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Effects of Pressure Reductions in a Proposed Siphon Water Lift System at St. Stephen Dam, South Carolina, on Mortality Rates of Juvenile American Shad and Blueback Herring

by *John M. Nestler, WES*
Carl R. Schilt, David P. Jones, AScI Corporation

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Prepared for U.S. Army Engineer District, Charleston

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by John M. Nestler

U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Carl R. Schilt

ASci Corporation
Fisheries Engineering Team, Columbia River Basin
40 Cascade Street, P.O. Box 1219
Stevenson, WA 98648

David P. Jones

ASci Corporation
Trotters Shoals Limnological Research Facility
P.O. Box 533
Calhoun Falls, SC 29628

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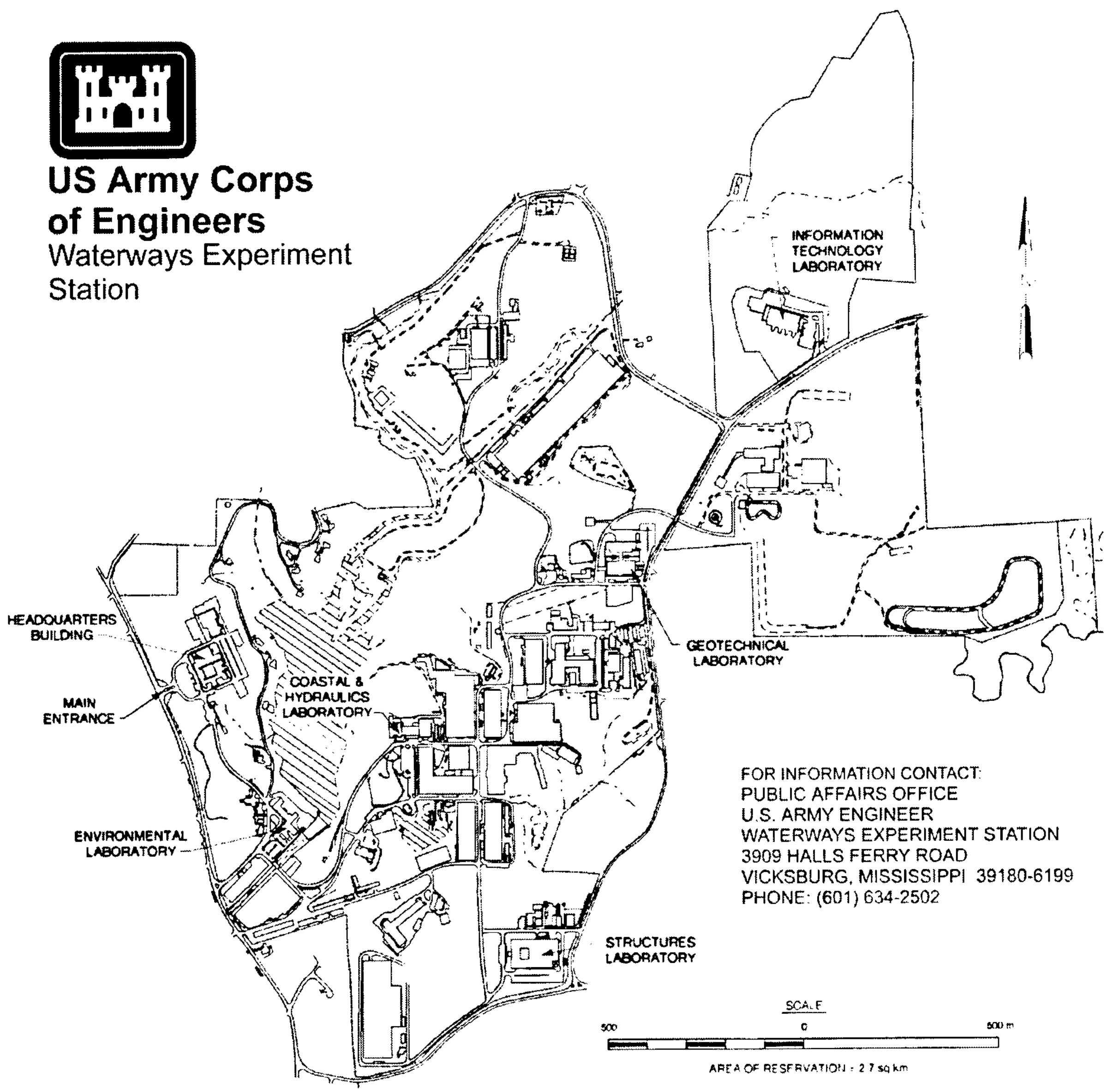

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Preface

The Environmental Laboratory (EL) of the U.S. Army Engineer Waterways Experiment Station (WES), Vicksburg, MS, and AScI Corporation, WES field site, Stevenson, WA, prepared this report for the U.S. Army Engineer District, Charleston. The authors are Dr. John M. Nestler, Water Quality and Contaminant Modeling Branch (WQCMB), Environmental Processes and Effects Division (EPED), EL, and Messrs. Carl R. Schilt and David P. Jones of AScI Corporation, McLean, VA.

The authors would like to express their appreciation for help provided by Messrs. Stuart Coale, Doug Cooke, Charles Murphy, and Kevin Murphy, South Carolina Department of Natural Resources, in planning and carrying out these experiments. Ms. Sara Brown, Charleston District, aided in the preparation and data collection. The St. Stephen Dam powerhouse manager, Mr. John Crawford, was most cooperative and helpful. Mr. Elmer Thomas, St. Stephen Dam chief mechanic, was especially knowledgeable and generous with ideas and materials.

The report was prepared under the direct supervision of Dr. Mark S. Dortch, Chief, WQCMB, and under the general supervision of Dr. Richard E. Price, Chief, EPED, and Dr. John Harrison, Director, EL. Technical reviews by Mr. Tom Cole and Ms. Toni Schneider, WES, and Mr. Gary Weeks, AScI Corporation, are appreciated.

At the time of publication of this report, Director of WES was Dr. Robert W. Whalin. Commander was COL Robin R. Cababa, EN.

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Conversion Factors, Non-SI to SI Units of Measurement

Non-SI units of measurement used in this report can be converted to SI units as follows:

Multiply	By	To Obtain
cubic feet per second	0.02831685	cubic meters per second
feet	0.3048	meters
gallons (U.S. liquid)	3.785412	liters
inches	2.54	centimeters
pounds (force) per square inch	6.894757	kilopascals

1 Introduction

Background

St. Stephen Dam on the Santee River in South Carolina presently provides for upstream migration passage of adult American shad and blueback herring with a fish lift that is used to move upstream migrating fish from the afterbay to the forebay. Upstream migrating fish, which are thought to navigate by orienting into flow, appear to have difficulty finding the lift while the powerhouse is operating. Apparently, attracting flows released at the base of the lift are insufficient to provide an adequate attracting stimulus within the greater flow field produced by generation. The Charleston District is considering a plan to increase attracting flows to the St. Stephen Dam fish lift using a siphon-lift system that will convey an approximate additional 500 cubic feet per second (cfs) of water from the forebay to the lift entrance. The siphon will lift water from a minimum elevation in the forebay of EL (elevation) 70 above mean sea level (msl) to a high point of EL 79.5 msl to clear the dam. The siphon then drops to close to the tailwater elevation of EL 42 msl. Representatives from the South Carolina Department of Natural Resources (SCDNR) have suggested that the siphon system be considered as a route downstream for adult and juvenile American shad and blueback herring during the fall seaward migration. SCDNR staff maintains that fish passage through the siphon system could be less injurious to the fish than is the current passage route through the powerhouse or spillway.

The siphon system may take the form of two or more similar pipes. (One possibility is three separate, parallel 48-in.-diam pipes). Pipe diameters, rates of flow, pipe materials and construction, and the nature and siting of the outfall may all be critical for fish survivorship. This study deals only with the possible effects of rapid pressure changes.

Problem

Fish passing through the siphon system may experience a substantial pressure drop that depends both upon the water surface elevations in the forebay and afterbay and upon the high point of the siphon. Although a variety of modifications to the original siphon design has been proposed, each will cause passing fish to experience a pressure low calculated to approach 0.0 pounds per square inch (psi) as they pass through the siphon system. The total maximum change in pressure that a fish passing through the system could experience is calculated as a pressure drop of 26.7 psi at a maximum St. Stephen Dam forebay pool elevation of EL 76 msl. This estimate is based on the following considerations. St. Stephen Dam is less than 100 ft above sea level. Since air pressure changes little with altitude, it is reasonable to use the standard sea level air pressure (14.7 psi) for these calculations. Submergence in water adds about 0.445 psi per foot (or one atmosphere = 14.7 psi per 33 ft) of depth. The planned lowest point in the siphon, near the entrance, is EL 51 msl or 25 ft underwater at maximum pool level of EL 76 msl. Fish at a water depth of 25 ft would experience pressure of about 14.7 psi atmospheric pressure plus about 11.125 psi (0.445 psi/ft × 25 ft) water pressure or about 25.82 psi (taken as 25.8 psi).

If the siphon produced a low pressure near zero psi (the lowest possible pressure), then the pressure drop experienced by a fish in the system would approximate a reduction from 25.8 psi to zero psi, a pressure drop of 25.8 psi. It was this pressure drop that formed the basis of the experiments described here.

The potential damage of pressure changes to fish having gas bladders (a gas-filled internal chamber with which a fish can regulate its buoyancy) may be mitigated by the presence of a direct connection, the pneumatic duct, between the bladder and the gut of the fish. Fish with a pneumatic duct connecting the gas bladder with the gut (collectively called the "physostomous" fishes) may be less likely than are others (those without such ducts are collectively called "physoclistous" fishes) to suffer injury from decompression because the excess pressure within the gas bladder may vent through the duct. Blueback herring and American shad have this duct and an additional anal duct that may also provide a vent via the gut. Relatively little work has been done on the effects of pressure changes on fish survivorship. Limited testing (Hogan 1941), in which atmospheric pressure (14.7 psi) acclimated fish including adult herring were subjected to rapidly reduced pressures (a pressure change of 12.23 psi, from 14.7 psi to about 2.5 psi over a period of 15 sec), resulted in a slight increase in mortality rate (4 percent). The total maximum pressure change that fish passing through the siphon system at St. Stephen Dam are expected to experience (a reduction of 25.9 psi) considerably exceeds the only tested condition for effects of rapid pressure reduction on herring that could be found in the literature. The rate of pressure change (Harvey 1963) and life stage of fish (Tsvetkov, Reichle, and

Shriner 1972) are also important considerations. In general, the pneumatic duct and anal duct are not adapted for rapid release of gas, and their capacity for venting can be exceeded under rapid decompression.

The District instructed the U.S. Army Engineer Waterways Experiment Station (WES) to perform experiments to evaluate the potential negative effects of the siphon pressure environment on juvenile blueback herring and American shad.

2 Methods

Fish Capture and Holding

Fish used for pressure testing were captured onsite. For each of the two series of tests discussed here, SCDNR personnel operated the fish lift so as to trap downstream migrating juvenile American shad and blueback herring in the fish lift, where they remained, otherwise unrestrained, overnight in water about 10 ft deep. The next morning (the day of the test), the water level in the fish lift was dropped to about 3 ft, and a large number (at least a thousand) of small herring (both American shad and blueback herring) were slowly crowded into a corner of the fish lift. A net pen (4-ft cube) hung from a polyvinyl chloride (PVC) pipe float was slowly slid under the fish and brought up around about 300 of them so that they were confined in the pen without being chased or touched by a dip net. Extreme care in the capture of experimental fish was important because herring are very fragile and can easily be injured by handling. After two pens with experimental populations of fish were established, larger fish that might compromise the experiments were removed. The water depth was then raised to about 5 ft deep so that a worker in a wetsuit could stand and walk in the fish pen to handle pens and fish. The water was maintained at about that depth for the remainder of the tests. Survivorship pens were maintained and monitored in the fish lift, which was operated so that a constant supply of new water was flowing through without substantially changing the water depth. For each treatment, the worker in the fish lift carefully counted 20 fish, as described below, into a 5-gal plastic bucket, which was then lifted by electric hoist to the deck level for the application of treatments. The exception to that protocol was "Treatment E" (see below), in which the fish never left the fish lift level.

After each treatment (except for Treatment E), the bucket and its contents of 20 fish were carried back to the hoist, lowered back down into the fish lift, and then gently emptied (by submerging the bucket and then slowly inverting it) into the appropriate 4- by 4- by 4-ft net pen (knotless 3/16 in.-web). Each pen was suspended from a 4-ft-square float made of 2-in.-diam PVC pipe. Each pen had a flap top that was loosely attached for the first set of experiments. For the second set, Velcro tape was used to seal shut the three open sides of the flap lid. For the first set of experiments, the pens' bottoms were held down by 4-ft squares of reinforcing rod in the bottoms of the pens. The rod abraded and sometimes poked holes in the pens, probably contributing to the incursion of untreated fish. For the second series of experiments, the rod was replaced by standard lead line. Each test group of fish, once it was placed into its unique survivorship pen, became an experimental unit.

Two series of experiments were conducted, the first beginning on November 13, 1997, and the second beginning December 3, 1997. The second series of experiments were conducted after the conclusion of the first series of experiments because entry of fish into the incompletely covered net pens biased results in the first set of experiments. In the first set of experiments, more fish were consistently recovered from the net pens at the conclusion of the tests than were initially introduced into the net pens (almost twice the number initially introduced in some cases). The same treatments that were used in the first series of tests were repeated a second time about 2 weeks later after attaching tops to the net pens. The tops were held closed with Velcro brand hook and loop closures, which were bonded to the PVC floats and the net tops. In the second series of tests, a total of 380 blueback herring and 34 American shad were evaluated. Total length and fork length were determined for fish used in the second series of tests.

Pressure Testing Apparatus

The relative pressures to be expected within the siphon system were produced using a pressure-reduction testing system (PRTS). The vertically hanging apparatus is comprised of an uppermost aluminum pressure chamber made from a standard 18-in.-diam food-canning pressure cooker with an 8-in. hole cut in the bottom and an 8-in. pipe flange welded on the bottom around the hole. The flange inserts into an 8-in.-diam suction hose about 56 ft long, which is fitted with a pneumatically closed pinch valve at the bottom end (Figure 1). The pinch valve could be remotely operated by compressed air, and the rate at which it opened or shut could be controlled to allow it to roughly approximate the pressure history likely to be experienced by a fish passing downstream in the proposed siphon pipe. The aluminum pressure cooker had a removable top secured by hex head nuts. A fitting on the pressure chamber allowed an air hose to be attached so that pressure within the chamber could be raised above ambient. Another fitting connected via an air hose to a pressure gauge. Pressure seal between the pressure cooker and its lid was achieved with a rubber gasket between the vessel and its lid, held in place by Poli-grip brand dental adhesive. The entire assembly could be raised or lowered by a crane.

Decrease in pressure within the pressure chamber is determined by its height above the water surface (and hence the vertical drop between the chamber and the water surface) at the time when the pinch valve is opened. Preliminary experiments without fish were done to determine the

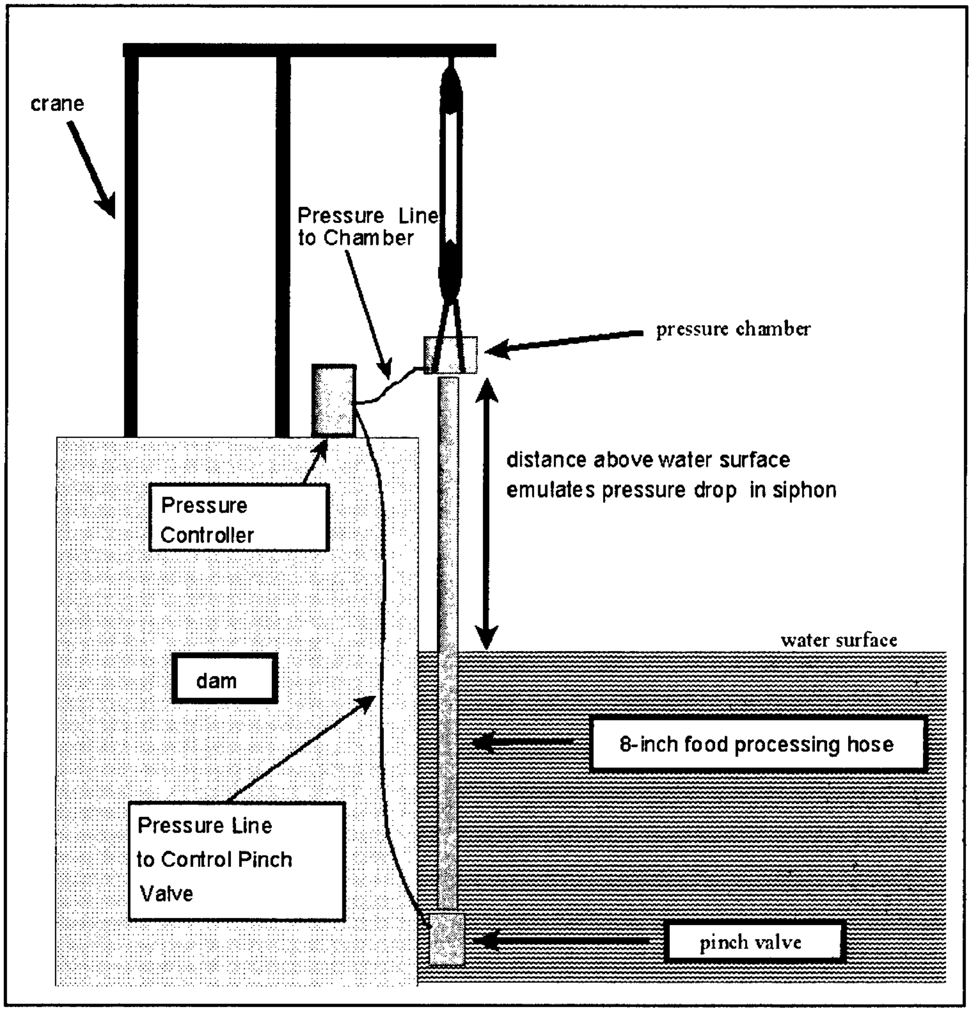

Figure 1. Schematic diagram of pressure-reduction testing system (PRTS)

appropriate altitude to raise the PRTS in order to produce the predetermined pressure reductions.

Experimental Protocols

Prior to each treatment involving the PRTS (one control treatment did not) the entire apparatus, pinch valve open, was lowered by crane until the top rim of the pressure chamber was just above the water. The pinch valve was then closed and sealed by pressurizing the valve chamber, which trapped water inside the PRST. The PRTS was then raised to deck level to receive fish.

The following sequence of treatments and controls was employed:

Treatment A = Fish were removed from one of two storage net pens as described above and placed into a covered bucket. The bucket was lifted by electric hoist to deck level, carried by hand to the PRTS, and placed into the chamber. The PRTS was topped off with ambient water, and then its cover was secured with hex head nuts. Pressure within the PRTS was raised to 12 psi above ambient (14.7 psi is ambient—the extra 12 psi represents the pressure at the lowest point in the siphon at highest pool, 25 ft underwater) to about 26.7 psi. The PRTS was raised to provide a pressure of approximately 9.5 psi, producing a total pressure drop of about 17.2 psi (26.7 psi minus 9.5 psi) when the pinch valve was opened. The fish were held at a 26.7 psi for 30 sec, and then the pinch valve was opened to allow the enclosed water column to drop and thereby reduce the chamber pressure to 9.5 psi. At the conclusion of the test, the pinch valve was closed, the chamber was vented, and the PRTS returned to deck level so that the top could be removed and the bucket with the test fish could be lifted out.

Treatment B = This treatment was the same as Treatment A, but the lowest pressure was reduced to about 5.4 psi. The high pressure was the same as in Treatment A.

Treatment C = This treatment was same as Treatment A, but the lowest pressure was reduced to about 3 psi. The goal was 0.0 psi, but that goal was not achieved. The high pressure was the same as in Treatment A.

Treatment D = This treatment is the same as Treatment A except that no change in pressure was administered. The bucket was placed in the PRTS as above, and the PRTS was raised to the height specified for Treatment C (the most extreme pressure treatment and therefore the highest altitude for the pressure vessel). The lid was bolted on as in the other treatments; time was allowed for both the high- and low-pressure steps, but no pressure changes were applied. This treatment controlled for possible stresses inherent in hoisting and carrying the bucket as well as the stress of the apparatus itself.

Treatment E = Fish were netted and counted into the bucket from the fish storage net pen and poured directly to the holding pen without being hoisted to the deck or placed in the PRTS. This treatment controlled for holding, transfer, and capture stress.

Fish for each treatment were caught in small groups (usually no more than four at a time) by slowly crowding them into a corner of a storage net pen and dipping them out with a soft, knotless dip net. Fish were counted from the dip net directly into the water-filled treatment bucket. They were only in the dip net for a few seconds and were not touched by hand. After 20 fish were counted into the bucket, it was covered with a piece of soft knotless webbing held on by an elastic band to prevent fish from jumping out of the bucket. The bucket was then hoisted up to the deck level, except for Treatment E in which fish were transferred immediately to holding pens.

For the other treatments (A-D), the bucket was hoisted to deck level and carried to the pressure chamber (about 50 ft away), and the entire bucket, fish included, was placed into the aluminum pressure chamber. The chamber was sealed and raised to an experimentally predetermined height that would provide the appropriate pressure reduction when the submerged pinch valve was opened. After the chamber was raised to this height, it was charged with compressed air (except in Treatment D) to a predetermined setting that would simulate the positive pressure associated with the depth of the lowest point of the siphon system. By opening a valve in the line from the pressure cooker chamber to the dam's compressed air system, the pressure was raised in the chamber until the gauge read 12 psi above ambient, which is 26.7 total psi, just above the target high pressure of 25.8 psi (see above). This was to model the deepest part of the siphon system at EL 51 msl. The fish were allowed to acclimate for 30 sec, and then the pinch valve was opened slowly to gradually produce the predetermined pressure reduction, generally over about a 20-sec time period. This is approximately the same travel time that fish would take to pass through the proposed siphon lift system.

At the conclusion of the pressure test, the pinch valve was closed; the chamber was vented to return its internal pressure to ambient pressure (14.7 psi); and the chamber was returned to the deck level. The top of the pressure chamber was then removed, and the bucket was immediately carried to the hoist and lowered back down into the fish lift where the fish survivorship pens were held. A worker wading in the fish lift in water about 4 ft deep carried each experimental unit to its net pen, and the fish were gently poured into the pen. Approximately 4 to 6 min passed between introduction of fish into the PRTS and their release back into net pens. Except for transfer and counting into the bucket, fish were never netted during any part of the experiment. Each treatment-replicate (experimental unit) received its own holding net pen. Water level in the fish lift was maintained at about 4 ft deep throughout the experiments.

The strategy was to sample the range of anticipated pressure environments that fish passing through the siphon might experience (Tables 1 and 2) and to achieve as low a pressure (as near 0.0 psi) as possible. The high pressure was the same in all pressure treatments (A, B, and C), corresponding to the 25-ft depth of the lowest point in the siphon at the highest pool level. The low pressure varied across three levels (Treatments A, B, and C) with the most extreme "C" treatment being an attempt to achieve a true (0.0 psi) vacuum. Unfortunately, pressures could not be produced lower than about 3 psi, so that no treatment subjected fish to the lowest possible pressure that could be produced in the proposed system. Each experimental unit consisted of a total of 20 blueback herring and American shad. Since differentiating these species accurately involves close examination of mouth structures, fish were captured indiscriminately for each experimental unit; species was determined after fish death. For the first series

Table 1
Summary of Pressure Treatments for Blueback Herring and American Shad for First Series of Experiments (Absolute pressure difference (last column) is the difference between the highest absolute pressure (third from last column) and lowest absolute pressure (second to last column). See text)

Treatment	Replicate	Highest Gauge Pressure, psig	Lowest Gauge Pressure, in. of Hg	Negative Pressure Referenced to Ambient, psi	Highest Absolute Pressure, psi	Lowest Absolute Pressure, psi	Absolute Pressure Difference, psi
A	1	12.5	-9.5	-4.66	27.23	10.0636	17.17
	2	12.5	-9	-4.42	27.23	10.3092	16.92
	3	12	-9	-4.42	26.73	10.3092	16.42
	4	12.5	-10	-4.91	27.23	9.818	17.41
	5	12	-9	-4.42	26.73	10.3092	16.42
B	1	13	-16	-7.86	27.73	6.8708	20.86
	2	13.5	-17	-8.35	28.23	6.3796	21.85
	3	11	-18	-8.84	25.73	5.8884	19.84
	4	12.5	-18	-8.84	27.23	5.8884	21.34
	5	14.5	-18	-8.84	29.23	5.8884	23.34
C	1	12.5	-19.5	-9.58	27.23	5.1516	22.08
	2	14.5	-20	-9.82	29.23	4.906	24.32
	3	12	-21	-10.32	26.73	4.4148	22.32
	4	12.5	-21	-10.32	27.23	4.4148	22.82
	5	14	-21.5	-10.56	28.73	4.1692	24.56
D	1	0	0	0	14.73	14.73	0
	2	0	0	0	14.73	14.73	0
	4	0	0	0	14.73	14.73	0
	5	0	0	0	14.73	14.73	0
E	1	0	0	0	14.73	14.73	0
	2	0	0	0	14.73	14.73	0
	3	0	0	0	14.73	14.73	0
	4	0	0	0	14.73	14.73	0

of tests, experimental treatments comprised five replicates, and controls comprised four replicates (Table 1). For the second series of tests, four blocks including all five treatments (A–E) were done (Table 2). Each block was completed before the next was begun, and the treatments were independently randomized within each block. For the second series of experiments, four blocks of five treatments made 20 experimental units (the limit set by space available in the fish lift for the holding pens), but the first block was eliminated due to evident contamination of the test bucket (see below). This has implications for statistical power, which will be discussed later.

Table 2
Summary of Pressure Treatments for Blueback Herring and American Shad for Second Series of Experiments (Variables similar to Table 1. See text)

Treatment	Replicate	Highest Gauge Pressure, psig	Lowest Gauge Pressure, in. of Hg	Negative Pressure Referenced to Ambient, psi	Highest Absolute Pressure, psi	Lowest Absolute Pressure, psi	Absolute Pressure Difference, psi
A	2	12	-11	-5.4	26.73	9.32	17.41
	3	12	-10.5	-5.16	26.73	9.57	17.16
	4	12	-10.5	-5.16	26.73	9.57	17.16
B	2	12	-19	-9.33	26.73	5.4	21.33
	3	12	-19	-9.33	26.73	5.4	21.33
	4	12	-19	-9.33	26.73	5.4	21.33
C	2	12	-21.5	-10.56	26.73	4.17	22.56
	3	12	-24	-11.79	26.73	2.94	23.79
	4	12	-24	-11.79	26.73	2.94	23.79
D	2	0	0	0	14.73	14.73	0
	3	0	0	0	14.73	14.73	0
	4	0	0	0	14.73	14.73	0
E	2	0	0	0	14.73	14.73	0
	3	0	0	0	14.73	14.73	0
	4	0	0	0	14.73	14.73	0

Fish that were dead at the end of the pressure test or that were dead upon entry into the net pen were removed and counted and are listed as -6.0 hr in the figures. Fish that showed any signs of life were counted as living at the -6.0 hr check and were left in the pen. After all treatments were completed and all survivors had been placed into the appropriate holding pen, then all pens were checked in the order that they received fish; dead fish were removed for measurement, species identification, and tabulation under Hour 0.0. At and after the 0.0-hr check, fish that could not right themselves were counted as dead and removed. Thereafter, the net pens were surveyed every 6 hr (plus or minus no more than 30 min) for 96 hr. Each time the pens were surveyed, the water temperature and oxygen level (in milligrams/liter) were measured with a Yellow Springs Instrument Co. Model 51-B oxygen and temperature meter.

Data Treatment and Statistical Analysis

Effects of the proposed siphon lift system's pressure changes on the mortality rate of blueback herring and American shad were estimated by comparing treatment mortality rates to control mortality rates in both the first and second series of experiments. Only preliminary data analyses showing general trends are presented for the first series of experiments because of uncontrolled entry of nontreatment fish into the net pens. Initial analysis of the data from the second series of tests indicated that high mortality was consistently associated with the first replicate of all treatments. The first replicate for each treatment was performed prior to any additional testing so that one randomized order of Treatments A–E was completed (the first block) before the next randomized order of the treatments (the second block) and so on. The bucket used to contain the fish for the treatments may have been unknowingly contaminated between the conclusion of the first series of experiments and the beginning of the second series of experiments. The decision was made to disregard the first replicate of each experiment for the second series of experiments.

Also, at the conclusion of the second series of experiments when the net pens were emptied to count and measure fish, some net pens had up to 24 fish instead of the 20 that were initially introduced. How the additional fish entered the net pens is not known since the net pens were closed around the perimeters with Velcro closures. Total fish counts were adjusted downward to a maximum of 20 when more than 20 fish were obtained in a net pen. Initially, both the unadjusted and adjusted data were used. However, only the adjusted data set was used for most analyses. The following analyses were performed on data collected during the second series of experiments:

a. Data characterization

(1) Lilliefor's test to determine if distribution is normal for each treatment

(2) Levene statistic to determine if variances are equal

b. Analysis of variance (ANOVA)

(1) Parametric ANOVA (used if the data are normally distributed)

(2) Nonparametric ANOVA (used if the data are not normally distributed)

(3) Tukey's Multiple Range test

(4) Regression analysis of mortality as a function of pressure drop

(5) Evaluation of time history of mortality rate

c. Power analysis

3 Results

Mean fork and total fish lengths for the second series of tests are presented for blueback herring and American shad separately (Table 3). For the November tests, the fish lift water temperature ranged from 12.5 to 15.6 ºC, and the oxygen concentration ranged from 8.6 to 9.8 mg/L. For the December tests, water temperature ranged from 10.0 to 14.2 ºC, and oxygen concentration ranged from 8.0 to 9.1 mg/L.

Table 3
Summary of Fish Lengths Used in Last Pressure Tests

	Blueback Herring Fork Length, cm	American Shad Fork Length, cm	Blueback Herring Total Length, cm	American Shad Total Length, cm
Mean	8.44248	10.38182	9.537467	11.90909
1 Standard Deviation	0.438329	0.77478	0.495877	0.878338

For the second series of experiments, the hypothesis that the data were normally distributed could not be rejected (Table 4 – Lilliefor's Test). Tests for homogeneity of variances indicated that variances were equal, and for the unadjusted data, the authors determined that the data did not have equal variances. However, for both tests, the data were considered too sparse to conclusively state either case. Consequently, both parametric and nonparametric ANOVA was performed on the data.

Table 4
Summary of Lillefor's Test to Determine if Distribution Is Normal and Levene's Test to Determine if Variances Are Equal for Second Series of Experiments

Lilliefor's Test				
	Unadjusted data		Adjusted data	
Treatment	Lilliefor	Levene	Lilliefor	Levene
A	0.2684	0.206	0.2042	0.041
B	0.2416		0.3028	
C	0.2269		0.1977	
D	0.3672		0.1919	
E	0.4040		0.2274	

The results from both parametric and nonparametric tests for the second series of tests were similar. For the unadjusted data, both tests showed that mean mortalities were not significantly different at a = 0.05 (Tables 5 and 6). Figure 2 depicts a box and whiskers plot of the first series of experiments, and Figure 3 depicts a similar plot for both unadjusted and adjusted data for the second series of experiments. For the adjusted data from the second series, both tests were either significantly different at a = 0.05 or very close to significantly different, suggesting that there is an effect of pressure on fish mortality (Tables 5 and 6). Tukey's multiple range test for the unadjusted data indicated that no tests were different from any other tests at a = 0.05 (Table 7). However, Tukey's multiple range test on the adjusted data indicated that Treatment C mortality rate was different (higher) than the results from other treatments at the same level of significance. There was no statistical difference at a = 0.05 between any of the means for the first series of experiments.

Table 5
Summary of Nonparametric Analysis of Variance (ANOVA)

Nonparametric (Kruskall - Wallace) Test That Treatment Means Are Equal			
Data Type	Chi-square	DF	Significance
Unadjusted	6.4025	4	0.1710
Adjusted	9.2497	4	0.0509

Table 6 Summary of Parametric Analysis of Variance (ANOVA)						
Parametric Test That Treatment Means Are Equal						
Data Type	**Source**	**DF**	**Sum of Squares**	**Mean Squares**	**F Ratio**	**F Probability**
Nonadjusted	Between Groups	4	0.1078	0.0269	1.1154	0.3857
	Within Groups	15	0.3623	0.0242		
	Total	19	0.4701			
Adjusted	Between Groups	4	0.0933	0.0233	3.6099	0.0453
	Within Groups	10	0.0646	0.0065		
	Total	14	0.1580			

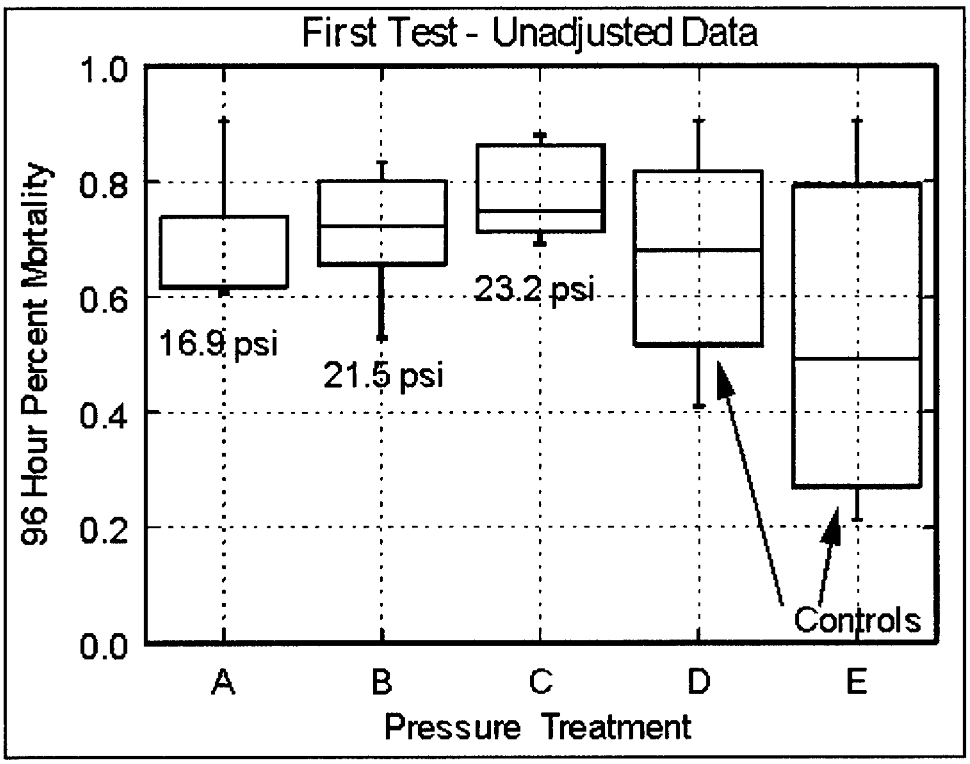

Figure 2. Box and whiskers plot of mortality rates for unadjusted data from first series of experiments (All pressures refer to total pressure change, not absolute pressure)

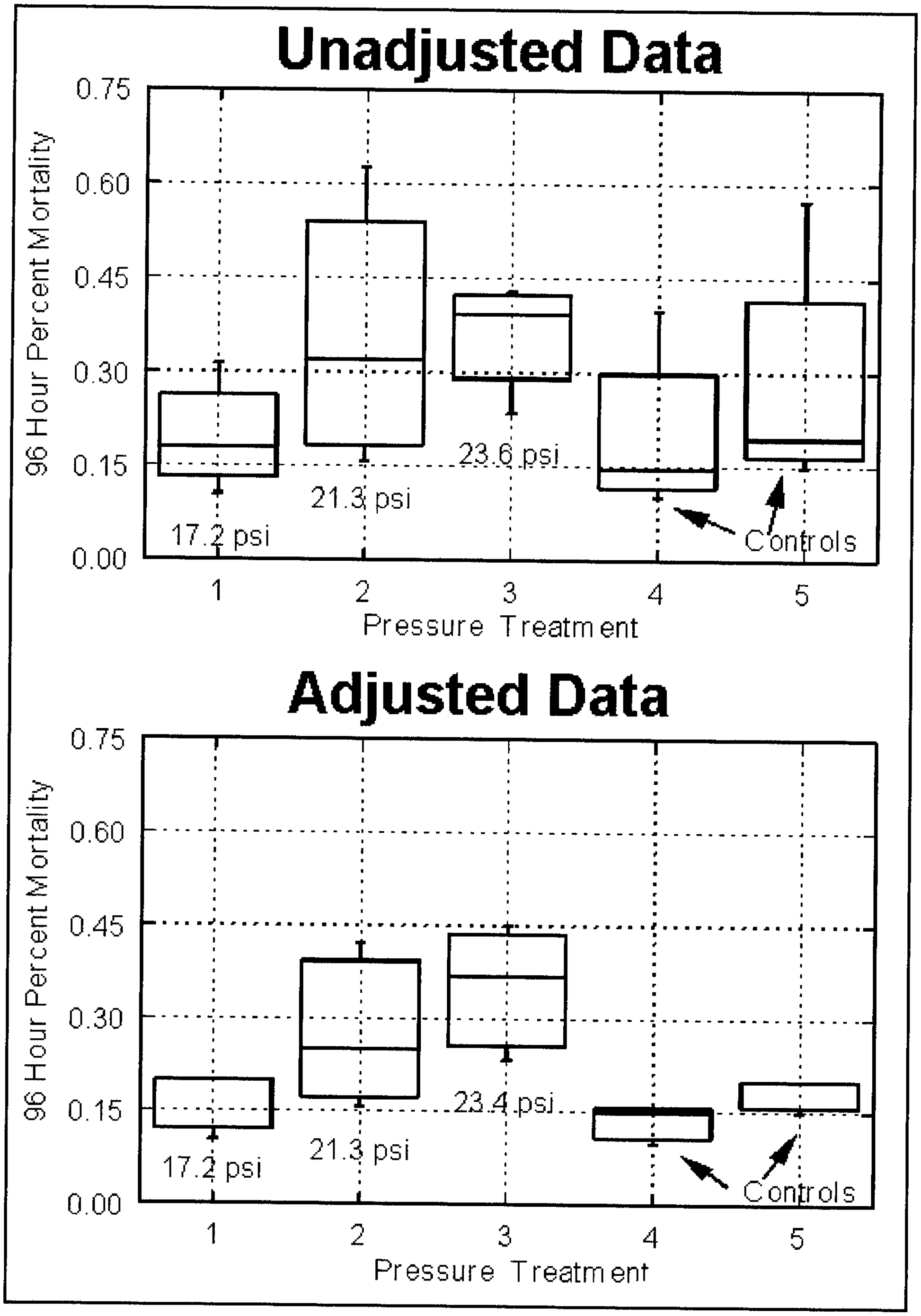

Figure 3. Box and whiskers plot of mortality rates for unadjusted and adjusted data from second series of experiments (All pressures refer to total pressure change, not absolute pressure)

Table 7
Tukey's Multiple Range Test for Unadjusted and Adjusted Data

	Tukey's Multiple Range Test			
	Unadjusted		Adjusted	
Treatment	Mean	Range	Mean	Range
D	0.1986	a	0.1314	a
E	0.1945	a	0.1541	a
A	0.2780	a	0.1802	a
B	0.3591	a	0.2654	a
C	0.3622	a	0.3441	b**

Note: ** = significant difference at a = 0.05

Simple linear regression analysis of pressure versus mortality rate on the adjusted data identified a significant linear relationship between the two variables at a = 0.05 (Figure 4). However, the treatments did not represent a wide range of pressure drops, which functionally reduces the degrees of freedom an unknown amount and would tend to make the results of the analysis less significant. That is, the range of pressure reductions presented extended only from about a 17.2-psi reduction in Treatment A to about a 23.6-psi reduction for Treatment C, and regression on such a narrow set of values is problematic. However, both the first and second series of experiments demonstrate the same basic pattern with mortality rate of the controls and the 17-psi pressure reduction being very similar and a dramatic increase in mortality rate with pressure drops of more than 17 psi (Figures 2, 3, and 4). This pattern suggests that the effects of pressure reduction are small and linear to about a pressure reduction of about 17 psi, and then the effects increase more rapidly to a pressure reduction of about 24 psi.

The time history of mortality rate for the second set of experiments provides the most compelling evidence of a pressure effect. The time history of mortality rate clearly indicated some common traits among all of the treatments as well as some substantial differences (Figures 4 and 5). All treatments show an initial increase in mortality rate during the first 30 hr of the holding period (Figure 5—first highlighted area) with Treatments B and C showing a higher immediate mortality rate. There also appears to be an increase across all treatments over the last 24 hr of the holding period (Figure 5—second highlighted area). During the middle 42 hr, Treatments B and C, the two treatments with the greatest pressure effects, showed a constant mortality rate, whereas Treatment A (the least extreme pressure drop) and the two controls (no pressure drop) showed little or no mortality over this same time period.

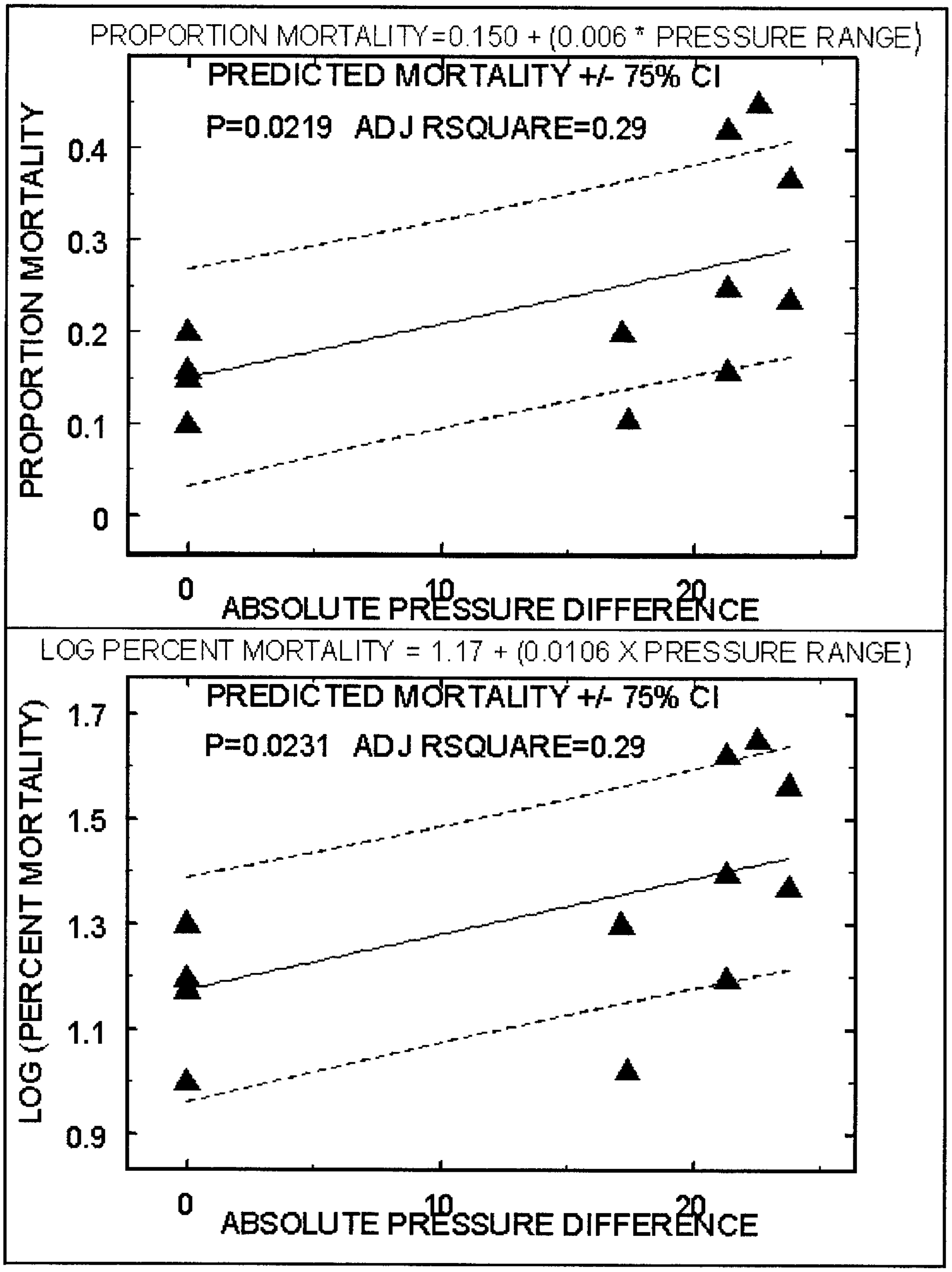

Figure 4. Results of simple linear regression between pressure range and mortality rate for unadjusted and adjusted data (Regressions based on adjusted data)

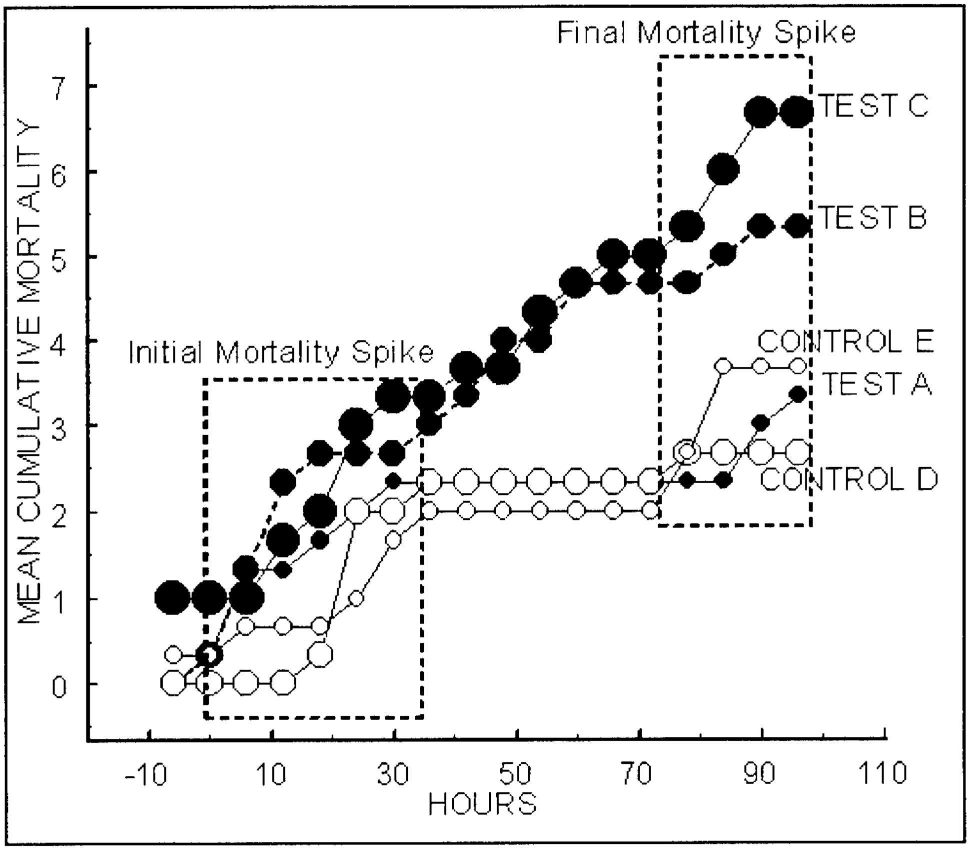

Figure 5. Time history of mean mortality for each treatment

4 Discussion and Conclusions

One of the liabilities of working with small data sets is that the power of the analysis will suffer. That is, as the numbers of replicates decrease, it becomes increasingly easy to fail to reject the null hypothesis of no real difference among the treatment means. Power analysis is performed to estimate the assurance with which one correctly rejects the hypothesis of equal means at a reference probability level. Power analysis (Peterman 1990) on the second series of experiments indicated that one would be able to correctly reject the hypothesis that the five-treatment (A-E) mortality rate means are equal about 55 percent of the time at a = 0.05 for a difference of 20 percent between the means. The power of the analysis to detect a difference of 30 percent between means at a = 0.05 jumps to about 92 times out of 100 tests (Figure 6).

In these experiments, there was an observable increase in mortality rate with increasing pressure drop. The unadjusted data from the second series do not meet significance criteria for difference in mean mortality rate among treatments. After the adjustment (discarding the first, probably contaminated replicate of each treatment and truncating the total fish counts from each experimental unit at 20), the differences become significant (ANOVA) or nearly so (Kruskall-Wallace). Giving up the first block of replicate severely reduced statistical power, which is the resistance to falsely accepting the null hypothesis of equality of means.

After the adjustment of the second data set, the nonparametric Kruskall-Wallace test did not show a significant difference among means (Tables 5 and 6), with a test statistic of 0.0509, just missing technical significance at 0.05. Nonparametric tests are more conservative than are parametric tests, so it is not surprising that the parametric ANOVA did show significance with the adjusted data (Tables 5 and 6), and Tukey's Multiple range test (Table 7) found Treatment C to be different from the others. Although the justification for using the parametric is questionable since it is difficult to evaluate the parameters of normality and equality of variances, the nearness of the nonparametric test to significance leads one to argue for a determination of practical significance. The unadjusted data do not approach significance, probably because many of the fish in all of

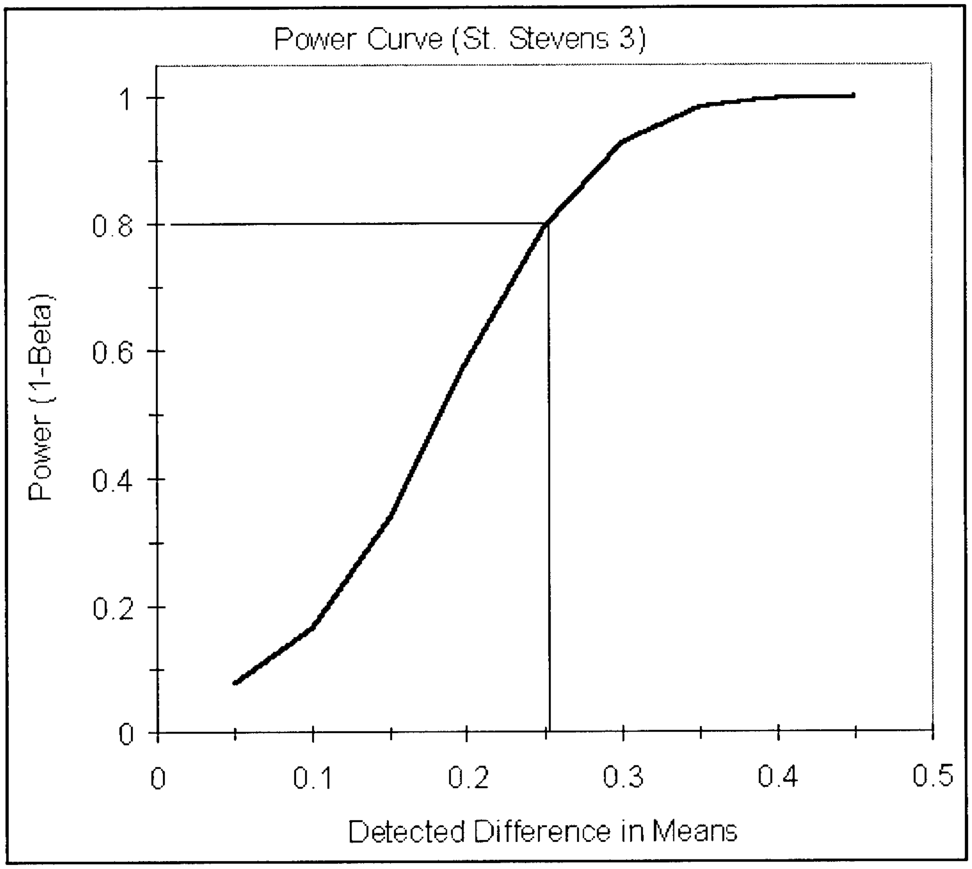

Figure 6. Results of power analysis for second series of experiments

the first block treatments, including controls, died. This is attributed to the contaminated bucket.

This is a case where a pragmatic and reasoned evaluation of the data is better than strict reliance on the outcome of a hypothesis test. "Statistical tests are aids to (hopefully wise) judgement, not two-valued logical declarations of truth or falsity" (Abelson 1995). In this unfortunately small and therefore low-power experimental situation, it would be wise to consider the clear trend of increase in mortality rate with increasing pressure more persuasive than the marginal lack of significance. The fact that trend does not allow the rejection of the hypothesis (that mortality rates among treatments and controls are equal) is more likely a reflection of the small sample size than of no real effect on the fish.

The results of the testing indicated that the PRTS, while not able to match the pressure changes to be expected in the proposed siphon system, was able to duplicate a range of pressure changes and to roughly approximate the pressure time history of a fish's passage through the siphon lift system. Control and handling mortality were relatively low (approximately 15 percent), so that the experimental method was sensitive to relatively small changes in mortality rate caused by the treatments. Temperature and oxygen concentrations in the fish lift where the survivorship pens were kept were always well above any potential for stressing the fish.

The results of the second series of experiments demonstrated that abrupt reductions in pressure, occurring in a time sequence similar to that of the intended fish passage, cause an observable increase in mortality rate as the severity of the pressure change increases. Tests indicated the mortality rate of juvenile American shad and blueback herring to be considerably less than 100 percent. However, for the two treatments showing the greatest change in pressure, there appears to be a mortality rate of approximately 20 percent to be anticipated with pressure changes less than those predicted for the proposed siphon lift system. This finding was also consistent with findings from the first series of experiments. Findings were generally consistent with literature estimates of mortality associated with passage through a zone of similar low pressure. The lowest pressure tested was approximately the same as used in previous literature tests. The effect of this pressure change according to Hogan (1941) was small, about 4 percent, and close to the effect observed in the pressure difference of 17 psi, an increase in mortality rate of about 3 to 5 percent depending upon which control was used. The increased mortality rate between the lowest pressure drop tested (Treatment A) versus the two greatest pressure drops tested (Treatments B and C) appeared to increase nonlinearly. The nonlinear increase in mortality rate associated with the most extreme pressure change tested suggests that small differences in pressure regime between the installed system and the simulation may be important.

It is especially important to emphasize that this study was able to produce neither the amount of pressure reduction (25.8 psi) nor the absolute vacuum (0.0 psi) predicted for some design alternatives. There is a trend linking mortality with pressure drop at the pressures tested, so that the more severe pressure regime currently predicted for operation would likely produce more damage to passing juvenile herring or American shad.

That this apparatus did not achieve the lowest possible pressure (0.0 psi) that may occur in the actual siphon system is of particular concern. Such a pressure, if the actual siphon does achieve it, may have especially damaging effects in the fish's bodies due to the dissolved gasses in them. The lowest pressures produced were about 3 psi. Although this study was not able to produce 0.0 psi because of limitations of the system employed, the study produced a total pressure drop in the most extreme treatment, C, of about 23.7 psi (26.7 psi – 3 psi). That is less of a drop than the most extreme change (25.8 psi, see Chapter 1) that a fish could experience passing through the proposed siphon lift system. The most extreme treatment, C, was about 2 psi less extreme in total pressure change than the proposed pipe system is expected to be and was about 3 psi above what may be a critical pressure (near 0 psi) in terms of gas bubble formation and other pressure-related trauma to the fish.

Since both pressure reduction and lowest pressure achieved was short, one suspects that results underestimate mortality rates due to pressure change only in the proposed system (if the proposed system achieves a minimum pressure approaching 0.0 psi). The pressure drop from 3 psi to zero psi, which was not produced, is likely the most damaging pressure change, especially with regard to embolism due to dissolved gasses coming out of solution in blood and other tissues and to possible pressure-induced damage to gas-filled structures such as the gas bladder and the air-filled structures associated with the ears.

This study does not address other possible sources of mortality (including but not limited to mechanical damage such as descaling and impact trauma or increased vulnerability to predation) that may be associated with passage through the proposed system.

There may be opportunities to reduce mortality by reducing the pressure range to which fish passing through the system may be subjected. The nonlinear increase in mortality rate as a function of pressure range suggests that small reductions in pressure range may produce relatively large reductions in fish mortality rate. An intake design that provided a shallower low point in the transit would reduce the high-pressure component and so reduce the amount of pressure drop. Designers might consider providing the shallowest intake and passage that fish behavior and upstream pool elevations will permit.

The viability of using the siphon lift system to pass outmigrating juvenile American shad and blueback herring is dependent upon the mortality rate associated with the installed siphon lift system compared with their present passage through the powerhouse. The mortality rate associated with the siphon lift system may still change depending upon small design changes associated with the lift system. The mortality rate associated with passage through the powerhouse is unknown and would be difficult and expensive to estimate. However, experience at other projects suggests that it is likely well under 100 percent and may be less than the mortality to be expected through the siphon system as presently designed.

Increased predation is an additional and often overlooked effect of passing fish through a bypass system. A bypass outfall artificially concentrates migrants and makes them more vulnerable to predators attracted there, whereas generation is more likely to distribute them widely in the tailrace. In the Columbia River, siting the outfall of bypass systems in areas where predators cannot hold is a major design consideration.

5 Recommendations

The following recommendations are offered for the siphon lift system.

a. All possible design changes that reduce the pressure reduction range and raise the pressure minimum that juvenile fish will be subjected to as they pass through the siphon should be pursued. Any reduction in the pressure range will produce greater than linear benefits to the fish. The intake to the siphon system should be as close to the surface as hydraulically feasible.

b. Studies should be conducted on the installed siphon system to determine actual mortality associated with passage. These studies should not be difficult or expensive because fish insertion and recovery through the siphon system is much easier than through a turbine. WES can probably perform such a study or assist with the experimental design if directed to do so by the Charleston District. If mortality rates from passage so dictate, downstream migrants may need to be excluded from the siphon system and encouraged to pass through the turbines.

c. It is possible to conduct mortality studies of fish passing through the powerhouse. However, the cost of such studies can be high (around $200K for a comprehensive study). It may be wiser to use funding to incorporate design changes into the siphon system to minimize pressure range and increase pressure minimum than it would be to expend funds to determine mortality through the powerhouse.

d. It is reasonable to think that fish predators will concentrate at the outfall of the siphon water lift system. Coordinating this possibility with the SCNR is recommended. They may or may not consider this a problem. It may be possible to site or add design features to the outfall to reduce the effectiveness of predators.

e. Behavioral technology has been shown to be effective in redistributing American shad and blueback herring. It is reasonable to expect that one may be able to attract fish toward or repel them away from the siphon intake once one determines the optimum pathway for bypassing fish.

f. Normally, postconstruction surveys are conducted to estimate the numbers of fish passing through the system and how the operation of the system and the powerhouse together may influence the effectiveness of fish passage. These authors recommend that these surveys be conducted to optimize both the operation of the system and the effectiveness with which fish are passed.

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John M. Nestler, Carl R. Schilt, David P. Jones

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13. ABSTRACT *(Maximum 200 words)*

This report presents results of studies to predict the mortality rate of juvenile blueback herring (*Alosa aestivalis*) and American shad (*A. sapidissima*) associated with reduced pressure as they pass downstream through a proposed siphon water lift system at S. Stephen Dam, South Carolina. The primary function of the siphon is to increase attracting flow to better guide upstream migrating adult herring of both species into the existing fish lift for upstream passage. The U.S. Army Engineer district, Charleston, wishes to consider the siphon as an alternative bypass route through the dam for downstream migrating juvenile and adult herring. A pressure-reduction testing system that emulates some of the pressure characteristics of the siphon was used to determine the approximate percentage of juvenile fishes that could be reasonably expected to be killed passing through the reduced pressures anticipated for the siphon water lift system. The testing system could duplicate the range of pressure change anticipated for the siphon lift system but could not obtain pressures lower than 4.1 psi, whereas pressures for some design alternatives may approach the theoretical minimum pressure of 0.0 psi. Study results indicate that the mortality rate is probably about 20 percent. Power analysis indicates that mortality rate above 30 percent is unlikely. Conducting additional mortality studies is recommended to refine predicted mortality rates. Measures should be taken to prevent juvenile fish from entering the siphon lift system if excessive mortality rates are observed.

14. SUBJECT TERMS

Alosa aestivalis	Fish mortality
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Effects of reduced pressure	Juvenile shad
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