Evaluation of a Low-Frequency, Sound-Pressure System for Guiding Juvenile Salmon

Away from Turbines at Bonneville Dam, Columbia River

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Abstract -- In June 1995, we evaluated the effectiveness of a 122-m long array of 25 low-frequency transducers for guiding juvenile salmon away from turbine units 9 and 10 at Powerhouse I of Bonneville Dam, Columbia River, Oregon. Juvenile salmon included sub-yearling and yearling chinook (<u>Oncorhynchus</u> <u>tshawytscha</u>), yearling coho (<u>O</u>. <u>kisutch</u>), yearling steelhead (<u>O</u>. <u>mykiss</u>), and yearling sockeye (<u>O</u>. <u>nerka</u>). Generated sounds were dominated by 300 and 400 Hz frequencies and transmitted as 2-s crescendos, with repeated amplitude ramps from 0 to about 160 dB referenced to 1 µPa at 1 m every 2 s. We found no significant differences in the mean number of fish passing north or south across the upstream end of the array, where the angle of incidence of flow was only about 5 degrees, during sound-on and sound-off treatments. The power of these one-tailed t-tests ($\alpha = 0.05$) for detecting 50 % differences in means was 82 % for fish passing north across the array and 99 % for fish passing to the south. We also counted smolts in front of four turbine intakes using fixed-aspect hydroacoustic equipment and found no significant differences in the mean number of smolts upstream of intakes during 4-h sound-on and sound-off treatments. The statistical power of 4-h tests was ≥ 98 % for detecting differences in means as small as 20 % at $\alpha = 0.05$ in a two-tailed analysis of variance and a one-tailed t-test. In 1997, we used net-pen tests to help corroborate and interpret the negative results obtained in the 1995 field experiment. We evaluated reactions of captive schools of sub-yearling chinook and coho and yearling sockeye to the same 300 - 400 Hz signal in a net pen. We observed no startle reactions and found that the frequency of avoidance of the signal was $\leq$ the frequency of coincidental avoidance during control trials without sound. After exposure to the 300 and 400 Hz signal, one school of sub-yearling chinook exhibited non-directional startle responses to 150- or 180-Hz sound, indicating that those fish could respond. We conclude that the 300 and 400 Hz signal did not influence the behavior or distribution of juvenile salmon in either study.

The need to safely bypass juvenile salmon around dams on the Snake and Columbia rivers has generated interest in non-intrusive behavioral methods, including underwater sound, to guide animals into bypass systems. Sound has been successfully used to control the behavior of some species of fishes. Perhaps the best-documented case has been for clupeids of the genus Alosa, which have been shown to perceive and avoid intense ultrasound in the range of 40-140 kHz (Dunning et. al 1992; Nestler et al. 1992; Ross et al. 1993; Ploskey et al. 1995; Mann et al. 1997). Recent psychophysical studies reported that American shad can detect and respond to sounds up to 180 kHz (Mann et al. 1997). Atlantic salmon (Salmo salar) and juvenile Pacific salmon were shown to perceive and respond to very low frequency sounds (<35 Hz) (Knudsen et al. 1992, 1994, 1997; Taft et al. 1995; Mueller et al. 1998).

Less consistent results have been obtained in studies attempting to redistribute and protect fish with low frequency, sound-pressure waves. Examples of unsuccessful applications of low-frequency sounds can be found in Smith and Anderson (1984) and Electric Power Research Institute (1994a and b). Most controlled experiments also failed to alter the swimming behavior of juvenile salmonids with low-frequency sounds without high particle displacement (e.g., Moore and Newman 1956; Burner and Moore 1953, 1962; Taft et al. 1995). However, a blend of 300 and 400 Hz sound up to 160 dB (referenced here and elsewhere to 1 µPa at 1 m) successfully diverted about 57.2 % of the juvenile salmon from the Georgiana Slough off the Sacramento River (Hanson Environmental 1993, 1995). Confidence intervals on mean guidance efficiency ranged from 47.4 to 65.0 %, and efficiency was higher during the ebb tide than during the flood tide. Sounds dominated by frequencies of 500 Hz, 700 Hz and 900Hz with amplitudes > 150 dB guided up to 94% of salmon smolts past the headrace of the Buchanan Hydroelectric Facility (Loeffelman et al. 1991a & b).

In this paper, we describe two consecutive, complimentary studies. The first study evaluated an array of 25 low-frequency-sound transducers simultaneously emitting 2-s crescendos

of sound dominated by 300- and 400-Hz frequencies to guide juvenile salmon away from two turbines at Powerhouse I, Bonneville Dam, Columbia River, Oregon. The second, follow-up study evaluated the effectiveness of the same sound signal for eliciting avoidance responses from juvenile salmon in a net pen. Out-migrating smolts in the Columbia River included sub-yearling and yearling chinook salmon (Oncorhynchus tshawytscha), yearling coho salmon (O. kisutch), yearling steelhead trout (O. mykiss), and yearling sockeye salmon (O. nerka). Juvenile fish tested in the net pen included sub-yearling coho and chinook and yearling sockeye salmon.

<div align="center">Methods</div>

Study Site

The Bonneville Project, located approximately 68 km east of Portland, Oregon at river mile 145.5, is among the most complex on the Columbia River. From the Oregon shore north toward Washington, it is composed of a navigation lock, Powerhouse I with 10 turbines, Bradford Island, an 18-gate spillway, Cascades Island, and Powerhouse II with 8 turbines. Forebays of powerhouses I and II and the spillway are separated by portions of Bradford and Cascades islands. Principal passage routes for out-migrating salmon smolts include the spillway and two powerhouses, but within each powerhouse, passage can be through ice/trash sluiceways, turbines, or the juvenile bypass system. Juvenile salmon may enter a bypass after being diverted by traveling screens in the upper part of turbine intakes to gatewell slots and orifices opening to a bypass channel. Bypassed smolts reenter the river downstream of the powerhouses.

Sound Transmission System

In the last week in May 1995, an array of low-frequency sound transducers was installed at the north end of Powerhouse I (Figure 1). Plastic floats were attached at 4.6-m intervals along a 122-m-long, 1.27-cm diameter, stainless-steel cable. The upstream end of the cable was secured to the shore of Bradford Island immediately below the exit of the adult fish ladder. The free end was towed downstream and attached to a pad-eye on the pier between intakes 8C and 9A (Figure 1).

After the cable and floats were secure and the array tightened against the current with block and tackle, transducers were suspended at depths of 1.5 to 6 m along the upstream half of the array and at alternating 6-m and 12-m depths along the downstream half.

Energy Engineering Services Corporation (EESCO) synthesized the sound signal that was later amplified by Peavey CS800X amplifiers and transmitted from 25 Model 215 moving-coil transducers (Argotec Incorporated, Fort Lauderdale, Florida). The transmitted signal was synthesized from recordings of sounds made by about 50 75-125 mm long juvenile chinook salmon obtained from Bonneville fish hatchery in May, 1995. Smolts were placed in about 114 liters of hatchery water in a clear plastic bag suspended from a 2-m high A-frame made of wood. Sounds were sampled with a Bruel and Kjaer 8104 hydrophone connected to a B&K 2635 charge amplifier and recorded to tape in a Sony digital-audio-tape recorder. The hydrophone was placed inside the plastic bag with the test fish. The repelling signal was synthesized using a Data Precision 2020 polynomial waveform generator and EESCO's patented tuning process. The signal was a blend of tones dominated by 300 and 400 Hz frequencies (Figure 2) and transmitted simultaneously from all 25 transducers as a crescendo ramping from 0 to about 160 dB ‖ 1 μPa at 1 m every 2 s. The conceptual basis provided by EESCO was that fish could be guided by sounds similar to those that they emit.

On 31 May, sound-on and sound-off measures of sound-pressure along the array verified that all 25 transducers were transmitting and provided preliminary estimates of signal-to-noise ratios. On June 17 and 18, sound pressure levels were again sampled near the transducer array under sound-on and sound-off conditions to verify the adequacy of sound coverage and to recheck the ratio of signal to noise. Background and transmitted sounds were detected with a Bruel and Kjaer Model 8105 hydrophone and a Kistler Model 5004D charge amplifier with a linear frequency response from 6 Hz to 180 kHz. Frequencies and amplitudes were measured using an oscilloscope and frequency analyzer.

We used a BioSonics ES 2000 Echosounder multiplexing up to six 6-degree, 420-kHz, single-beam transducers for sampling of fish to evaluate the guidance performance of the EESCO-designed array. Salmon do not detect or respond to sound frequencies as high as 420 kHz, and therefore the hydroacoustic monitoring system should not have influenced the behavior of juvenile salmon. Source levels and receiving sensitivities for the transceiver and each transducer were determined through system calibrations using a standard transducer in April, 1995 and in December, 1995. The calibration information for each transducer was used to select receiver gains (the amount of signal amplification). The criteria for selecting receiver gains was based on avoiding echo saturation from the largest targets of interest while amplifying echoes from fish with a target strength as low as -55 dB $\parallel 4\pi m^2$. The receiver gain for each transducer was selected to provide equal output voltages for on-axis targets of the same target strength (acoustic reflectivity). The sounder was controlled with BioSonics Dual-beam Multiplex software running on a 66 MHz, 486 Austin laptop computer with a BioSonics Echo Signal Processing (ESP) board.

We used two sets of transducers to evaluate the performance of the EESCO array (Figure 1). One set, located on the dam, was used to determine the distribution of juvenile salmonids as they approached intakes. The second set was placed at the upstream end of the EESCO array and used to monitor fish behavior as they approached the array and first encountered the 300 and 400 Hz sounds.

Four 6-degree, single-beam transducers were mounted on 3.7 m steel booms that pivoted from a mid-point elevation (25.3 m) on piers so transducers could be easily deployed and retrieved without SCUBA divers. These down-looking transducers were aimed out into the forebay 31 degrees from the vertical and 7 degrees laterally off the centerline of the pier so the beam was centered between piers (Figure 1).

We had two sampling regimes. From 1 through 23 June, we fast-multiplexed four 6-degree down-looking transducers for continuous sampling each hour except from 0900 to 1000 hours daily, when we downloaded data. At night from 24 through 30 June, we sampled only one-half time on the fast multiplex of down-looking transducers. The remaining fraction of night hours was used to sample fish behavior with a pair of two horizontal-looking transducers located at the upstream end of the EESCO array (Figure 1). During half-time-sampling hours at night, the four down-looking transducers were fast multiplexed during two randomly selected 15-min periods each hour.

Echoes from targets in the water column were plotted by range on the ordinate and time on the abscissa to create an echogram. Fish traces appear on an echogram as a series of three or more consecutive points representing echoes within 10 cm and 0.2 s of their nearest neighbor. We identified traces most likely to be salmon smolts moving through sampling volumes by applying tracking filters in the ESP Echo software. Fish-trace criteria for visual tracking included range from the transducer (6-24 m), number of echoes in a trace (3 to 20), average slope (-1 to -0.01 m / ping), mean echo strength (-55 to -43 dB $\| 4\pi m^2$ before 19 June and -55 to -46 dB $\| 4\pi m^2$ on or after 19 June), and trace linearity (0.9950 to 1.0). The length of the largest smolt sampled in the juvenile bypass system each week by the National Marine Fisheries Service was used to estimate maximum echo strength with an equation relating fish length and target strength (Love 1977).

Fifty hourly echograms collected in June were visually tracked using ESP Echo software, i.e. fish traces were visually selected, and trace statistics were written to a computer file, one trace at a time. These echograms also were automatically tracked by applying the same filtering criteria and writing all auto-tracked fish to disk. Visual tracking of a 1-h sample may require an hour, whereas auto-tracking the same file requires only a few minutes. We regressed the number of

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visually tracked fish (VT) on the number of auto-tracked fish (AT) and used the resulting

regression equation:

$$(VT = 135.765 + 0.451 \times AT; r^2 = 0.82; N = 54)$$

to process all remaining data from the auto-tracking program. All auto-tracked fish counts were

converted to visually tracked counts by substituting numbers of auto-tracked fish in the equation

above and solving for visually tracked fish.

Every tracked fish was weighted to correct for differences in the cross-sectional area of the

conical acoustic beams with range from the transducer, as follows:

$$\text{Weighted Number} = MAX\_D / (MID\_R \times TAN(B0/2) \times 2),$$

where MAX_D is the width of the intake (down-looking transducers) or maximum beam diameter

(horizontal transducers) in m, MID_R is the mid-point range of a fish trace in m, TAN is the

tangent, and B0 is beam angle in degrees. This expansion was necessary to allow us to estimate

passage of juvenile salmon without bias associated with range-dependent sample volume.

We monitored the swimming direction of smolt-sized fish as they passed through the sound

array using two 6-degree, single-beam transducers deployed from a raft located at the upstream

end of the array (Figure 1). The transducers were mounted within 0.2 m of each other at the

bottom of a 2.4-m-long vertical pole and were aimed 6 degrees apart and 22 degrees below the

horizontal plane. Transducers were lowered to a depth of 1.5 m and oriented so that each one

sampled along an opposite side of the upstream end of the sound array. These adjacent transducers

overlapped one another by a few degrees for large targets that could be detected > 6 degrees off the

main axis of the acoustic beam.

We recorded all smolt-sized traces of echoes at ranges of 6 to 30 m from the transducers

and classified them according to their direction of movement (north or south). Smolt-sized targets

had to be within 3.2 m of the array at a range of 30 m from the transducers and closer to the array

at ranges < 30 m to be detected by the 6-degree beam. On a computer echogram, we assigned different colors to echoes from each transducer to facilitate identification of the direction of fish movement. For example, echoes from a trace moving across the array from south to north would first appear as yellow indicating their presence in the beam outside the sound array. If the fish moved through the area of overlap in the acoustic beams, colors of adjacent echoes would alternate ping by ping due to the fast multiplex of the transducers (e.g., yellow and red). Echoes from fish that continued north through hydroacoustic beam inside of the sound array would be red. A fish moving from north to south would create a trace that was red and then yellow, indicating it was detected first in the inside beam and second by the outside beam.

Experimental Design

The test schedule from 1800 hours on 1 June through 0100 hours on 21 June, 1995 consisted of 4-h alternating sound-on and sound-off treatments. The sequence of on and off treatments was reversed on successive days by duplicating the treatment from 0100 to 0500 hours during the 0500-0900-hour period. This schedule provided a different treatment for every 4-hour period on successive days to alleviate inherent diel passage patterns that could confound treatment comparisons. On 17 June, two consecutive 4-h sound-on treatments were necessary from 0900-1700 hours to accommodate sound-field measurements. This change was offset by having two consecutive sound-off treatments during that same time on the next day.

Sampling of the 4-h treatments provided 464 samples, i.e., 19.33 days × 6 4-h periods / d × 4 intakes). However, only 388 samples were considered adequate for analysis. The 76 incomplete samples were missing 2 or more hourly counts per treatment because hourly data files were too noisy or too large to be processed. Occasional noisy data resulted from reverberation in the hydroacoustic sample volumes when wind and waves entrained air bubbles in the water

column. Data files plagued by noise usually were collected in the afternoon between 1400 and 1700 hours.

From 21 June through 30 June, sound treatments were switched from alternating 4-h treatments to alternating 24-h treatments. Down-looking transducers provided 5 d of sound-on samples and 5-d of sound-off samples for each of four intakes. For evaluating effects of sound treatments on the number of fish crossing the upstream end of the array, we processed four 1-h samples collected nightly between 2100 and 0100 hours from 25 June through 30 June. Processing provided 12 1-h sound-on estimates and 12 1-h sound-off estimates of the number of fish moving north and south across the array.

Data Analyses

We used one-tailed, paired t-tests on hourly counts of fish moving north and south across the upstream end of the array to evaluate effects of sound-on and sound-off treatments. The one-tailed test was appropriate because we expected the sound-on treatment to reduce but not increase the number of fish.

Fish counts made during the first hour of each 4-h treatment were not used to evaluate treatment effects. The first hour was considered a transition when fish presumably would begin altering their swimming direction and distribution relative to the array. We averaged counts during the last 3 h of each 4-h treatment to obtain a mean hourly rate and variance, which improved the normality of the data and made them more appropriate for parametric statistical tests. The 4-h-treatment data were analyzed in two ways. First, we ran a 3-way analysis of variance (ANOVA) on the 388 h of processed data using two sound treatments, six 4-h blocks / day, four intakes, and all possible interactions terms as independent variables. The mean hourly count of fish during the last three hours of each 4-hour sample was the dependent variable. Duncan's multiple-range tests were used to determine which means differed significantly. Second, we ran paired t-tests on sound effects because several assumptions of ANOVA were questionable, e.g., equality of variances and

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independence of counts among 4-h sample blocks and among adjacent intakes. For t-tests, we paired the average fish count for the last 3 h of each 4-h treatment with the average count for the same three hours under the alternate treatment on the next day. One t-test was for the intake south of the array and the other was for the sum of average hourly rates for the three intakes north of the array (Figure 1). Averaging counts for three intakes and testing differences in paired treatments reduced degrees of freedom relative to those in ANOVA but avoided troubling assumptions of spatial and temporal independence of samples.

A second experimental design used alternating 24-h sound-on and sound-off treatments for 10 d (21-30 June 1995) to determine whether longer treatment duration would alter the results. The 24-h treatments eliminated the possibility that smolts could move inside the array during a 4-h sound-off treatment and pass during subsequent sound-on treatments. We compared mean rates of detection of smolt-sized targets in a two-way ANOVA with sound treatment, intake, and sound × intake as independent variables and the mean hourly rate of passage as the dependent variable.

Net-Pen Study

In June 1997, we evaluated responses of yearling sockeye and sub-yearling coho and chinook salmon to the same 300 and 400 Hz signal tested at Bonneville Dam in 1995. The net pen study allowed for direct observation of salmonid behavioral response to the low-frequency signals in a controlled environment to help verify findings in the 1995 field study at Bonneville Dam. These tests were conducted near the Hiram M. Chittenden Locks in Seattle, Washington. A 4-m long, 1.5-m diameter cylindrical frame was constructed of five aluminum hoops attached to 4-m long pieces of aluminum channel. Four underwater cameras were mounted on aluminum hoops of the frame at 1-m intervals beginning at one end of the frame. Cameras were aimed into the interior of the frame, which was then covered with 3.2-mm mesh webbing. The webbing was pursed and tied at both ends. Schools of 15-30 juvenile salmon were introduced or removed from the pen by lifting one end of the pen completely out of water and opening the purse on the lower end. The

horizontal pen was suspended below floats at a depth of 1 m. Most fish were obtained from the

Isaquah Fish Hatchery, although some were captured in the fish ladder at the Locks.

A Model 215, moving-coil transducer from Argotec, Incorporated was located within 0.2

m of the end of a horizontal net pen. A Model 7560 Techron amplifier was used to drive the

transducer. We tested a blend of 300 and 400 Hz sounds in repeated crescendos that ramped from

0 to 170 dB ‖ 1 μPa at 1 m in 2 s intervals. Pure 150 or 180 Hz sound also were presented on

several occasions to qualitatively test smolt responsiveness to low-frequency sounds.

The four monochrome video cameras (Sony SSC-M350), fitted with 105-degree wide-

angle lenses and encased in underwater housings, were sampled sequentially with a Robot MV94e

multiplexer at about seven frames per s each. Multiplexed images were recorded on tape in a Sony

EV-C200, Hi 8 video camera recorder and replayed through the multiplexer to obtain a composite

view from all four cameras. The field of view of each camera was divided into two parts so that

fish counts could be assigned to eight physical locations in the net pen. The midpoint of each of

the eight locations was a known distance (m) from the stimulus source. Video processing involved

replaying a video tape, stopping the tape at approximately 5 s intervals to count fish in each of

eight locations, and recording the sum of numbers by location. The sum of fish counted in every

location was multiplied by the mid-point distance of the location from the stimulus source.

Weighted distances were averaged to obtain a mean location for the center of the school at 5-s

intervals through time.

Tests of fish responses to the 300 and 400 Hz blend of sounds consisted of 6-10 trials per

fish school and three control trials. Fish were placed in the net pen and allowed to calm down for

30-60 min before testing. Short 2-min trials consisted of a 30-s pre-trial without sound, a 1-min

exposure to sound, and a 30-s post-trial period without sound. The 2-min controls were the same

as 2-min trials except that no sound was transmitted during the 1-min exposure period that began

30 s into the control.

A common behavior of juvenile salmonids in the net pen involved repeatedly moving from one end of the pen to the other, which we referred to as pacing. Pacing made difficult an assessment of effects of stimuli during brief sound exposures because apparent avoidance could be the result of the starting position and direction of movement of an actively swimming school of test fish. When fish were not pacing, we looked for movement away from the source. Under these conditions, a comparison of the end position relative to the start position was sufficient to assess avoidance. However, when fish were pacing, we had to evaluate effects based upon changes in behavior before, during, and after exposure. We also determined whether the slope of a regression line fitted to mean position of a school 5 s before exposure until the end of exposure differed significantly from zero. This approach used all of the temporal positions to assess effects, whereas end minus starting positions could be affected by the period of pacing cycles if fish were pacing the pen. We compared the frequency of avoidance in test and control schools to determine whether the signal elicited avoidance.

Results

Physical Conditions

Flows along the upstream two-thirds of the array from 0 to 8 m of depth were about 0.65 m / s and mostly parallel to the cable (Figure 1). The downstream one-third of the array was bowed by flow crossing the EESCO array at increasingly steep angles of 20-30 degrees. Within 5 m of the downstream pier attachment, surface flows were moving parallel to the face of the powerhouse and across the array toward the north. Velocities at the mouth of turbine intakes just inside trash racks were about 0.9 m / s. Water depths ranged from about 3 m at the upstream end of the array to about 22 m at the downstream end.

Each turbine at Powerhouse I has three intakes and passes about 283 m^3 / s of flow depending upon head and wicket-gate openings. Turbine units 4 and 6 were inoperable throughout this study, but the other eight turbines operated nearly continuously. Two ice-trash sluice gates at

intake 7A and 10C were open throughout this study. River flows ranged from 6,117 to 10,181 m^3 / s, and the spillway passed about 2,120 m^3 / s during the day and from 3,400 to 4,240 m^3 / s at night.

Sounds transmitted in the Bonneville forebay and in the net-pen tests consisted of a 2-s crescendo with a maximum source level of about 160 dB and primary frequencies of 300 and 400 Hz (Figure 2). Signal to noise ratios for these frequencies were lowest at the downstream end of the array (3.3-4.3) and highest (> 5.0) in the middle and at the upstream end. The spectrum of sounds presented to fish in net-pen tests was identical to those used in the forebay at Bonneville Dam (Figure 2), but maximum source levels were about 170 dB.

Array Effects on Smolt Behavior

Mean hourly counts of smolt-sized targets moving inward or outward across the upstream end of the EESCO array did not differ significantly under sound-on and sound-off treatments (Table 1). The power of these one-tailed t-tests to detect 50 % decreases in the number of fish crossing the array of sound transducers was 82 % for fish moving north and 99 % for fish moving south at $\alpha = 0.05$. In all, we tracked 1,136 smolt-sized targets ($< - 43$ dB $\parallel 4\pi m^2$) within 3.2 m of the array (i.e., beam width at maximum range) during sound-on treatments and another 929 targets during sound-off treatments from 2100 to 0000 hours over 6 d.

Array Effect on Densities Near Intakes

Juvenile bypass data showed that the percent of larger yearling smolts declined while the percent of sub-yearling smolts increased during June (Figure 3). By changing maximum echo-strength criteria for identifying smolt-sized traces from -43 dB $\parallel 4\pi m^2$ in early June to -46 dB $\parallel 4\pi m^2$ after 16 June, we were more selective against non-smolts, particularly American shad that became more abundant in late June. Numbers of smolt-sized traces counted in the forebay upstream of four intakes each day were significantly correlated ($r = 0.54$; ; $P = 0.0018$; $N = 31$)

with estimated numbers of smolts passing through the juvenile bypass system that collected fish screened from the upper part of 24 functional intakes at the powerhouse. Juvenile bypass data also revealed a strong diel pattern to smolt passage through turbines with most fish passing just after sunset and higher passage at night than during the day (Figure 4).

The hourly rate of passage of smolt-sized fish immediately upstream of turbine intakes at the downstream end of the array did not differ significantly between 4-h sound-on and sound-off treatments. A three-way ANOVA detected significant differences in the hourly rate of passage among 4-h sample periods and intakes but not between sound treatments or any interaction terms (Table 1). The statistical power of this two-tailed ANOVA exceeded 98 % for detecting differences in means as small as 20 % at $\alpha = 0.05$. Passage estimates were significantly lower during the 2200-0200-hour period than estimates for other 4-h periods of the day. In addition, counts at intake 9a and 10b were higher than counts at intake 9c and 8c (Table 1). Paired t-tests also indicated that sound treatments did not significantly reduce the passage of fish moving toward Intake 8c south of the array or toward the three intakes north of the array (Table 1; Figure 5). The power of these one-tailed t-tests to detect 20 % differences in means exceeded 98 % at $\alpha = 0.05$. A two-way ANOVA showed no significant differences in fish counts among 24-h sound treatments, intakes, or the interaction of sound treatment and intake (Table 1). However, the power of this two-tailed test was only 70 % to detect a 50 % difference in means at $\alpha = 0.05$.

Reactance Testing in a Net Pen

We observed no evidence of avoidance of the 300 and 400 Hz blend of sound in 46 of 53 2-min trials on sub-yearling chinook. Only 7 of 53 (13.2 %) regression lines fitted to school positions when sound was being transmitted (0.5-1.5 min into each trial) had significant positive slopes, indicating some movement away from the sound source (Figures 6-8). The slopes of these seven lines ranged from 0.28-0.59 m min^{-1}. In 46 sound trials, fish did not move away from the

sound source, and slopes of regression lines fitted to school positions when sound was on did not differ from zero (45 slopes) or were negative (1 slope). In 20 control trials without sound, the frequency of movement away from the quiet transducer was 30 % (6 of 20 trials) compared to 13 % for sound-on trials.

We also observed no avoidance response by one school of sub-yearling hatchery coho in nine separate 1-min trials (Figure 9) or by one school of yearling sockeye collected from the adult fish ladder in 12 separate trials (Figure 10). The hatchery coho were much more active and likely to pace the pen than the sockeye collected from the fish ladder. No regression lines fitted to school positions during sound exposure had slopes significantly different from zero.

In addition to the low frequency of avoidance during sound-on periods for all species tested, we rarely observed abrupt changes in swimming direction or speed when sound was initially transmitted 0.5 min into trials (Figures 6-10). In contrast, we observed clear non-directional startle responses of one school of sub-yearling chinook salmon exposed to 150 or 180 Hz tones with amplitudes of 170 dB. In many instances, fish moved toward the sound source while the 300 and 400 Hz sound was being transmitted, particularly when fish were pacing the pen (e.g., Figure 7, 8, 9).

Discussion

We conclude that the complex 300 and 400 Hz blend of sounds transmitted from an array of 25 transducers did not have a significant effect on the behavior or distribution of juvenile salmon at Bonneville Dam. However, failure to detect a sound-treatment effect at Bonneville Dam could have resulted from low statistical power, compromised performance of the array by environmental conditions, or failure of transmitted sounds to elicit avoidance from fish. Performance of any sound device could be compromised by entrainment of otherwise responsive fish through the sound field or masking of transmitted sound by ambient sound in the forebay.

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Most statistical tests performed on the Bonneville field data had ample power to detect differences smaller than those observed in previous studies. For example, Kodiak trawl samples at the Georgiana Slough showed that the guidance efficiency of the acoustic array averaged 57.2 % for chinook smolts (Hanson Environmental, Incorporated 1995). Loeffelman et al. (1991a & b) reported that 94 % of steelhead smolts and 81 % of chinook smolts were guided past nets in the headrace of the Buchanan Hydroelectric Project on the St. Joseph River, Michigan. They transmitted a crescendo of sound dominated by 500, 700, and 900 Hz frequencies with amplitudes > 150 dB. The power of our one-tailed t-tests to detect 50 % differences in the number of smolt-sized fish moving north and south across the upstream end of the array was 99 and 82 %, respectively at $\alpha = 0.05$. Fish had to be within 3.2 m of the array when they were sampled or they could not have been detected. The power of tests on 4-h treatment data from transducers sampling at intakes exceeded 98 % for detecting differences as small as 20 %. The test on 24-h treatment data from intake transducers had the lowest power (70 % for detecting 50 % differences).

An effective sound array could fail if fish were entrained in flow and could not avoid the stimulus. The smallest smolts likely were entrained in the highest velocity flows at the Bonneville site. However, we did not detect differences in the mean number of fish crossing the upstream end of the array under sound-on and -off treatments. The angle of incidence of flow across the upstream end of the array was about 5 degrees as opposed to ≥ 30 degrees at the downstream end. Approximately equal numbers of sub-yearling-sized fish were observed moving north and south across the upstream end of the array. If these fish were entrained, most would have crossed the array from south to north. It also is unlikely that the currents could sweep yearling and larger sub-yearling smolts across the sound array if fish were avoiding the array. Before 16 June, over 30 % of all smolts sampled in the juvenile bypass were yearlings. Empirical evidence also indicates that many smolts hold upstream of intakes during the day and pass after dusk, which must mean that

many can resist entrainment. Densities of smolt-sized fish in the forebay were significantly higher during daylight hours than from 2200 to 0200 hours (Table 1), while water velocities approaching the dam were similar. In contrast, fish passage through turbines and the juvenile bypass was much lower during the day than at night (Figure 4). High daytime counts by forebay transducers could result if many fish were milling around the forebay and some were detected more than once. Reduced holding and milling after dark, perhaps due to a loss of visual cues for orientation, would explain lower counts by forebay transducers and increased bypass counts as daytime accumulations of fish moved through turbines and the bypass.

Signal to noise ratios > 3.0 for the EESCO array at Bonneville should have been adequate to elicit responses but were substantially lower than those reported by Hanson Environmental, Incorporated (1995). Background noise levels were 17-40 dB higher at Bonneville (116-139 dB) than they were at the Georgiana slough (88-99 dB). The upstream end of the array at Bonneville dam had sound amplitudes that were 5 times higher than the background noise and yet it failed to guide fish.

Response testing in a net pen indicated that the most likely reason for the failure of the signal to guide juvenile salmon at Bonneville Dam was a lack of response by fish to the predominant frequencies. We conclude that the sub-yearling chinook, coho, and sockeye salmon tested in a net pen did not respond to the 300 and 400 Hz blend of sounds produced by a Model 215 transducer. The frequency of avoidance during sound exposure was low and comparable to the frequency observed for control schools of sub-yearling chinook, coho, and sockeye salmon. Some test fish exhibited non-directional startle responses to 150 or 180 Hz tones but did not startle when exposed to 300 and 400 Hz crescendos of similar amplitude (170 dB). Observations of responses for some specimens to 150 and 180 Hz sound were important because they indicate that test specimens were not deaf or inherently unresponsive.

Our results do not answer the question of whether the juvenile salmon could not hear sound pressure at 300 or 400 Hz. Basic physiological measures of response, such as change in heart rate, in smolts exposed to a mix of 300 and 400 Hz sound would provide answers to this fundamental question, but were beyond the original scope of our study. These data could be obtained using simple behavioral paradigms that enable investigators to measure hearing thresholds (e.g., Lu et al. 1996).

Most of what is known was about hearing of Pacific salmonids must be deduced from literature from related species. Behavioral experiments on salmonid hearing have repeatedly shown that these fish can detect high amplitude sound at frequencies up to about 400 Hz but with reduced sensitivity above 150 Hz (Hawkins and Johnstone 1978; Knudsen et al. 1992, 1994). In addition, physiological studies, recording from brain regions innervated by the ear and lateral line of steelhead indicated that this salmonid does not detect sounds above 400 Hz, and the best sensitivity was at much lower frequencies (Wubbels et al. 1993). These studies have also shown that under the sound field conditions that exist in the far field of sound sources, where sound pressure dominates (Kalmijn 1988), salmon have very poor hearing capabilities. Popper (1976, 1977) believed it is very likely that salmonids do not have a functional pressure to particle motion transducer as an element in their hearing that would enable them to detect the pressure component of a sound field for far field detection (Kalmijn 1988; Popper and Fay 1993). When Knudsen et al. (1992) recast data on salmonid hearing thresholds as determined by Hawkins and Johnstone (1978) from sound pressure to particle acceleration (m sec^{-2}), they found a flat hearing threshold from 5 to 150 Hz. Above this frequency the thresholds increased steeply until a loss of detection capability occurred above about 380 Hz (Knudsen et al. 1992). Knudsen et al. (1994) showed that even if a fish detects a sound, it might not behaviorally respond to the sound. Knudsen et al. (1994) found that the same Atlantic salmon smolts that responded vigorously and without habituation to infrasound did not respond at all to 150 Hz sound pressure waves, although they could hear it.

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Given the nature of the sound field generated by the moving coil transducers, it seems reasonable that the lack of response of the salmonid smolts was most likely due to two factors: 1) most of the energy in the sound field was contained in frequencies above the range of maximum hearing sensitivity for salmonids, and 2) with the possible exception of a region very near each source (range less than 0.5 m), there was no energy at infrasound frequencies (≈ 10 Hz) of sufficient particle displacement to elicit an avoidance response. High intensity, high particle motion infrasound has been shown, by several independent investigators, to elicit a repeatable, distinct avoidance response from salmonid juveniles (Knudsen et al. 1992, 1994, 1997; Mueller et al. 1998).

In retrospect, the most cost effective and efficient order of study would have been to conduct controlled reactance tests in a net pen first and then a field test of an array of transducers, if warranted. Had we taken this approach, field tests probably would not have been conducted. Given the sequence of study, we nevertheless believe that the combination of results from the field and net-pen studies provided compelling evidence of a lack of effectiveness.

Acknowledgments

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Figure Captions

Figure 1. Plan view of the north end of Powerhouse I forebay at Bonneville Dam showing the configuration of test and monitoring transducers. The 122-m long array of 25 low-frequency sound transducers was attached upstream to the north shore and downstream to a pier between turbine units 8 and 9. Response of smolts to sound-on and sound-off treatments were evaluated by comparing counts of echo traces from fish in four down-looking, single beam, 420 kHz transducers deployed just below the water's surface from intake piers and in two horizontal acoustic beams sampling areas on either side of the upstream end of the test array.

Figure 2. Frequency spectrum from part of a 2-s crescendo of 300 and 400 Hz sound transmitted from a Model 215 transducer.

Figure 3. Length frequency distribution of salmon smolts sampled in the juvenile bypass channel of Powerhouse I, Bonneville Dam, in June 1995 by the National Marine Fisheries Service. Frequency is shown for the maxima of 25-mm length classes and their corresponding acoustic target strength calculated with Love's (1977) regression equation.

Figure 4. Mean diel pattern of smolt passage through turbines and the juvenile bypass system at Powerhouse I, Bonneville Dam, based upon average hourly trap samples taken on 9, 10, 21, and 24 June 1995 by the National Marine Fisheries Service. Bars indicate the percent passing per hour and the line shows the cumulative percent.

Figure 5. Plot of differences in mean rates of fish passage through hydroacoustic beams immediately upstream of four turbine intakes of Powerhouse I, Bonneville Dam during 4-h sound-on and sound-off treatments in June 1995.

Figure 6. Mean position of sub-yearling chinook schools (CH1-CH3) in a horizontal net pen during successive trials of 300 and 400 Hz sound transmitted in repeated 2-s crescendos. In each 2-min-trial plot, sound was off from 0 to 0.5 min, on from 0.5 to 1.5 min, and off again

from 1.5 to 2.0 min. The ordinate depicts distance from the sound source. Plots with text

designating the slope of a line fitted to sound-on positions were trials with some avoidance.

Figure 7. Mean position of sub-yearling chinook schools (CH3-CH5) in a horizontal net pen

during successive trials of 300 and 400 Hz sound transmitted in repeated 2-s crescendos. In

each 2-min-trial plot, sound was off from 0 to 0.5 min, on from 0.5 to 1.5 min, and off again

from 1.5 to 2.0 min. The ordinate depicts distance from the sound source. Plots with text

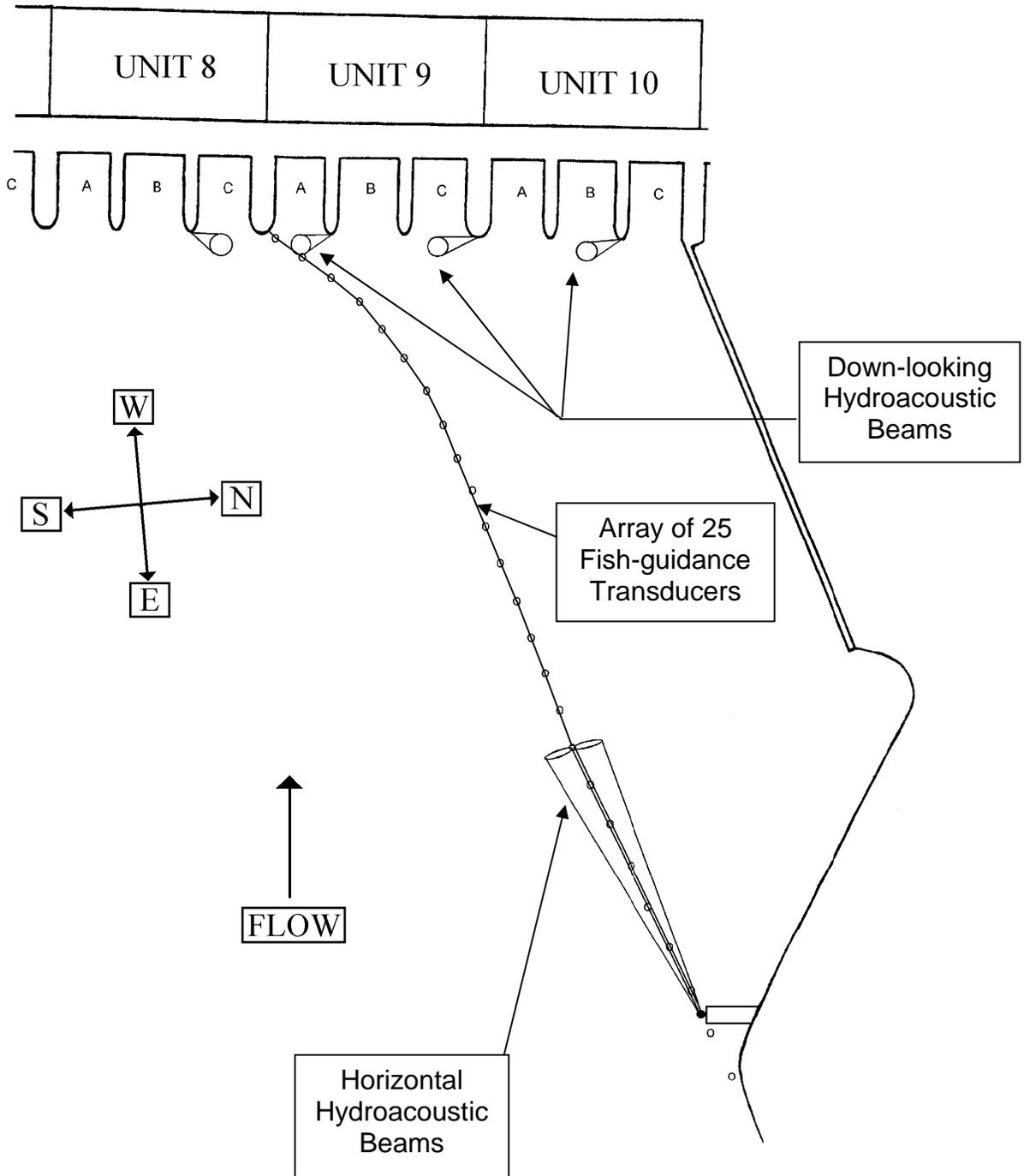designating the slope of a line fitted to sound-on positions were trials with some avoidance.
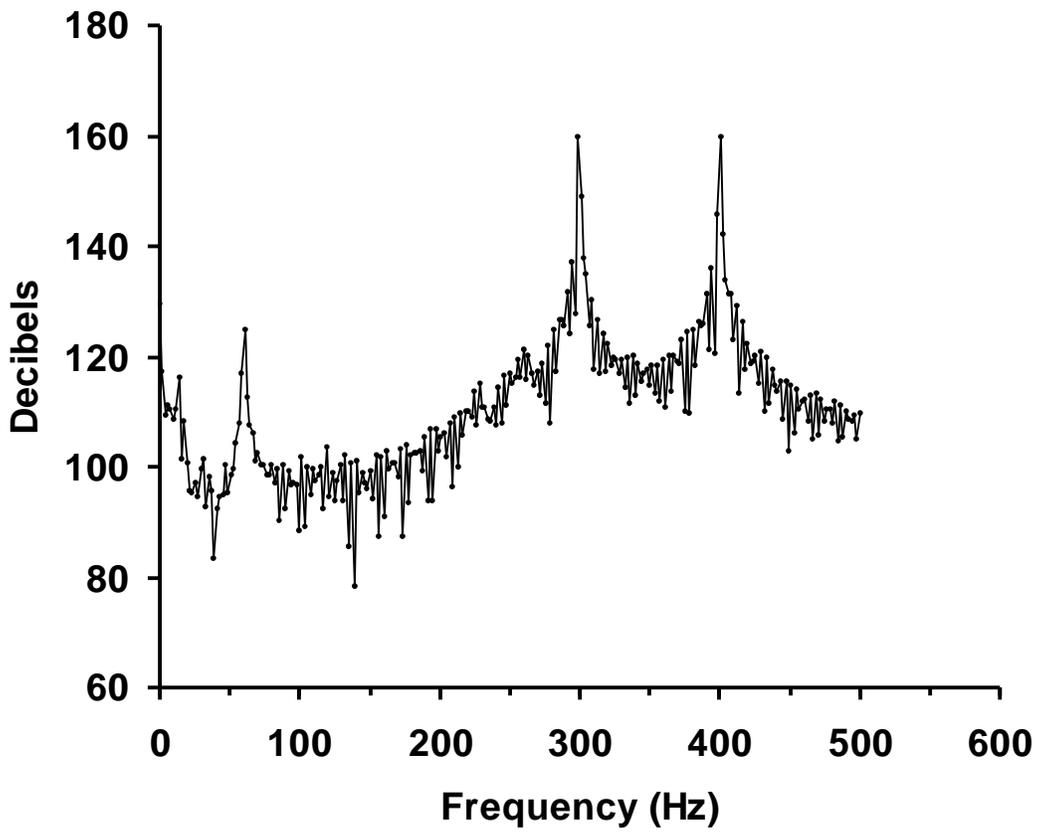
Figure 8. Mean position of sub-yearling chinook schools (CH5-CH6) in a horizontal net pen

during successive trials of 300 and 400 Hz sound transmitted in repeated 2-s crescendos. In

each 2-min-trial plot, sound was off from 0 to 0.5 min, on from 0.5 to 1.5 min, and off again

from 1.5 to 2.0 min. The ordinate depicts distance from the sound source. Plots with text

designating the slope of a line fitted to sound-on positions were trials with some avoidance.
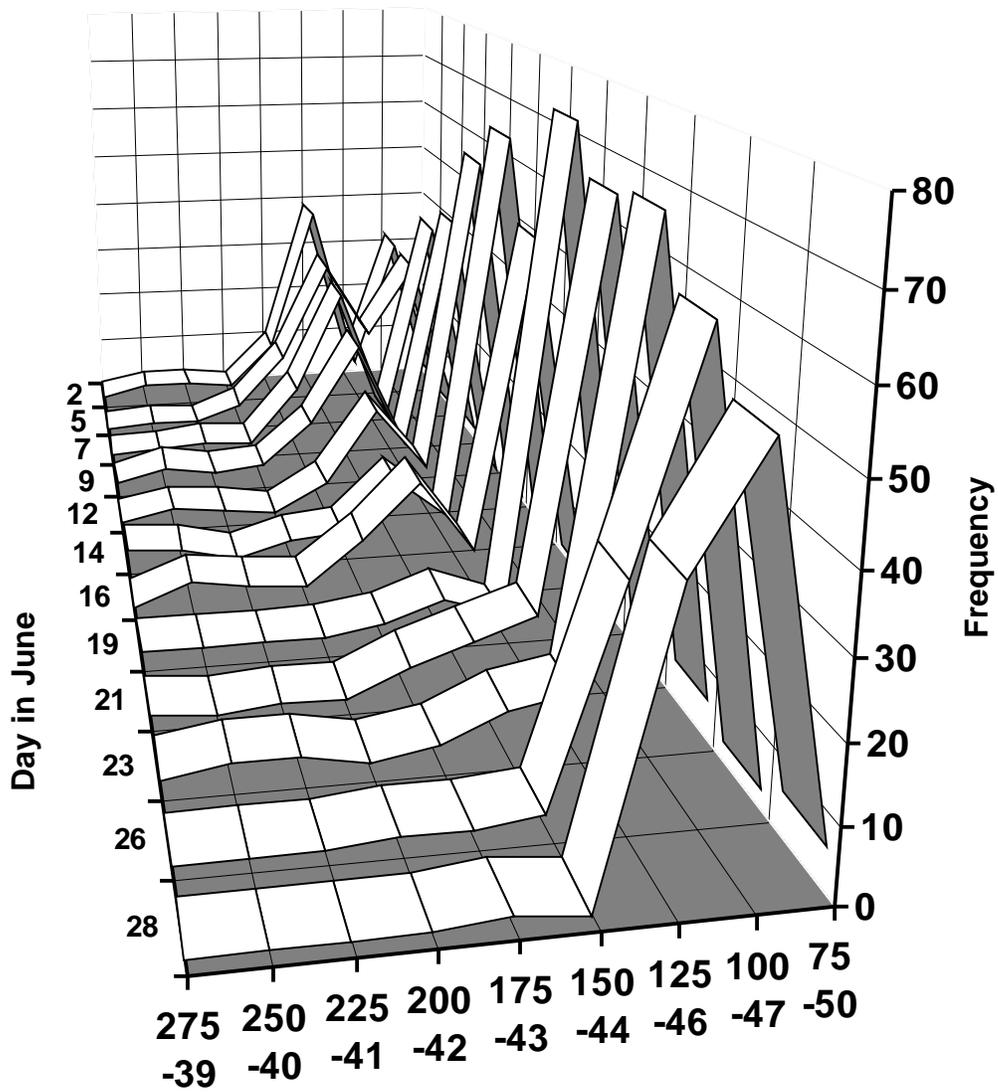
Figure 9. Mean position of a sub-yearling coho school in a horizontal net pen during successive

trials of 300 and 400 Hz sound transmitted in repeated 2-s crescendos. In each 2-min-trial plot,

sound was off from 0 to 0.5 min, on from 0.5 to 1.5 min, and off again from 1.5 to 2.0 min.

The ordinate depicts distance from the sound source. Plots with text designating the slope of a

line fitted to sound-on positions were trials with some avoidance.

Figure 10. Mean position of a yearling sockeye school in a horizontal net pen during successive

trials of 300 and 400 Hz sound transmitted in repeated 2-s crescendos. In each 2-min-trial plot,

sound was off from 0 to 0.5 min, on from 0.5 to 1.5 min, and off again from 1.5 to 2.0 min.

The ordinate depicts distance from the sound source. Plots with text designating the slope of a

line fitted to sound-on positions were trials with some avoidance.

UNIT 8   UNIT 9   UNIT 10

C   A   B   C   A   B   C   A   B   C

W

S   N

E

FLOW

Down-looking
Hydroacoustic
Beams

Array of 25
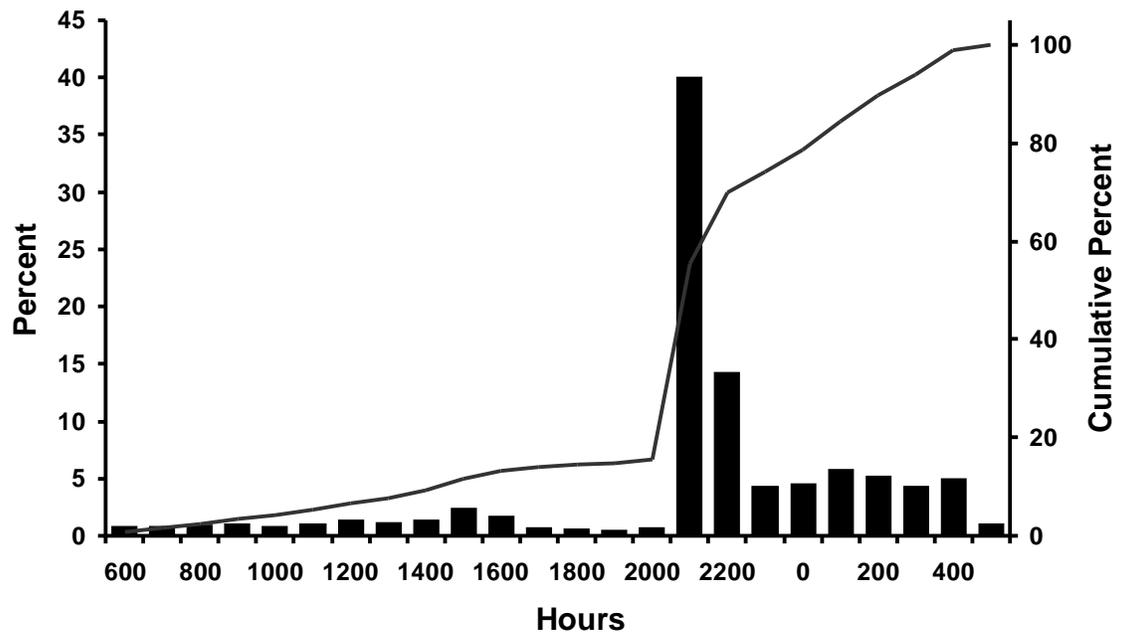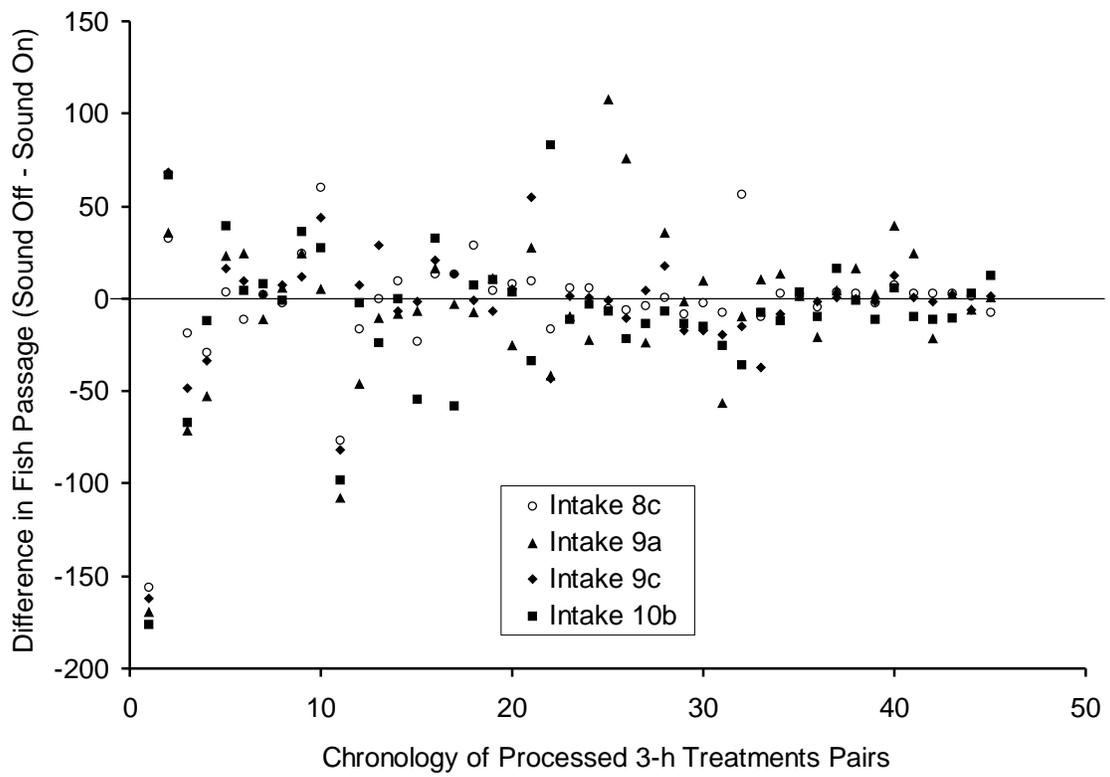Fish-guidance
Transducers

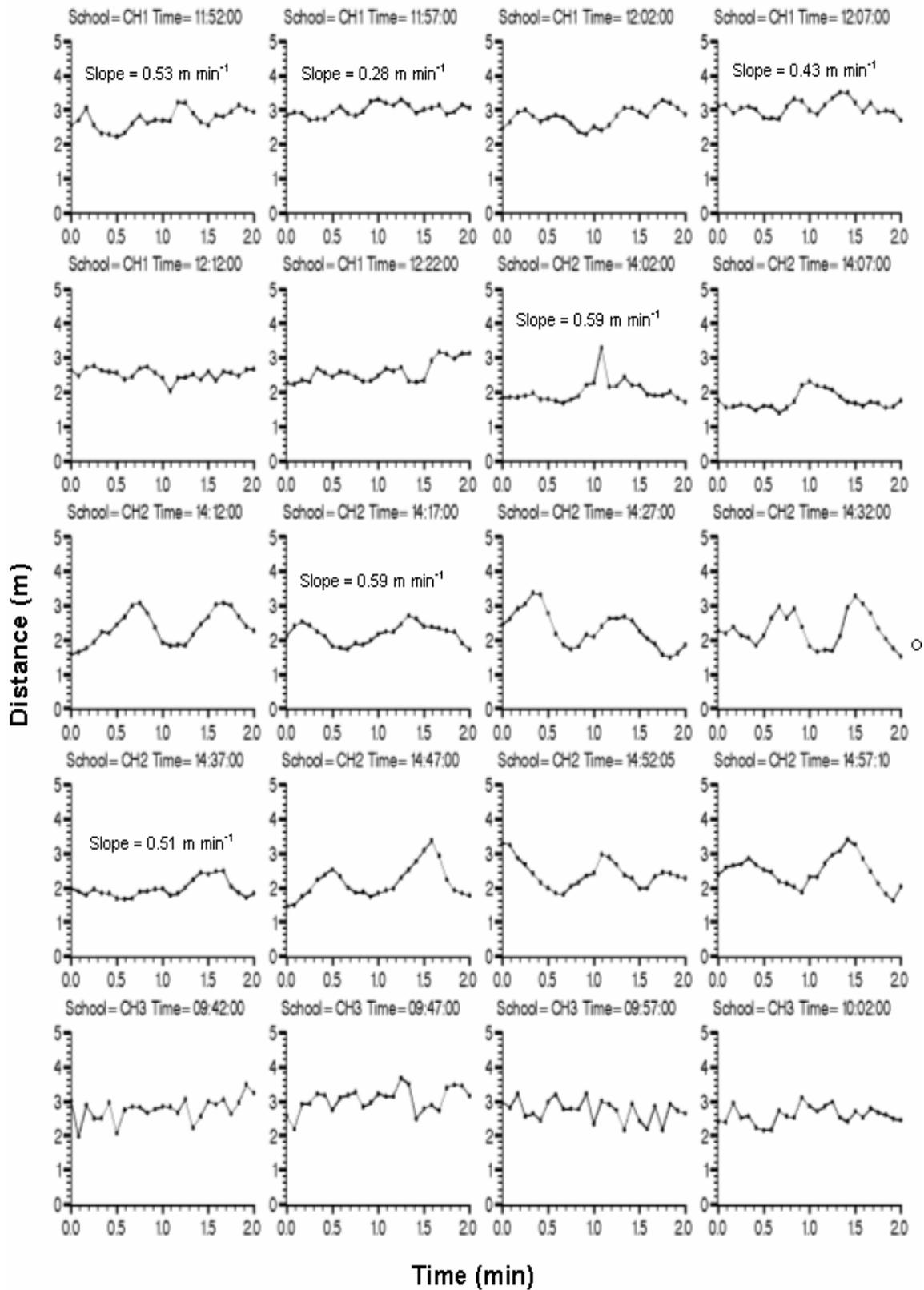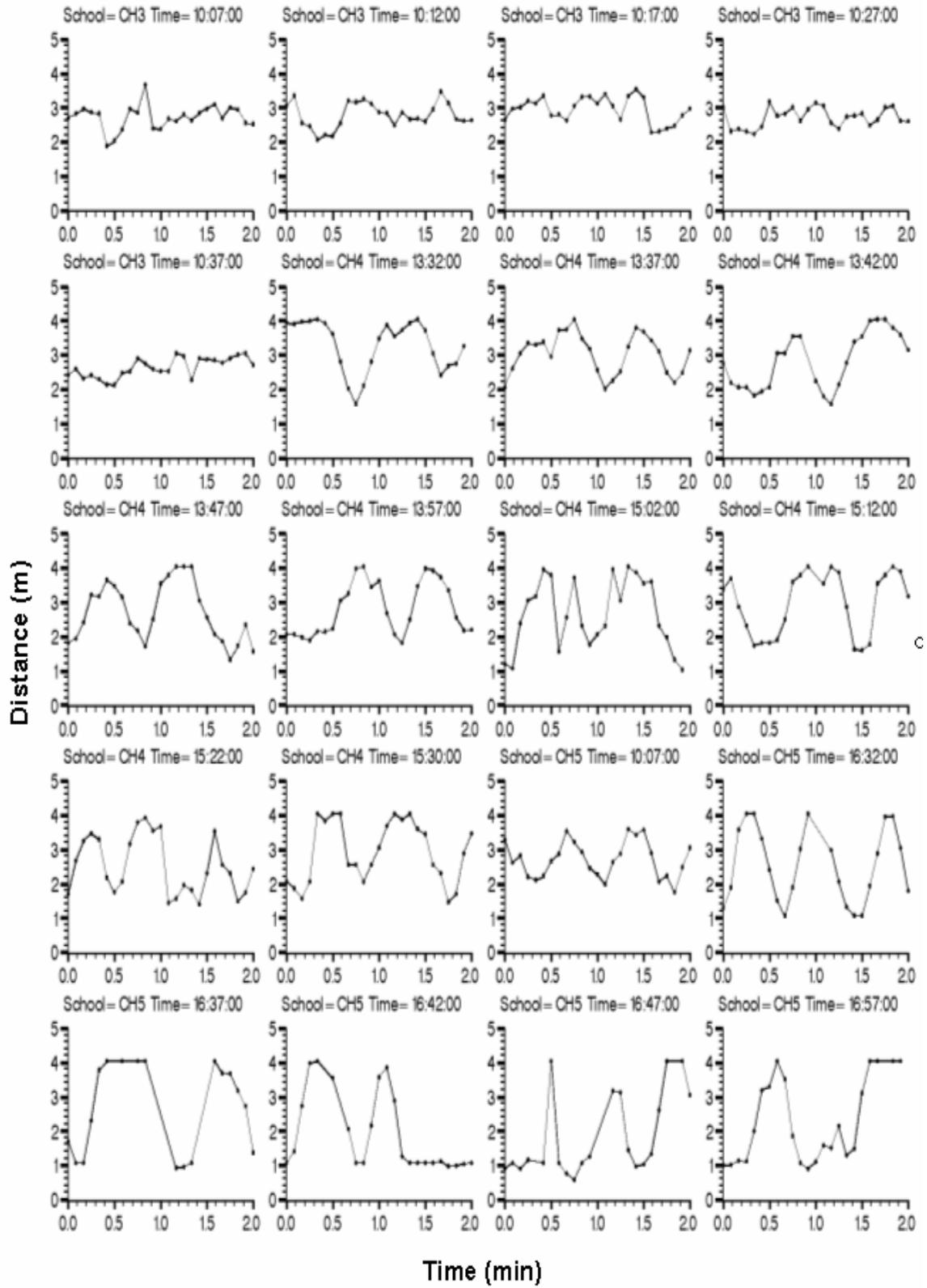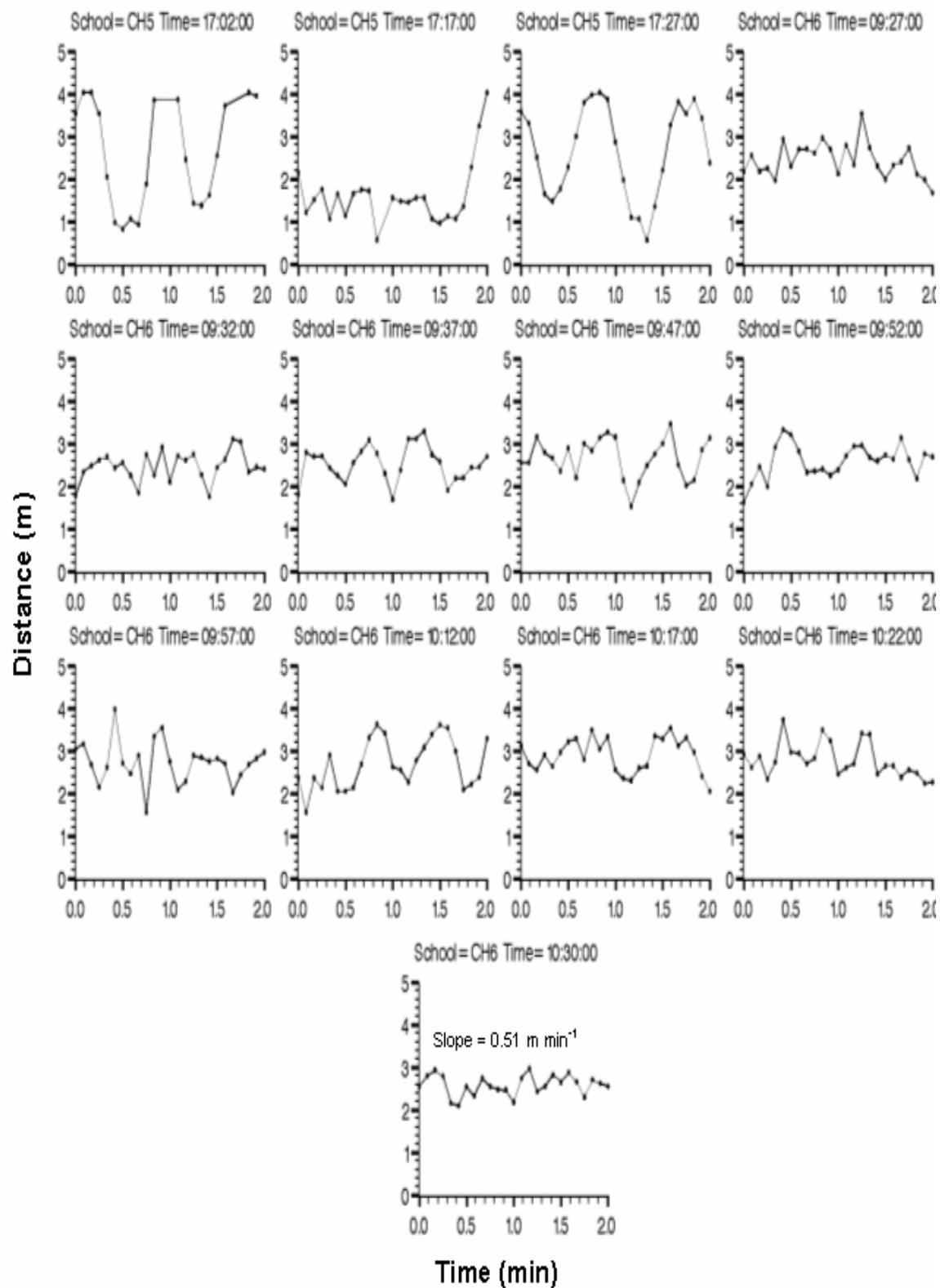Horizontal
Hydroacoustic
Beams

Figure 1

Figure 2

Figure 3

Figure 4

Figure 5

Figure 6

Figure 7

Figure 8

Figure 9

Figure 10