# ANALYSIS OF SOUND SPECTRA IN YELLOWSTONE LAKE IN RELATION TO ORIENTATION AND HOMING MOVEMENTS OF CUTTHROAT TROUT (*Salmo clarki*)

by

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Vita

The writer was born in Billings, Montana, 25 March 1938, to Mr. and Mrs. Quentin W. Stober. He resided in Monarch, Montana and graduated from Belt Valley High School in 1956. He attended Washington State University, Pullman, Washington in 1956-57 and Montana State University from 1957-60 and was graduated with a B. S. degree in Fish and Wildlife Management. In September 1960 he entered graduate school at Montana State University and was employed as a part-time fisheries biologist by the Montana Fish and Game Department. He was graduated with a M. S. degree in Fish and Wildlife Management in March of 1962. He spent six months on active duty with the U. S. Army Reserve following graduation. He was employed by the U. S. Public Health Service, Division of Water Supply and Pollution Control, Pesticide Pollution Studies, Southeast Water Laboratory, Athens, Georgia from December 1962 to September 1965. In December 1965 he married Angie N. Hollingsworth of Carrollton, Georgia. He returned to graduate school at Montana State University as a Graduate Research Assistant on a grant from the Office of Naval Research and a FWPCA Training Fellowship from 1965-68.

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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.

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 $\mu$A 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

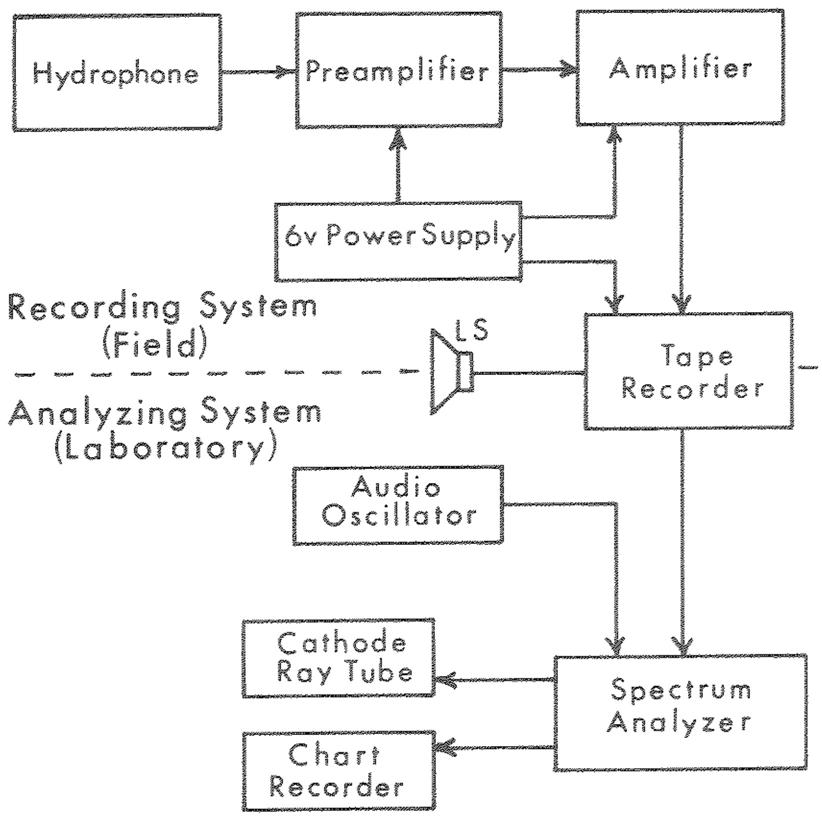


Figure 1. Diagram of the acoustic recording and laboratory sonic analysis systems.

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 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.

| | Depth (meters) | | | |
|---|---|---|---|---|
| Buoy (meters from shore) | 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

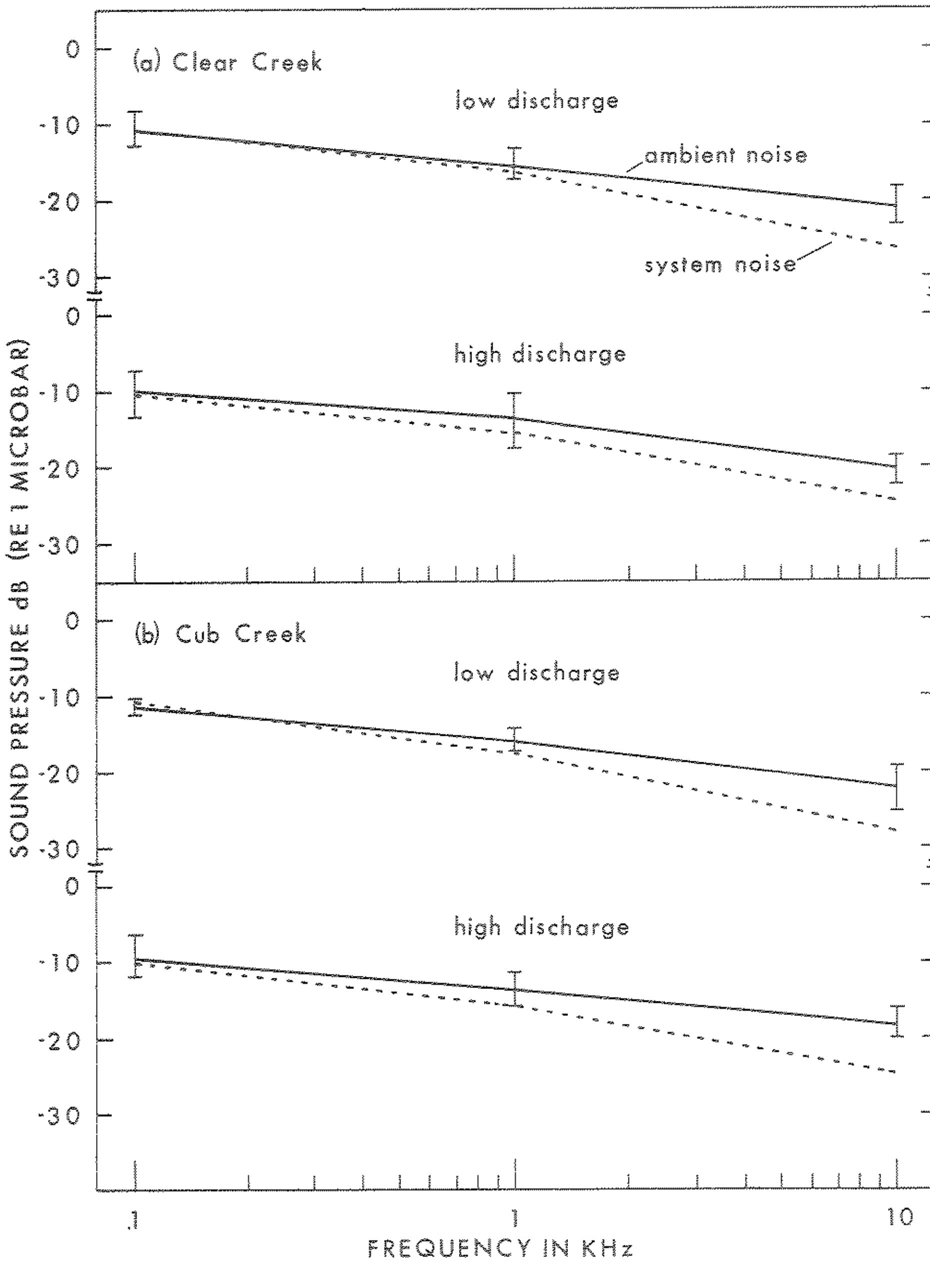


Figure 3. Comparison of mean ambient noise spectra for Clear and Cub Creek stream-mouths (lake surface calm) at low stream discharge (mean 1.7 $m^3/s$, Clear; $\sim$0.9 $m^3/s$, Cub) and high stream discharge (mean 6.8 $m^3/s$, Clear; $\sim$4.0 $m^3/s$, Cub).

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

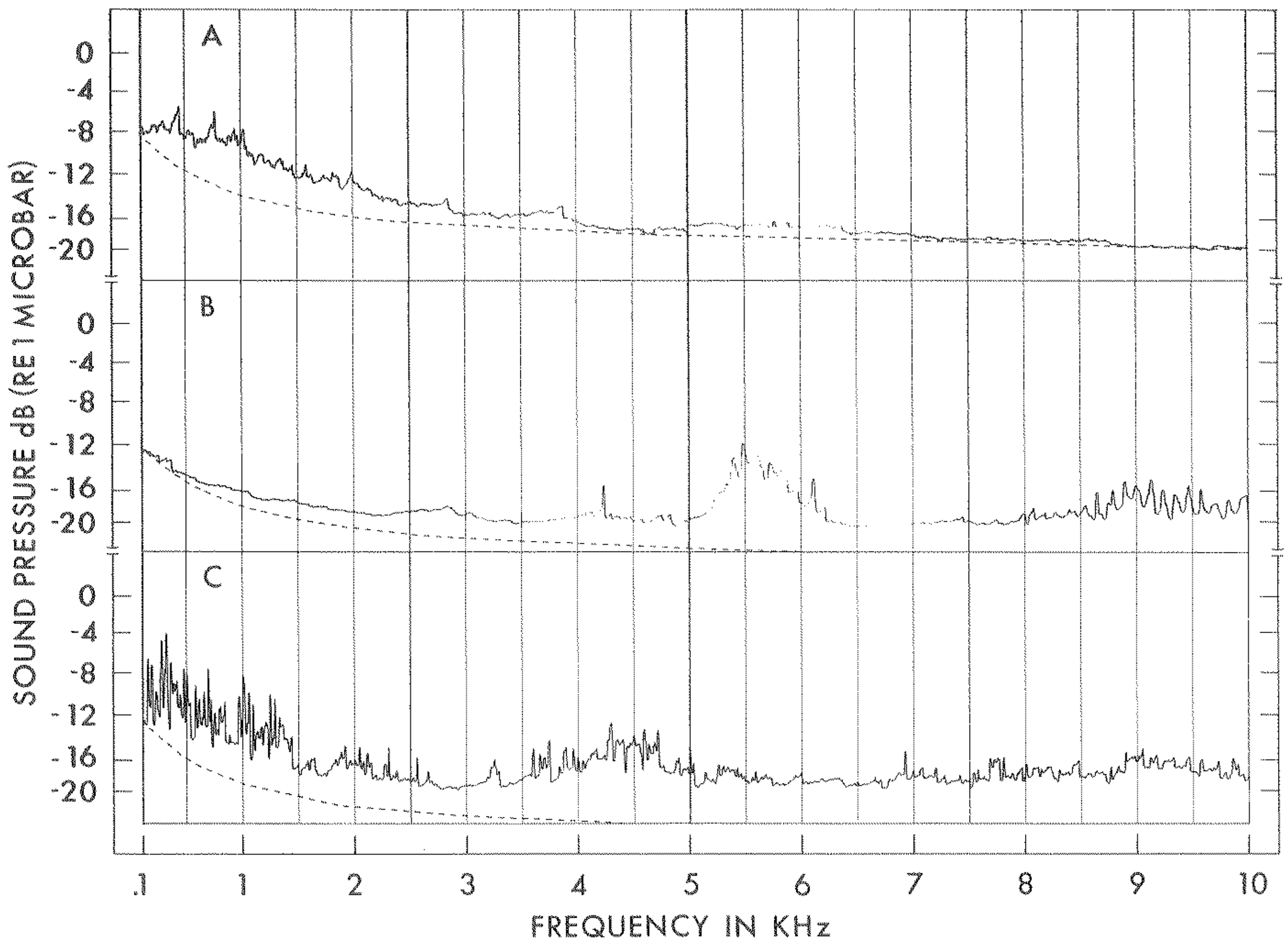


Figure 5. Ambient noise spectra showing two noise sources: (A) cavitation and/or flow noise; (B) surf-beats; (C) both cavitation and/or flow noise and surf-beats. System noise dashed line.

influenced by system noise and in some cases completely masked by it (Fig. 3b low discharge at 0.1 KHz). Only those recordings which were made during surf-beats or local cavitation and flow noise provided a good upper estimate of the ambient background. A comparison of my work to others is shown in Fig. 6. The standard curve for my system noise is plotted in relation to zero sea state (Knudsen, 1948), a partial spectrum determined for Pend Oreille Lake (Lomask and Saenger, 1960) and an empirical lower limit determined by Wenz (1962). This shows that system noise prevented the determination of low level ambient noise in Yellowstone Lake. The relationship of ambient noise to system noise is further represented in Fig. 5. Fig. 5A presents a low ambient background and the most closely associated system noise. Fig. 5B and C in succession were recordings during periods of higher ambient backgrounds. In these two recordings the association with system noise decreases as the ambient noise increases.

## Cutthroat Trout Sounds

The spawning run of cutthroat trout in the tributaries of Yellowstone Lake provided a unique situation in which to observe and record fish sounds. Since cutthroat trout predominate in the lake there was little interference from other species. The clarity of the water and slow rate of flow in the stream-mouth enhanced the observations of the fishes activities.

Eighty-four cutthroat trout sounds were analyzed from several hundred recorded in Clear and Cub Creek pools. The principal frequency of each fish sound analyzed was plotted to determine the rate of occurrence throughout

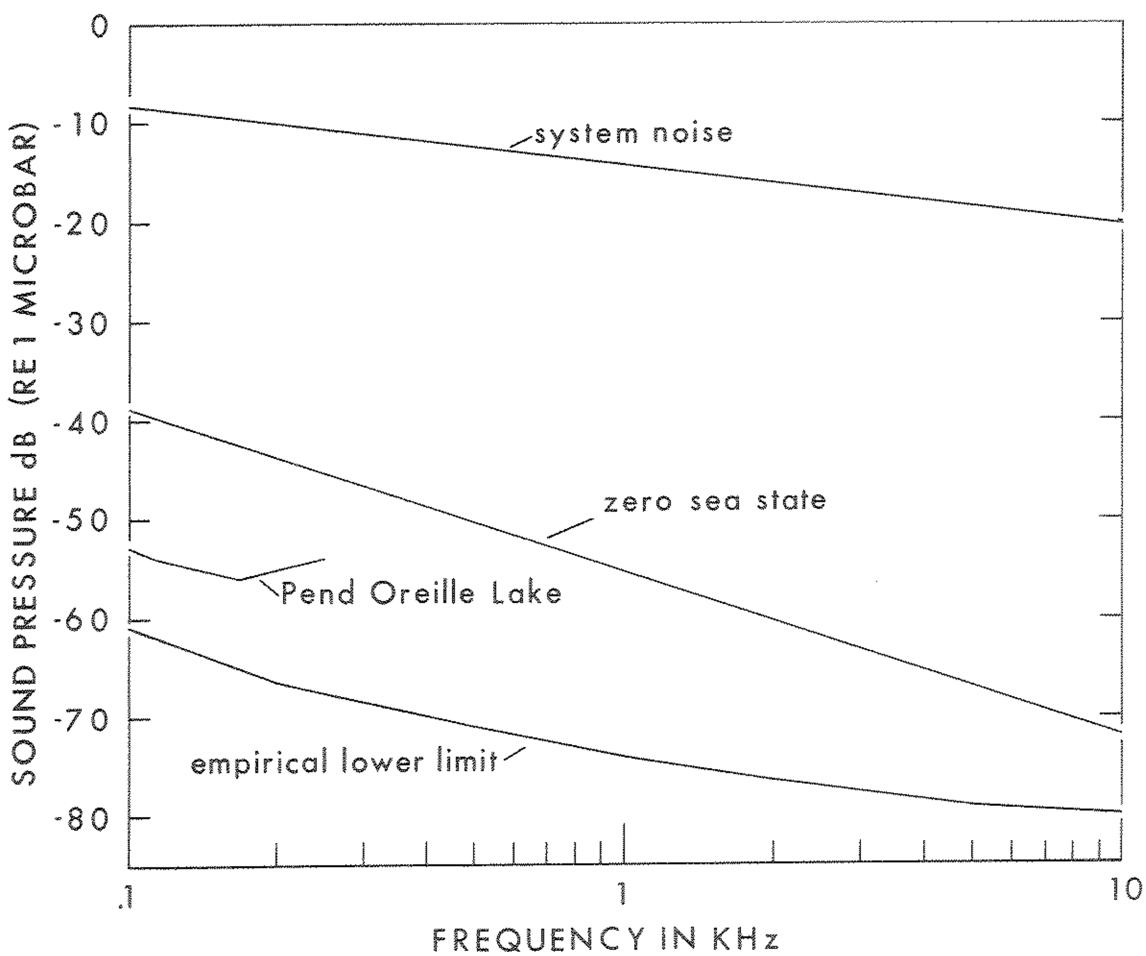


Figure 6. Comparisons of the standard system noise curve to ambient noise spectra for zero sea state (Knudsen, 1948), Pend Oreille Lake (Lomask and Saenger, 1960) and an empirical lower limit (Wenz, 1962).

the spectrum (Table 1).

Table 1. Rate of occurrence of the principal frequencies of 84 fish sounds.

| Freq. (Hz) | No. | Freq. (Hz) | No. | Freq. (Hz) | No. |
|---|---|---|---|---|---|
| 0 | 0 | 750 | 5 | 1500 | 2 |
| 50 | 0 | 800 | 3 | 1550 | 0 |
| 100 | 3 | 850 | 3 | 1600 | 0 |
| 150 | 18 | 900 | 0 | 1650 | 0 |
| 200 | 6 | 950 | 2 | 1700 | 1 |
| 250 | 0 | 1000 | 1 | 1750 | 2 |
| 300 | 0 | 1050 | 1 | 1800 | 0 |
| 350 | 0 | 1100 | 0 | 1850 | 0 |
| 400 | 1 | 1150 | 1 | 1900 | 0 |
| 450 | 0 | 1200 | 2 | 1950 | 2 |
| 500 | 2 | 1250 | 0 | 2000 | 0 |
| 550 | 1 | 1300 | 0 | 2100 | 0 |
| 600 | 9 | 1350 | 0 | 2200 | 0 |
| 650 | 9 | 1400 | 1 | 2300 | 0 |
| 700 | 7 | 1450 | 1 | 2400 | 1 |

A high rate of repetition occurred in a band from 100 to 200 Hz with a principal frequency at 150 Hz and in the band from 600 to 850 Hz. Other principal frequencies were found but these sounds did not occur repeatedly.

An analysis representative of fish sounds in the band from 100 to 200 Hz with a principal frequency of 150 Hz was plotted (Fig. 7). All sounds have been plotted in relation to average system noise. This sound occurred as a single "thump" or a rapid series of "thumps" and was produced when fishes gave a sudden tail-flip and quickly changed directions. There were no preparatory events by the fish prior to this sound. This was apparently a startle reaction and was only observed when a sea-gull or osprey flew over the water. It could also be induced when the observer suddenly came into view or when objects were cast over the stream. No harmonic qualities were

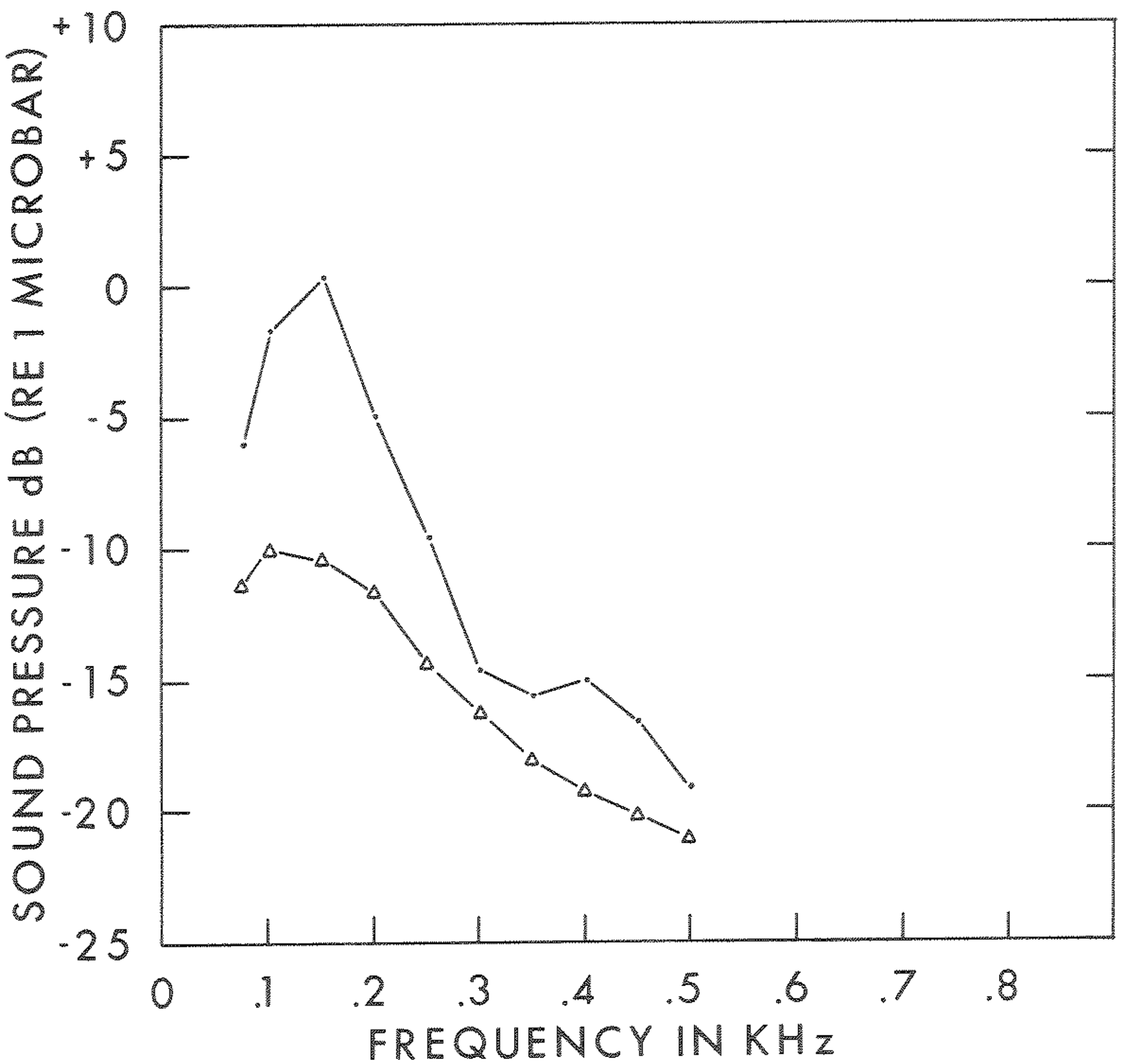


Figure 7. Analysis of a fish sound ("thump") in the band from 100 to 200 Hz with a principal frequency of 150 Hz. Line connecting triangles is average system noise.

identified in this sound. Observed sound pressures at the principal frequency (150 Hz) ranged from a maximum pressure of +1.9 dB to a minimum of -8.9 dB with a mean at -3.6 dB re 1 microbar.

The sounds with principal frequencies in the 600 to 850 Hz band were of a more variable nature. No predominant center frequency existed but there was a higher number of occurrences in the lower frequencies of this band. These sounds were "squawks" which occurred after a fish had risen to the surface, created a splash and returned to its approximate original position. At times a visible bubble trail was emitted from the gills upon return but quite frequently the "squawk" occurred several seconds after the fish had assumed its position near the bottom. An analysis representative of fish sounds in this band with a principal frequency at 700 Hz was plotted (Fig. 8). The "squawk" did not exhibit any recognizable harmonic qualities. The graph indicates the sound trailed out at higher frequencies and eventually became masked by the system noise. Observed sound pressures in this band ranged from a maximum at +6.6 dB to a minimum at -13.4 dB with a mean at -1.8 dB re 1 microbar.

An analysis representative of an intermittent sound with a principal frequency at 1450 Hz was plotted (Fig. 9). This sound was a "squeak" and would infrequently occur following a "squawk" and often be of very low intensity. No harmonic qualities were evident.

A time base is shown in Figure 10 for the "squawk" and the "squeak". These ordinarily occurred soon after a fish had surfaced. The splash caused by surfacing is shown at 1.6 seconds followed by a low intensity "squawk"

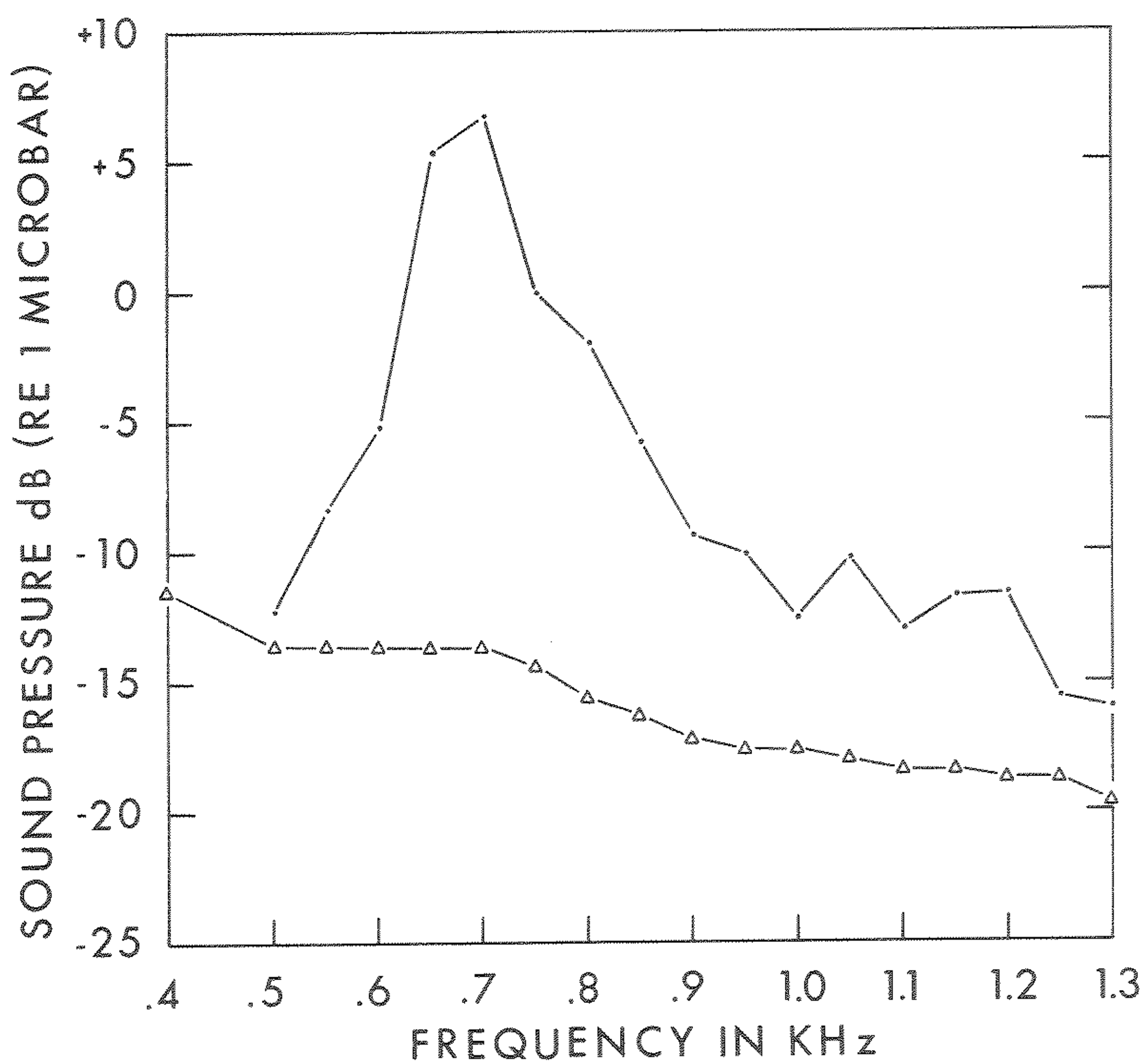


Figure 8. Analysis of a fish sound ("squawk") in the band from 600 to 850 Hz with a principal frequency of 700 Hz. Line connecting triangles is average system noise.

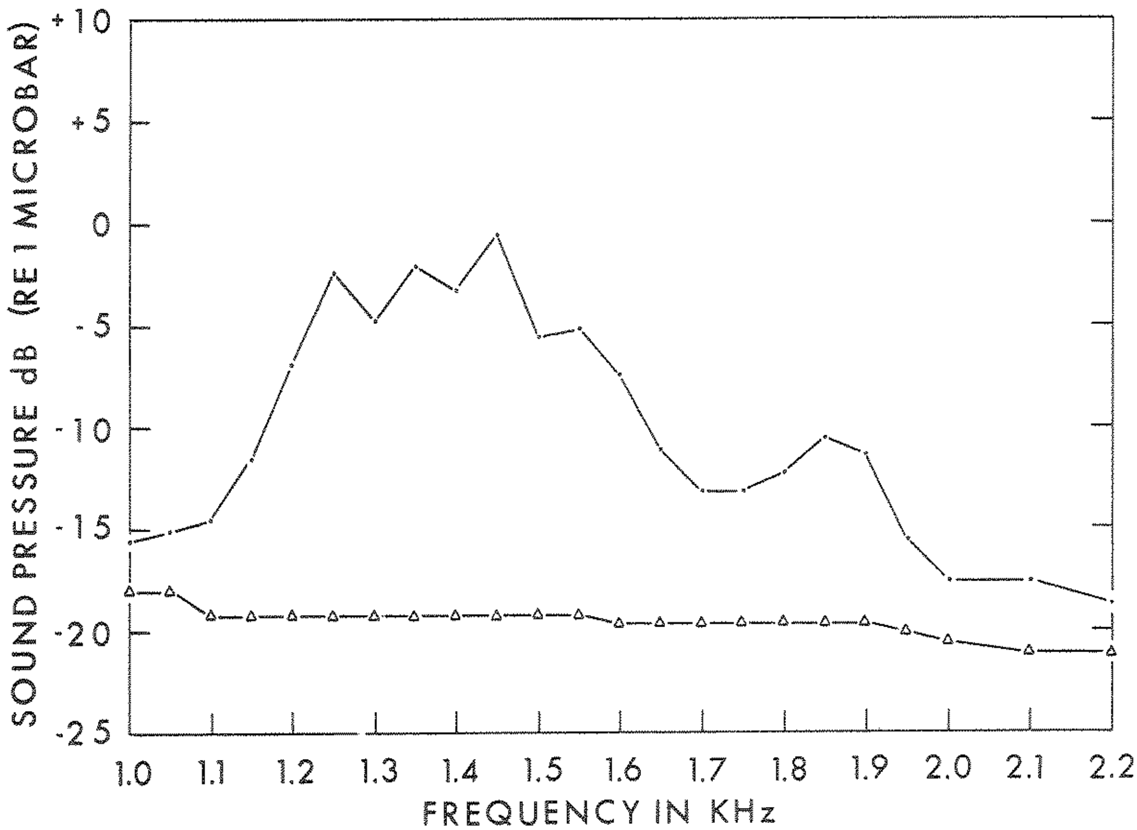


Figure 9. Analysis of a fish sound ("squeak") with a principal frequency of 1450 Hz. Line connecting triangles is average system noise.

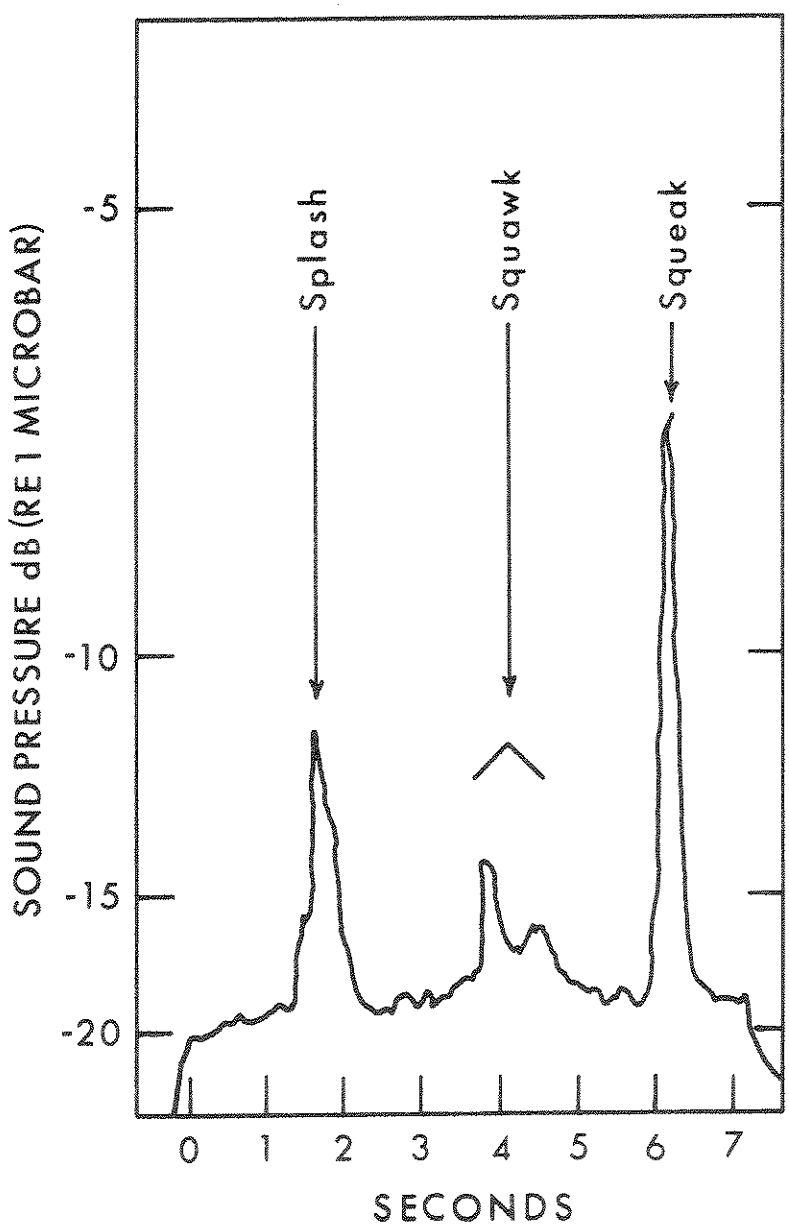


Figure 10. Sequence of fish sounds in relation to fish surfacing (splash).

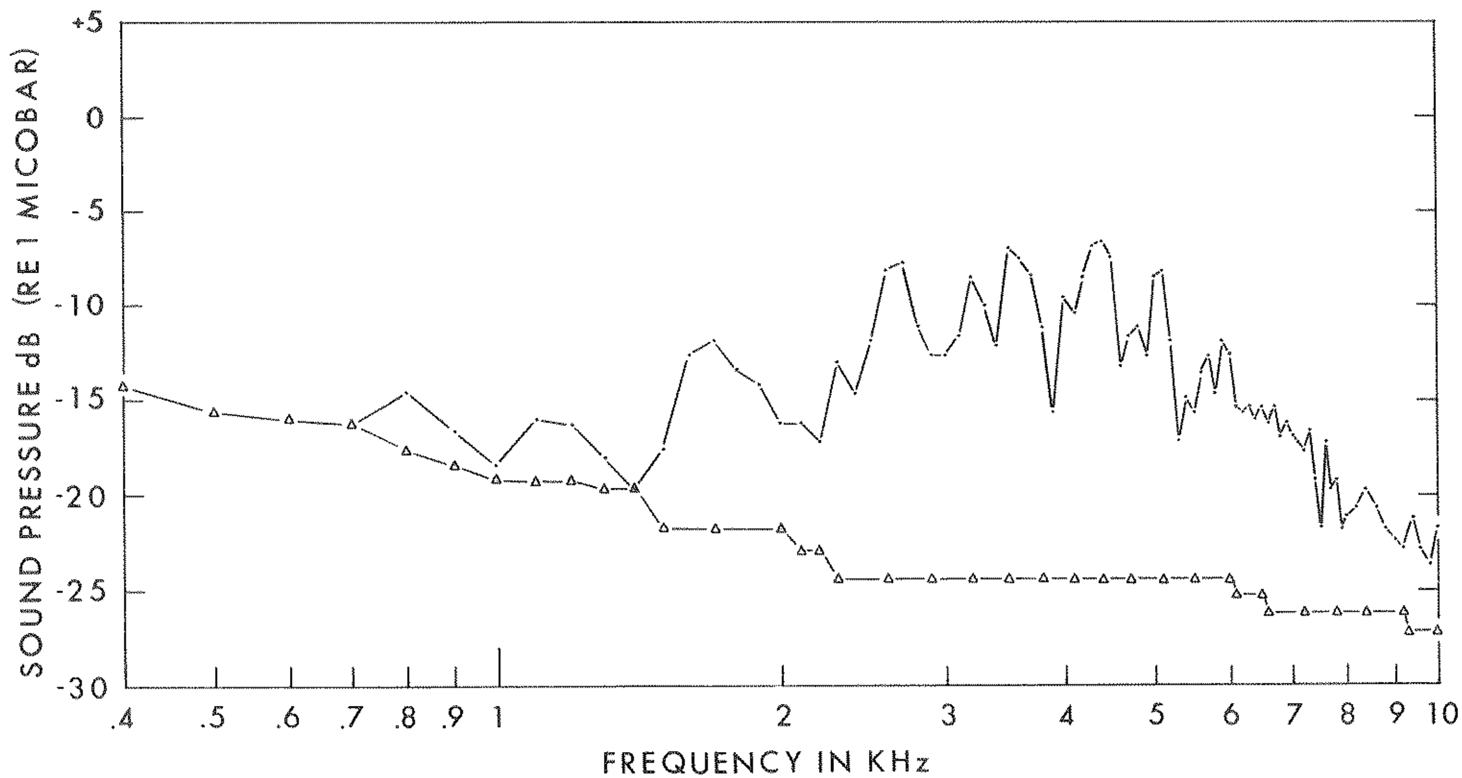


Figure 11. Spectrum of sound resulting from shifting gravel which occurred when a cutthroat trout dug a redd. Line connecting triangles is average system noise.

at 3.8 seconds and a "squeak" at 6.2 seconds. The time intervals between are variable for different fish but do indicate the order of events.

Another sound was analyzed which occurred when a cutthroat trout was digging a redd (Fig. 11). When a fish turned on its side and gave a few tail beats there occurred a characteristic gravel rustle as the bottom materials were moved. Most of the energy of this sound is above 700 Hz with maximum pressures above 2 KHz. This sound was usually recorded at very low intensities.

## Cutthroat Trout Audiogram

A total of 29 audiogram tests were conducted. The initial tests using the conditioned response technique employed low voltage electrical shock as the unconditioned stimulus (US). Voltage levels employed ranged from 3 to 100 volts across the caudal peduncle with only an occasional positive response occurring at 25 and 50 volts. The US was varied from a single instantaneous pulse to a series of pulses lasting up to 10 seconds. Occasionally a conditioned response could be established after several exercises but results were generally inconsistent. A conditioned response was not obtained after several trials on 16 individuals and therefore it was abandoned. The cutthroat trout used in these experiments became lethargic in a short time when subjected to electrical shock and would not respond.

Light was selected as a possible alternative US. A sudden on-set of the 200 watt light from total darkness gave the desired physiological reactions in one instance. A fish was partially conditioned to a 250 Hz sound during a 10-day training exercise lasting about one hour per day. Three other individuals failed to elicit a conditioned response. This technique was then reversed and a one second period of darkness was used as the US and the 200 watt light was on at all other times. Three fish were trained with this technique. Of the three, two failed to respond and the other was conditioned rapidly at 160 Hz in 29 trials over a period of 25 hours and gave four consecutive positive responses on initial testing. This was the best conditioned response obtained but it only lasted for two or three trials during threshold determination without reinforcement. After each positive and negative response during testing a reinforcement was administered to prevent extinction but there was a continual degradation in the conditioned response with time. The stair case technique was used but no threshold determination could be made before extinction was complete.

Training and testing periods as well as rest intervals were varied over the course of the study to find a working combination. Training periods lasted from 30 minutes to two hours. Rest intervals ranged from 2 to 24 hours. Four one-hour training periods per day over 2 or 3 days left the fish in better physical condition than long periods of confinement and testing. Physiological responses tended to become very erratic after 2 or 3 days of concentrated training and testing. Fish response to conditioned stimuli and US was generally best on the first few tests following a rest period of two or more hours and quickly diminished as trials proceeded.

Six fish were tested without a conditioning procedure and were found to have a natural response to sound stimuli in varying degrees. The frequency range of perception for each fish was determined. The highest frequencies eliciting response were as follows: 160, 300, 450, 550, 550 and 650 Hz. This gave an average upper limit of about 443 Hz. The lower limit was 50 Hz in all cases and the intensities were presented at a -5 dB re 1 microbar. This natural response generally became too weak or disappeared completely before threshold could be determined with the exception of one fish.

One fish had an extremely well developed natural response to sound stimuli which allowed a partial threshold determination. Testing was carried out in the order of the following frequencies beginning at 160, 300, 50, 500, 400, 90 and 160 Hz with respective thresholds at -31, -15, -33, -6, -18, -37 and -37 dB re 1 microbar. The threshold on the last two test frequencies showed a drop from initial determinations. These results were not attainable with any other fish.

## DISCUSSION

Ambient noise measurements. Sound pressures of extremely low levels characterize the ambient noise of inland lakes. The minimum background levels in Yellowstone Lake are probably much lower than those recorded. Difficulties arose when making sound pressure measurements because ambient noise levels were frequently below the electrical noise levels of the instrumentation. If these low level sounds are to be detected equipment with much lower residual noise is mandatory. Detection of acoustic noise requires amplification of the low level electrical signals developed in the hydrophone. Regardless of the quality of the amplifier there remains a residual signal in the input circuit due to thermal noise. Albers (1965, pp. 177-178) discusses this problem and suggests techniques for minimizing system noise. More recently Payne (1967) described equipment available with improved signal-to-noise characteristics that exceed at some frequencies the lower empirical limit determined by Wenz (1962, Fig. 6). However, in order to obtain better signal-to-noise characteristics it is necessary to reduce the frequency band to 3 to 3200 Hz. A reduced frequency band with an improved signal-to-noise ratio would have been an improvement in my study because the frequencies above this band are probably above the range of detection by salmonids. Measurements obtained in this study approach an upper estimate of the ambient noise levels in near-shore areas at times when sound pressures were caused by cavitation and/or flow noise and surf-beats. Ambient noise levels were too low to detect during periods of low stream flow and no wind.

Cutthroat trout sounds. Mechanisms by which fish make sounds were not determined in my study. The high degree of repetition at 150 Hz of the "thump" sound seems significant. This sound was associated with a sudden tail flip. Nothing in my work shows whether it was intrinsic or extrinsic. It may be produced by muscular contraction in the caudal peduncle or by a hydrodynamic pressure wave created as the fish moved suddenly forward. The latter would be the least likely since most hydrodynamic fish sounds have principal frequencies below 100 Hz (Moulton, 1960 and Tavolga, 1965). All adult cutthroat in a pool seemed to be capable of producing this sound. No observations were made on small individuals. At times only one fish produced the "thump" and this caused all others in the pool to dart off in various directions suggesting that it may be a warning signal. The "squawk" sound could be the result of a change in the volume of air in the gas bladder resulting from gas passing through the pneumatic-duct of a fish.

Audiogram. It is difficult to compare my work to that of others due to differences in methodology and objectives. However, some comparisons can be made. VanDerwalker (1967) also worked with a natural startle reaction. He found that salmonids responded to frequencies mainly below 170 Hz but as high as 280 Hz. This agrees generally with my results, however, I found response as high as 650 Hz. Fish became less sensitive to repeated sound exposure in my study but did not in his.

The determination of an audiogram was seriously interfered with by building vibrations and other extraneous noice which at times interrupted the conditioning process. The measurement of tank ambient noise was precluded by the high system noise of the recording apparatus which prevented comparison of pure tone sound to ambient background. The input amplifier was unsatisfactory for the production of sufficient sound intensities to determine a threshold value for all fish. In addition a uniform sound field around the fish was not possible due to acoustic reflections, standing waves and distortions which in the small tank and at the low frequencies used also plagued other workers. These could be eliminated by working in a free-field environment. Even with all of these improvements there would be no guarantee of developing an audiogram because the cutthroat trout may require other techniques.

Orientation. There are indications that acoustical cues are available to cutthroat trout. The low sound intensities measured in the lake are within the range of fish perception. The audiograms of marine non-ostariophysian species bear this out. Low level sound intensities may be detected by fish in Yellowstone Lake. McCleave (1967) and Jahn (1966, 1968) reported that when cutthroat trout are released from a mid-lake point they frequently head toward shore and follow the shoreline to the stream-mouth. The shore might be detected acoustically, at least during periods of wave action, even though noise emanating from the shoreline would probably have little influence on the ambient noise levels at mid-lake. Noise generated by surf-beats is mostly above 700 Hz and therefore would probably go undetected by cutthroat trout. Only the noise generated by cavitation and/or flow would have possible significance. This would be found only in the immediate area of a stream-mouth under calm lake conditions. Current may be of much greater influence and serve as a more positive cue than underwater noises. If fish recognize characteristic noises they should be able to detect a stream as they cross a stream-mouth.

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