Analysis of sound spectra in Yellowstone Lake in relation to orientation and homing movements of cutthroat trout (Salmo clarki)

by Quentin Jerome Stober

A thesis submitted to the Graduate Faculty in partial fulfillment of the requirements for the degree of DOCTOR OF PHILOSOPHY in Zoology
Montana State University

Abstract:
Underwater ambient noise in the stream-mouths of Clear, Cub and Pelican Creeks was investigated in relation to orientation and homing of cutthroat trout (Salmo clarki). A maximum estimate of the noise spectrum was determined from 0.1 to 10 KHz during periods of high stream discharge and wave action. Minimum noise spectra were not determined because of instrument noise interference. Two noise sources contributed to ambient pressure spectrum levels in the stream-mouths (1) cavitation and/or flow noise and (2) surf-beats. The former is mainly composed of frequencies below 4 KHz while the latter is above 5 KHz. Four cutthroat trout sounds were recorded and analyzed. The "thump" sound occurred when fish were alarmed and gave a sudden tail-flip. The principal frequency was 150 Hz in the band from 100 to 200 Hz. The "squawk" sound had principal frequencies in the band from 600 to 85O Hz and was probably due to gas passing through the pneumatic-duct. The "squeak" sound was infrequent and usually of low intensity. A sound with maximum energy above 2 KHz was created when a trout shifted bottom materials while preparing a redd. A partial audiogram was obtained from testing 29 cutthroat trout. The conditioned response technique was applied using shock or light as the unconditioned stimuli and both were unsuccessful.

A natural response to sound stimuli was found in six fish with an average upper frequency limit of 443 Hz. Threshold determinations were attempted on a few occasions after conditioning was achieved, however, the conditioned response could not be reinforced and extinction was rapid. Electrical and physical problems to be avoided in further underwater sound research are pointed out and discussed.

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Abstract

Underwater ambient noise in the stream-mouths of Clear, Cub and Pelican Creeks was investigated in relation to orientation and homing of cutthroat trout (*Salmo clarki*). A maximum estimate of the noise spectrum was determined from 0.1 to 10 KHz during periods of high stream discharge and wave action. Minimum noise spectra were not determined because of instrument noise interference. Two noise sources contributed to ambient pressure spectrum levels in the stream-mouths (1) cavitation and/or flow noise and (2) surf-beats. The former is mainly composed of frequencies below 4 KHz while the latter is above 5 KHz. Four cutthroat trout sounds were recorded and analyzed. The "thump" sound occurred when fish were alarmed and gave a sudden tail-flip. The principal frequency was 150 Hz in the band from 100 to 200 Hz. The "squawk" sound had principal frequencies in the band from 600 to 850 Hz and was probably due to gas passing through the pneumatic-duct. The "squeak" sound was infrequent and usually of low intensity. A sound with maximum energy above 2 KHz was created when a trout shifted bottom materials while preparing a redd. A partial audiogram was obtained from testing 29 cutthroat trout. The conditioned response technique was applied using shock or light as the unconditioned stimuli and both were unsuccessful. A natural response to sound stimuli was found in six fish with an average upper frequency limit of 443 Hz. Threshold determinations were attempted on a few occasions after conditioning was achieved, however, the conditioned response could not be reinforced and extinction was rapid. Electrical and physical problems to be avoided in further underwater sound research are pointed out and discussed.

Analysis of Sound Spectra in Yellowstone Lake in Relation to Orientation and Homing Movements of Cutthroat Trout (*Salmo clarki*)

INTRODUCTION

Orientation and homing studies on the cutthroat trout (*Salmo clarki*) in Yellowstone Lake have been carried out by Jahn (1966), McCleave (1967) and Jahn (1968) with emphasis on olfaction and vision. They found that homing could not be explained in terms of visual and olfactory mechanisms alone. Since fishes perceive low level acoustic noise by means of the acoustico-lateralis system, it was hypothesized that cutthroat trout might cue to the acoustic spectrum produced by streams. The present study had as its objectives to determine if characteristic ambient acoustic-pressure spectrum levels occur in the area of spawning tributaries, to record and analyze cutthroat trout sounds and to determine an audiogram for this fish. The field portion of this study was conducted during June and July of 1966 and 1967 and the laboratory portion from August 1967 to November 1968.

Underwater ambient noise has received much attention in the marine environment, especially since 1940. This is summarized in the work by Knudsen *et al*. (1948) and the review of the recent literature by Wenz (1962). In contrast, the freshwater environment has received little study. Lomask and Saenger (1960) made ambient noise measurements in Pend Oreille Lake, Idaho (maximum depth 351 m and area 345 km^2). No other studies with ambient noise measurements in freshwater were found.

Much information is available concerning sound production of marine fishes (Fish, 1959; Tavolga, 1960, 1965; Moulton, 1963; etc.) and relatively little for freshwater species. Of the freshwater fishes studied, most soniferous species are from the cyprinids (Stout and Winn, 1958) and siluroids (Hubbs and Miller, 1960), both ostariophysian families. No sounds have been reported for salmonids, all of which are non-ostariophysians.

Audiograms have been determined for many species of fishes. Kleerekoper and Chagnon (1954) reviewed the early literature and reported a threshold curve for the creek chub. Tavolga and Wodinsky (1963 and 1965) have done extensive work on several species of marine teleosts. Enger (1966) and Buerkle (1967 and 1968) conducted acoustic threshold experiments on the goldfish and atlantic cod, respectively. No information is available concerning an acoustic threshold of the salmonids. Attempts to guide salmon (Moore and Newman, 1956) and trout (Burner and Moore, 1962) with sound have generally failed.

Description of Study Area

Field studies were conducted on Yellowstone Lake and on the mouths of certain tributaries. The lake has an area of 354 km^2, a maximum depth of 98 m (42 m mean) and lies at an elevation of 2,358 m msl (Benson, 1961) in Yellowstone National Park, Wyoming. The tributaries studied include Clear, Cub and Pelican Creeks. These flow into the northeast part of the lake. The stream-mouth is defined as that portion of the stream influenced by wave action and changes in lake water levels and that part of the lake influenced by stream current.

The stream-mouth of Clear Creek included 107 m of stream adjacent to the lake and a distance extending 120 m out into the lake from shore. This also included 100 m along the lake shore on either side of the stream. The stream and lake bottoms in this area were composed largely of rubble with occasional boulders. In the lake the rubble and boulders were firmly anchored. The shore consisted of small loose rubble and sand which readily shifted during wave action. Estimated discharge from Clear Creek during the time when sound recordings were made ranged from 0.8 to 7.2 m^3/s with maximums occurring during June. Clear Creek entered the lake at about a 45 degree angle to the shoreline and remained relatively stable throughout the study.

The stream-mouth of Cub Creek included 110 m of stream adjacent to the lake and a distance extending 90 m out into the lake from shore. This also included 100 m along the lake shore on either side of the stream. The stream bottom was predominantly small to medium rubble and the lake bottom was the same as that found at Clear Creek. The shore materials were more abundant and less stable than those at Clear Creek. Estimated discharge from Cub Creek during the time when sound recordings were made ranged from 0.9 to 4.0 m^3/s. The position where Cub Creek entered the lake shifted several meters from time to time depending on wave conditions and discharge from the stream. Cub Creek entered the lake at about a 10 degree angle in relation to the shoreline.

While the stream-mouth of Pelican Creek included about 1,045 m of stream, only 30 m were navigable with the equipment used. A distance extending 90 m out into the lake from shore and 100 m along the lake shore on each side was studied. The stream and lake bottoms were almost entirely of fine sand. The shore was also composed of sand which remained relatively stable because spits extended well out into the lake on both sides of the stream-mouth which reduced the effects of wave action. No discharge measurements were made, but this stream is much larger than either Cub or Clear Creeks. Pelican Creek entered the lake at about a 90 degree angle to the shoreline and remained stable throughout the study.

A control area was established adjacent to the shore between the mouths of Clear and Cub Creeks which are 1.5 km apart. This area was chosen for its lack of tributaries. A distance extending 90 m into the lake and 100 m along the shore in each direction was included. Lake bottom and shore materials were similar to those found in the Clear and Cub Creek areas.

MATERIALS AND METHODS

Lake depths in the stream-mouths and control area were obtained with an echo sounder (Bendix Model DR-23S). Temperature profile data were taken with a bathythermograph (G. & M. Inst. Co.). Wave heights were measured peak to trough with a wave gage.

Depth changes were recorded on Clear and Cub Creeks with a relative depth meter. This unit consisted of a float housed in a 10 cm pipe coupled through a pulley system and Geodyne clock to a Rustrak recorder. Stream velocities were measured with a Gurley current meter. Discharge was computed at high and low stages. A correlation of relative depth in μA to discharge in m^3/s was made. This curve provided discharge readings for times when underwater ambient noise recordings were made. Due to large fluctuations in depth on Cub Creek several adjustments were made in order to keep the recorder on scale. As a result, depth recordings could not be used to compute a curve from two velocity measurements. Only the discharge rates obtained from high and low velocity readings were used for Cub Creek.

Reference points 30 m apart were established by placing marker buoys (10 cm square styrofoam floats) on a line beginning 30 m from shore to the outer limit of each stream-mouth. The floats were placed in the center of the visible stream current extending into the lake. Buoys were placed similarily in the middle of the control area perpendicular to the shoreline. All underwater ambient noise measurements were made at these points of reference.

The acoustic recording system (Fig. 1) consisted of an omnidirectional hydrophone (Massa Model M-115 BS) with built-in preamplifier. The hydrophone employed a pair of ammonium dihydrogen phosphate (ADP) crystal assemblies as sensing elements. The frequency response was essentially flat from 10 Hz to 10 KHz. The sensitivity was a -99 dB re 1 volt per microbar at the end of 152.5 m of cable. The amplifier was a (Millivac Type VS-68 B) low noise, high impedance portable unit with a gain of 60 dB. The self contained batteries supplied power to the hydrophone preamplifier. The amplifier was modified to include a tuned 18.6 KHz filter to eliminate communication signals which interfered with underwater recording operations. A two track battery operated tape recorder (Uher 4000 Report-L) with a frequency response of 40 Hz to 20 KHz (tape speed of 19 cm/s) completed the system. The recording level control was set to zero dB in all cases in order to obtain the optimum ratio of signal to noise.

Self-noise of the hydrophone and cable was held to a minimum by suspending the system from 10 cm square styrofoam floats each attached by a 60 cm line and spaced five meters apart along the cable. The cable was held off the lake bottom and allowed to sag between floats. This reduced transmission of self-noise to the hydrophone. The float nearest the hydrophone was a cone (d = 20 cm, h = 20 cm) floated point down. This prevented the slapping noise which would have occurred if a square float had been used. This system worked satisfactorily in shallow water and at low wave heights. No measurements were made during extreme wave heights because the hydrophone struck the lake bottom at such times. During all ambient noise recordings

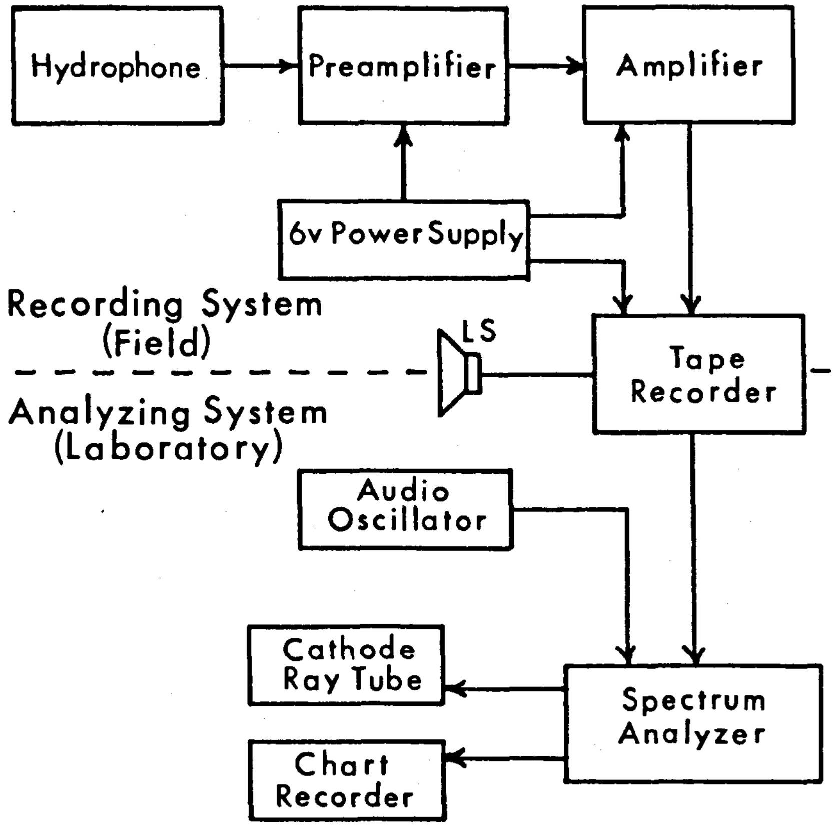

Figure 1. Diagram of the acoustic recording and laboratory sonic analysis systems.

the amplifier and tape recorder were aboard a 7.32 m boat anchored 90 to 150 m from the hydrophone. Each time a recording was made the hydrophone was either anchored near or tied to a marker buoy at a depth no greater than 50 cm.

The analytical system (Fig. 1) consisted of a Panoramic SY-1 Sonic Analysis System (Metrics Division, The Singer Co.) which provided the cathode ray tube and chart recorder readouts. The analyzer block contained a Model LP-1aZ Sonic Spectrum Analyzer and a C-2 Auxiliary Function Unit. Ambient noise analyses were made from continuous four minute tape recordings. Individual recordings were separated and identified with a two second piece of timing tape. Only the frequency range from 0.1 to 10 KHz was considered and this was analyzed in two bands from 0.1 to 5 KHz and 5 to 10 KHz. All recordings were played into the analyzer for each frequency band and for the same four minute time period. A representative level versus frequency noise envelope was obtained as a chart recording. During analysis the tape recorder input was monitored through a loud speaker. An audio oscillator (Hewlett-Packard Model 200-CD) was used to set the center frequency during analyses.

System noise was recorded with the hydrophone placed in a sound proof box in an area free from electrical or acoustical interference. This recording was made and analyzed at the same system settings as those for underwater ambient noise and a standard curve was obtained. All ambient noise curves were compared with this standard in order to determine if they were greater than system noise. Ambient noise was then plotted in relation to system noise.

Fish sounds were detected with the same recording system described above. The hydrophone was suspended in Clear or Cub Creek pools with a float and anchor near concentrations of fish. The amplifier and tape recorder were placed on the bank. Visual and audio observations were made simultaneously without disturbing the fish. Fish sounds were recorded and stored on magnetic tape. The tapes were played and the loudest sounds were selected for analyses. A two-second piece of timing tape was used to isolate a section of tape containing a fish sound. A level versus time plot was made for each center frequency by tuning the spectrum analyzer through successive 50 Hz bands. Input was continuously monitored through a loud speaker. An audio oscillator was used to tune the center frequency of the spectrum analyzer each time. When a sound was analyzed the major pip amplitude for each center frequency and a mean of the background intensities were plotted as the average system noise.

An attempt was made to determine an audiogram for the cutthroat trout using the technique which employed a change in cardiac and respiratory rhythms as a conditioned response to pure sound stimuli. The experimental fish used included the Yellowstone cutthroat trout and Lahontan cutthroat trout (Salmo clarki henshawi). The latter were obtained from brood stock held at a local fish hatchery and were more satisfactory for experimental purposes. The specimens used were four generations removed from wild stock and easily maintained on fish food pellets. These fish ranged in size from 30.7 to 35.3 cm (total length). Wild sexually mature cutthroat trout from

Yellowstone Lake deteriorated very rapidly in the laboratory and refused to eat commercial fish-food preparations. All fish brought to the laboratory were maintained at least one week before tests were begun.

The experimental equipment (Fig. 2) consisted of a test tank, 122 cm in diameter by 76 cm deep, constructed of polyester plastic resin reinforced with fiberglass mounted on 1.6 cm thick rubber pads to partially insulate it from floor vibrations. The inside walls and bottom were lined with 5 cm thick rubberized horsehair (Tavolga & Wodinsky, 1963) to decrease the background noise. This did not eliminate reflection or standing waves. The outside walls and bottom were covered with rock wool insulation (5 cm thick) to reduce the transmission of room noise. The tank was covered with a light-tight plywood shell 33 cm in height. A 200 watt light was mounted inside the top of this shell. Water was circulated continuously through the tank except during the critical periods of tests.

Sound used to condition the fish was produced with an audio oscillator connected through a switching unit, impedance matching transformer (UTC, Type LS-33) and dB attenuator (Hewlett-Packard Model 350 C/D) to a wide band transducer (Model J-9). The transducer was suspended near one side of the tank. The sound pressure measurement system was the same as that described for ambient noise measurements. Input and output voltages were monitored on an oscilloscope (Heath Model 10-14). Calibration of sounds in the tank showed which frequencies would not be distorted when presented to the fish. These were the only ones used in training and testing the fish.

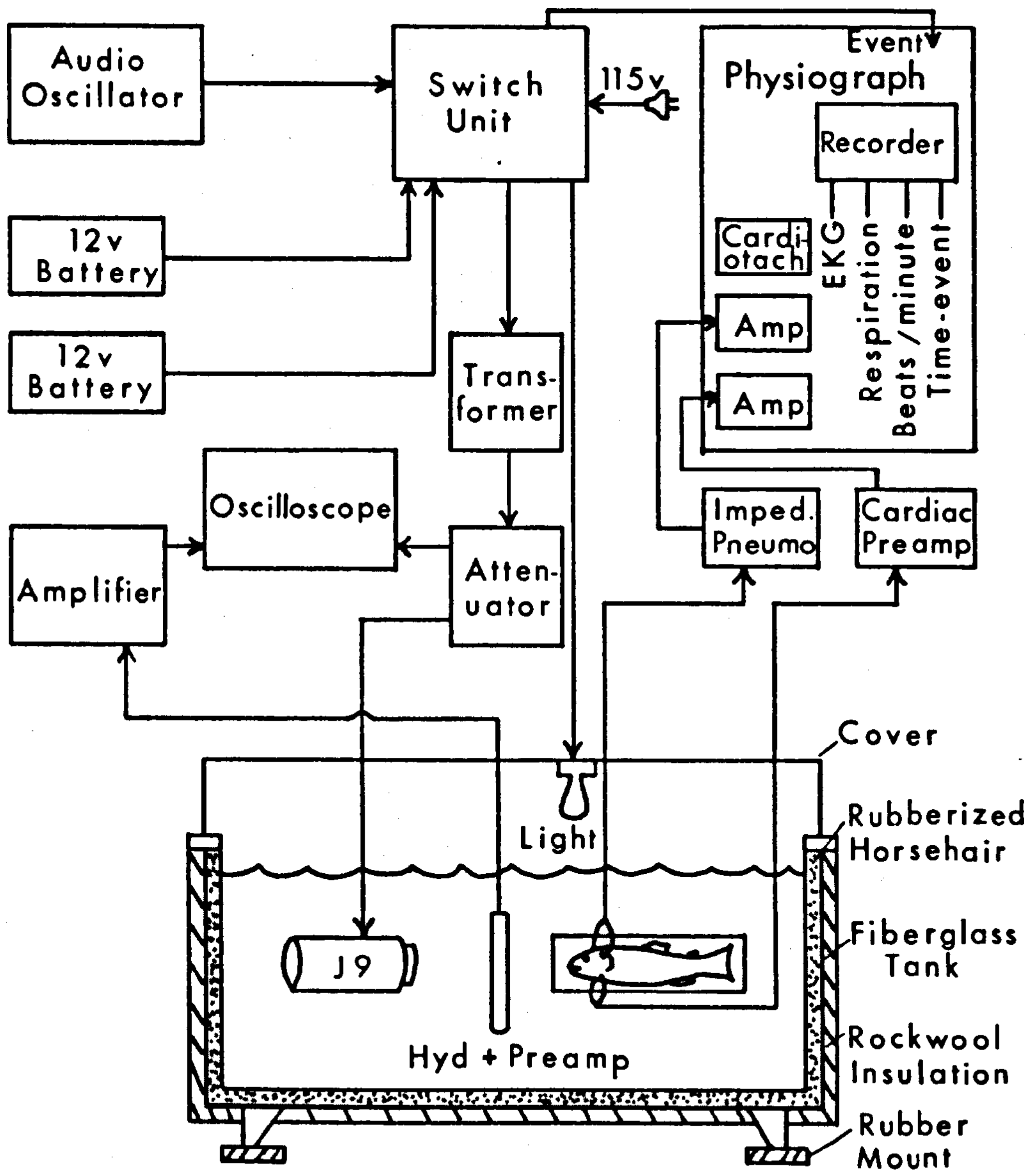

Figure 2. Diagram of instrumentation and cross-section of experimental tank.

The switching unit, powered by two twelve volt batteries, controlled the presentation of conditioned (sound) and unconditioned (light) stimuli on a random schedule. Between 50 and 80 pulses per hour could be obtained. Each pulse activated the sound immediately and the light after four seconds, both of which terminated at the end of 6 seconds. This sequence constituted one conditioning exercise. After several unsuccessful attempts to condition fish this unit was modified to include an amplifier that would produce a 20 volt output to increase the sound intensities within the tank. Unfortunately these modifications did not provide the increased output needed. The maximum intensity which could be obtained was -5 dB re 1 microbar. This could be produced without the switch unit and the latter was replaced with a hand operated photoconductive switch and light switch for the remainder of the tests. The same pulse intervals were maintained with a standard five minute interval between pulses.

Each fish was anaesthetized with MS-222. Two electrodes (No. 24 Nichrome wire) were threaded into the body cavity on each side of the pericardial region with a large needle. These electrodes (McCleary and Bernstein, 1959) were insulated except for a 0.6 cm section 1.3 cm from the end on which a button had been attached to keep them from pulling out of the fish. They picked up the action potentials of the heart and transmitted them to a cardiac preamplifier, physiograph (E. and M. Inst. Co., Inc., Houston, Texas, Physiograph "Four") and were recorded on channel one (Fig. 2). One disc electrode was attached to each opercle with a minigator clip. These electrodes picked up the action potentials of the operculum and transmitted them to an impedance pneumograph, physiograph and were recorded on channel two. A cardiotach module was used in the physiograph to give a recording of heart beats per minute on channel three. Channel four recorded time and number of conditioning exercises.

A fish was confined to a specific location during experiments by placing it in a cage (38 x 7.5 x 5 cm) made of plexiglass (0.6 cm thick) with numerous perforations. The cage had a small door in one end for easy entry and removal of fish. The other end was adjustable to accommodate fish of different lengths. Sound pressures were monitored where the head of the fish was confined.

Each fish so prepared was placed into the cage and connected to the physiograph. Its electrocardiogram and respiratory rhythms were observed and if these appeared normal (indicating proper electrode placement), then it was allowed 12 to 24 hours to adjust to this new situation before testing began.

When the association of sound and light was established during conditioning, the onset of sound caused an alteration in cardiac and respiratory rhythms. This positive response was characterized by a delayed or missing cardiac potential and/or by a sudden severe depression in the respiratory rhythm. A negative response was one where there was no change in cardiac or respiratory rhythms in response to a sound. Testing attempted to elicit positive responses of the fish to decreasing sound pressures. This entailed decreasing and sometimes increasing sound pressures by 5 dB steps in order to confirm a previous response.

RESULTS

Ambient Noise Measurements

Ambient noise measurements were made at points along a line of marker buoys placed in each stream-mouth and in the control area as described above. The lake depths taken at the buoys indicated a gradual slope away from shore except in the Pelican Creek stream-mouth where depths were nearly uniform. The distances from shore to each buoy and the depths in meters follow.

Buoy (meters from shore)	Depth (meters) Clear Creek	Cub Creek	Pelican Creek	Control Area
30	2.1	0.6	1.5	3.4
60	3.0	0.9	1.5	4.3
90	4.3	1.2	1.2	4.6
120	5.5			

Ambient noise spectra were determined for Clear and Cub Creeks at high and low stream discharge rates. Recordings were made at selected times when lake surface conditions ranged from flat-calm to waves less than 6 cm high. Under this range of surface conditions no major differences in ambient noise were observed. High stream discharge was responsible for creating waves and turbulence in the lake. Ambient noise spectra were obtained from recordings by the analytical procedure described above. The points of each curve at 0.1, 1 and 10 KHz were selected and the intensities were converted to dB re 1 microbar and plotted as straight-line semi-logarithmic graphs (Fig. 3 and 4). The ambient noise spectra for Clear Creek (Fig. 3a) are

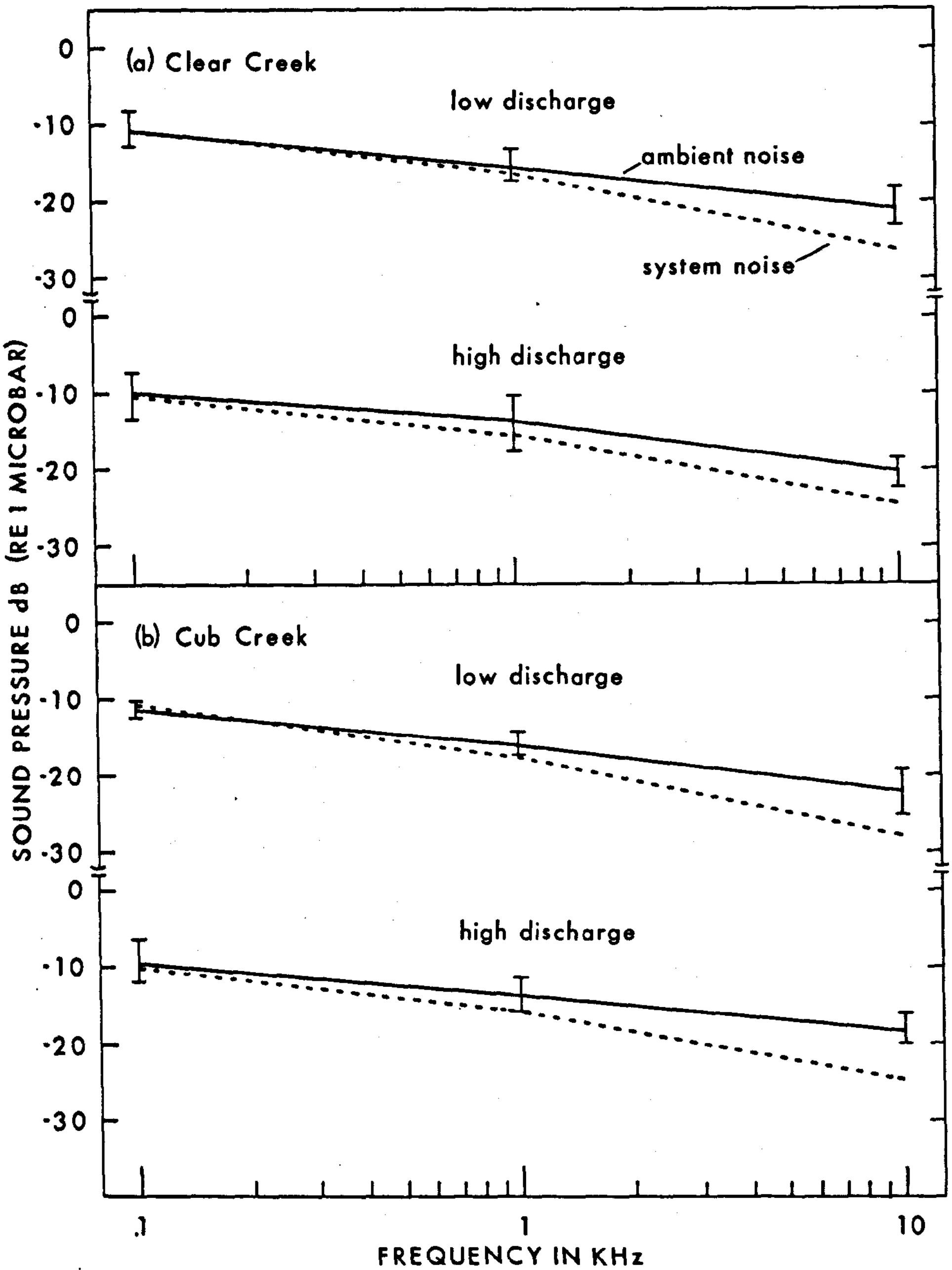

Figure 3. Comparison of mean ambient noise spectra for Clear and Cub Creek stream-mouths (lake surface calm) at low stream discharge (mean 1.7 m^3/s, Clear; ~0.9 m^3/s, Cub) and high stream discharge (mean 6.8 m^3/s, Clear; ~4.0 m^3/s, Cub).

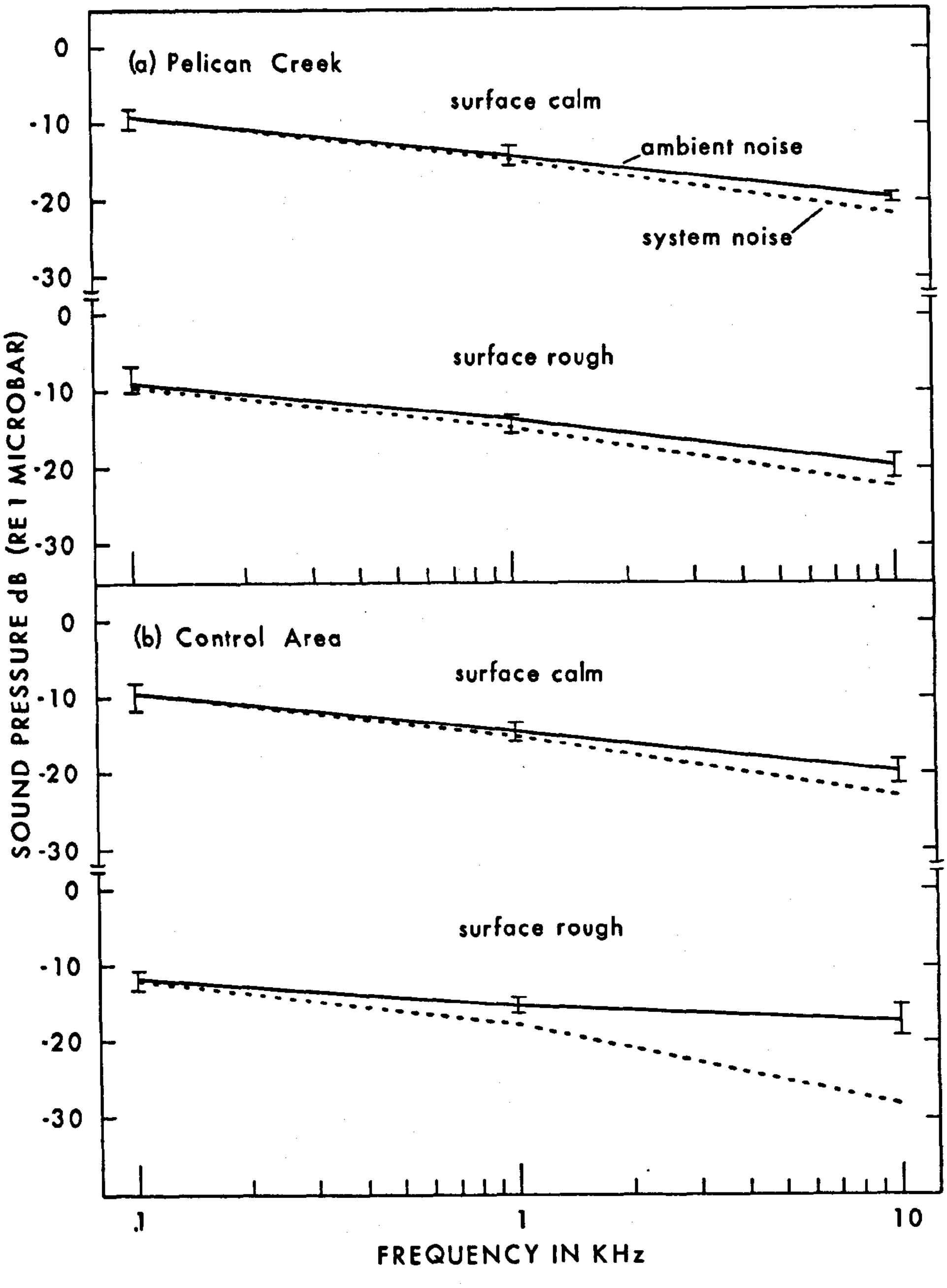

Figure 4. Comparison of mean ambient noise spectra for Pelican Creek stream-mouth and control area for calm surface conditions (flat-calm to 0.06 m waves) and rough surface conditions (waves 0.06 to 0.5 m, Pelican Cr.; 0.06 to 0.25 m, control area).

averages obtained from 10 recordings during low stream discharge (mean 1.7 m^3/s) and 14 recordings at high-discharge (mean 6.8 m^3/s). The mean ambient noise spectrum for low-discharge are approximately -11, -15.5 and -21 dB at 0.1, 1 and 10 KHz, respectively while the mean spectrum for high-discharge are approximately -10, -14 and -20.5 dB at 0.1, 1 and 10 KHz, respectively. The mean spectrum for high-discharge is higher by approximately 1, 1.5 and 0.5 dB at 0.1, 1 and 10 KHz respectively than the mean spectrum at low-discharge. The slopes of both mean spectra are about 1.5 dB per octave from 0.1 to 1 KHz and 2 dB per octave from 1 to 10 KHz. Ambient noise fluctuated over a wider intensity range (-7 to -13 dB at 0.1 KHz and -10 to -18 dB at 1 KHz) at high-discharge than at low (-8 to -12.5 dB at 0.1 KHz and -13 to -17 dB at 1 KHz). The higher frequencies show less fluctuation at high-discharge (-18.5 to -22.5 dB at 10 KHz) than at low-discharge (-18 to -23.5 dB at 10 KHz). A close association exists between mean spectra and system noise. At 0.1 KHz the system and ambient noise follow the same curve at low-discharge, but deviate slightly at high-discharge. A separation exists at 1 KHz (2 dB) at high-discharge but at 10 KHz the deviation between system and ambient noise is about equal. Temperature profiles were taken during the study but since no ambient noise recordings were made at depths greater than 50 cm, temperature effects were considered negligible.

The ambient noise spectra for Cub Creek (Fig. 3b) are averages obtained from 11 recordings during low stream discharge of near 0.9 m^3/s and 9 recordings at high-discharge of near 4.0 m^3/s. The mean ambient noise spectrum for low-discharge is approximately -11.5, -16 and -22 dB at 0.1, 1 and 10 KHz, respectively while the mean spectrum for high-discharge is approximately -9.5, -13.5 and -18.5 dB at 0.1, 1 and 10 KHz, respectively. The mean spectrum for high-discharge is higher by approximately 2, 2.5 and 3.5 dB at 0.1, 1 and 10 KHz respectively, than the mean spectrum at low-discharge. The slopes of both mean spectra are about 1.5 dB per octave from 0.1 to 1 KHz and 2 dB per octave from 1 to 10 KHz. Ambient noise fluctuated over a wider intensity range (-6 to -12 dB at 0.1 KHz and -11 to -16 dB at 1 KHz) at high-discharge than at low (-10 to -12 dB at 0.1 KHz and -14 to -17 dB at 1 KHz). The higher frequencies show less fluctuation at high-discharge (-16 to -20 dB at 10 KHz) than at low-discharge (-19 to -25 dB at 10 KHz). A close association exists between mean spectra and system noise. The mean spectrum for low-discharge at 0.1 KHz indicate that mean system noise masked the extremely low ambient noise. At higher frequencies as well as at high-discharge the mean ambient noise intensities deviate above the mean system noise. Deviation was 2 dB at 1 KHz for high-discharge but at 10 KHz deviation was about equal.

Ambient noise spectra were determined for Pelican Creek and the control area comparing calm surface conditions to rough. Calm surface conditions ranged from flat-calm to light-swell (less than 6 cm waves) which did not cause turbulence on the surface. Rough surface conditions included waves greater than 6 cm high. Recordings were made at selected times when wave action was the greatest cause of underwater ambient noise. Surface conditions in the Pelican Creek stream-mouth were measured at a maximum of 0.5 m (rough conditions) which occurred during a sudden wind squall. No turbulent flow was observed to affect surface conditions in the Pelican Creek stream-mouth during these recordings. Surface conditions in the control area were measured at a maximum of 0.25 m (rough conditions) which occurred during a persistent breeze.

The ambient noise spectra for Pelican Creek (Fig. 4a) are averages obtained from 9 recordings made during calm surface conditions and 6 recordings under rough surface conditions. The mean ambient noise spectrum for calm conditions is approximately -9, -14 and -19.5 dB at 0.1, 1 and 10 KHz, respectively while the mean spectrum for rough conditions is approximately -9, -13.5 and -19.5 dB at 0.1, 1 and 10 KHz, respectively. The mean spectrum for rough conditions is 0.5 dB greater than for calm conditions at 1 KHz. The slopes of both mean spectra are about 1.5 dB per octave from 0.1 to 1 KHz and 2 dB per octave from 1 to 10 KHz. Ambient noise fluctuated over a wider intensity range (-6.5 to -10 dB at 0.1 KHz and -18 to -21 dB at 10 KHz) under rough conditions than at calm (-8 to -10.5 dB at 0.1 KHz and -19 to -20 dB at 10 KHz). The range of fluctuation was identical at 1 KHz (-13 to -15 dB) for both mean spectra. There is a close association with mean system noise. Deviation of mean spectra from mean system noise occurred under rough surface conditions at 0.1 KHz and increased to 1 dB at 1 KHz and 3 dB at 10 KHz.

The ambient noise spectra for the control (Fig. 4b) are averages of 15 recordings at calm surface conditions and 3 recordings under rough conditions. The mean ambient noise spectrum for calm conditions is approximately -9.5, -14.5 and -19.5 dB at 0.1, 1 and 10 KHz, respectively, while the mean spectrum for rough conditions is approximately -12, -15.5 and -17 at 0.1, 1 and 10 KHz, respectively. The mean spectrum for rough conditions is 2.5 and 1 dB at 0.1 and 1 KHz lower than the mean spectrum at calm conditions. However, for rough conditions the mean spectrum is 2.5 dB higher at 10 KHz than the spectrum at calm conditions. The slope of the mean spectrum for calm conditions is about 1.5 dB per octave and that for the mean spectrum for rough conditions is 1.0 dB per octave from 0.1 to 1 KHz. For the mean spectrum from 1 to 10 KHz the slopes are 1.8 dB per octave for calm and 0.5 dB per octave for rough conditions. Ambient noise fluctuated over a wider intensity range (-8 to -12 dB at 0.1 KHz and -13 to -16 dB at 1 KHz) under calm surface conditions than for rough (-10.5 to -13 at 0.1 KHz and -14 to -16 dB at 1 KHz). However, a greater fluctuation occurred at 10 KHz (-15 to -19 dB) for rough surface conditions than for calm (-18 to -21.5 dB). Mean ambient noise was again closely associated with mean system noise at calm conditions but a marked deviation occurred in the mean spectrum for rough surface conditions, especially from 1 to 10 KHz. The deviation between ambient noise and system noise is 2 and 11 dB at 1 and 10 KHz, respectively. The recordings used to obtain the information above are the only instances in which a direct correlation existed between intensity level and distance from shore. The ambient spectra intensity levels show a decrease with distance from shore indicating a major noise source at the shoreline. The spectral energy ranged from about 2 to 10 KHz.

Two noise sources contributed to the ambient noise in the stream-mouth (1) cavitation and flow noise in the immediate vicinity of the hydrophone due to surface waves or high stream discharge and (2) surf-beats on shore due to wave action shifting shore materials. Cavitation and flow noise (Fig. 5A) has major significance in the frequencies below 4 KHz. There is a lack of any significant high frequency components. Surf-beats (Fig. 5B) occurred during one recording when a boat wake reached shore. The lake surface at this time was flat-calm except for a boat wake traveling toward shore. This wake did not create a rise in ambient noise until it reached the beach. The pips (surf-beats) seen above 8 KHz are those which occurred as each wave broke on shore. The general increase in background from 5 to 6 KHz occurred when a trailing series of waves reached shore at an acute angle. This series of waves ran down a length of shoreline. Each wave caused an individual pip (surf-beat) but the wave series created an overall rise in the ambient noise due to the angle of incidence with the shore. Each surf-beat contributed to the one before it, adding to a general rise in the ambient noise which did not subside until all the waves were dissipated on shore. The absence of low frequency noise below 5 KHz is significant. Figure 5C illustrates the combination of both noise sources during high stream flow and wave action on shore. The major pips above 5 KHz are due to surf-beats and those below 4 KHz are due to cavitation and flow noise with a zone of overlap from 4 to 5 KHz. The rise in the ambient spectra seen in Fig. 4b for rough surface conditions is due to surf-beats creating a greater acoustic pressure at higher frequencies.

Ambient noise levels in the stream-mouths are probably much lower than shown, especially for calm conditions. All recordings of ambient noise were