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STOCK ASSESSMENT BY ECHO INTEGRATION AND ITS APPLICATION TO JUVENILE SOCKEYE SALMON IN LAKE WASHINGTON

By Richard E. Thorne and James C. Woodey

January 28, 1970 • University of Washington
College of Fisheries • Fisheries Research Institute

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WSG 70-2

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UNIVERSITY OF WASHINGTON 98105
Prepared under the
National Science Foundation
SEA GRANT PROGRAM

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This investigation was partially supported
by NSF Grant GH-40,
under the SEA GRANT Program

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Washington Sea Grant Publication No. 70-2

Sea Grant encourages the interdisciplinary approach - and teamwork of industry, agencies and academic institutions - in developing and conserving marine resources.

The State of Washington Department of Fisheries gave financial assistance in the work reported. Its cooperation and assistance are very much appreciated.

FOREWORD

Work has been under way for more than two years in the development of an acoustical integrator as part of the University of Washington program under the National Sea Grant College Act. A technical description of the integrator and necessary calibration tests have been discussed in two previous circulars. The present report contains some additional calibration studies but also results of the first practical application of the integrator in the enumeration of the stock of pre-smolt sockeye salmon in Lake Washington.

Three groups contributed financial support or made available equipment and manpower. The same groups shared the results, although with a different emphasis. Washington State Department of Fisheries needed a numerical estimate of young salmon migrating to sea in the spring of 1969 in order to formulate harvest policies for the anticipated record year of 1971. Two University of Washington groups, the Division of Marine Resources and the College of Fisheries, were primarily interested in biological data and performance tests of the integrator.

Aside from the scientific results achieved, the effort initiated a pattern of cooperative studies between University groups and resource management agencies. It is expected that other projects in acoustical stock assessment will be organized along the same lines.

Ole A. Mathisen

STOCK ASSESSMENT BY ECHO INTEGRATION AND ITS APPLICATION TO JUVENILE SOCKEYE SALMON IN LAKE WASHINGTON

INTRODUCTION

Traditionally, the magnitude of pelagic fish populations has been estimated either directly from recoveries of marked members or indirectly from catch per unit of effort. These methods require substantial effort, cost, and historical data; the use of acoustic equipment is a promising alternative.

The echo sounder was first used in the estimation of fish populations in 1941 (Cushing, 1967). It was used subsequently in several population studies, including estimates of the relative density of young sockeye salmon in several Alaskan lakes (Rogers, 1967). Early population studies were qualitative and often subjective because of the difficulty of interpreting echograms. Several types of electronic apparatus for quantifying the returning signals have been described, including a pulse counter (Mitson and Wood, 1961), a pulse length counter (Carpenter, 1967), and an echo integrator (Dragesund, Olsen, and Hoff, 1965).

An echo integrator for use in the estimation of fish populations was designed and built by Mr. H. W. Lahore as a Master's thesis in electrical engineering, University of Washington, with funds provided under the Sea-Grant program. The first part of this paper describes an investigation into the relationship between the integrated echo strength of the echo integrator and number of juvenile sockeye salmon. The second part details an estimation of the pelagial population of presmolt sockeye salmon in Lake Washington by means of the echo integrator.

PART I. INVESTIGATION OF THE RELATIONSHIP BETWEEN INTEGRATED ECHO VOLTAGE AND NUMBER OF SOCKEYE SALMON

Underwater Acoustics

The energy from a point source of sound spreads out spherically in an isotropic medium. As the area of the sphere increases, the intensity per unit of area decreases. Assuming no absorption of the acoustic energy, we have the following relationship:

$$\text{Power} = \text{intensity} \times \text{area} = \text{constant}.$$

The echo sounder has a planar radiator rather than a point source. This produces a beam of sound whose width is dependent on the type and size of the transducer. Fig. 1 shows side views of the acoustic beam transmitted by a 38-kHz sounder from a 10-cm x 32-cm transducer.

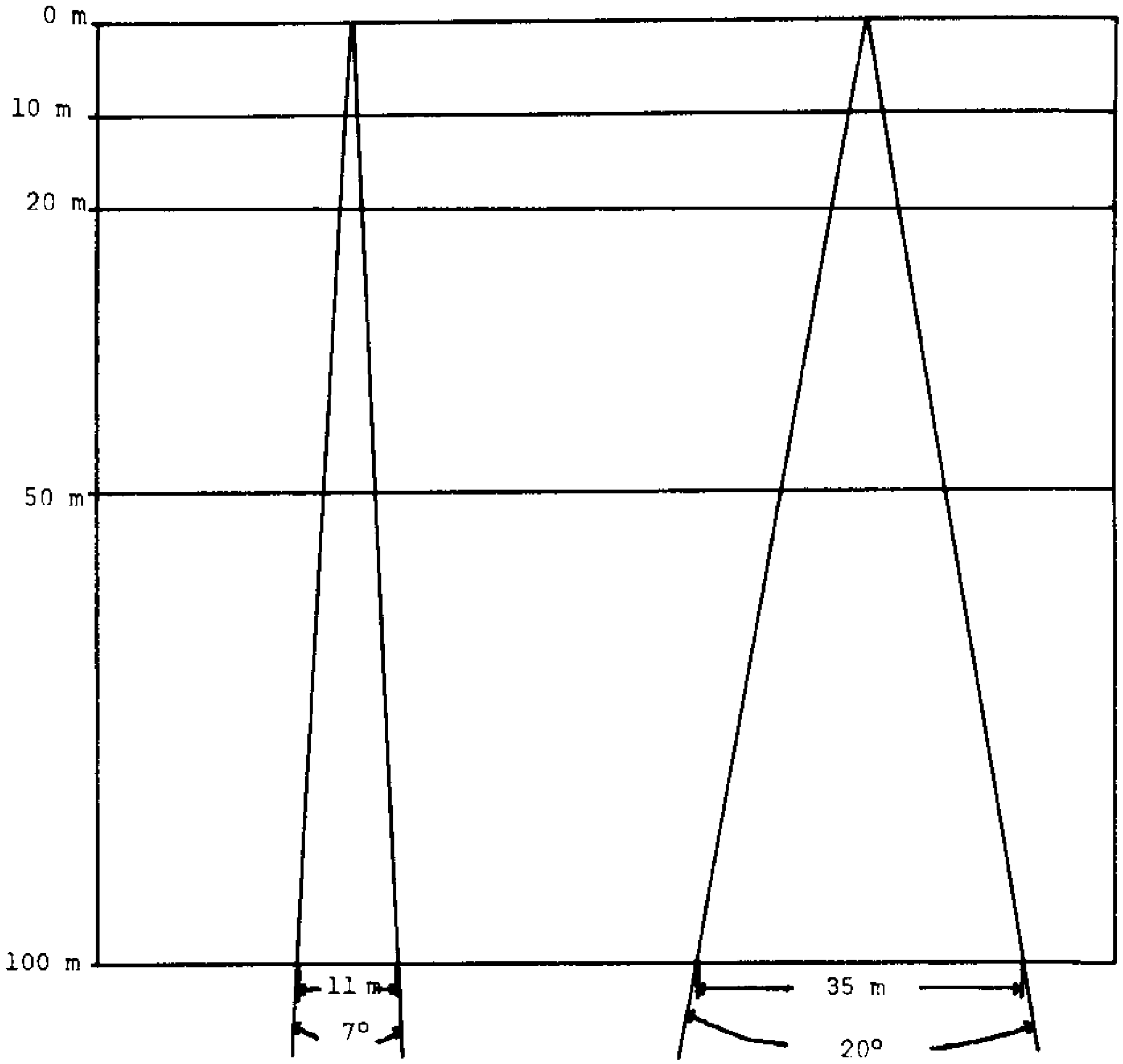

Fig. 1. Side views of the acoustic beam transmitted by a 38-kHz echo sounder from a 10-cm x 32-cm transducer.

The product of intensity times area is a constant for any radius, R, from the transducer:

$$I_1R_1^2 = I_2R_2^2 .$$

Setting $R_1 = R_0$ = reference depth of 1 m, we have

$$I_0 = I_2R_2^2 \quad ,$$

that is, the intensity per unit of area at a depth of 1 m is R_2^2 times as much as the intensity received at a depth, R_2. Acoustic intensity is generally measured on a logarithmic scale in decibels (dB). Thus

$$10 \log I_0 = 10 \log I + 20 \log R .$$

A target, such as a fish, will act as a point source of sound as it produces echoes. The intensity of the reflected echo as it is received at the transducer will have been reduced by 20 log R from the value of the echo intensity 1 m from the target. Total spreading loss equals 40 log R, or is proportional to the fourth power of the depth.

It is obvious from the above characteristics of the echo-sounding cone that consideration of the depth must be made when an echo sounder is used to estimate fish abundance. When an instrument that counts the number of discrete echo targets is used in conjunction with an echo sounder, the number of targets is related to the volume of the echo-sounding cone for the depth interval being considered. When a large depth interval is examined with a counter, the total count is biased by the fish targets in the deeper portions because of the relatively greater volume being examined.

The echo integrator measures the summed echo strength of all targets within the examined depth interval rather than the number of targets. In a simple case of individual fish targets from the same size and species of fish, the number of targets observed would be the integrated total divided by the echo strength of one target at the depth being considered. Then the density of fish would be the number of targets observed divided by the volume sampled by the echo sounder. As with the counter, the number of fish observed would be a function of depth for any given density, and the total number would be biased by the deeper portions of the depth interval. Since the source of this bias is the increasing area of the echo-sounding cone with depth, it is possible to eliminate the bias by weighting the returns inversely by the volume. This process is essentially a transformation of the echo sounder cone to an equivalent cylinder. Thus if the intensities of the returning echo targets were multiplied by 20 log R, or in proportion to the square of the depth, instead of 40 log R, the total spreading loss, the return from any given density of fish would be independent of the depth from which the echoes originate.

The echo sounder does not measure acoustic intensity directly, but rather acoustic pressure, which is proportional to the square root of the acoustic intensity. Thus the echo sounder actually measures the square root of the fish echo intensities. This fact has several important effects on the use of an echo integrator. First, a one-way spreading loss correction of 20 log R, which is defined as a correction in proportion to the square of the depth for intensity, is a correction in proportion to the depth when acoustic pressure is measured. Second, while the intensity is proportional to the number of fish, the pressure is proportional to the square root of the number of fish. The consequence of measuring pressure rather than intensity becomes further complex when one considers individual targets as a result of the fact that the square root of one is equal to one. Thus integrated acoustic pressure is proportional to the number of fish, just as integrated acoustic intensity is, when one is considering individual targets, but is proportional to the square root of the number of fish when one is considering multiple fish targets. Further, while a depth correction of 20 log R makes the received signal from any given density of fish independent of depth when one is measuring either pressure from multiple fish targets or intensity from all targets, no correction for depth is necessary when one is relating integrated acoustic pressure to density of individual fish targets. This is a result of the fact that the echo strength of individual fish targets in terms of acoustic pressure decreases in proportion to the square of the depth, exactly at the same rate that the area of the cone increases.

Description of the Echo Integrator

The University of Washington echo integrator was used in conjunction with a Simrad EH2E echo sounder aboard the University of Washington research vessel Commando. The echo sounder has a frequency of 38.2 kHz and a pulse length of 0.5 msec. The sounder transducer measures 10 x 32 cm and produces a sound beam of 7 x 20 degrees between 3 dB points (Fig. 1).

A block diagram of the echo integrator system is shown in Fig. 2. The time base of the system is triggered by a pulse from the echo sounder. Using this time base, the circuit turns on the relay for the depth interval to which it has been set. The signal from the sounder receiver is put through the relay contacts to the integrator, peak detector, and pulse counter. The peak detector indicates the maximum amplitude of the signal in the gated time interval. The pulse counter indicates the number of pulses received in the gated interval that have been over a certain amplitude.

In the echo integrator that was used through January 1968, the signal from the echo sounder was taken from the stylus output. It had no time-varied-gain (TVG) circuit. The design was then modified and a TVG circuit of 20 log R installed. In the modified echo integrator system, the signal was taken from the IF part of the echo sounder. A more detailed description of the echo integrator and its associated electronics is given by Lahore (1969).

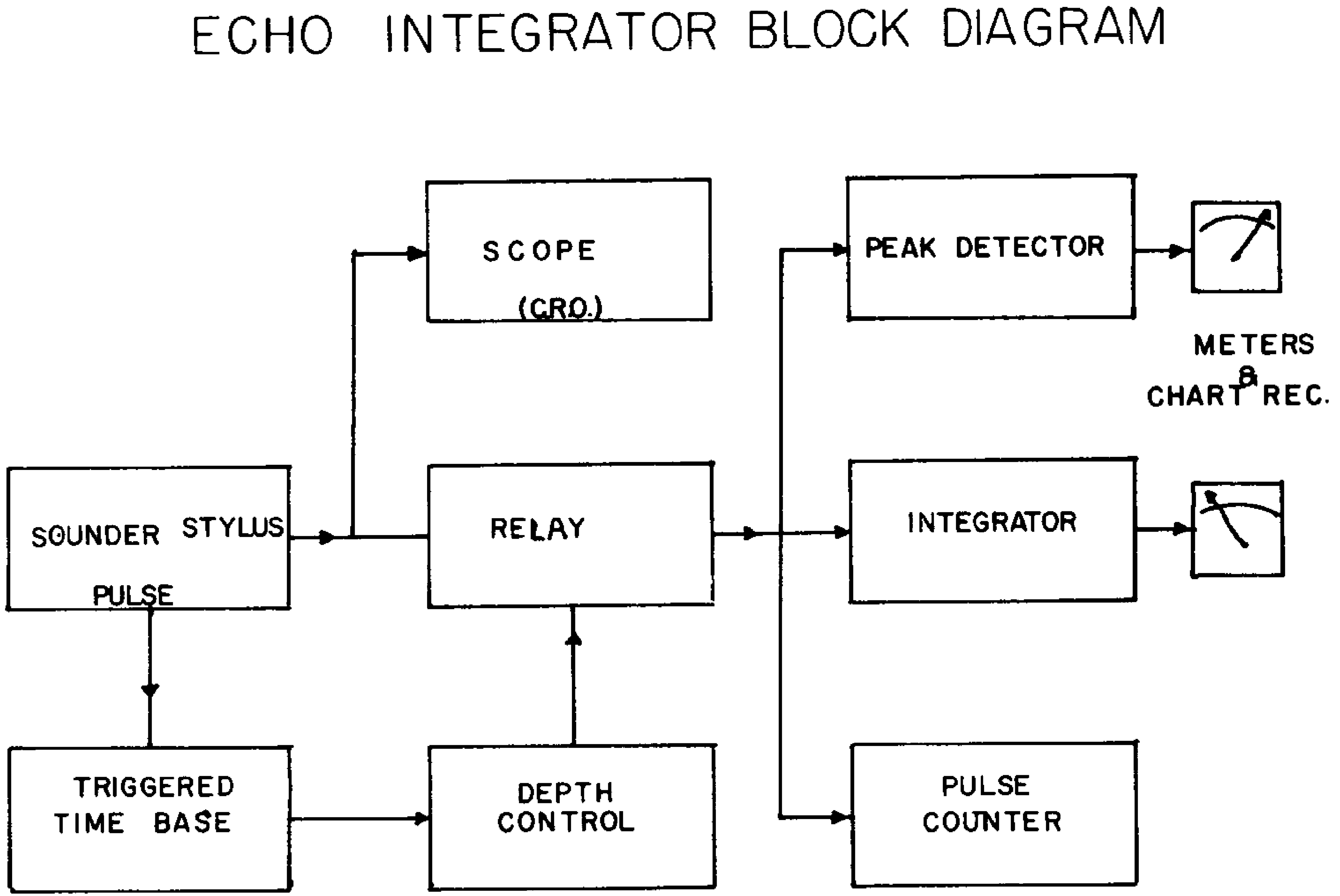

Fig. 2. Block diagram of the echo integrator system.

The Research Area

Lake Washington is a large lake (89.6 km^2) located in the lowlands of Western Washington and slightly inland from Puget Sound. The mean depth of the Lake is 33 m, and the maximum depth is 67 m. The lake basin has steep sides and a relatively level bottom. The central region is mainly 45-65 m deep, sloping gradually upwards at the north and south ends. Major tributaries enter the Lake at both ends, the Cedar River at the south end and the Sammamish River at the north end.

Surface water temperatures range from between 4 and 6 C in winter to over 21 C in midsummer. Thermal stratification is established in May and is stable through October. The thermocline is typically located in the 10-20 m depth interval.

Juvenile sockeye salmon preponderate in the pelagic fish fauna of Lake Washington. Longfin smelt are abundant. Several other species are found in the pelagic zone, but are less numerous and more sporadic in occurrence. The longfin smelt are landlocked, mature at age II, and spawn in the winter months.

The juvenile sockeye reside in Lake Washington from the time of emergence from the Cedar River spawning grounds until seaward migration in April and May of the following year. The fry assume a pelagic existence soon after lake entry and remain in the pelagial zone throughout their residence period.

Field Procedure

The relationship between integrated echo voltage and the number of juvenile sockeye salmon was investigated during five cruises on Lake Washington between August 1968 and January 1969. The integrated echo voltage was compared with the catch of fish in a 10-ft Isaacs-Kidd midwater trawl (Isaacs and Kidd, 1953). The midwater trawl had 1-1/2-inch stretch mesh in the forward sections and 1-1/4-inch stretch mesh in the cod end. The cod end was also equipped with a 1/2-inch stretch mesh liner. Net hauls were generally 10 min at a speed of 2.5 m/sec and were made mostly at night. Integration was made simultaneously with the net hauls, generally over a 4-m depth interval, centered at the estimated mean depth of the net. Net position was estimated from the length of towing wire and was checked subsequently against bathykymograph (Marine Advisors, Inc., model T-1c) records. The fish were enumerated by species and their sizes were recorded. The entire samples were preserved for later analysis. Integration output was divided by the time in 600-sec units and the depth interval in meters to obtain an integration rate per meter.

Results

A sample echogram and integrator output is shown in Fig. 3. Integration and catch data for the various hauls are given in Table 1. The catches were subdivided into three size categories. The medium size category of fish, from 7 to 15 cm, included the juvenile sockeye salmon

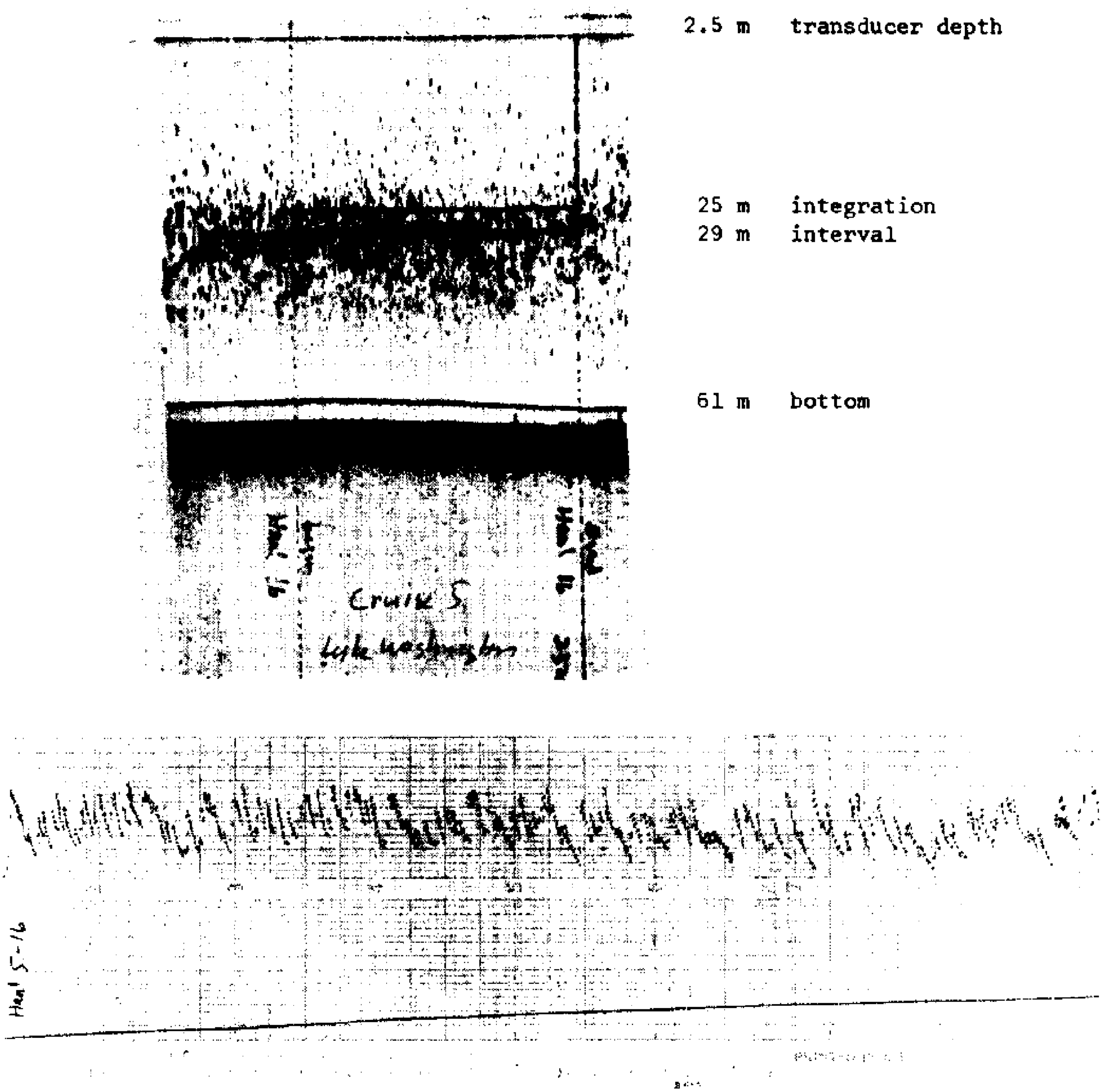

Fig. 3. Echogram, peak detector, and integration recordings taken at night, October 26, 1968. The integration output is shown on the lower channel of the Rustrak Chart paper; the peak detector output is recorded on the upper channel.

Table 1. Integration rates/m and catches of fish (by size category) for the various hauls, August 1968 to January 1969.

Date	Time	Depth (m)	Duration	Integration	Number of Fish		
					Small	Medium	Large
August 13-14, 1968	Day	3-7	10 min	21	0	0	0
	"	13-17	"	9.0	0	0	0
	"	20-24	"	15	0	0	0
	"	24-28	"	2.9	4	0	0
	"	8-12	"	7.5	5	0	0
	Night	3-7	10 min	21	2	0	0
	"	13-17	"	54	0	8	0
	"	24-28	"	14	7	100	7
	"	18-22	"	75	4	19	8[*]
	"	24-28	"	21	7	109	5
September 24-25, 1968	Night	10-14	10 min	23	5	14	0
	"	16-20	"	67	9	49	0
	"	21-25	"	172	4	145	1
	"	21-25	"	317	2	179	1
	"	13-17	"	80	11	2	0
	"	16-20	"	80	9	32	1
	"	21-25	"	104	1	73	3
	"	48-52	"	24	0	23	0
October 26-27, 1968	Night	12-16	10 min	34	8	5	0
	"	19-23	"	139	13	58	1
	"	25-29	"	160	18	42	0
	"	25-29	"	186	7	92	1
	"	28-32	"	200	2	89	0

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[*] All adult sockeye salmon.

Table 1. Integration rates/m and catches of fish (by size category) for the various hauls, August 1968 to January 1969 - Continued

Date	Time	Depth (m)	Duration	Integration	Number of fish		
					Small	Medium	Large
October 26-27, 1968 (cont.)	Night	12-16	10 min	51	13	12	3
	"	19-23	"	145	33	29	1
	"	25-29	"	323	3	124	1
	"	32-38	5 min	162	1	47	0
	"	46-50	10 min	60	6	25	2
December 2-3, 1968	Night	12-16	10 min	0.6	3	0	0
	"	19-23	"	24	3	1	0
	"	25-29	"	30	5	12	0
	"	12-16	"	5.0	4	8	0
	"	19-23	"	12	8	3	0
	"	25-29	"	82	15	40	0
	"	32-38	"	64	10	49	0
	"	46-50	"	26	38	3	0
January 2-3, 1969	Night	19-23	10 min	20	8	3	1
	"	27-31	"	121	5	8	10
	"	19-23	"	30	14	12	0
	"	25-29	"	97	8	36	1
	"	32-38	5 min	279	6	48	2
	"	46-50	"	180	13	33	1
	"	19-23	10 min	13	1	5	1
	"	25-29	"	28	0	9	0

mixed with occasional adult smelt. Large fish, over 16 cm, were overyearling sockeye, squawfish, and peamouth chub. Small fish, less than 6 cm, included sticklebacks, cottids, and juvenile smelt.

The data were analyzed by a multiple linear regression model of the form:

$$\text{(model 1)} \quad I = \underline{a} + \underline{b}_s N_s + \underline{b}_m N_m + \underline{b}_l N_l \ ,$$

where I equals the integration rate/m,

N_s equals the number of small fish per 10 min tow,

N_m equals the number of medium fish per 10 min tow,

N_l equals the number of large fish per 10 min tow,

and $\underline{a}$, $\underline{b}_s$, $\underline{b}_m$, and $\underline{b}_l$ are constants.

The multiple regressions were calculated in a stepwise fashion; the independent variables were added one at a time in the order of their reduction of the residual variance.

The August cruise was not included in the analysis because of the use of different transmission power and the presence of large numbers of adult sockeye salmon. For all four cruises analyzed, the $\underline{a}$ coefficients were not significantly different from zero, so the data were further analyzed by a multiple regression model of the form:

$$\text{(model 2)} \quad I = \underline{b}_s N_s + \underline{b}_m N_m + \underline{b}_l N_l .$$

As in model 1, the regressions were calculated in a stepwise fashion. For all four cruises, the medium size category was the most significant independent variable in the regression. Table 2 gives $\underline{b}_m$, standard error of $\underline{b}_m$, and the linear correlation coefficient for each month for the model:

$$\text{(model 3)} \quad I = \underline{b}_m N_m \ .$$

Integrations are plotted against catches of fish in the medium size category for each of the four months in Figs. 4-7.

In September and December, the coefficients other than $\underline{b}_m$ were not significantly different from zero ($p = 0.05$). In October, $\underline{b}_s$ was significant, while in January, $\underline{b}_l$ was significant. Table 3 gives the significant coefficients in the model 2 regression equation, their standard errors, and the multiple linear correlation coefficients for these two months.

Table 2. Correlation coefficients, regression constants, and standard errors of regressions constants for four cruises, September 1968 to January 1969, model 3.

Month	b_m	Standard error	Correlation coefficient
September	1.54	0.16	0.963
October	2.34	0.21	0.965
December	1.64	0.24	0.933
January	2.89	0.31	0.963

Table 3. Correlation coefficients, significant regression constants, and their standard errors for October 1968 and January 1969 model 2.

Month	b_s	Standard error	b_m	Standard error	b_1	Standard error	Multiple R
October	2.38	0.90	2.11	0.18	*		0.981
January	*		2.46	0.05	10.08	0.50	0.9995

*Not significant.

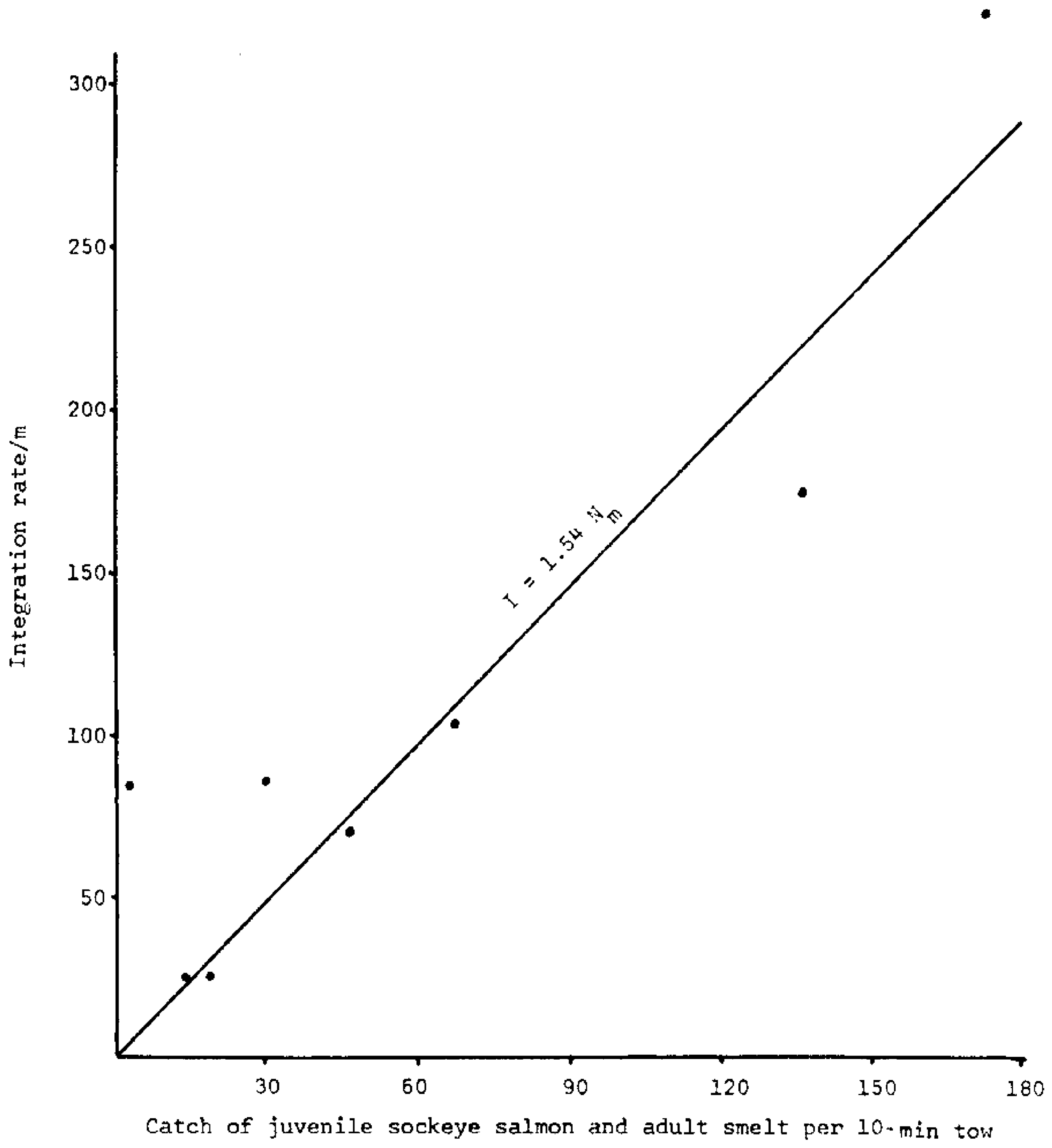

Fig. 4. Relationship between integration rates/m and catches of juvenile sockeye salmon and adult smelt per 10-min tow, September 24-25, 1968.

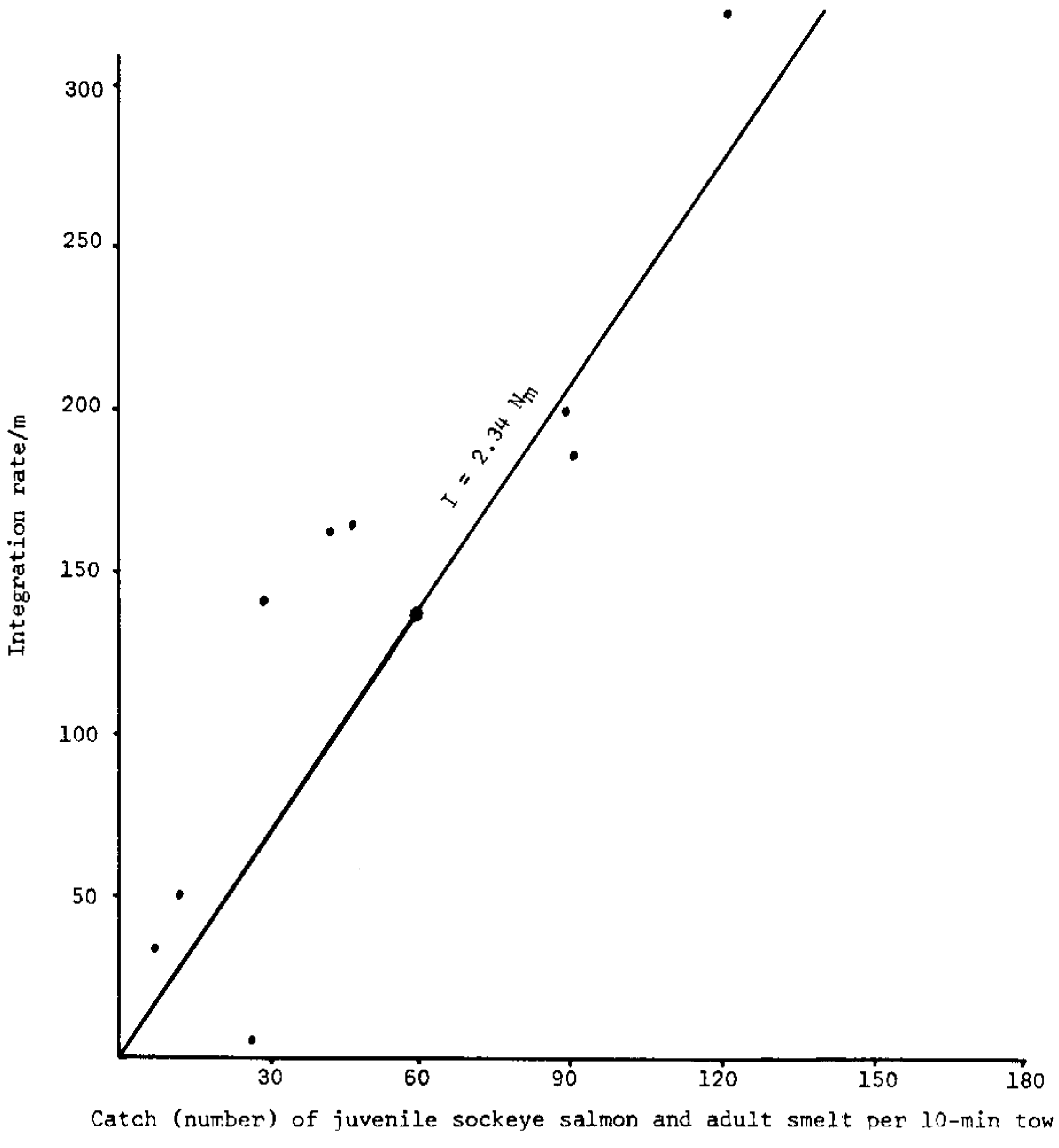

Fig. 5. Relationship between integration rates/m and catches of juvenile sockeye salmon and adult smelt per 10-min tow, October 26-27, 1968.

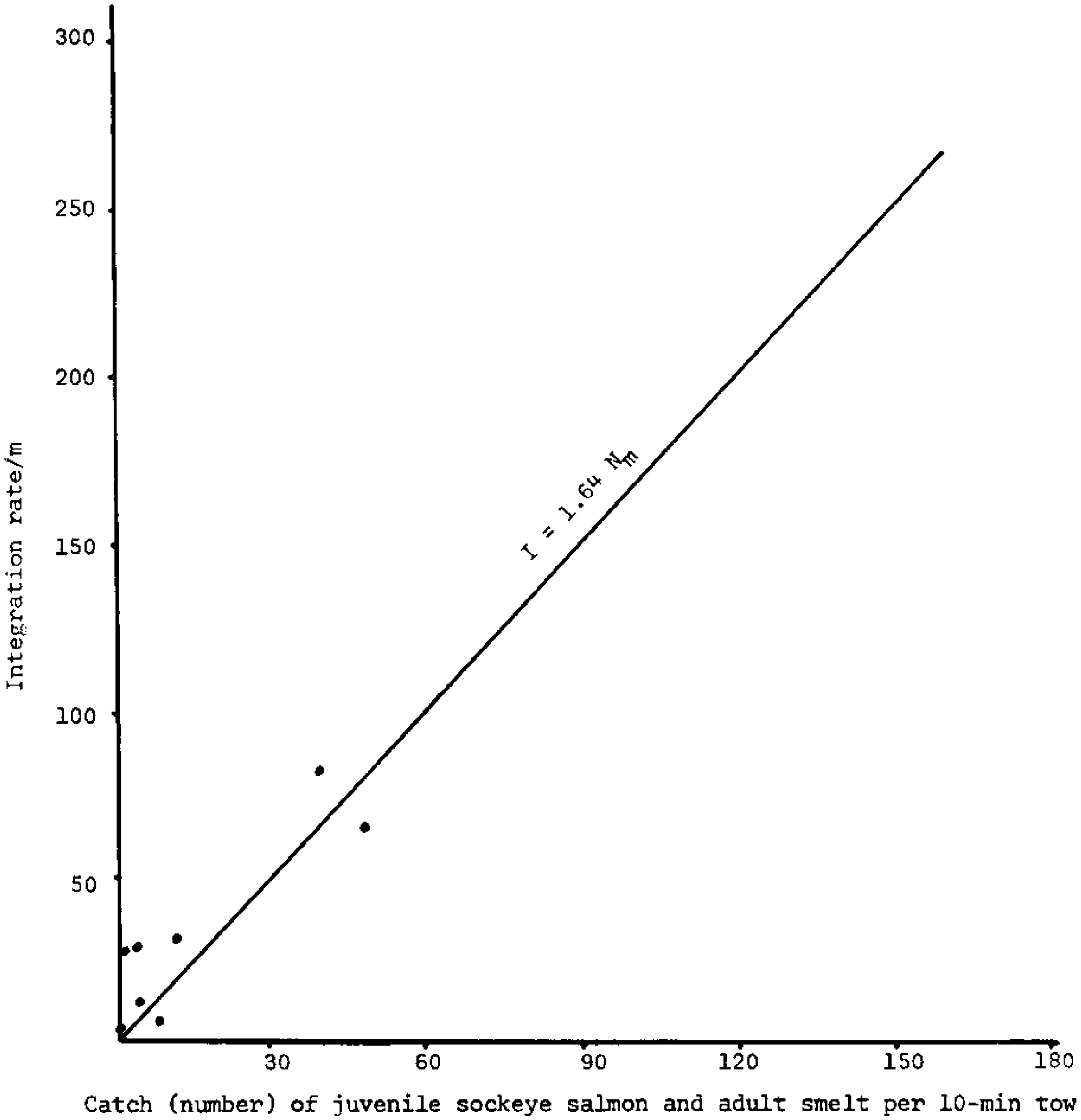

Fig. 6. Relationship between integration rates/m and catches of juvenile sockeye salmon and adult smelt per 10-min tow, December 2-3, 1968.

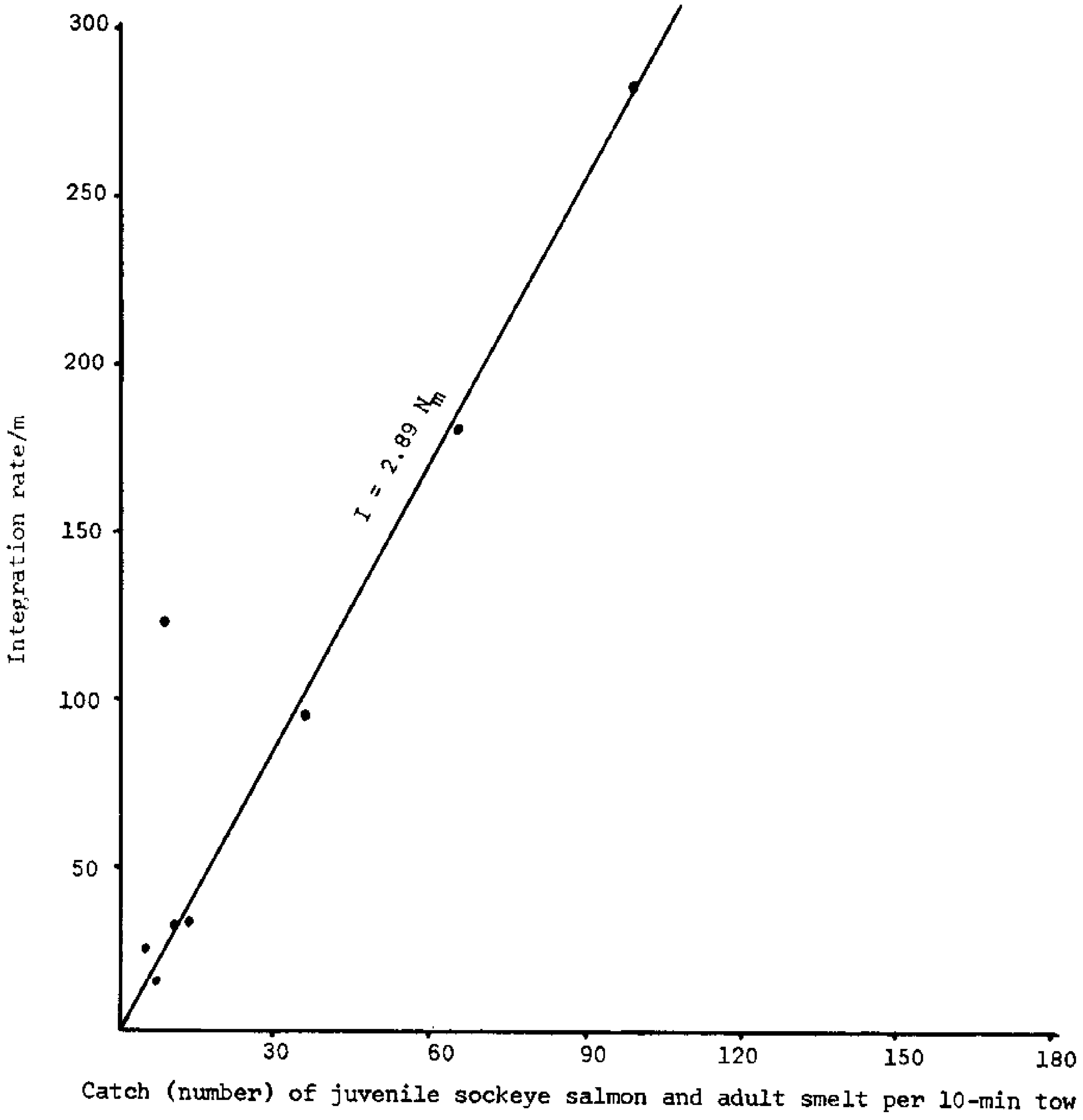

Fig. 7. Relationship between integration rates/m and catches of juvenile sockeye salmon and adult smelt per 10-min tow, January 2-3, 1969.

Discussion and Conclusions

Thorne and Lahore (1969) found that the relationship between integration rate and density of hake was linear over a range of low densities where echo targets represented mostly individual fishes. At greater densities than one fish per pulse resolution volume, where fish echoes consisted of several targets, the integration rate was related to the square root of the number of fish. In the case of the juvenile sockeye salmon, integration was linearly related to net catch; correlation coefficients were greater than 0.9 for all four cruises. Assuming that net catch is a reliable indication of fish density, we find that the results show a linear relationship between integration rate and density over the range of densities encountered in Lake Washington. Since the fish are widely dispersed at night, there is no reason to expect any significant interaction between net efficiency and density. The highest catch encountered was 182 fish in a 10-min tow. Since the net sweeps approximately 10,000 m^3 in 10 min, the highest density encountered at 100% net efficiency is one fish per 55 m^3. Since the echo sounder had a pulse length of 0.5 m/sec, it could resolve individual targets differing more than 37.5 cm in distance from the transducer. Since the cross-sectional area of the cone at the depth of highest fish density (23 m) was approximately 10 m^2 (Fig. 1), the pulse resolution volume at this depth was less than 4 m^3. Therefore, unless net efficiency was less than 7%, even the highest densities encountered were below an average density of one fish per pulse resolution volume, and probably almost all the echoes represented individual fish targets. The fact that a good linear fit was obtained by the use of integration rates without a depth correction also suggests that the targets were individual fish.

For the calculation of the regression lines, the fish in a catch were classified into three size categories. The contribution of any size category to the integration was a function of the density of fish, the target strength of the fish, and the efficiency of the net in capturing the fish. These last two factors were functions of the fish size. Only on two occasions was a regression coefficient other than $\underline{b}_m$ significant in the regression equation. This was a result of the preponderance of the juvenile sockeye. A much greater amount of data would be necessary for us to accurately evaluate the effects of the other size categories.

The magnitudes of the $\underline{b}_m$ values for the four months were similar. Some degree of increased integration for a given catch was expected from growth of the fish; average juvenile sockeye weight approximately doubles between September and January. Increased integration for a given catch of juvenile sockeye over a period of months would also result from decreased net efficiency in capturing the larger fish.

PART II. ESTIMATION OF THE NUMBER OF PRESMOLT SOCKEYE SALMON IN LAKE WASHINGTON

Introduction

After establishing that the relationship between echo integration and abundance of juvenile sockeye was linear, we undertook to estimate the abundance of presmolt sockeye in Lake Washington. Objectives of the population estimation were twofold: to investigate the practicality of the echo integration technique and to provide an estimate that could be used as a basis for predicting the expected adult return in 1971.

The primary consideration for conducting the survey during the month of February was to obtain a population size estimate before seaward migration but after the greatest part of the natural mortality in freshwater had taken place. In addition, by February the majority of age II longfin smelt had moved to the littoral to spawn, and the new year class had not appeared in the midwater zone. The juvenile sockeye at this time were the preponderant fish both in numbers and biomass, thus error associated with inclusion of other fishes in the survey zone would be minimal.

Materials and Methods

The population estimate was based on the results of echo integration over a number of transects distributed over the main basin area of the Lake (Fig. 8). The Lake basin was divided into seven regions on the basis of uniformity of depth and natural and man-made features. The number and length of the transects were adjusted on the basis of the relative abundance of fish observed on the first night of the survey. The transects extended inshore to the 30-m depth contour.

During the transects, the integration interval extended from a depth of 10 m to about 55 m, or when the bottom was less than 55 m, to as close to the bottom as was possible without incorporation of any part of the bottom pulse.

The transecting series was done during the nights of February 11 and 13 aboard the Commando. The starting time was 1930 PST on February 11 and 2015 February 13. Approximately five hours were required for the completion of a series of transects. No transects were run in the seventh (G) region on February 13 since no fish were observed there during the February 11 series.

Since the young sockeye salmon grow rapidly, a relationship between integration rate and fish density was determined with net hauls at about the same time as the population estimation. In addition, we attempted to determine the efficiency of the net by counting the number of individual echoes in the integration interval with the electronic pulse counter.

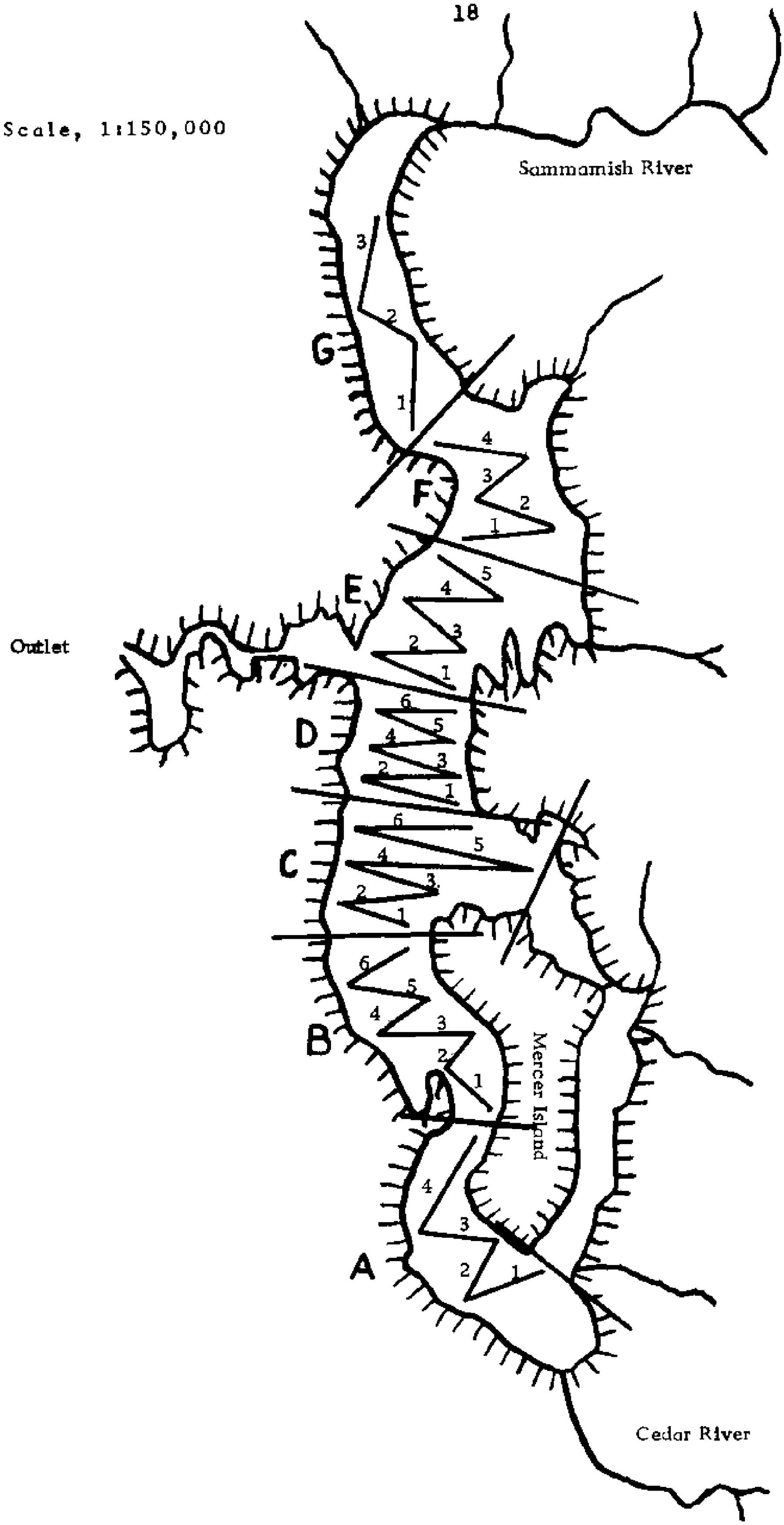

Fig. 8. Distribution of transects over Lake Washington.

The integration calibration procedure was similar to that discussed previously. A relationship was determined between the integration rate per meter of depth interval and the net catch per 10^4 m^3, the theoretical amount filtered by the 10-ft Isaacs-Kidd midwater trawl in a 10-min haul. Net hauls were made at various depths, throughout the lake at night on February 10, 12, and 13. For this population survey we used an echo integrator of the modified design with a TVG circuit of 20 log R to correct for one-way spreading loss. This system was used before it was realized that a correction for spreading loss was unnecessary when one is dealing with individual fish targets. Thus the integration values contain a bias in proportion to the depth. The error introduced by this bias is minor, however, since almost all of the fish were present in a narrow depth band from 20 to 40 m, and the same bias was present in both the transects and the calibration. There were some electronic difficulties with the new circuitry, however. As a result of these difficulties, the February 10 data could not be used in the analysis. Adjustments were made during the day February 13, and the calibration hauls for the February 13 transects were made in the middle of that series of transects.

Results

Results of Calibration

Integration and catch data for the three nights are given in Table 4. Integration rate/m is plotted against numbers of sockeye per 10^4 m^3 in Fig. 9 for the hauls on February 12 and 13. Two major differences from the results of the previous months' investigation are apparent. First, there is a definite noise level. The gating level in the modified system with the time-varied-gain circuit was insufficient to block all of the low-level noise. Second, a greater variability is present for the higher integration rates in the February 12 data. This greater variability may be the result either of fluctuation in the integrator itself as a result of unstable components in the time-varied-gain circuit or of the fact that the sockeye were larger and more concentrated than in previous months.

The noise level can be determined by two methods. If a regression model in the form of

$$N = \underline{a} + \underline{b}I$$

were applied to the data, the noise level could be determined by the intercept on the abscissa. When N = 0, $I = -{}^{a}/_{b}$. The noise level can be determined also by measurement of the integration rate when no fish are observed on the echogram. Both of these methods were tried on February 12, and a noise level of 12 v/(m x 600 sec) was found in both cases.

Since the variability increased with increasing integration rates, we decided to use a weighted linear regression to analyze the data. First, a noise level of 12 v/(m x 600 sec) was removed from the integration

Table 4. Integration rates/m and catches of fish (by size category) for the various hauls, February 10, 12, and 13.

Date	Region	Depth (m)	Duration	Integration	Number of fish Small	Medium	Large
February 10	A	20-24	10 min	3.5	9	8	0
	A	26-30	"	8.9	7	27	8
	C	20-24	"	4.7	5	16	0
	C	26-30	"	7.9	11	22	0
	C	33-37	5 min	19.2	4	40	0
	C	40-44	"	20.3	8	56	0
	E	15-19	10 min	1.9	1	0	0
	E	23-27	"	2.7	1	0	0
February 12	A	11-19	7 min	14.3	6	4	0
	A	18-23	5 min	17.5	9	9	0
	A	23-28	"	30.9	6	31	1
	B	17-23	"	14.0	4	4	0
	B	25-31	"	33.3	10	28	0
	B	32-38	"	55.0	11	61	2
	B	39-45	"	40.0	14	85	3
	B	29-41	"	73.0	11	52	1
	C	25-31	"	30.0	9	17	0
	C	35-41	"	42.0	7	71	2
	C	32-44	"	58.0	2	56	4
	F	27-33	10 min	15.0	3	4	0
	E	25-31	5 min	17.0	1	13	0
	E	19-25	"	14.0	2	4	0
	E	19-37	"	23	0	16	0
	E	31-37	"	21	2	11	0
February 13	C	37-43	10 min	25	8	133	7
	C	34-46	"	30	3	192	4

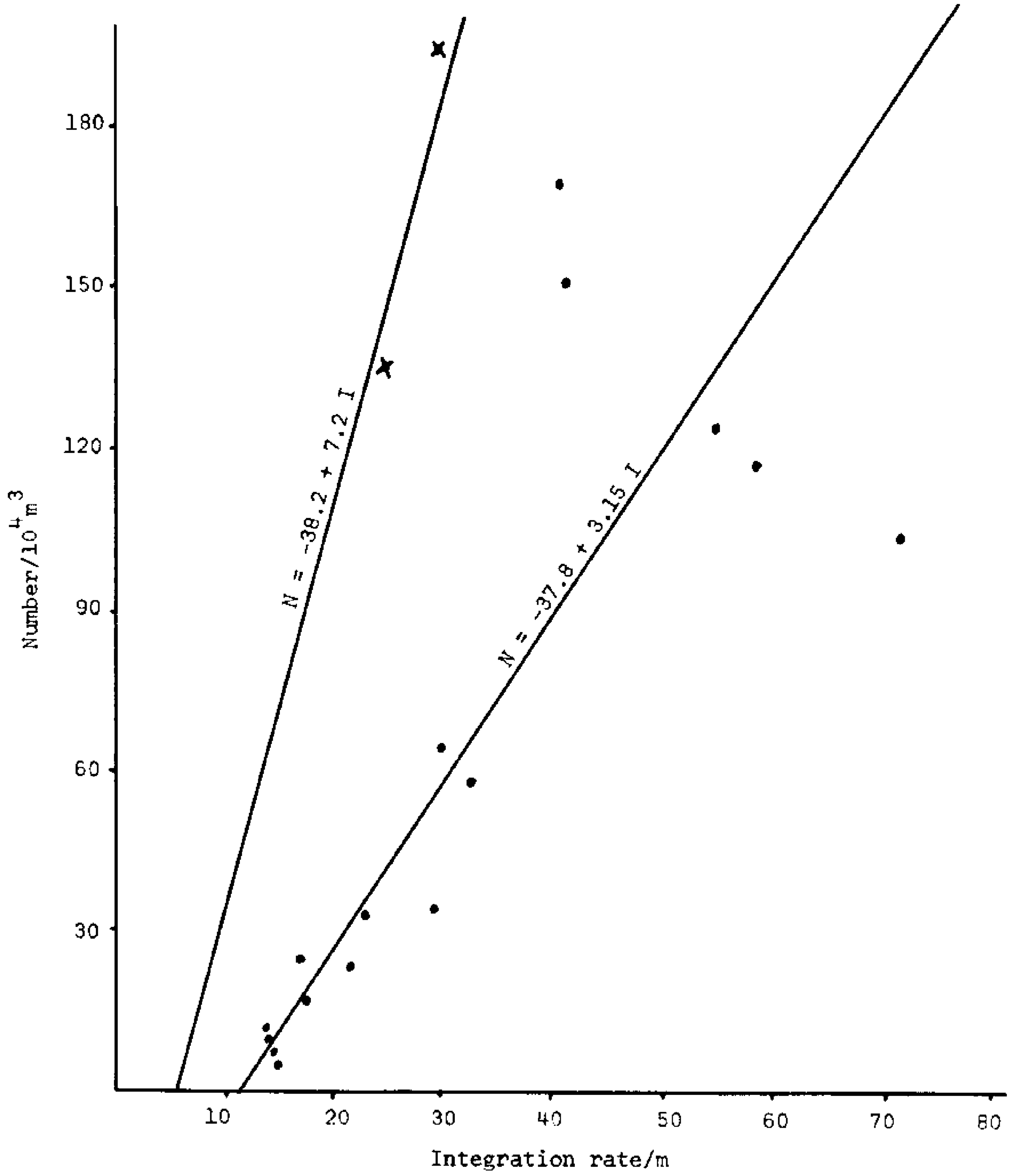

Fig. 9. Relationship between catches of presmolt sockeye and integration rates/m, February 12 and 13, 1969.

data. Then a regression model was determined in the form of

$$N = \underline{b}I,$$

where observations N have a variance proportional to I^2. Then the formula for $\underline{b}$ is

$$\underline{b} = \frac{1}{n} \sum_{i=1}^{n} \left(\frac{N_i}{I_i} \right)$$

and the variance of $\underline{b}$ is

$$\text{var } \underline{b} = \frac{\sum_{i=1}^{n} \left[\frac{N_i}{I_i} - \left(\frac{\overline{N}_i}{I_i} \right) \right]^2}{n(n-1)} .$$

For the hauls on February 12, $\underline{b}$ = 3.15 and var $\underline{b}$ = 0.111. The calibration line for the February 13 data was fitted through the mean of the two hauls. This integration was 43.8% of that expected for the same catch on the basis of the February 12 calibration line. Then the noise level for the February 13 data was taken to be 43.8% of the February 12 noise level. Thus the calibration line for the February 13 data is:

$$N = 7.2\ I\ ,$$

with a noise level of 5.3 v/(m x 600 sec).

The Population Estimate

The transect integration values, durations, and integration rates are given in Table 5. The transect integration rate represents the average density of fish along the transect times the average integration interval. Since the depth factor is already included in the transect integration rate, tentative plans were made for determining the presmolt sockeye population in each transect area simply by multiplying the integration rate for the transect, the surface area represented by the transect, and the slope of the calibration line. Then the total lake population would be the sum of the populations in each of the transect areas. This procedure was modified for three reasons: (1) the presence of a noise level necessitated an estimation of the mean integration depth interval in any case for determination of the magnitude of the noise component; (2) a considerable effort would be required for determination of the areas represented by each transect; (3) since only two transect series were run, the estimate of the lake population variance would be based on only two observations in each of the transect areas. Because of these considerations, a slightly different procedure was followed. For each transect the integration rate was divided by the average integration depth interval for determination of the average integration rate/m. Then the noise level was subtracted for the purpose of obtaining a corrected integration rate/m, and the corresponding density of fish determined from the appropriate calibration line. Then a weighted mean density was determined

Table 5. Transect integrations, durations, and integration rates, February 11 and 13

Transect	February 11			February 13		
	Duration (sec)	Integration	Rate	Duration (sec)	Integration	Rate
A-1	420	490	700	362	174	285
A-2	245	290	710	264	132	295
A-3	217	200	553	255	117	275
A-4	568	600	635	577	300	310
B-1	285	550	1160	303	216	430
B-2	142	255	1075	134	156	700
B-3	434	1295	1790	402	490	730
B-4	288	990	2065	288	440	915
B-5	383	1710	2680	394	630	960
B-6	256	1050	2460	270	390	865
C-1	227	750	1960	239	380	955
C-2	426	1270	1790	387	535	830
C-3	431	1215	1690	382	420	660
C-4	755	1820	1445	760	750	590
C-5	734	1830	1500	760	800	630
C-6	410	1170	1710	427	590	830
D-1	451	1070	1420	446	620	835
D-2	385	720	1120	376	500	800
D-3	356	560	945	344	470	820
D-4	349	490	845	349	440	755
D-5	364	525	865	375	405	650
D-6	348	515	890	360	360	600
E-1	417	645	930	366	330	540
E-2	455	665	875	451	430	570
E-3	391	420	645	376	285	455
E-4	435	430	595	414	315	455
E-5	315	240	455	300	207	415
F-1	374	375	600	381	234	370
F-2	318	275	520	314	204	390
F-3	303	200	395	256	259	375
F-4	430	255	355	435	222	305
G-1	336	171	305			
G-2	310	146	280			
G-3	357	129	215			

for each of the six regions for both series (the seventh region was not considered since few fish were encountered there). These weighted mean densities were multiplied by the volume surveyed in the various regions, and a population estimate for each of the regions was obtained. The weighting used was in proportion to the relative duration spent on the transects except for transects E-1 and E-2, which were weighted by one-half the duration because of their close spacing. This weighting was approximately in proportion to the relative area represented by the transect.

This procedure resulted in virtually the same total lake population estimate as the originally planned procedure, but differed in two ways: (1) we determined density from the integration rates/m and multiplied it by the volume to obtain an estimate instead of multiplying density times depth by the area; (2) we determined a population estimate for each region, consisting of 4-6 transects, rather than for each transect area. By assuming the density along each transect to be an estimate of the average density in that region, we were able to calculate a variance based on 4-6 times as many observations.

Table 6 gives the average integration depth interval, corrected integration rate/m, and average density along each of the transects on February 11 and 13. The population estimates for the various regions and for the total lake are given in Table 7.

Table 7. Population estimates for the various regions and for the entire lake

Region	Area ($10^{+4} m^2$)	Integration interval		Population estimation (10^{+3})		
		Feb 11	Feb 13	Feb 11	Feb 13	Mean
A	619.3	19.6	21.9	848	801	825
B	606.7	30.9	32.9	2,983	2,587	2,785
C	901.5	34.8	34.6	3,439	3,391	3,415
D	509.6	40.2	40	884	1,967	1,426
E	787.7	37.4	35.8	622	1,604	1,113
F	573.9	33.3	30.7	144	787	466
G	552.4	24.7		0	-	0
Total	4,551.1			8,920	11,137	10,030

Variance of the Estimate. There is variability around the mean integration in each region, and variability around the calibration line. The average integration rate/m along each transect was used as an estimate of the average integration rate/m in each region. Then the variance of the average integration rate/m in the i^{th} region is:

Table 6. Integration depth intervals, corrected integration rates/m, and average densities for transects on February 11 and 13

Transect	February 11			February 13		
	Integration Depth (m)	Integration Rate/m	Density (number/ $10^4 m^3$)	Integration Depth (m)	Integration Rate/m	Density (number/ $10^4 m^3$)
A-1	17	29.2	92.0	20	9.0	64.8
A-2	18	27.4	86.3	22	8.1	58.3
A-3	20	15.6	49.1	22	7.2	51.8
A-4	22	16.9	53.2	23	8.2	59.0
B-1	24	36.3	114	25	11.9	85.7
B-2	29	25.1	79.1	29	18.8	135
B-3	30	47.7	150	33	16.8	121
B-4	32	52.5	165	36	20.1	145
B-5	34	66.8	210	35	22.1	159
B-6	35	58.3	184	37	18.1	130
C-1	37	41.0	129	34	22.8	164
C-2	32	43.9	138	34	19.1	138
C-3	31	42.5	134	32	15.3	110
C-4	33	31.8	100	36	13.1	94.3
C-5	36	29.7	93.6	40	12.2	87.8
C-6	42	28.7	90.4	40	15.5	112
D-1	40	23.5	74.0	40	15.6	112
D-2	41	15.3	48.2	40	14.7	106
D-3	40	11.6	36.5	40	15.2	109
D-4	40	9.1	28.7	40	13.6	97.9
D-5	40	9.6	30.2	40	11.0	79.2
D-6	40	10.3	32.4	40	9.7	69.8
E-1	38	12.5	39.4	40	8.2	59.0
E-2	37	11.6	36.5	39	9.3	67.0
E-3	35	7.5	23.6	34	8.1	58.3
E-4	37	4.1	12.9	35	7.7	55.4
E-5	35	1.0	3.2	34	6.9	49.7
F-1	35	5.1	16.1	32	6.3	45.4
F-2	36	2.4	7.6	32	6.9	49.7
F-3	31	0.7	2.2	32	6.4	46.1
F-4	30	0	0	28	5.6	40.3
G-1	26	0	0			
G-2	24	0	0			
G-3	22	0	0			

$$\text{var } \overline{I}_i = \frac{\sum_{j=1}^{n} [(I_{ij} - \overline{I}_i)^2 \, W_{ij}]}{(\Sigma \, W_{ij}) \, (n-1)}$$

where the weights are the same as in the population calculations. The total variance of the population in each region can be estimated by combining the variance in the calibration line with that in the transects. The approximate variance is:

$$\text{var } N_i = V_i^2 \, [\underline{b}^2 \text{var } \overline{I}_i + (\overline{I}_i)^2 \text{var } \underline{b}],$$

where V_i is the volume of the i^{th} region. The variance of the total lake estimate is the sum of the variances of each region. Table 8 gives the variances for the regions and the entire lake. The final total estimate was 10,030,000 fish with two standard deviations equal to 1,344,000 fish.

Table 8. Variances of the mean population estimates for the various regions and for the entire lake based on February 11 and 13 transects.

Area	Number of observations	Mean population (in thousands)	Variance (10^6)
A	8	825	12,780
B	12	2,785	129,520
C	12	3,415	164,950
D	12	1,426	59,690
E	10	1,113	54,360
F	8	446	30,000
Total		10,030	451,300

This treatment of the data to obtain a variance estimate involved several assumptions and approximations. First, the average density found along any transect within a region is considered to be an estimate of the average density within the entire region. Since the transects were not randomly placed within the region, it is assumed that the fish were randomly distributed within the region. In actuality, there appears to have been a general trend in fish distribution: density peaked near the middle of the lake and decreased toward both ends. Thus the variance determined includes an additional component due to nonrandom distribution.

The combined variance formula assumes a regression model in the form:

$$N = \underline{b}I.$$

In actuality a noise level was present. Since a variance formula with a two-parameter regression line would be exceedingly complex, it was assumed that the noise level was a fixed constant without error. There is some justification for this since the noise level was independently determined by two different methods.

Since the variability of the regression line was derived exclusively from the February 12 data, the calibration for the February 13 data was considered as a constant factor used to standardize all transect data to the February 12 series. This assumption was necessary since it was impossible to determine the variance around a regression line of only two points. Because of the various questionable aspects of the February 13 data, the population and variance analysis was rerun on the basis of the February 11 transects alone. The result was a mean of 8,920,000, with two standard deviations equal to 1,434,000 (Table 9).

Table 9. Variances of the mean population estimates for the various regions and for the entire lake based on February 11 transects.

Area	Number of observations	Mean population (in thousands)	Variance (10^6)
A	4	848	25,740
B	6	2,983	205,270
C	6	3,439	204,540
D	6	884	32,060
E	5	662	40,480
F	4	144	5,310
Total		8,920	513,700

Counting Data

An electronic echo counter was used to count the number of discrete echoes encountered. Net efficiency was estimated by a comparison of the net catches per 10^4 m^3 and the echo counts per unit volume observed by the echo sounder. The echo sounder was not calibrated, so the sounding cone was assumed to be defined by 7-degree by 20-degree beam angles (Fig. 1). Net efficiencies estimated for 10 hauls ranged from 25% to 188% with a mean near 100%.

Discussion and Conclusions

The distribution of the Lake Washington presmolt sockeye salmon was characterized by a lack of patchiness at night. The fish were dispersed in a broad layer, and the average density changed quite regularly from lows at each end to a peak near the center of the lake. The technique used to determine the variance around the average density in each region included an additional component of variability, since the fish distribution within the region was not random. Since the distribution was not patchy, however, the variability associated with fish distribution was quite small.

Ideally in an estimate of this type, all the variability in the estimate would be a result of uneven fish distribution. Because of difficulties associated with the new time-varied-gain circuit, however, the main source of variability and error was probably in the integrator itself. The TVG circuit was not completed until the day before the scheduled survey, so there was insufficient time for testing and calibration. The TVG curve shifted after the February 10 hauls; then appeared to stabilize for the February 11 transects and the February 12 hauls. A slight adjustment made during the day on February 13, however, apparently had adverse effects. The calibration curve changed more than expected from the adjustments made and appeared to shift during the transect series on February 13. The two February 13 calibration hauls were made between transects of the B and C regions. Comparison of the February 11 and February 13 estimates by region shows close agreement for regions A through C. After the transect of the C region on February 13, a break was taken in the transecting. The last three regions then appeared to have a greater integration rate than expected from either the previous transects or from the return on the echogram. The difference in the total population estimates for the two nights was 2.22 million. The difference in estimates for the D, E, and F regions was 2.71 million. These considerations lead us to believe that the February 11 estimate is more reliable, and that the difference in the estimates is due to a change in the integrator after the halfway point break in the February 13 series.

Another possible source of error and variability in the estimate is the bias due to the TVG circuit. Fortunately, although the depth interval examined was quite large (10 to 55 m), almost all of the fish were located between 20 and 40 m. Examination of the calibration data by depth shows that bias due to depth is completely masked by other sources of variability.

Several other sources of error could be present in the population estimate. First, only 53% of the surface area of the Lake was included in the transects, and even within the transects the integration did not include all depths. Since the area within the transects included 90.6% of the area over depths in excess of 100 ft, and since the sockeye were primarily in deeper water, the error involved from this source is probably minimal. The integration did not include the upper 10 m, since we did not capture sockeye in net hauls above 15 m. There were undoubtedly fish missed near the bottom, especially in region B, where the layer of fish were very close to the bottom. The lower integration depth was adjusted manually, and was generally 1 or 2 m above the bottom. However, this is also an area where it was not possible to make net hauls, so that the fish in the region near the bottom may have been other than presmolt sockeye.

The calibration curves were based on catch of sockeye in the net hauls. In applying this relationship over the entire lake, we are assuming that the proportion of echoes that represent sockeye remained relatively constant. Our trawl data were taken from all regions of the Lake, over nearly all depths, so we are confident that the calibration curve is representative of the entire Lake.

An unknown portion of the juvenile *Oncorhynchus nerka* in Lake Washington are young nonmigratory kokanee. The proportion is small and difficult to measure. A series of hauls run in June 1969 after the main sockeye outmigration resulted in a catch of only 18 yearling sockeye. It is known from sport fishing data, however, that the age II kokanee move into the littoral at this time. The age I kokanee may behave similarly, thus residing where they cannot be sampled with the midwater trawl.

Finally, the estimate contains a basic error since it is based on net hauls. The counting technique to determine the net efficiency was not entirely satisfactory, since the effective sounding volume of the echo sounder was not precisely determined. The deeper hauls tended to have an efficiency greater than 100%. This fact suggests that the threshold level of the counter was too high to include all of the fish targets within the assumed sounding cone. We intend to do further research on the counting technique, and also on a technique to calibrate the integrator directly from *in situ* fish target strength measurements, so we will be able to apply a correction for net efficiency when further information becomes available.

ACKNOWLEDGMENTS

The authors wish to express their appreciation to several individuals for major contributions to this investigation. Suggestions for the statistical analysis were given by Professor Douglas G. Chapman and Dr. William H. Lenarz. Mr. Henry W. Lahore developed the echo integrator and kept the system operational. Aid in the field work for the population estimation was provided by several members of the Washington State Department of Fisheries.

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