More recently, attention has been focused on the potential for protecting larval fish from entrainment mortality at power plants. This study presents the results of a laboratory study designed to evaluate the ability of several species of larval fish to avoid entraining flows through wedge-wire stationary screens ("fish avoidance" concept). This concept features small opening screens, low inlet velocities, and an unobstructed bypass and is dependent on the ability of the larvae to detect and swim away from the screens. This study was designed to test this concept in a flowing water environment.

All species tested showed some ability to avoid entrainment and many species showed considerable avoidance of entraining flows. Safe bypass or avoidance of entrainment was generally related inversely to slot size and velocity through the screen. Best results were shown for the 0.5 mm slot and 7.6 cm sec^{-1} (.25 fps) slot velocity. At least one of the smallest species tested showed appreciable avoidance of the largest slot size, 2.0 mm, tested. From a biological point of view this screening concept has the potential for protecting all fish of the "impingeable" size as well as a large portion of the "entrainable" size.

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ACKNOWLEDGEMENT

Appreciation is extended to the following agencies for their assistance in supplying larval fish: Department of Conservation of Natural Resources, Alabama Game and Fish Commission; Department of Natural Resources, Georgia Game and Fish; Minnesota Department of Natural Resources; Tennessee Wildlife Resources Agency; and the U.S. Fish and Wildlife Service. Funds for these studies were supplied by the Office of Power, TVA.

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INTRODUCTION

In recent years attention has been given to the practicability of protecting larval fish at water intakes. Two basic concepts of larval fish protection at power plant intakes are currently being evaluated by TVA. In one concept fine-mesh screens are used to prevent entrainment of fish larvae into the plant. The fish are retained by the continuously traveling screens and safely transferred to a bypass to be returned alive to the source water body. This concept ("impinge-release") could be applied to both vertical traveling screens in which the larvae are transported above the surface of the water and horizontal traveling screens (Prentice and Ossiander 1974) in which the larvae remain submerged throughout the screening process.

A second screening concept, reported here, for protecting larval fish at water intakes depends on the ability of the fish to swim away from the intake ("fish avoidance"). Basic fish protection requirements of this concept are a screen with sufficiently small openings and sufficiently low water velocities through the screen to enable larvae to swim away from the screen. This concept is being evaluated for application to a stationary screen.

Larval fish just a few days old are capable of orienting to low water velocities (Tomljanovich et al. 1977). Sazaki et al. (unpublished report, California) tested swimming abilities of larval and juvenile king salmon, steelhead trout, and striped bass. They found that 90 percent of the 10-12 mm striped bass tested were able to maintain themselves in a current of 6.1 cm sec^{-1} (0.2 fps) for six minutes while 90 percent of the 50 mm fish were able to maintain themselves in an 18.3 cm sec^{-1} (0.6 fps) current for six minutes.

Several applications of the fish avoidance concept have been suggested for possible use at low-volume power plant intakes. Stober et al. (1974) conducted studies on the use of rapid sand filters for protecting larval and juvenile fish and large invertebrates from entrainment into power plant intakes. McSwain and Schmidt (1976) reported on the use of a gabion screen in combination with perforated pipes buried in river-run gravel to protect juvenile salmon in the Merced River in California. Water passes through the gravel and perforated pipes at velocities low enough to prevent fish entrapment. Richards and Hroncich (1976) reported the development of a perforated pipe intake for the protection of fish at a 1.58 $m^3 sec^{-1}$ (55.7 cfs) water pumping station on the Columbia River. In this design, the pipes rested on supports above the river bed rather than in the substrate. The perforations were 9.5 mm diameter and the velocity through them was 15.2 cm sec^{-1} (0.5 fps). The approach velocity 9.5 mm from the screen was reduced to 6 cm sec^{-1} (0.2 fps).

The design of a fish avoidance screen is necessarily dictated by the swimming ability and behavior of the species of larval fish that are to be protected as well as the site specific physical characteristics of the intake location. If an intake based on this concept is successful in protecting larval fish, it will also provide protection for juvenile and adult fish which have greater swimming ability.

Objective

The study reported here was designed to estimate the ability of several species of larval fish to avoid impingement against and entrainment through a fish avoidance screen in flowing water. The stationary test screen used was made of slotted stainless steel with wedge-shape wire (Smith 1977).

The safe transport of larval fish past such an intake was expected to be influenced by the following design and biological criteria:

1. Overall screen dimensions and shape.
2. Width of screen slot opening.
3. Combination of slot (through-screen) and bypass water velocity.
4. Proportion of total flow withdrawn through the intake screen.
5. Orientation of the screen with respect to the river flow.
6. Differences in behavior, size, and swimming ability among different larval fish species.

Based on these considerations the following experimental variables were tested in a laboratory flume:

1. Orientations of a flat screen—horizontal and vertical.
2. Slot widths—0.5 mm, 1.0 mm, 2.0 mm.
3. Bypass and slot velocity combinations:

Bypass: cm sec^{-1}	7.6	15.2	30.5	61.0
(fps)	(0.25)	(0.5)	(1.0)	(2.0)
Slot: cm sec^{-1}	7.6	15.2	22.9	
(fps)	(0.25)	(0.5)	(0.75)	

4. Species tested:

muskellunge - *Esox masquinongy*

channel catfish - *Ictalurus punctatus*

bluegill	-	*Lepomis macrochirus*
largemouth bass	-	*Micropterus salmoides*
smallmouth bass	-	*Micropterus dolomieui*
striped bass	-	*Morone saxatilus*
walleye	-	*Stizostedion vitreum*

Glossary

Approach Velocity - The calculated or measured velocity of water in the flume upstream of the test screen through which water is withdrawn.

Avoidance (Avoided) - Refers to a significant difference between observed and expected proportion of fish which bypass the test screen in which observed is greater than expected.

Bypass Velocity - The velocity of the remaining portion of the total flow of water in the test flume after a portion has been withdrawn through the test screen. Bypass velocity is calculated or measured at a point immediately downstream of the test section being used in a particular experiment.

Entrainment - The transport of fish through a test screen by water current.

Entrapment - The arithmetic sum of number of fish entrained and number impinged.

Impingement - The process of a fish being forced against a test screen by water current and unable to escape throughout the duration of a test.

Larval Fish - Developmental stage of fish defined as extending from the period of hatching to full development of fin rays. Used throughout this report to refer to fish a few days to a few weeks of age. This period of development is divided into the prolarval stage (from time of hatching until absorption of yolk sac is complete, and fish begin actively feeding on plankton) and post-larval stage (larval stage after absorption of yolk sac).

Pooled - Refers to the summing of the three replicate observations for each test such that the totals are treated as representing a single observation.

Proportion Bypassed - Refers to that proportion of the total number of fish released at the upstream end of the flume which are collected downstream of the test section at the end of a test. In this report, proportion bypassed always refers to the mean of three replicate (pooled) tests.

Slot Velocity - The velocity of the portion of the total flow of water in the test flume which is withdrawn through the test screen. This is the calculated average velocity at a point between the wires of the screen.

MATERIALS AND METHODS

Description of Test Facility

The facility used in this experiment provided simulation of a range of water velocity conditions that would typically exist in a river or stream. The apparatus was designed to test the response of larvae to several combinations of approach and slot velocities, screen orientation, and amount of exposure to screen (length of screen). The facility was not designed to model a prototype.

The test apparatus consisted of a plexiglas flume (Figure 1) 11.9 m long by 39.4 cm wide by 39.4 cm deep. Half of the flume contained five consecutive 1.2 m long screen sections. Water could be withdrawn from

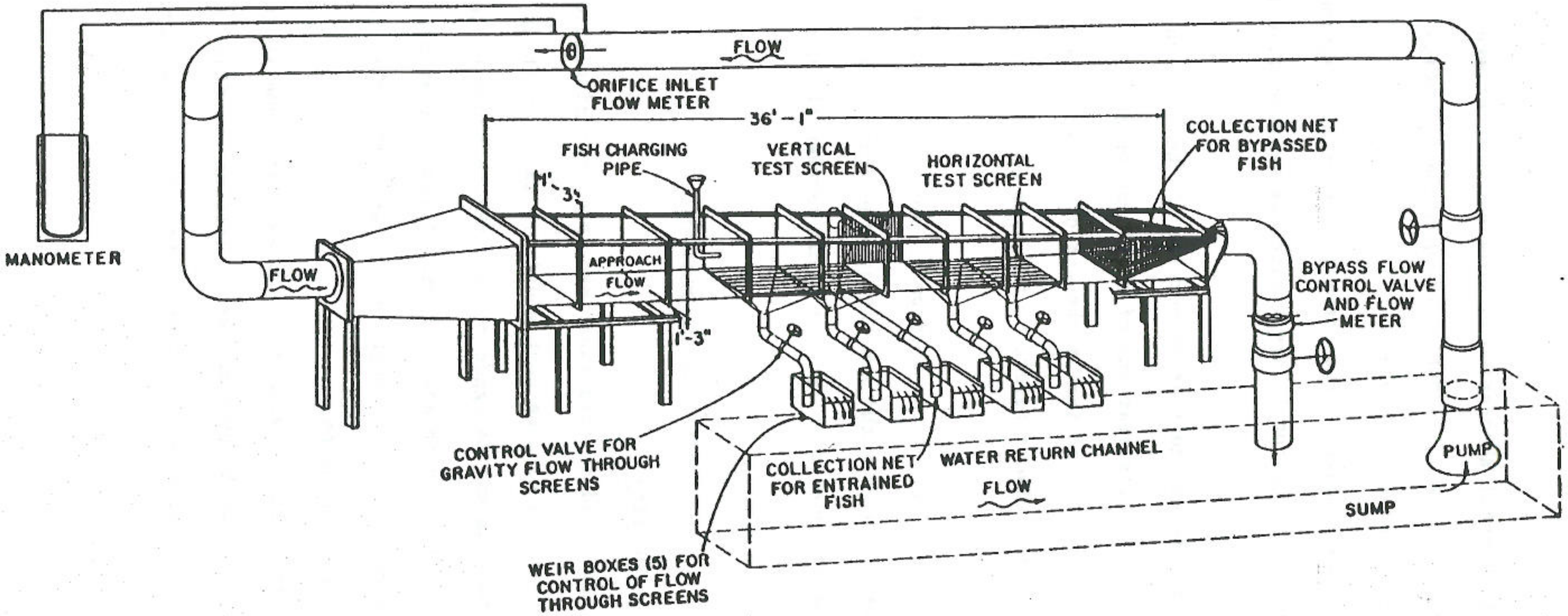

Figure 1. TVA ENGINEERING LABORATORY TEST FLUME FOR THE STUDY OF FISH BEHAVIOR NEAR STATIONARY SCREENS

one or more of the test sections through the slotted screen. The horizontal orientation of the screen on the bottom of the flume provided the condition of a downward vertical intake flow. To establish a horizontal intake flow one or more of the test sections could be rotated 90 degrees. In this position the screen constituted one wall of the flume. Smith (1977) described the design of the test flume and screening medium in detail.

Water temperature control was unavailable in the test flume. Water used in the laboratory is supplied from a 757 m^3 sump located beneath the laboratory. A few times each year the sump may be drained and refilled with chlorinated city water. To remove the chlorine and make the water suitable for testing fish, the water is aerated by circulating it through one or more test flumes or models. Since the water supply is changed infrequently, chlorine toxicity is rarely a problem. Water temperature is dependent on ambient weather conditions as well as the extent to which the several test flumes and models are operated. During the operation of the pumps which supply water to the flumes, heat is absorbed by the water; operation of several pumps during the summer months often causes water temperatures to exceed 27 C (80 F).

Acquisition and Pretest Holding of Fish Larvae

All species of test fish were acquired from state or Federal fish hatcheries, usually within one to three days after hatching. These larvae were transferred to the pretest holding laboratory via oxygenated water in insulated containers. At the laboratory the fish were held in 620 ℓ Living Streams or 890 ℓ circular tanks until transferred to TVA's Engineering Laboratory for testing. Oxygen was supplied to each tank via a central air system. During the pretest holding period (one to several days) those species in the postlarval stage of development were fed a diet of brine shrimp (Artemia salina) several times daily.

Description of Test Procedures

The response of fish larvae to the velocities and screens was tested using only two test sections, one with a vertically positioned screen and one section with a horizontally positioned screen. The two screen orientations were always tested separately. The test screen area was limited to one section in order to test the fish response under better defined velocity conditions. Withdrawal of water through all test screens simultaneously would have created large differences between approach and bypass velocity between the upstream end of section 1 and the downstream end of section 5. Restricting the initial tests to one section resulted in minimal differences between approach and bypass velocities and facilitated a better initial evaluation of the influence of velocity on fish entrapment. Testing was conducted as follows:

1. Test fish were transferred from "Living Stream" holding tanks to the Engineering Laboratory for testing via a 12 ℓ plastic container.
2. To adjust the temperature of the holding water to that of the flume water, the transfer container was immersed in flowing flume water. Water temperature was monitored periodically, and testing was not begun until the temperature in the container was within 2 C of the flume temperature. Exceptions to this procedure are discussed later in the report. During the

temperature adjustment period, the holding water was continuously aerated, and fish were carefully observed for overt signs of thermally induced stress.

3. Experimental conditions for a particular test (screen position, screen slot width, and water velocities) were selected.
4. Flows were established and velocities checked with a Marsh-McBirney Model 722 water current meter.
5. Three replicate groups of test fish (estimated to be about 100-200 each) were siphoned from the acclimation container into 500 ml beakers.
6. For each replicate observation, the fish from one beaker were released in the uppermost end of the flume by pouring approximately equal numbers into each of three Plexiglas tubes. This method was designed to distribute the fish homogeneously throughout the water column.
7. For each replicate test the behavior of the fish larvae was documented as they passed through the test section.
8. Each test was terminated after all the test fish either (1) passed through the test section (bypassed), (2) became entrapped (entrained or impinged), or (3) were still swimming against the current ten minutes after being released into the flume (counted as bypassed fish).
9. At the end of each replicate test the entrained fish were retrieved from a screened cup designed to intercept them after they passed through the test screen (Figure 1). Bypassed fish (including

those still swimming in the test flume) were collected in a cone-shaped net located in the bypass region downstream of the test section. A removable screened cup at the end of this net facilitated retrieval of the organisms.

10. After removal of the bypassed fish, the net was reinserted in the flume to collect the impinged fish. This was done by "sweeping" the test screen and allowing the impinged fish to drift downstream into the net.

11. The impinged, entrained, and bypassed fish either were counted immediately after the test or, when numbers in a category were large, were preserved in 5 percent Formalin and returned to the laboratory for counting.

12. Three replicate tests were next conducted at the same flows on the alternate screen orientation by diverting the entrainment flow to the adjacent test section.

13. Individual total length measurements from one or more selected samples were made on each day of testing. For each species tested, all fish from the same hatch appeared to be very similar in size throughout the testing period.

Numerical Analysis

The basic experimental question in this study was whether larval fish would respond to velocities through the test screen by avoiding entrainment and impingement as they were swept downstream past the test screen. It was hypothesized that if larval fish were essentially "planktonic" (i.e., displayed limited or no swimming response) the expected proportion of fish bypassed would be equal to that proportion of the total flow of water which was bypassed. A replicated goodness-of-fit procedure was applicable to the analysis of this experimental question. The "G" statistical parameter was selected because of ease of calculation and because it allowed a precise determination of within-replicate variability or "heterogeneity" (Sokal and Rohlf 1969).

The expected proportions bypassed and entrapped were determined by the unique bypass-slot velocity combination for each test. Differences between the horizontal and vertical orientations were analyzed by comparing the observed proportions of fish bypassed (pooled over replicate tests) with a paired t-test (Ostle 1963). Tabular and graphical presentations of the results were used to assist in the preliminary interpretations.

Since the proportion of water entrained among bypass-slot velocity combinations was not constant in this experiment, direct examination of the proportion of fish bypassed as a means of comparing fish response among slot velocities and between bypass velocities was not meaningful. Therefore, a variable, which was adjusted for the different expected entrainment values, was calculated using the formula:

$$Pr = \frac{Pb - \hat{Pb}}{1 - \hat{Pb}}$$

where Pr = "relative bypass," Pb = observed pooled proportion of fish bypassed, and $\hat{Pb}$ = expected proportion bypassed (based on proportion of total flow entrained through the screen for a given bypass-slot velocity combination). This variable (Pr) represents relative bypass as the ratio of the observed bypass ($Pb - \hat{Pb}$) to the maximum possible bypass (described by $1 - \hat{Pb}$). Thus, a score of 1.00 for any given test would indicate that all of the larvae had bypassed the screen, and a score of 0.00

was obtained when the observed proportion bypassed was equal to the expected proportion. A negative value indicated that a larger proportion was entrapped than was predicted by the expected proportion. However, since relative bypass was not bounded on the negative scale, the magnitude of a negative value had little comparative meaning. Graphical presentation of these data was used to assist in the interpretation of relationships among bypass and slot velocities and screen orientations.

RESULTS AND DISCUSSION

STRIPED BASS

Between April 12 and July 14, 1977, 894 tests were conducted on seven species of larval fish. Two experiments were conducted with striped bass, one during April with fish obtained from a coastal hatchery (Georgia) and one during June with fish obtained from an inland water hatchery (Tennessee). The June set of tests was conducted as a check of reproducibility of the results. In both sets, the fish were obtained as prolarvae (yolk sac stage). The average total length of the fish from selected samples was 5.6 mm in the first group and 5.9 mm in the second group. Because of fewer available specimens in the second group, these fish were not tested with the 0.5 mm slot screen or at the 7.6 cm sec^{-1} bypass velocity.

Water Temperatures

The first group of striped bass was tested during the period April 12-19, 1977. During this time the test and holding temperatures were relatively cool and did not appear to stress the fish. Holding temperatures ranged from 18.0 C to 19.4 C and test temperatures ranged from 17.0 C to 21.0 C. The maximum difference between holding and test temperature to which the fish were subjected was 2.1 C.

The second group of striped bass was tested on June 3 and 6, 1977. By this time, the water temperature used in the test facility had warmed considerably. Holding temperature on June 3 was 17.0 C while the temperature in the flume was 26.0 C. On June 6 the holding temperature was 19.0 C, whereas the test flume temperature ranged from 25.0 C to 25.5 C. Thus, the maximum difference between holding and test temperature to which the fish were subjected was 9.0 C.

<u>0.5 mm Slot (April Tests)</u>

The results of the experiments with striped bass indicated that these larvae were "entrainable" through all three slot widths tested. With the screen of 0.5 mm slot width, the goodness-of-fit tests indicated that all proportion bypassed values were significantly different from expected values (Table 1). In all cases, the observed numbers were greater than the expected values (Figure 2). Relative bypass tended to decrease as slot velocity increased, whereas a consistent trend with respect to increasing bypass velocity was not evident (Figure 3).

<u>1.0 mm Slot (April Tests)</u>

More entrainment occurred through the 1.0 mm slot than through the 0.5 mm slot. Of the 24 tests of 12 slot-bypass velocity combinations (12 with the horizontal and 12 with vertical screen), 19 yielded proportion bypassed values which were significantly different from the expected values (Table 1 and Figure 2). In 16 of these observed bypassed values were

Table 1. Results of "fish avoidance" screen investigations: comparison of observed proportion of striped bass bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations, slot sizes, and horizontal (H) and vertical (V) screen orientations. April experiment.

Slot Velocity (cm sec^{-1})	Slot Size (mm)	Bypassed Velocity (cm sec^{-1}) 7.6		15.2		30.5		61.0	
		H	V	H	V	H	V	H	V
		(0.570)		(0.720)		(0.840)		(0.910)	
7.6	0.5	0.996*	0.999*	0.991*	0.996*	0.989*	0.953*	0.964*	0.977*
	1.0	0.788*	0.535	0.964*	0.839*	0.907*	0.894*	0.949*	0.906
	2.0	0.705*	0.934*	0.905*	0.942*	0.920*	0.913*	0.906	0.869*
		(0.400)		(0.600)		(0.730)		(0.840)	
15.2	0.5	0.889*	0.779*	0.974*	0.817*	0.917*	0.930*	0.974*	0.956*
	1.0	0.916*	0.334*	0.834*	0.665*	0.871*	0.734	0.898*	0.793*
	2.0	0.552*	0.447	0.815*	0.728*	0.869*	0.804*	0.878*	0.881*
		(0.310)		(0.470)		(0.640)		(0.780)	
22.9	0.5	0.796*	0.456*	0.926*	0.624*	0.936*	0.804*	0.958*	0.924*
	1.0	0.717*	0.180*	0.826*	0.638*	0.921*	0.601	0.905*	0.728*
	2.0	0.526*	0.350	0.799*	0.538*	0.810*	0.777*	0.915*	0.799

*Replicated goodness-of-fit analysis indicated that the observed values were significantly different (α = 0.05) from the expected values.

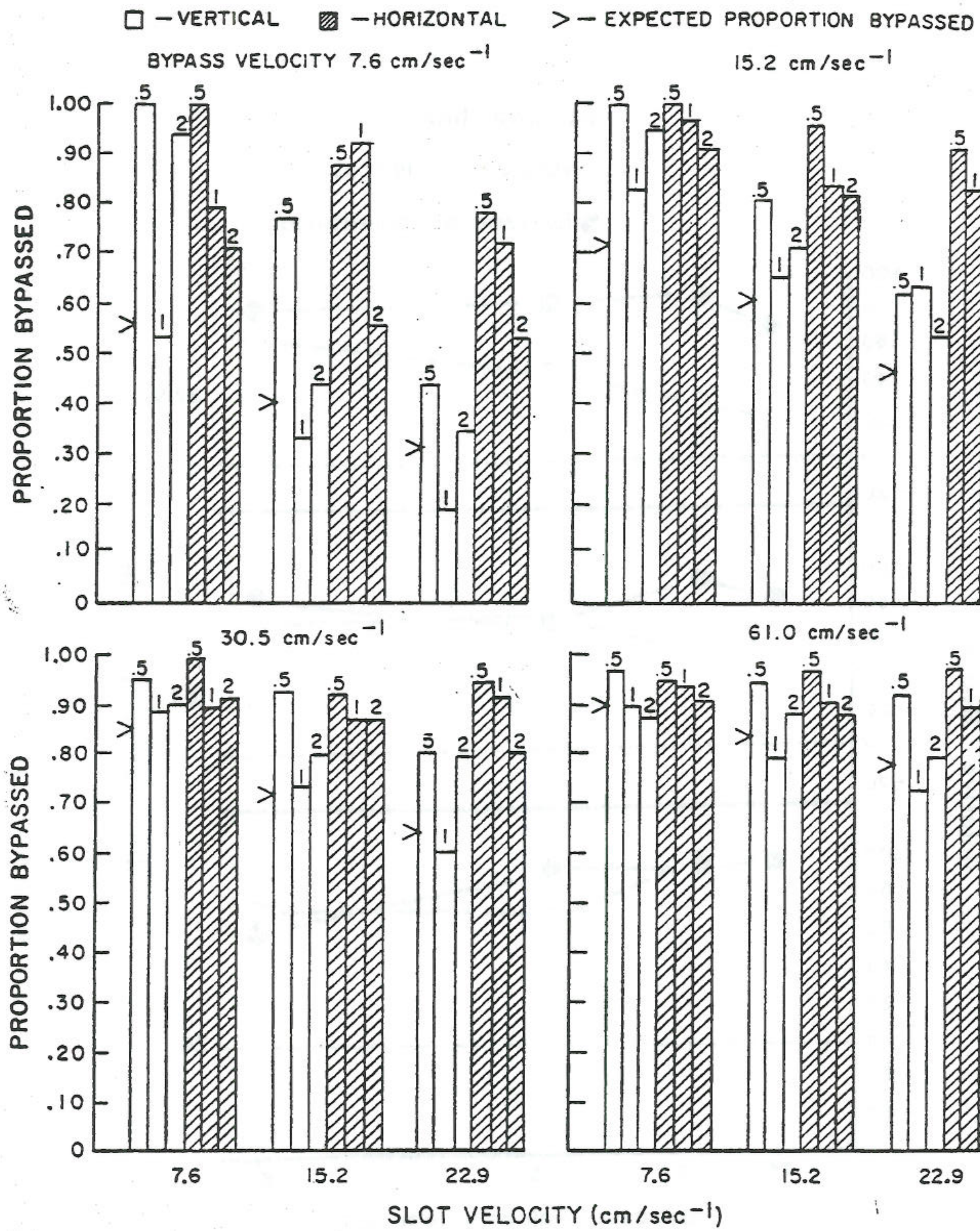

Figure 2. Results of larval fish screening studies ("fish avoidance" concept): proportion of striped bass bypassed by slot width (denoted in mm above each bar) and screen orientation for each slot and bypass velocity. April experiment.

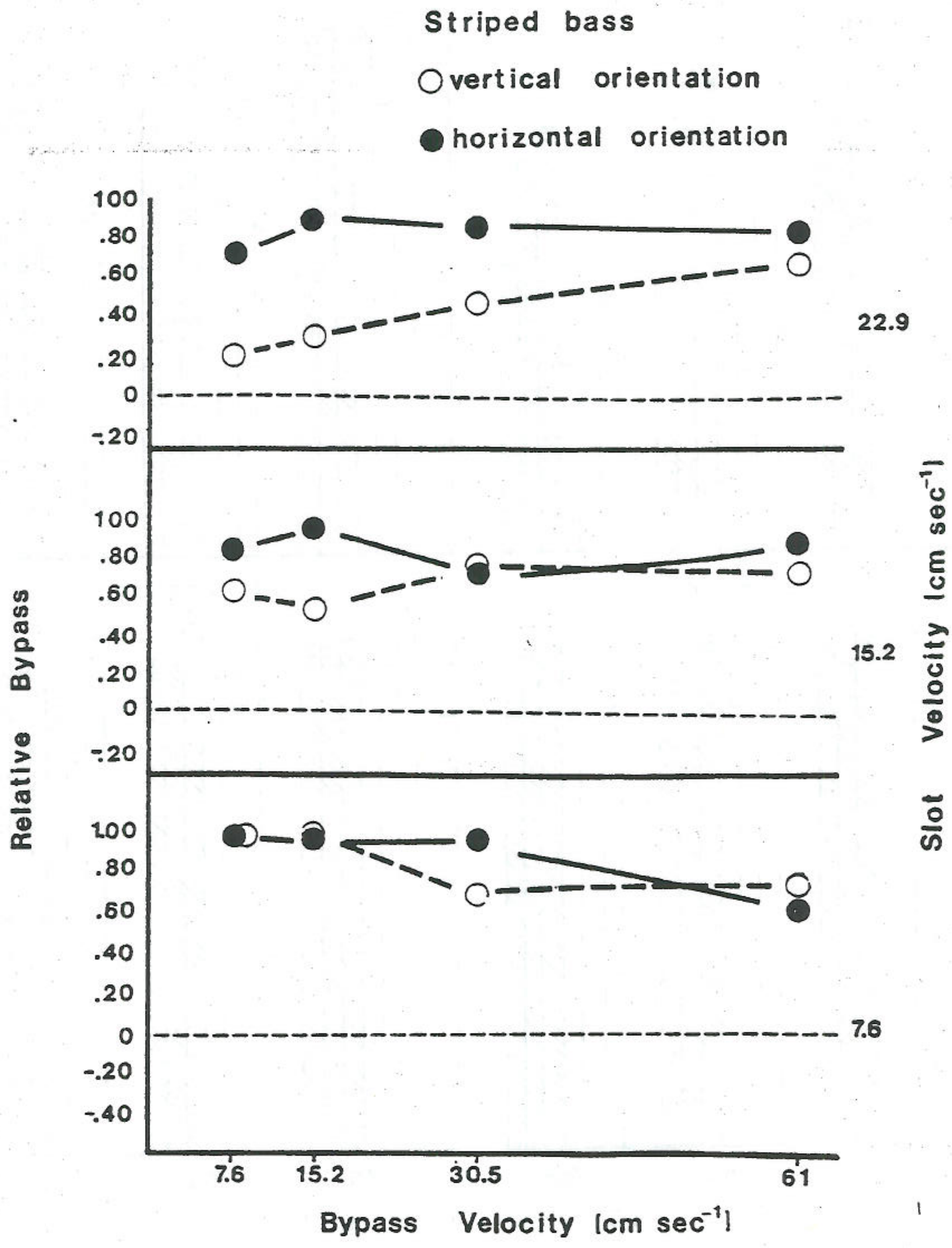

Figure 3. Results of larval fish screening investigations ("fish avoidance" concept) : relationship of relative bypass to bypass and slot velocity for striped bass. Slot width of the screen = 0.5 mm. April experiment.

greater than expected whereas three showed lower than expected proportion bypassed values. All of these lower than expected values were obtained from tests on the vertical screen. Trends among bypass velocities were not readily discernible; however, for both the 0.5 and 1.0 mm slots, low relative bypass at the lowest bypass velocity was observed (Figure 3 and 4). This was probably due to the longer residence time of the larvae in the test section; the ability of the larvae to reside in the test section for longer periods of time at this lowest bypass velocity resulted in a longer exposure time to the test screen and entrainment flow. In addition, at the lowest bypass velocity, turbulence and flow reversal at the downstream end of the test section (TVA 1977) caused some of the bypassed fish to be reexposed to the entraining flow.

2.0 mm Slot (April Tests)

The proportion bypassed values were significantly different from expected for the 2.0 mm slot (Table 1 and Figure 2) in 20 of 24 test combinations. Nineteen of these values were greater than expected. The test yielding the lower-than-expected value was the vertical orientation, 7.6 cm sec^{-1} slot velocity, and 61.0 cm sec^{-1} bypass velocity. This velocity combination represents the highest expected bypass (91 percent) of the 12 combinations. Low relative bypass at the lowest bypass velocity probably reflects reexposure, as described above, whereas relatively low bypass at the high bypass velocity may have been due to the apparent inability of the fish to orient sufficiently to respond to the entraining flow (Figure 5).

1.0 mm Slot (June Tests)

In the second experiment, proportion bypassed values were significantly different from expected in 13 of 18 tests. In all of these

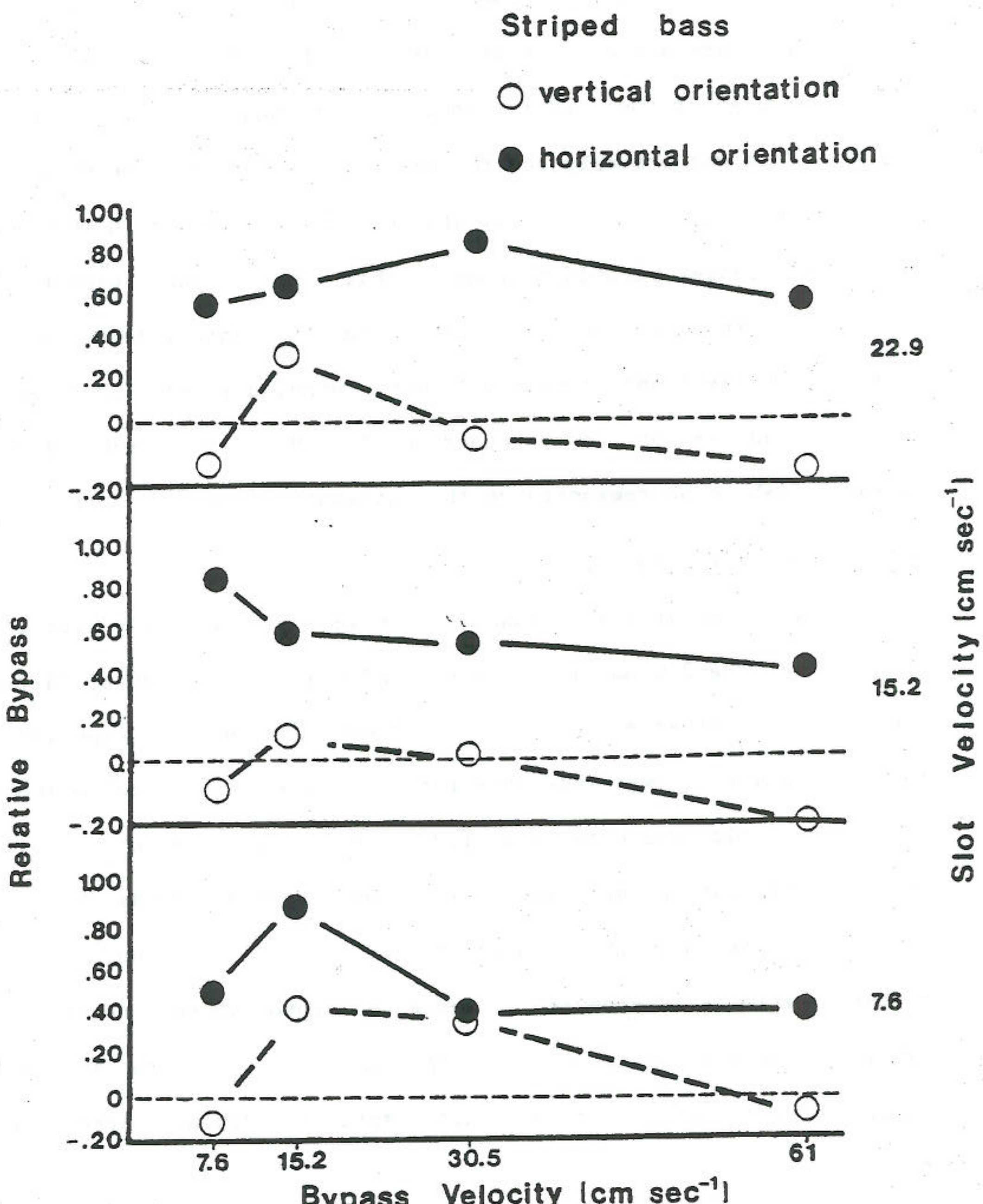

Figure 4. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for striped bass. Slot width of the screen = 1.0 mm. April experiment.

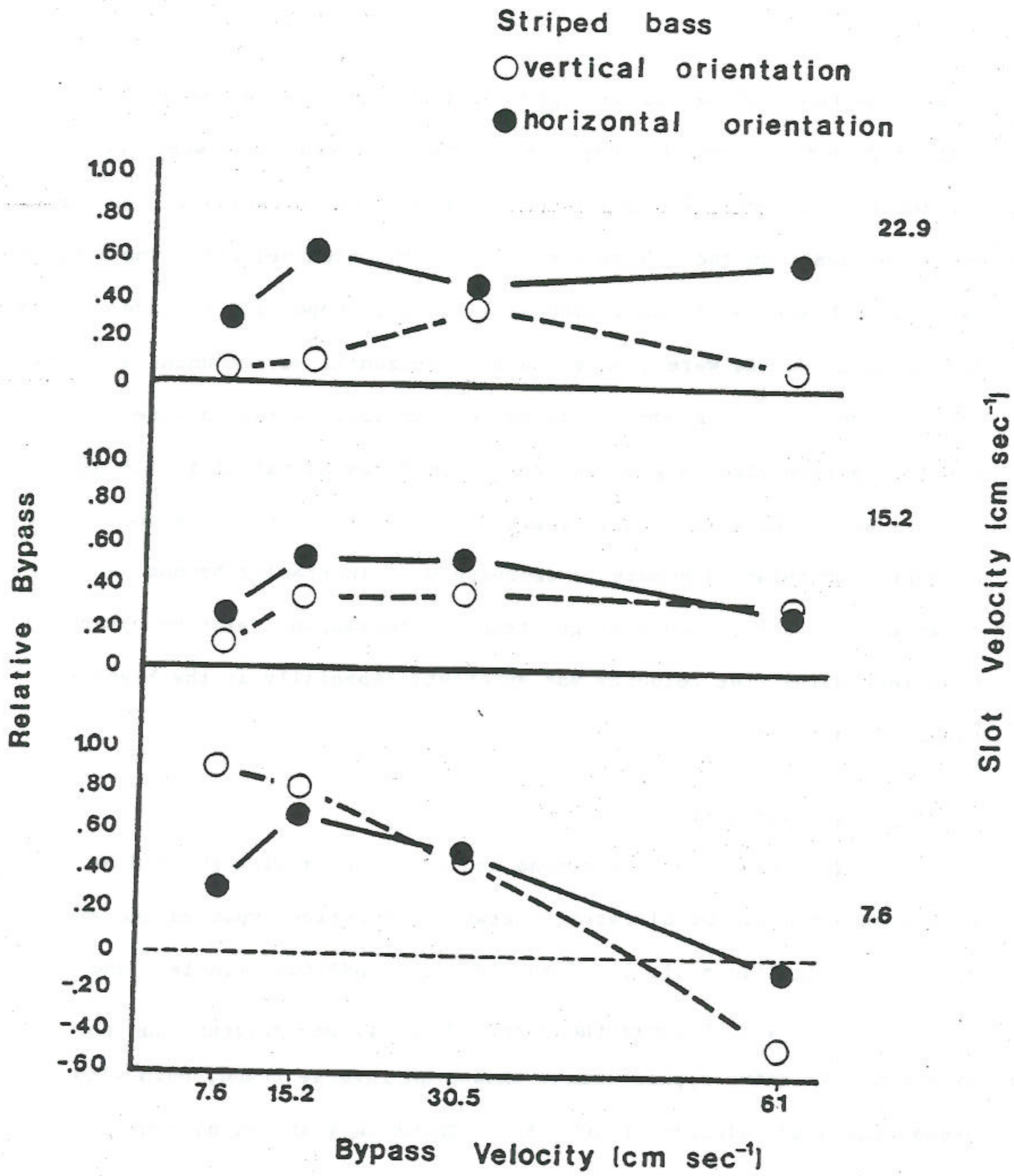

Figure 5. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for striped bass. Slot width of the screen = 2.0 mm. April experiment.

cases, the observed values were greater than the expected value (Table 2 and Figure 6). A nearly complete reversal in results between the horizontal and vertical orientation occurred from the April to the June series of tests on the 1.0 mm screen. For the nine velocity combinations used in both series of tests (Tables 1 and 2), proportion bypassed values in the April series were greater on the horizontal screen under all nine combinations. For the same velocity combinations tested in June, the vertical screen yielded greater proportion bypassed values in all nine cases. As in the April tests, there was a tendency in the second series of tests for relative bypass to decrease with increasing bypass velocity (Figure 7). Also, only a slight trend of decreasing relative bypass with increasing slot velocity was apparent, especially at the highest bypass velocities.

<u>2.0 mm Slot (June Tests)</u>

The results of the second series of tests with the 2.0 mm slot screen showed that the difference between proportion bypassed and expected bypass was significant in 11 of the 18 test conditions (Table 2 and Figure 6). In all 11 cases the observed bypass was greater than the expected. Relative bypass values showed an inverse trend, both with bypass and slot velocity (Figure 8). These data showed no consistent difference with respect to screen orientation.

During both experiments with larval striped bass, proportion bypassed values were greater with the 2.0 mm slot than with the 1.0 mm slot for one of the screen orientations (Tables 1 and 2). During the first experiment this phenomenon was true of the vertical screen, while in the second experiment this phenomenon occurred with the horizontal screen. This phenomenon was peculiar to the tests with striped bass.

Table 2. Results of "fish avoidance" screen investigations: comparison of observed proportion of striped bass bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations, slot sizes, and horizontal (H) and vertical (V) screen orientations. June experiment.

Slot Velocity (cm sec^{-1})	Slot Size (mm)	Bypass Velocity (cm sec^{-1}) 15.2 H	15.2 (expected)	15.2 V	30.5 H	30.5 (expected)	30.5 V	61.0 H	61.0 (expected)	61.0 V
7.6	1.0	0.780*	(0.720)	0.971*	0.916*	(0.840)	0.959*	0.941	(0.910)	0.967*
	2.0	0.978*		0.985*	0.966*		0.971*	0.919		0.898
15.2	1.0	0.702*	(0.600)	0.922*	0.773*	(0.730)	0.942*	0.808	(0.840)	0.906*
	2.0	0.950*		0.894*	0.949*		0.892*	0.813		0.801
22.9	1.0	0.663*	(0.470)	0.884*	0.655	(0.640)	0.895*	0.760	(0.780)	0.809
	2.0	0.817*		0.794*	0.853*		0.700	0.786		0.801

*Replicated goodness-of-fit analysis indicated that the observed values were significantly different ($\alpha = 0.05$) from the expected values.

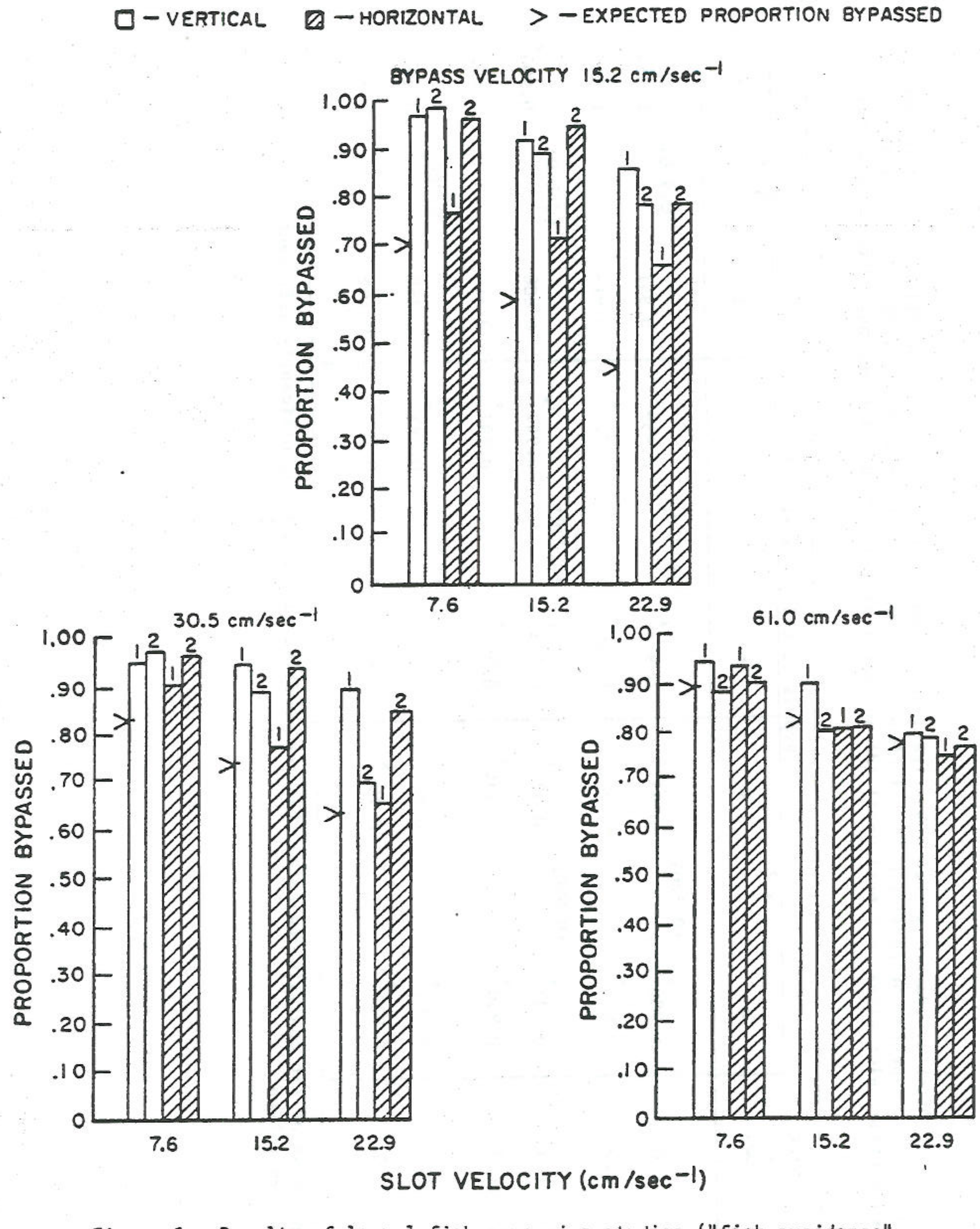

Figure 6. Results of larval fish screening studies ("fish avoidance" concept): proportion of striped bass bypassed by slot width (denoted in mm above each bar) and screen orientation for each slot and bypass velocity. June experiment.

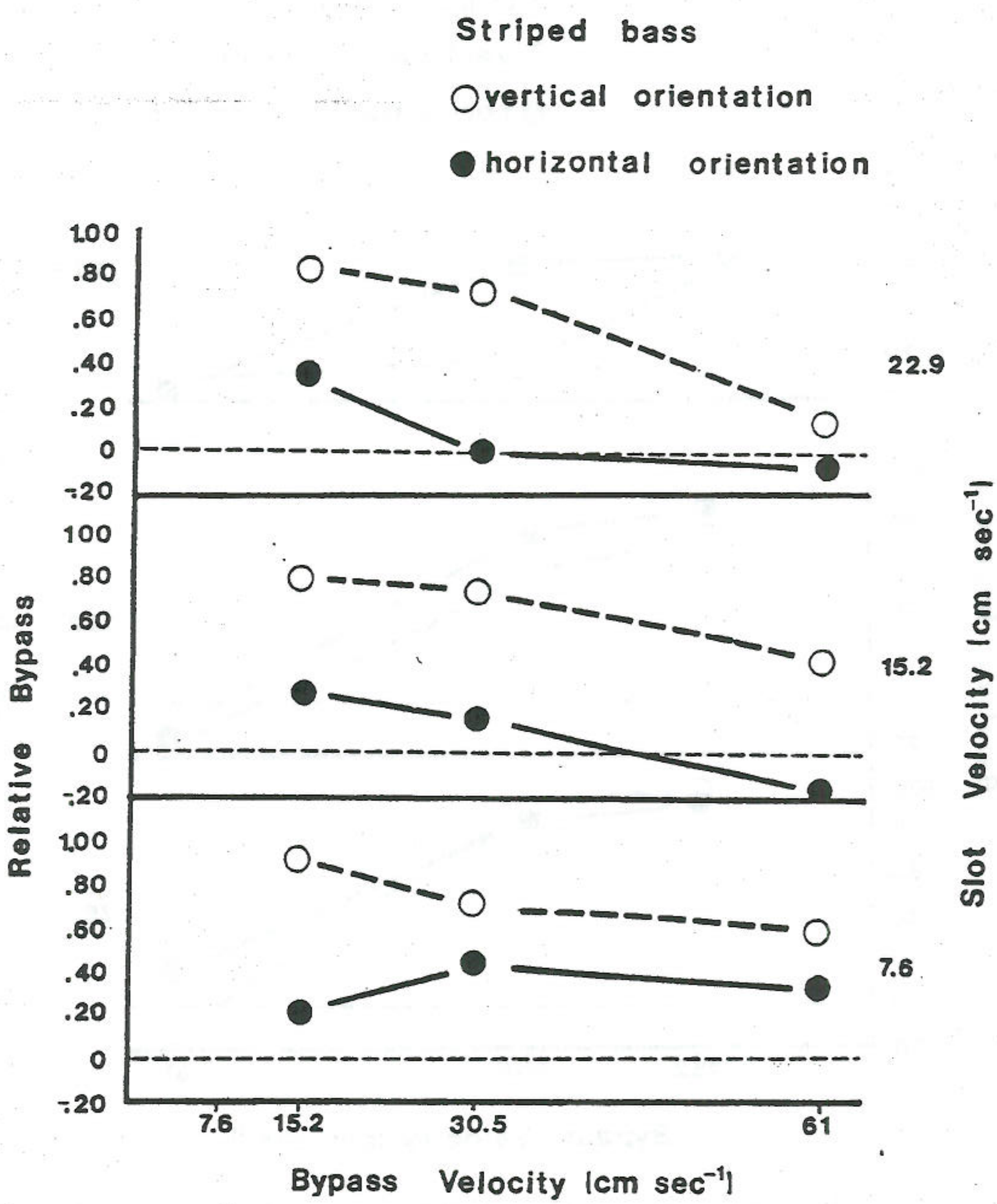

Figure 7. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for striped bass. Slot width of the screen = 1.0 mm. June experiment.

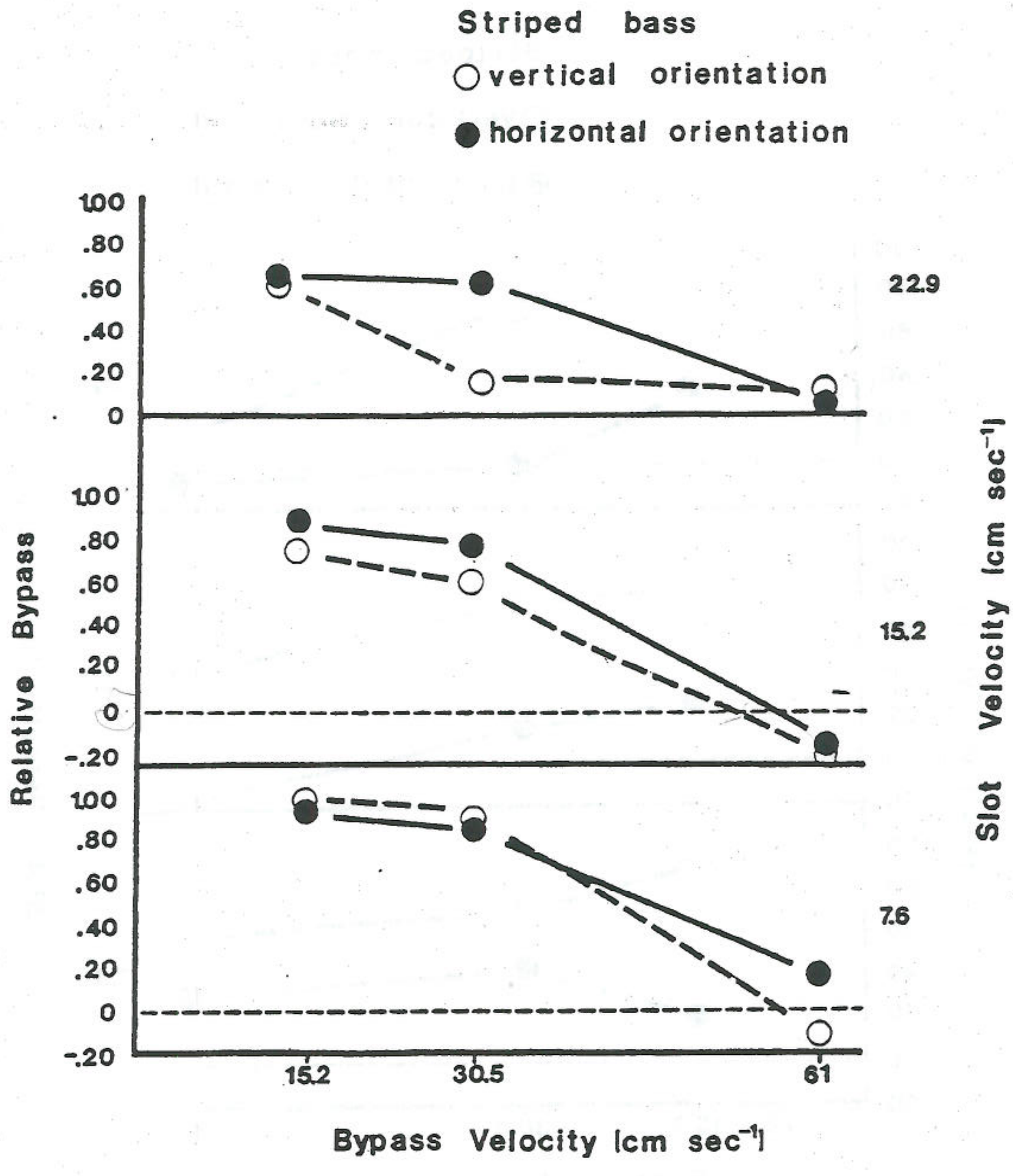

Figure 8. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for striped bass. Slot width of the screen = 2.0 mm. June experiment.

There were no obvious differences in the size or overt behavior of the two groups of larval striped bass tested in this study. Larval striped bass are an open water species. In both experiments, the fish were observed to orient into the current, react to the entraining current by vigorous swimming, and to move toward the flume water surface. However, in spite of the apparent similarity of the two groups of fish, each group responded quite differently to identical velocity conditions in the test flume. These two groups of fish probably showed differences in genotype since they were obtained from different populations. Subtle differences in behavior (associated with genetic differences) may have accounted for large differences in response to entraining currents in the test facility.

Apparent stress to the latter group of fish, probably due to the elevated flume water temperature, may have adversely affected the reproducibility of the results. Midway through the second set of tests, the test fish appeared to be suffering from acclimation to flume water temperature. At that point we began to introduce the fish into the test chamber directly from the transfer container without acclimating the fish to the test temperature. The response of the fish to the test conditions seemed to improve. Apparently the short exposure time to the test conditions as well as the lack of apparent immediate thermal shock when charged into the flume water, resulted in the increased response to th test conditions.

LARGEMOUTH BASS

Due to a limited number of available specimens, a partial series of tests was conducted with larval largemouth bass using the screens with

0.5 and 2.0 mm slot widths. Further, since this species appeared to show relatively strong swimming behavior, tests were conducted only at the three highest bypass velocities.

Tests were conducted on April 28 and 29 and on May 4 and 5. On these days, the average total lengths from selected samples were 9.5 mm, 9.8 mm, 10.4 mm, and 11.6 mm, respectively. Relatively high standard deviations (1.08, 1.06, 0.08, and 1.76 mm, respectively) are a result of obtaining the fish from hatchery ponds rather than laboratory incubators.

Throughout the largemouth bass test period, water temperatures in the flume remained fairly cool and constant, ranging from 19.3 C on April 28 to 20.5 C on May 5. Pretest holding temperatures were similar to the test temperatures, ranging from 20.0 C to 20.5 C.

<u>0.5 mm Slot</u>

This species was infrequently entrained through the 0.5 mm slot. Goodness-of-fit tests indicated that every bypass-slot velocity combination and screen orientation yielded proportion bypassed values which were significantly different from the expected values (Table 3 and Figure 9). In every test, the observed value was greater than the expected value. Similarly, relative bypass with the 0.5 mm slot was nearly constant (1.00) at all bypass-slot velocity combinations and both screen orientations (Figure 10).

<u>2.0 mm Slot</u>

Some testing was conducted with the 2.0 mm slot, with the most complete information at the 15.2 cm sec^{-1} bypass velocity. In 9 of 10 test conditions, goodness-of-fit tests showed a significant difference

Table 3. Results of "fish avoidance" screen investigations: comparison of observed proportion of largemouth bass bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations, slot sizes, and horizontal (H) and vertical (V) screen orientations.

Slot Velocity (cm sec^{-1})	Slot Size (mm)	Bypass Velocity (cm sec^{-1}) 15.2 H		15.2 V	30.5 H		30.5 V	61.0 H		61.0 V
7.6	0.5	1.000*	(0.720)	0.981*	0.997*	(0.840)	0.998*	1.000*	(0.910)	1.000*
	2.0	0.915*		0.990*	0.989*		0.997*			
15.2	0.5	1.000*	(0.600)	0.982*	0.990*	(0.730)	0.991*	1.000*	(0.840)	1.000*
	2.0	0.850*		0.696*	0.908*		0.973*			
22.9	0.5	0.938*	(0.470)	0.976*	1.000*	(0.640)	1.000*	0.990*	(0.780)	0.997*
	2.0	0.505		0.867*						

*Replicated goodness-of-fit analysis indicated that the observed values were significantly different ($\alpha = 0.05$) from the expected values.

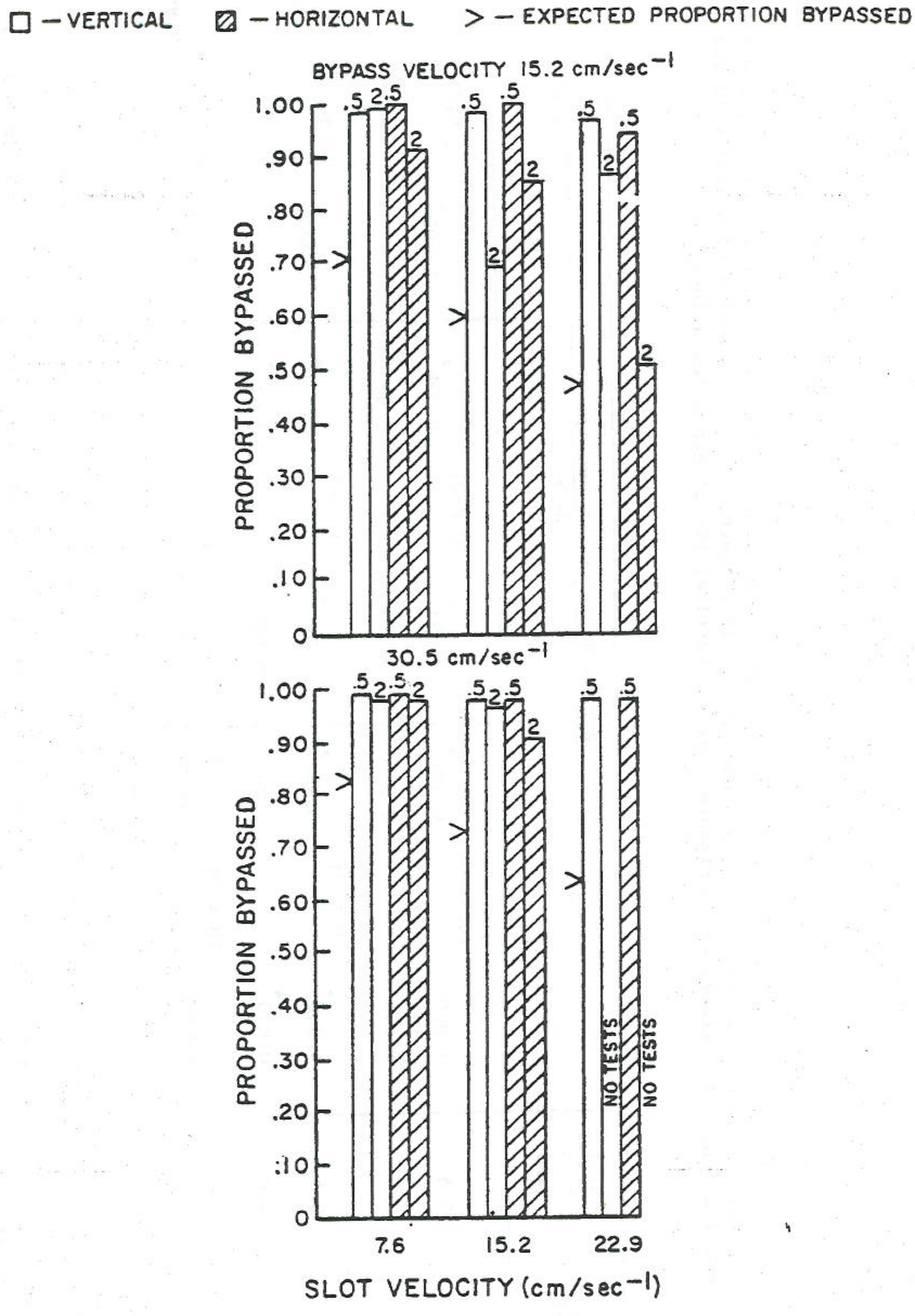

Figure 9. Results of larval fish screening studies ("fish avoidance" concept): proportion of largemouth bass bypassed by slot width (denoted in mm above each bar) and screen orientation for each slot and bypass velocity.

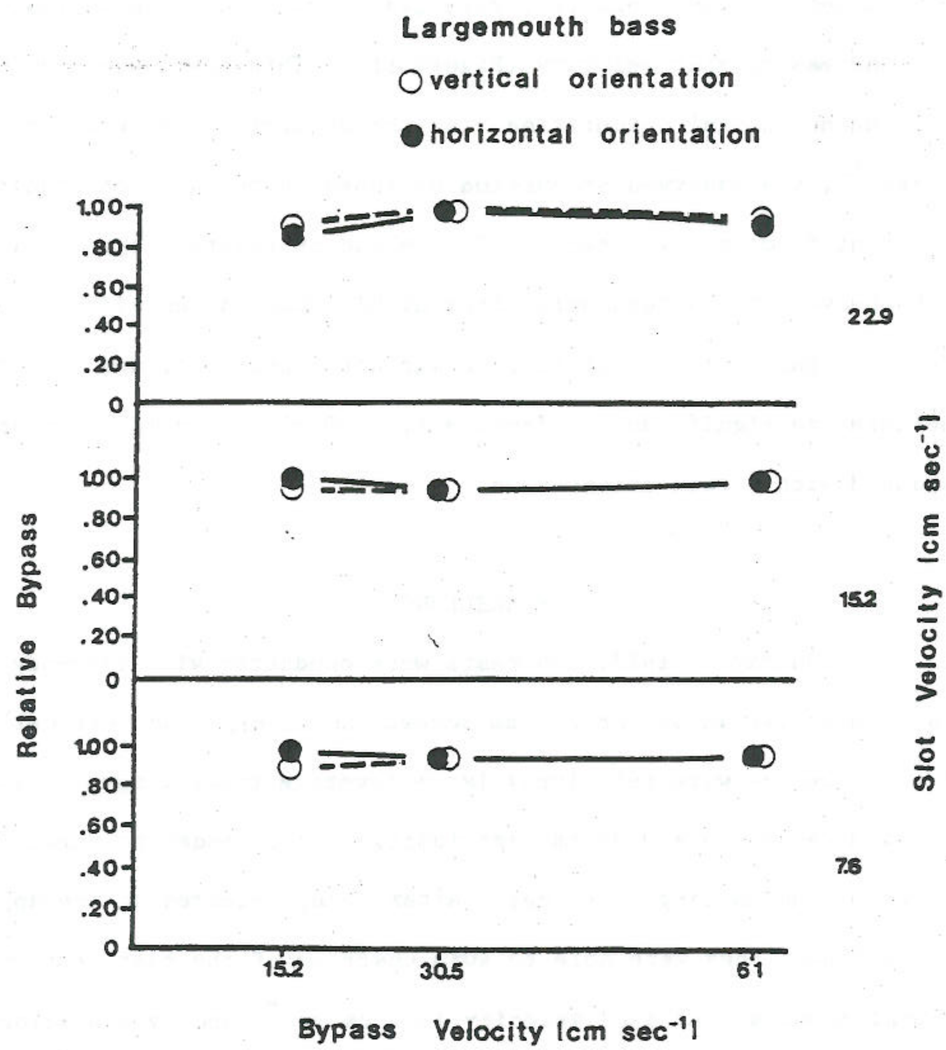

Figure 10. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for largemouth bass. Slot width of screen = 0.5 mm.

between observed and expected proportion bypassed (Table 3 and Figure 9). Observed values were always greater than expected. At the 15.2 cm sec^{-1} bypass velocity, relative bypass tended to decrease with increasing slot velocity (Figure 11). This trend was most pronounced with the horizontal orientation. At the greatest slot velocity (22.9 cm sec^{-1}), the observed proportion bypassed (0.50) was not significantly different from the expected (0.47). Although relative bypass values with the vertical screen were often higher than values with the horizontal screen (Figure 11), the difference was not consistent, and a paired t-test indicated no significant difference ($t = -0.862$, $df = 13$) of proportion bypassed with screen orientation.

MUSKELLUNGE

On May 9, 1977, two tests were conducted with five-day-old muskellunge larvae on the 2.0 mm screen (horizontal and vertical). Prolarvae of this species were relatively large (average total length = 11.5 mm, standard deviation = 0.29 mm) and inactive, and tended to remain on the bottom of the holding container. After being released at the upper end of the flume, they were able to swim upstream of the test section for several minutes. At slot velocity 15.2 cm sec^{-1} and bypass velocity 7.6 cm sec^{-1}, all fish were entrained through both the horizontal and vertical screens. Their behavior indicated a general inability to sense and avoid the entraining flow. Although they displayed "burst" responses (sudden vigorous swimming) near the screen, they were incapable of avoiding the intake currents and 100 percent entrainment resulted. No further tests were conducted until May 17 when the fish had grown to 15.3 mm (average length). On this date, three sets of horizontal and three

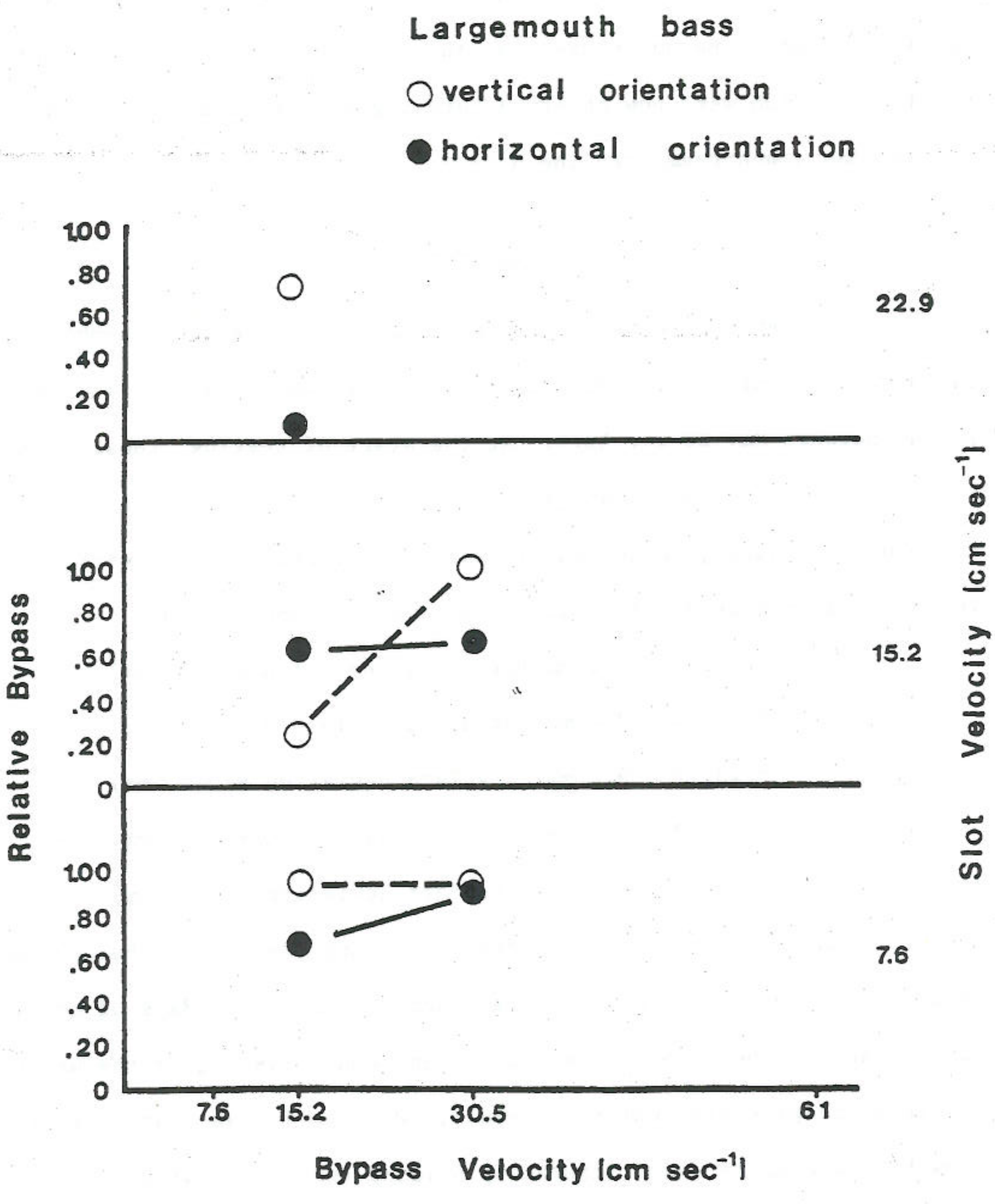

Figure 11. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for largemouth bass. Slot width of screen = 2.0 mm.

sets of vertical tests were conducted (slot velocity 15.2 cm sec^{-1} and bypass velocities 7.6, 15.2, and 30.5 cm sec^{-1}). Although the fish again appeared to be quite passive, an avoidance response was observed (Table 4). Fish were now observed bursting away from the 2.0 mm slots and passing downstream into the bypass.

WALLEYE

A complete series of tests, including 12 velocity combinations, two screen orientations, and three slot sizes, was conducted with walleye larvae between May 20-24, 1977. At the start of testing, these larvae were four days old. Since all hatched on the same day and all were still in the prolarval stage, there was little size variation. The average total length on each test day for fish from selected samples was:

5/20/77 - 9.2 mm (standard deviation = 0.24 mm)
5/21/77 - 9.4 mm (standard deviation = 0.27 mm)
5/23/77 - 9.4 mm (standard deviation = 0.27 mm)
5/23/77 - 9.5 mm (standard deviation = 0.27 mm)
5/24/77 - 9.8 mm (standard deviation = 0.32 mm)

On the first scheduled day of testing (May 18) it became necessary to drain and refill the entire water supply. After two days of continuous circulation of the water to remove the chlorine, testing of the walleye was initiated despite high chlorine levels. Walleye larvae characteristically show high mortality under laboratory holding conditions within several days after hatching. Hence, it was necessary to begin testing as soon as possible after the fish were obtained. The short exposure time (0.5 to 5 minutes) to the chlorinated water was not expected to appreciably affect fish response in the tests.

Table 4. Results of "fish avoidance" screen investigations: comparison of observed proportion of muskellunge bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations with 2.0 mm slot and horizontal (H) and vertical (V) screen orientations.

Slot Velocity (cm sec^{-1})	Slot Size (mm)	Bypass Velocity (cm sec^{-1})								
		7.6			15.2			30.5		
		H		V	H		V	H		V
15.2	2.0	0.822*	(0.400)	0.961*	0.859*	(0.600)	0.919*	0.944*	(0.730)	0.994*

*Replicated goodness-of-fit analysis indicated that the observed values were significantly different ($\alpha = 0.05$) from expected values.

During the period May 18-24, continuous pumping of the water to remove chlorine elevated the temperature from 21.3 C to 25.0 C. Holding temperature ranged from 19.8 C on May 20 to 18.0 C on May 24, resulting in a maximum temperature change of 7 degrees on the last day of testing.

The condition of the walleye deteriorated with each passing test day. Initially, when the fish were still prolarvae and tested in relatively cool water, they were observed in good condition, swimming vigorously in the holding container as well as in the flume. By the second day of testing, a few cases of cannibalism were observed. By the middle of the second day the fish, which were adjusted to flume water temperature prior to testing, were in poor condition. They appeared to be lethargic and did not respond to the test chamber flows. At this point the fish were charged into the test facility without being adjusted to flume water temperature. The response of the fish in this case was noticeably improved. At the lowest bypass velocity (7.6 cm sec^{-1}), many of the unacclimated individuals were able to swim against the current for five minutes. The fish showed no obvious signs of thermal stress from being charged directly into the test flume without temperature acclimation.

By May 23 cannibalism was more prevalent and the fish again appeared to be in poorer condition than on the previous test day. Those fish that were attempting to swallow another fish showed obvious difficulty orienting to the current and appeared to be more readily entrained.

0.5 mm Slot

Larval walleye showed very high proportion bypassed values under all test conditions with the 0.5 mm slot screen. At all velocity combinations and screen orientations, the observed proportion bypassed was significantly different than the expected values (Table 5 and Figure 12). Relative bypass (Figure 13) was at or near 1.00 for all test conditions except the highest slot velocity (22.9 cm sec^{-1}). Most of the entrapment on this screen was in the form of impingement, indicating that this group of fish consisted of individuals too large to pass through the 0.5 mm slot. Of the several thousand test fish exposed to the screen, only five were entrained whereas 231 individuals were impinged.

1.0 mm Slot

Goodness-of-fit tests performed on test data from experiments with the 1.0 mm slot screen showed that proportion bypassed was significantly different from the expected for every combination of bypass and slot velocities as well as for both horizontal and vertical screen orientation (Table 5 and Figure 12). In only one case was the proportion bypassed less than the expected value (lowest bypass and highest slot velocity, horizontal screen). Relative bypass was highest (near 1.00) at the 30.5 and 61.0 cm sec^{-1} bypass velocities (Figure 14). At these high velocities there was little difference in relative bypass between the horizontal and vertical screens. At the lower bypass velocities, relative bypass decreased, especially at the higher slot velocities, and difference between screens increased.

2.0 mm Slot

Goodness-of-fit tests showed that with the 2.0 mm slot, proportion bypassed was significantly different (greater) from the expected value for all bypass-slot velocity combinations and screen orientations except one (Table 5 and Figure 12).

Table 5. Results of "fish avoidance" screen investigations: comparison of observed proportion of walleye bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations, slot sizes, and horizontal (H) and vertical (V) screen orientations.

Slot Velocity ($cm\ sec^{-1}$)	Slot Size (mm)	Bypass Velocity ($cm\ sec^{-1}$) 7.6 H	7.6 V	15.2 H	15.2 V	30.5 H	30.5 V	61.0 H	61.0 V
		(0.570)		(0.720)		(0.840)		(0.910)	
7.6	0.5	0.997*	0.995*	0.993*	0.990*	0.999*	0.995*	1.000*	1.000*
	1.0	0.987*	0.916*	0.980*	0.992*	0.996*	1.000*	1.000*	1.000*
	2.0	0.885*	0.953*	0.957*	1.000*	0.979*	0.994*	0.991*	1.000*
		(0.400)		(0.600)		(0.730)		(0.840)	
15.2	0.5	0.987*	0.996*	1.000*	0.999*	0.995*	1.000*	1.000*	1.000*
	1.0	0.657*	0.930*	0.934*	0.997*	0.987*	0.997*	1.000*	0.998*
	2.0	0.657*	0.798*	0.645	0.941*	0.905*	0.989*	0.961*	0.989*
		(0.310)		(0.470)		(0.640)		(0.780)	
22.9	0.5	0.837*	0.934*	0.985*	0.936*	0.996*	0.999*	0.994*	1.000*
	1.0	0.174*	0.743*	0.900*	0.981*	0.984*	0.998*	1.000*	1.000*
	2.0	0.522*	0.538*	0.630*	0.781*	0.782*	0.941*	0.884*	0.980*

*Replicated goodness-of-fit analysis indicated that the observed values were significantly different ($\alpha = 0.05$) from expected values.

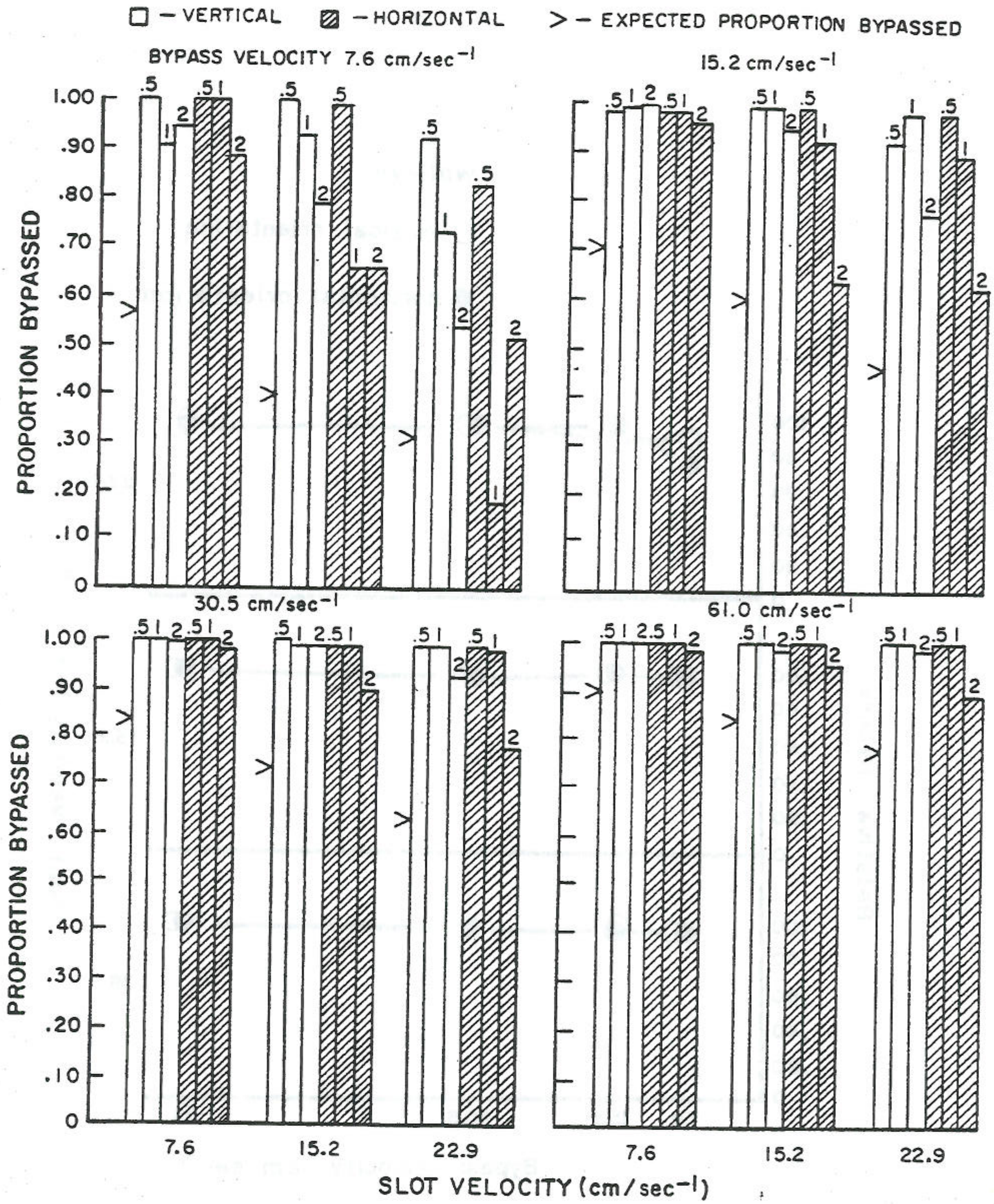

Figure 12. Results of larval fish screening studies ("fish avoidance" concept): proportion of walleye bypassed by slot width (denoted in mm above each bar) and screen orientation for each slot and bypass velocity.

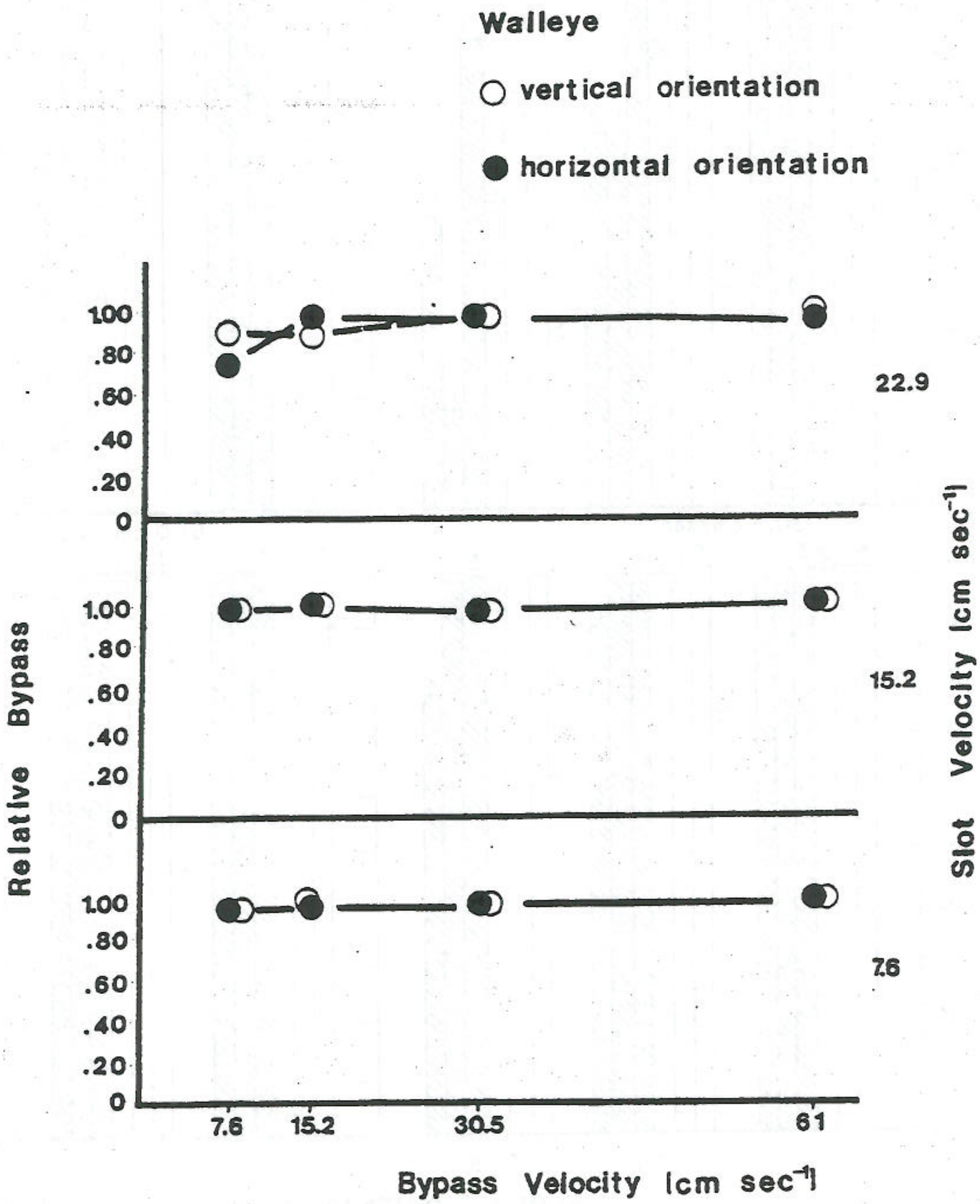

Figure 13. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for walleye. Slot width of screen = 0.5 mm.

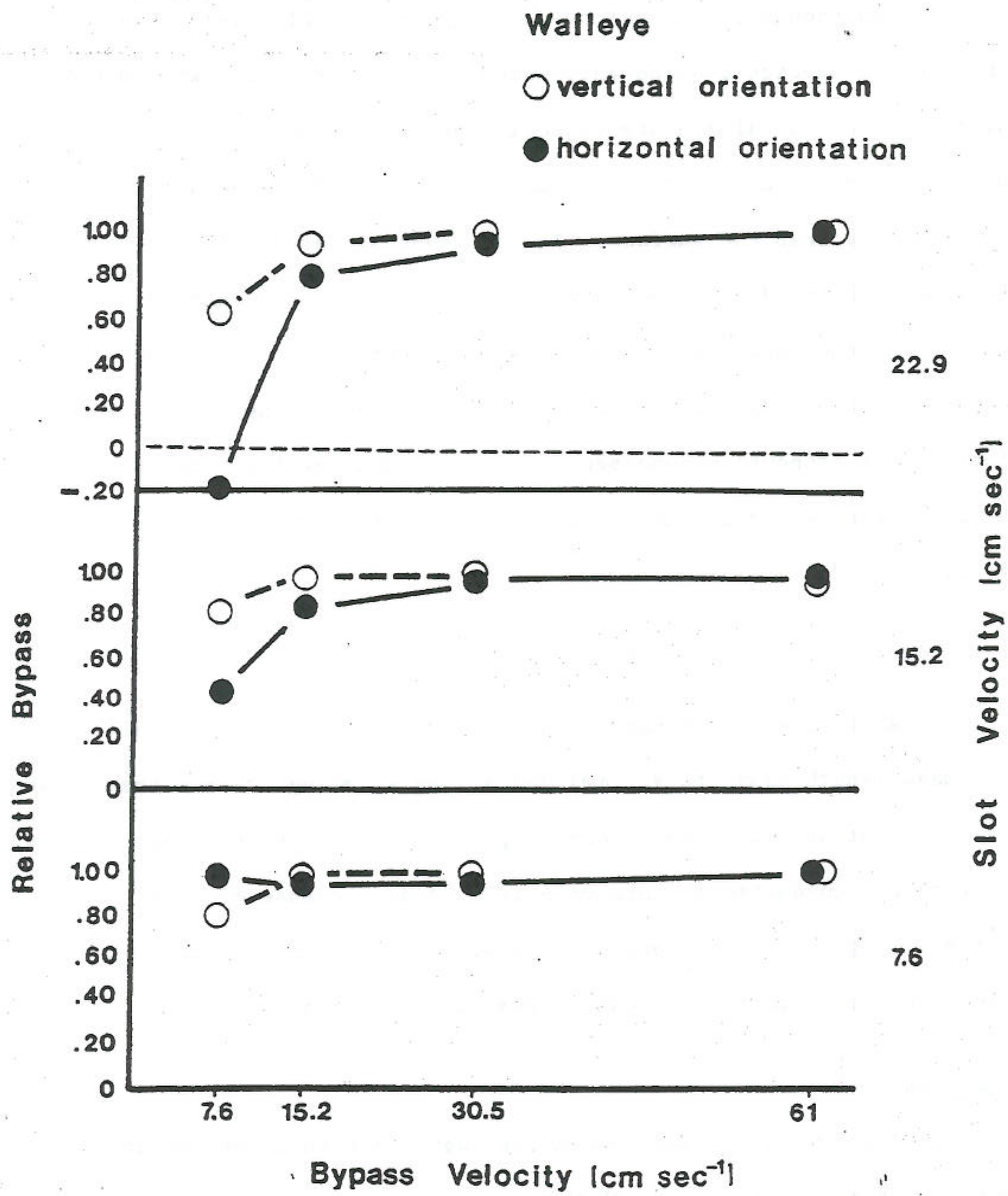

Figure 14. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for walleye. Slot width of screen = 1.0 mm.

Relative bypass at the 2.0 mm slot was lowest at low bypass and high slot velocities (similar to the results with the 1.0 mm slot, Figure 15).

Even though larval walleye appeared to be relatively weak swimmers, this species avoided entrainment under nearly all experimental conditions. Larval walleye are typically pelagic (Houde and Forney 1970), and in the flume they were usually distributed throughout the water column or near the surface. At the lower bypass velocities, walleye were observed to detect and actively swim against entraining flows through the horizontal screen. Walleye behavior with respect to the vertical screen was difficult to observe; however, the paired t-test indicated that proportion bypassed values with the vertical orientation were significantly greater than with the horizontal screen ($t = 2.95$, $df = 35$).

SMALLMOUTH BASS

Larval smallmouth bass, tested on May 25 and 26, were relatively large (mean length equal to 9.7 mm) and strong swimming. Since these fish would have swum against the lowest bypass velocity for prolonged periods, tests were not conducted at this velocity. Also, because of their relatively large size they were not subject to entrainment through the 0.5 mm slot; hence tests with this screen were omitted.

1.0 mm Slot

Very few larval smallmouth bass were entrained through the 1.0 mm screen. Goodness-of-fit tests showed that the proportion bypassed values

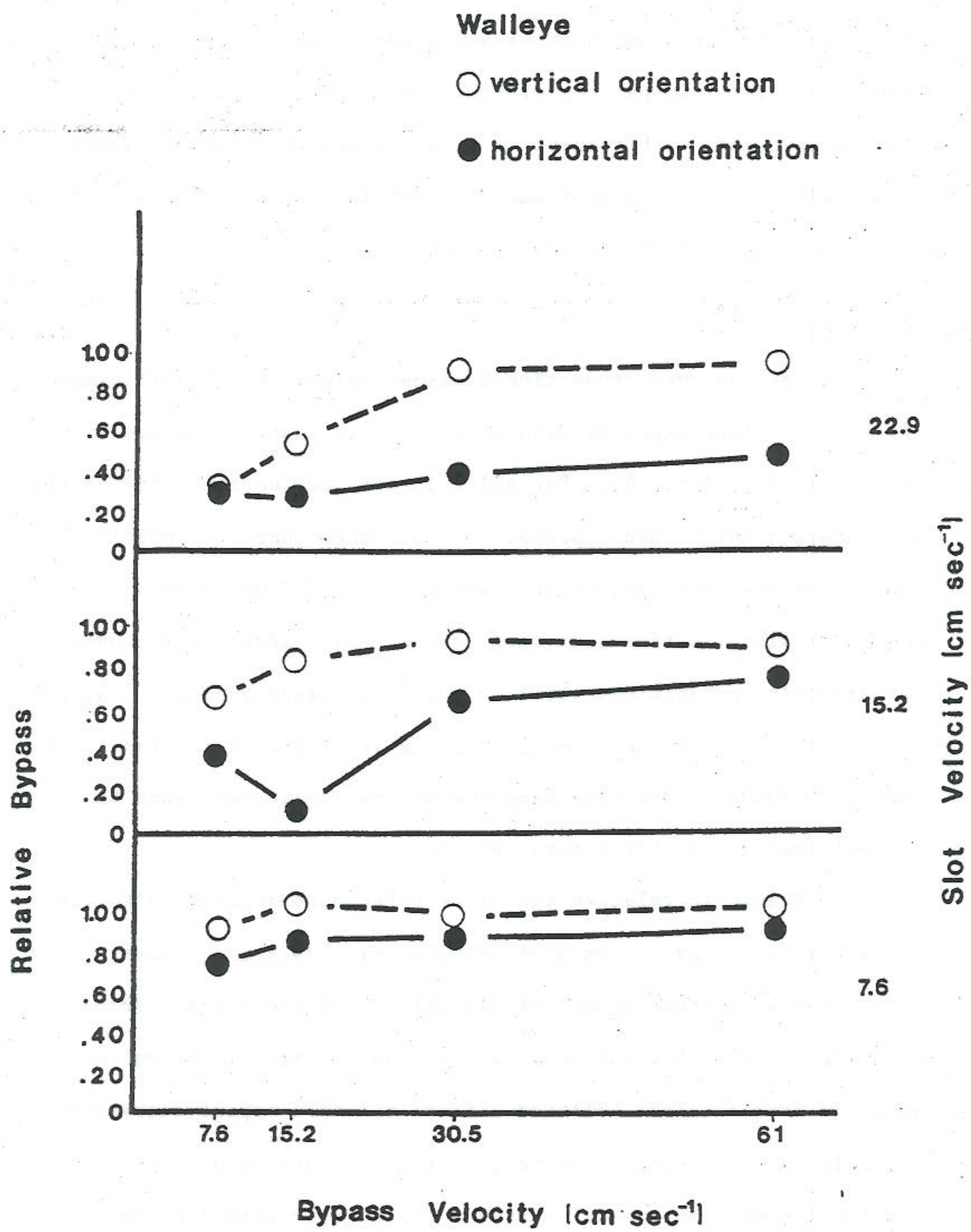

Figure 15. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for walleye. Slot width of screen = 2.0 mm.

were significantly different (greater) than expected values for all bypass slot velocity combinations and screen orientations tested (Table 6 and Figure 16). Comparison of relative bypass showed little evidence of trends with respect to bypass velocity or slot velocity (Figure 17). Relative bypass with the vertical screen was usually greater than with the horizontal screen.

2.0 mm Slot

The observed proportion bypassed values were significantly different from the expected values in 16 of 18 test conditions with the 2.0 mm slot (Table 6). For all velocity combinations, the observed values were greater than expected. In all these cases proportion bypassed values were similar or lower with the 2.0 mm compared to the 1.0 mm slot. Differences were particularly large for two bypass-slot velocity combinations (15.2 cm sec^{-1} bypass-22.9 cm sec^{-1} slot velocity and 15.2 cm sec^{-1} bypass-15.2 cm sec^{-1} slot velocity). This increased entrapment may have been due to the larger residence time in the test chamber at this bypass velocity.

Trends in relative bypass were far more apparent with the 2.0 mm than with the 1.0 mm slot (Figure 18). Relative bypass increased with increasing bypass velocity, with the biggest change occurring between 15.2 and 30.5 cm sec^{-1} velocities. Slot velocity seemed to have a slight additive effect; relative bypass decreased uniformly as slot velocity increased at all bypass velocities. As with the 1.0 mm slot, relative bypass was greater with the vertical orientation. Thus, larval smallmouth bass responded by avoiding entraining flows under all conditions tested in this experiment. In

Table 6. Results of "fish avoidance" screen investigations: comparison of observed proportion of smallmouth bass bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations, slot sizes, and horizontal (H) and vertical (V) screen orientations.

Slot Velocity (cm sec^{-1})	Slot Size (mm)	Bypassed Velocity (cm sec^{-1}) 15.2 H		15.2 V	30.5 H		30.5 V	61.0 H		61.0 V
7.6	1.0	0.932*	(0.720)	0.929*	0.987*	(0.840)	0.996*	1.000*	(0.910)	1.000*
	2.0	0.817*		0.920*	0.989*		0.996*	0.995*		1.000*
15.2	1.0	0.970*	(0.600)	0.980*	0.931*	(0.730)	0.972*	0.983*	(0.840)	1.000*
	2.0	0.617		0.817*	0.881*		0.972*	0.961*		0.989*
22.9	1.0	0.954*	(0.470)	0.977*	0.851*	(0.640)	0.981*	0.963*	(0.780)	0.990*
	2.0	0.486		0.726*	0.781*		0.943*	0.884*		0.980*

*Replicated goodness-of-fit analysis indicated that the observed values were significantly different ($\alpha = 0.05$) from the expected values.

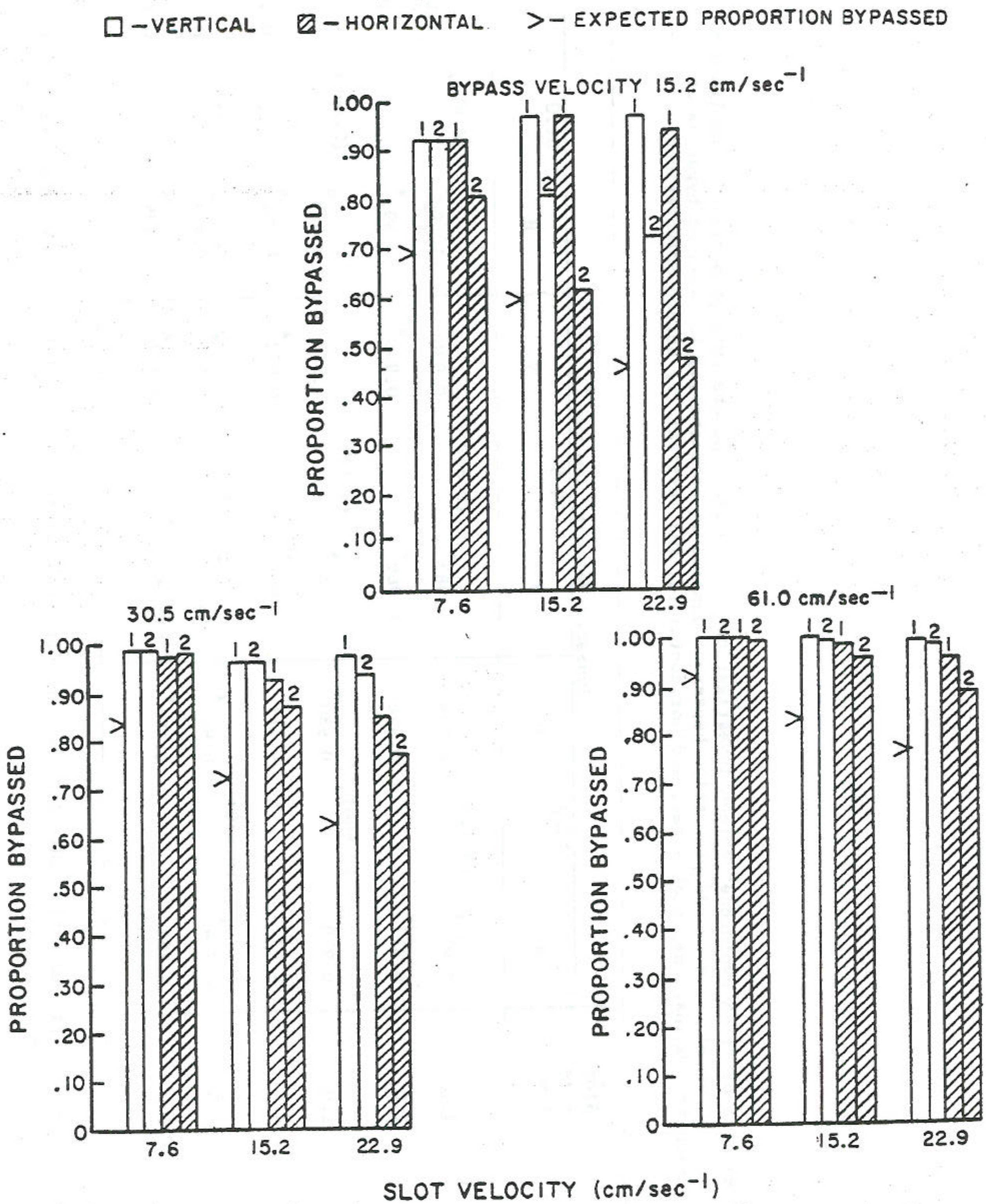

Figure 16. Results of larval fish screening studies ("fish avoidance" concept): proportion of smallmouth bass bypassed by slot width (denoted in mm above each bar) and screen orientation for each slot and bypass velocity.

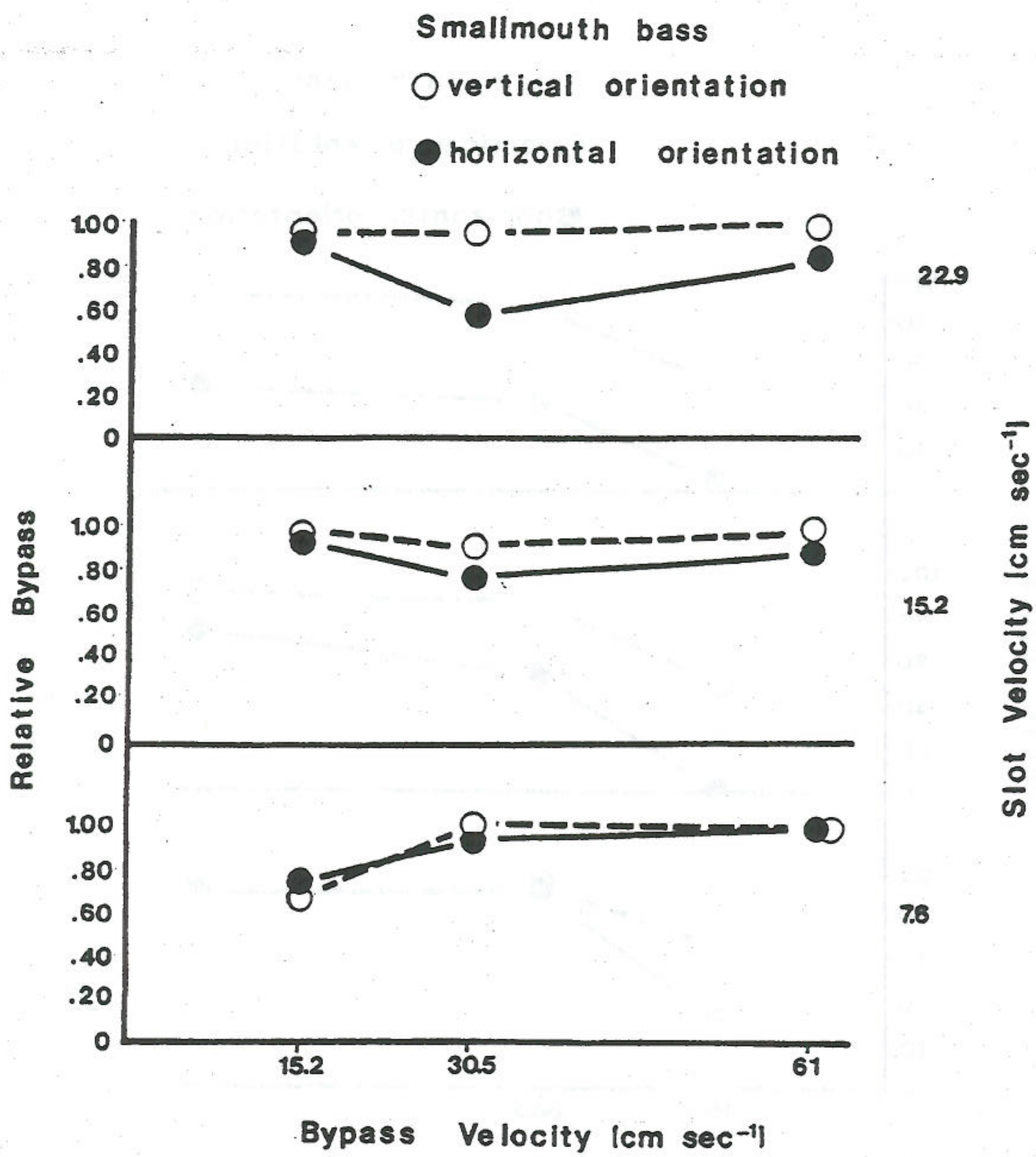

Figure 17. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for smallmouth bass. Slot width of screen = 1.0 mm.

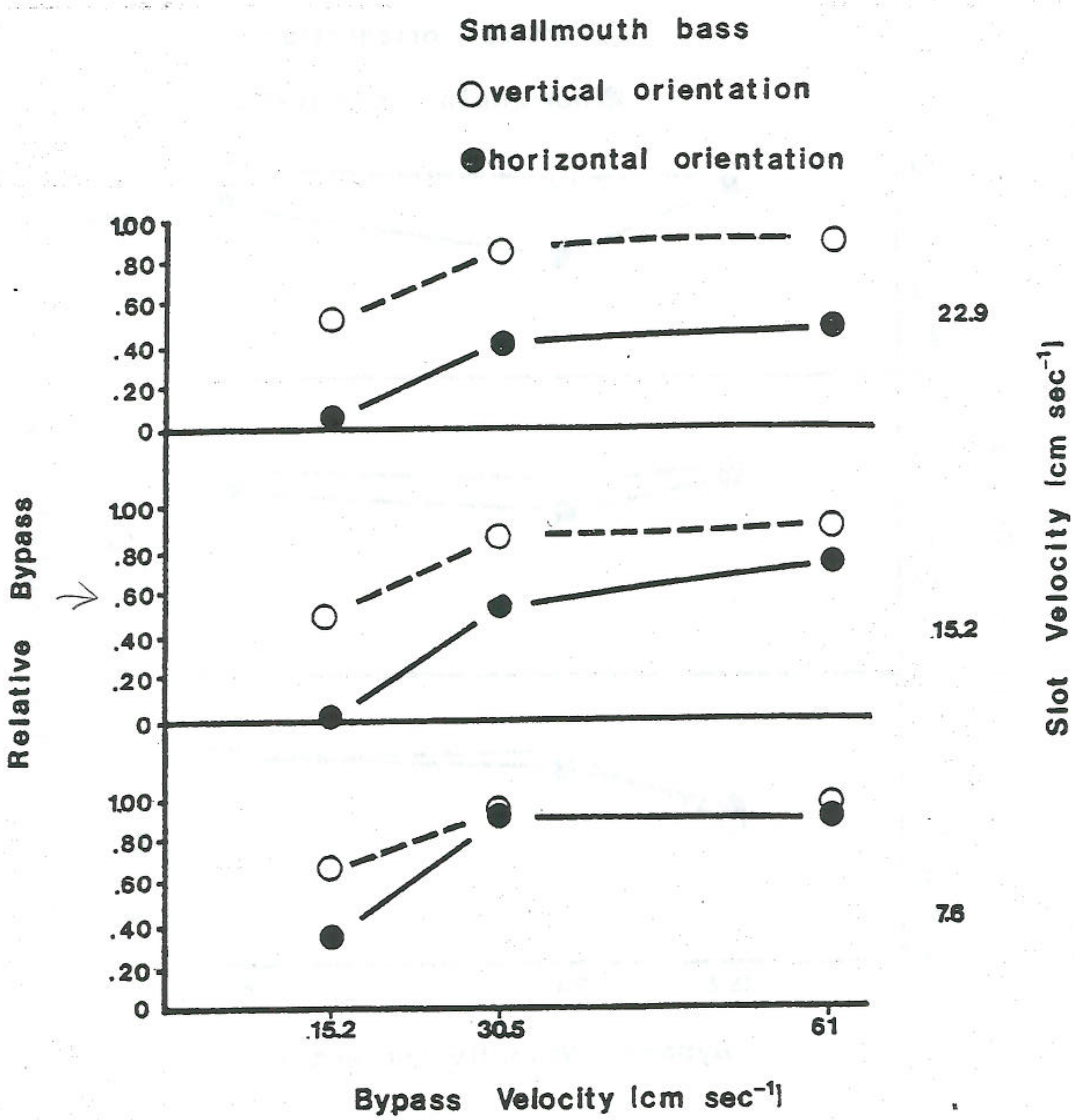

Figure 18. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for smallmouth bass. Slot width of screen = 2.0 mm.

the flume, this species usually remained near the bottom, which may explain the higher entrainment with the horizontal screen (paired t-test showed a significant difference: $t = 3.67$, $df = 17$).

CHANNEL CATFISH

Channel catfish larvae are relatively large. The four- and five-day-old individuals that were tested on June 9 and 10 were from the same hatch and showed only a narrow range in size. The average length, width, and depth of fish from selected samples were 13.4, 2.7, and 2.8 mm, respectively. Because of their relatively large size and strong swimming ability, testing was limited to the screens of 1.0 and 2.0 mm slot widths and three highest bypass velocities.

Water temperature in the test flume was 25.0 C on the first day of testing compared with 19 C in the holding tank. On the second day the fish were adjusted from 19.5 C in the holding tank to 24.0 C in the test flume.

1.0 mm Slot

No entrainment occurred through the 1.0 mm slot under any of the bypass-slot velocity combinations (Table 7 and Figure 19), suggesting that the fish were too large to pass through. Impingement totaled only five fish and occurred under only one test condition (15.2 cm sec^{-1} bypass and 22.9 cm sec^{-1} slot velocity).

Table 7. Results of "fish avoidance" screen investigations: comparison of observed proportion of channel catfish bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations, slot sizes, and horizontal (H) and vertical (V) screen orientations.

Slot Velocity ($cm\ sec^{-1}$)	Slot Size (mm)	Bypass Velocities ($cm\ sec^{-1}$) 15.2 H	15.2 (expected)	15.2 V	30.5 H	30.5 (expected)	30.5 V	61.0 H	61.0 (expected)	61.0 V
7.6	1.0	1.000*	(0.720)	1.000*	1.000*	(0.840)	1.000*	1.000*	(0.910)	1.000*
	2.0	0.894*		0.801*	0.995*		0.980*	0.987*		0.980*
15.2	1.0	1.000*	(0.600)	1.000*	1.000*	(0.730)	1.000*	1.000*	(0.840)	1.000*
	2.0	0.530*		0.381*	0.831*		0.810*	0.963*		0.944*
22.9	1.0	1.000*	(0.470)	0.971*	1.000*	(0.640)	1.000*	1.000*	(0.780)	1.000*
	2.0	0.234*		0.135*	0.605		0.430*	0.716*		0.847*

*Replicated goodness-of-fit analysis indicated that the observed values were different ($\alpha = 0.05$) from the expected values.

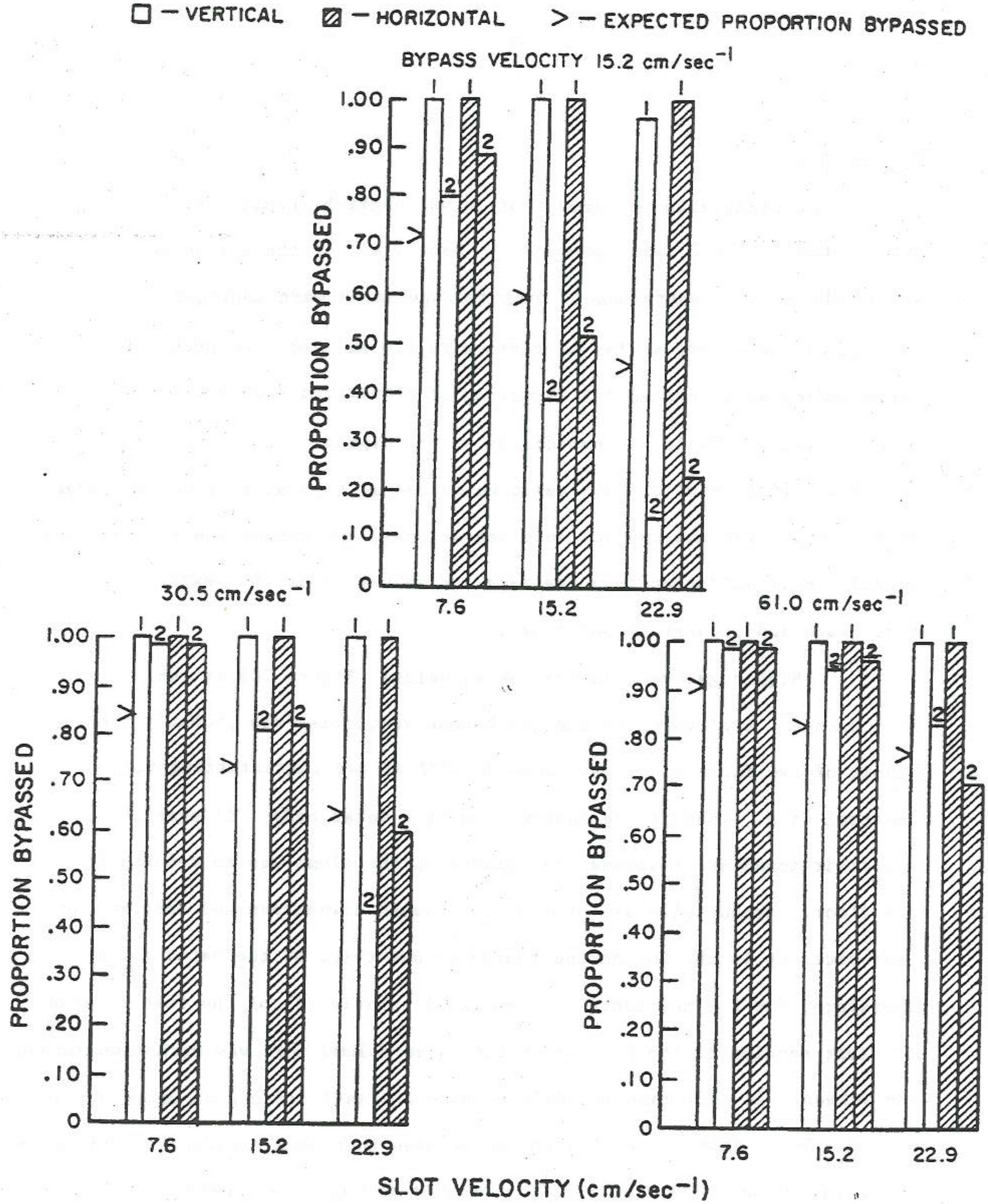

Figure 19. Results of larval fish screening studies ("fish avoidance" concept): proportion of channel catfish bypassed by slot width (denoted in mm above each bar) and screen orientation for each slot and bypass velocity.

2.0 mm Slot

Considerable entrapment of larval catfish resulted with this screen (Table 7 and Figure 19). Nearly all of the entrapment was in the form of entrainment; only two specimens were impinged throughout the entire series of tests with 2.0 mm slot. Goodness-of-fit tests indicated a substantial deviation of proportion bypassed from expected values (Table 7), especially at the highest (22.9 cm sec^{-1}) slot velocity. In five of the six tests conducted at this slot velocity (three bypass velocities and two screen orientations), the proportion bypassed was significantly different from the expected values (less than expected in four cases and greater in one case).

High negative relative bypass values (Figure 20) at the 22.9 cm sec^{-1} slot velocity and low bypass velocities are probably the result of two factors. First, channel catfish are characteristically demersal (i.e., inhabit the bottom area of a water body; Pflieger 1975), and their immediate response when placed in the flume was to descend to the floor. Essentially all of the fish passed downstream and entered the test sections in the bottom one-fourth to one-third of the water column. Therefore, for the horizontal screen tests, nearly all of the fish entered the test section in the portion of the water column that was withdrawn through the screen. In this case it would be more realistic to use an expected bypass of 0.0. Using this correction it can be seen that some avoidance occurred even under the highest (22.9 cm sec^{-1}) slot velocity and low bypass velocities. A second reason for negative relative bypass may be attributed to the strong swimming ability of these larvae. Because they were able to swim in the test section for several minutes, coupled with their apparent

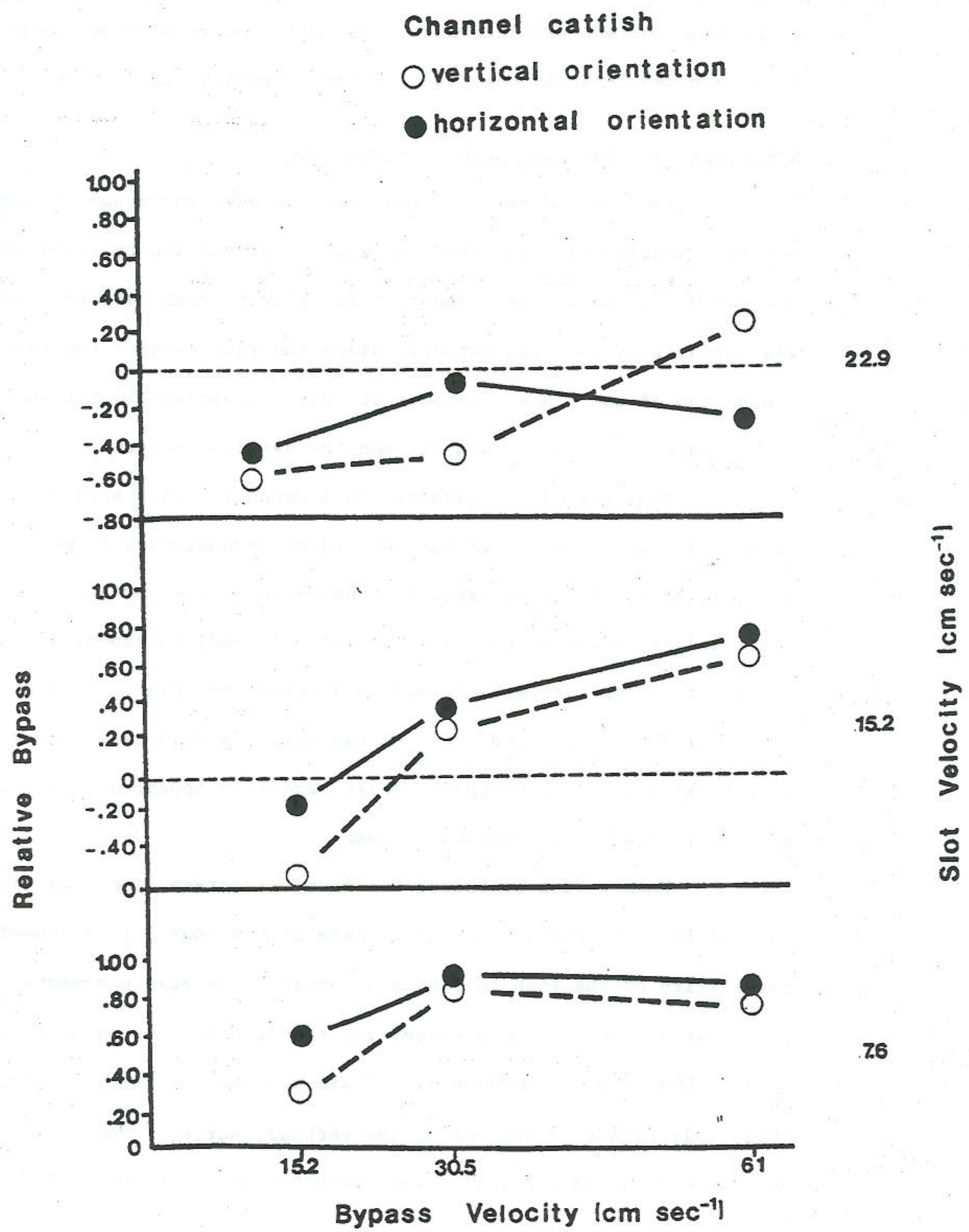

Figure 20. Results of larval fish screening investigations ("fish avoidance" concept): relationship of relative bypass to bypass and slot velocity for channel catfish. Slot width of screen - 2.0 mm.

preference for the bottom, their susceptibility and exposure time to the entraining current was increased. For all slot velocities, relative avoidance was least at the lowest bypass velocity (15.2 cm sec^{-1}).

Horizontal vs. Vertical Screen Orientation

For the 1.0 mm slot, too few fish were entrapped to compare screen orientations. For the 2.0 mm slot, proportion bypassed was greater with the horizontal screen in seven of nine velocity combinations (Table 7). This was opposite of what was expected since the fish entered the test section near the bottom of the flume. Because of this, the potential for entrapment was much greater for the horizontal than the vertical screen.

Two reasons are advanced to account for this apparent discrepancy: First, the fish appeared to be confused on encountering flume conditions and swam back and forth, exposing themselves to the vertical screen several times before bypassing the test section. Second, on exposure to the horizontal screen, the fish were able to maintain normal position and to generate the thrust needed to move and avoid entrapment. In this case, the water flow was pulling straight down on their bodies, and they appeared less affected than by a horizontal flow (vertical screen).

When a fish contacted the vertical screen, the flow vector was perpendicular to the dorso-ventral axis of the body. This seemed to impair the ability of the fish to generate thrust by lateral movements of the tail. It appeared that much more effort was required to burst away from the vertical screen than from the horizontal. These combined factors resulted in the relatively higher entrapment on the vertical screen. Nearly all of the entrainment on the vertical screen occurred near the bottom edge of the screen.

BLUEGILL

On July 14, 1977, a partial series of tests was conducted with early juvenile bluegill. The average total length of fish from several selected test groups was 21.5 mm. The test fish were active swimmers and appeared to be in good condition. Test temperature of the flume water was relatively high (27.2 C) but the fish did not appear to be stressed. Because of the fish's relatively large size and strong swimming ability, tests were conducted only with the largest slot, three highest bypass velocities, and two highest slot velocities.

2.0 mm Slot

Bluegill showed very little entrainment even through the 2.0 mm slot-width screens. Proportion bypassed values for all test conditions were significantly different (greater) from the expected values (Table 8). Relative bypass values were all uniformly high and showed little relationship to bypass or slot velocity or to screen orientation. The paired t-test analysis indicated no significant difference between the proportion bypassed values obtained with the two screen orientations.

SUMMARY

The ability of seven species of fish in the larval to early juvenile stages to avoid entrainment through stationary slotted screens was tested. The mean total lengths of these fishes ranged from 5.6 mm to

Table 8. Results of "fish avoidance" screen investigations: comparison of observed proportion of bluegill bypassed vs. expected proportion bypassed (denoted in parentheses) for various bypass-slot velocity combinations, and horizontal (H) and vertical (V) screen orientations.

Slot Velocity (cm sec^{-1})	Slot Size (mm)	Bypass Velocity (cm sec^{-1}) 15.2 H	15.2 (expected)	15.2 V	30.5 H	30.5 (expected)	30.5 V	61.0 H	61.0 (expected)	61.0 V
15.2	2.0 mm	0.957*	(0.600)	0.988*	1.000*	(0.730)	0.991*			
22.9	2.0 mm	0.989*	(0.470)	0.996*	0.992*	(0.640)	0.993*	1.000*	(0.780)	1.000*

*Replicated goodness-of-fit analysis indicated that the observed values were significantly different ($\alpha = 0.05$) from the expected values.

21.5 mm. These species exhibited a wide range in behavior, which affected their overall performance in the test flume. Within-replicate variability was usually high for most species and was probably due to behavioral characteristics which resulted in nonhomogeneous distributions of the fish in the water column.

The results of the 296 separate test conditions (excluding the first experiment with muskellunge) showed that for all three slot widths, the fishes tested could avoid entrapment to some extent.

0.5 mm Slot

In tests with the 0.5 mm slot, 66 replicated tests of the three smallest species (striped bass, walleye, and largemouth bass) resulted in avoidance. Walleye and largemouth bass showed nearly 100 percent bypass under all test conditions, whereas the smaller striped bass showed an inverse relationship of avoidance to slot velocity. Relative bypass was near 1.00 at the 7.6 cm sec^{-1} slot velocity, decreased to 0.45-1.00 at 15.2 cm sec^{-1}, and decreased still further at 22.9 cm sec^{-1} slot velocity.

Bypass velocity alone did not appear to affect the ability of the larvae to avoid the entraining currents. Differences in avoidance success between screen orientations were apparent only for striped bass at the highest slot velocities (greater avoidance shown with the horizontal screen). However, these differences may represent an artifact caused by flow reversal in the test section at low bypass velocities.

1.0 mm Slot

Five species were tested with this screen. Of 102 replicated test conditions using the 1.0 mm slot screen, 88 resulted in avoidance.

As expected, the larger species responded better than the smaller species. Smallmouth bass and channel catfish showed avoidance in all cases. Walleye, which were of a size that would make them susceptible to entrainment, showed avoidance under 23 of 24 replicated test conditions. Striped bass showed avoidance under 29 of 42 conditions. Overall, 9 of the 102 test conditions showed no significant difference between observed and expected bypass, and under five conditions significant differences between observed and expected were obtained in which observed was less than expected. Three of these five cases occurred at slot velocity 22.9 cm sec^{-1} and two occurred at slot velocity 15.2 cm sec^{-1}.

Comparison of the results for two species which were tested on both the 0.5 mm and 1.0 mm screens showed decreased avoidance on the latter screen for nearly all test conditions for striped bass, but for walleye, relative bypass remained near 1.00 under all conditions except the lowest bypass velocity.

A general relationship between slot velocity and relative bypass for the 1.00 mm slot was not shown. Walleye showed high avoidance at all slot velocities except at the lowest bypass velocity. In that case the lowest slot velocity resulted in high avoidance while the highest slot velocity yielded lowest avoidance. On the other hand, smallmouth bass showed lowest avoidance at the lowest bypass velocity. Striped bass showed no relationship of avoidance between the two variables. While there may have been a slight inverse relationship between avoidance response and slot velocity, this relationship was probably masked by (1) inconsistent results between species, (2) bias caused by flow reversal at the lowest bypass velocity, and (3) occasionally high variation among replicate observations (especially true for striped bass). While there occasionally seemed to be large differences in avoidance between screen orientations, this response varied considerably among species and even among replicate experiments with the same species (striped bass). Thus, overall, tests with the 1.0 mm slot showed no clear distinction in avoidance response between screen orientations.

2.0 mm Slot

All seven species were tested with the 2.0 mm slot screen. Bluegill were the largest fish tested and were not entrained through this screen. Furthermore, impingement was negligible for this species. The remaining six species were small enough in size to be potentially entrainable through the 2.0 mm screen.

Of the 128 replicated test conditions, avoidance was shown in 106 cases. In 16 cases no significant difference was found between observed and expected proportion bypassed and in six cases observed was less than expected. Of the smaller species tested, walleye larvae responded best. In 23 of 24 cases this species showed avoidance.

Species specific behavior greatly influenced avoidance responses with the 2.0 mm screen. In contrast with observations made concerning the two smaller slot widths, the smallest species did not show the lowest avoidance. Rather, channel catfish (the third largest species tested) showed the lowest avoidance of the six species. This phenonmenon was directly the result of the behavior of channel catfish (a "demersal" fish) in the flume. Nearly all of the species which were tested on a smaller slot screen showed greater entrapment with the 2.0 mm screen. The exception was striped bass, which showed greater avoidance with the 2.0 mm screen than the 1.0 mm screen. This unexpected phenomenon again emphasizes the influence of species specific behavior patterns.

Of the six "entrainable" species, the avoidance responses of four species were greater with the vertically oriented screen than with the horizontal screen. Conversely, channel catfish showed greater avoidance with the horizontal screen while striped bass did not show a consistent difference of avoidance between screen orientations.

Avoidance was greatest at the lowest slot velocity for five of the six entrainable species (muskellunge were tested only at a single slot velocity). For three of these species, the largest increase in entrapment seemed to occur from 7.6 to 15.2 cm sec^{-1} slot velocity.

CONCLUSIONS

The initial hypothesis that larval fish are incapable of detecting and responding to entraining flows was rejected. All of the larval fish species tested, except very young muskellunge, showed some ability to avoid entraining currents under most experimental conditions. Many species showed considerable avoidance, often resulting in nearly all of the fish in a given test avoiding entrapment.

Based on the results of this study, it is expected that river velocities within the range of bypass velocities tested would not appreciably affect the safe passage of transported larvae and adults. Although the effects of slot velocity and slot width were not clearly apparent, it was shown that at least one of the smallest species tested (walleye) could appreciably avoid entrapment with the largest (2.0 mm) slot. However, for the smallest species it was found that optimum protection was provided by the 0.5 mm slot screen.

Based on the results of the larger larvae and early juvenile fish tested, it is reiterated here that a fish avoidance screen as conceptually proposed would be capable of protecting essentially all fish in the early juvenile through adult life stages. In other words, an inriver well screen system could be designed to eliminate impingement of the sizes and species of fish normally collected on conventional vertical traveling screens.

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