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October, 1991

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ABSTRACT

Four mobile hydroacoustic surveys were undertaken to estimate the adult Fraser River sockeye salmon population size and distribution within the Strait of Georgia during August and September, 1986. Surveys were undertaken aboard separate vessels which deployed transducers in either a downlooking or uplooking mode of operation, in order to sample deep and shallow portions of the pelagic water column, respectively. Fish biomass estimates were generated by scaling echo integrator results by an estimate of fish target strength, determined *in situ* with the dual beam method. Results were scaled for sockeye salmon by determining the proportion of sockeye biomass within purse seine samples. Inclusion of the uplooking data set had a minor influence on the sockeye population estimate during surveys 1-3 and a large influence during survey 4 when sockeye were concentrated in shallow depth strata. When compared with the reconstructed sockeye population size based on the estimated late-run sockeye spawning escapements, it was apparent that the mobile hydroacoustic surveys underestimated the Strait of Georgia sockeye population size by a factor of about 50%. Possible causes for the underestimate include inadequate survey design and errors in the estimated target strength. Recommendations are made for improving future acoustic estimates of Fraser River sockeye salmon population size within the Strait of Georgia.

INTRODUCTION

Management of Pacific salmon *(Oncorhynchus sp.)* usually involves both pre-season forecasting and in-season decision making. In-season management of Fraser River sockeye salmon *(O. nerka)* by the Fraser River Panel of the Pacific Salmon Commission entails regulating the fishery so that escapement goals are achieved. Catches are allocated to the different user groups (Woodey 1987). Historically, the Pacific Salmon Commission has relied on riverine test-fishing and acoustic monitoring of sockeye populations as they migrated upstream past Mission, B.C., to estimate potential escapements of the major stocks. While this procedure provides accurate, timely data for summer-run stocks, it is less applicable for in-season management of late-run sockeye (including the Adams River, Lower Shuswap River, Harrison River, Birkenhead River, Weaver Creek, and Cultus Lake stocks) which typically delay their migration in the Strait of Georgia before migrating up the Fraser River. Ideally, a stock monitoring program would assess sockeye run size prior to, or during, their entry into the main fishing areas.

Adult sockeye returning to the Fraser access the river either via Johnstone Strait or Juan de Fuca Strait (Groot and Quinn 1987). Sockeye individuals from certain Fraser River stocks, including the Adams River run (currently the largest single sockeye stock within the Fraser river watershed), interrupt their migration and delay within the southern Strait of Georgia for a 2-6 week period (Gilhousen 1960). During this period, the sockeye salmon in the Strait of Georgia are almost exclusively from Fraser River stocks. These factors make the southern Strait of Georgia a strategic location for stock assessment. If sockeye populations within this area could be accurately enumerated, this valuable information would be available for making in-season management decisions.

Hydroacoustic methods (Burczynski 1982; Thorne 1983A; MacLennan 1990) potentially provide a cost-effective assessment technique to obtain sockeye abundance estimates within the southern Strait of Georgia. Such methods are attractive since the estimates are independent of the fishery and it is feasible to obtain results rapidly (within several days). Currently, there are no alternative methods available with comparable pelagic sampling power. As well, the recent development of a dual-beam SONAR system (Traynor and Ehrenberg 1979; Ehrenberg 1983) simplifies procedures for deriving estimates of fish target strength, one of the required parameters for hydroacoustic fish stock assessment.

During 1986, the Pacific Salmon Commission contracted Biosonics (Seattle) to undertake a hydroacoustic assessment of late-run Fraser River sockeye salmon in the vicinity of the southern Strait of Georgia (Ransom and Burczynski MS 1986). The main purpose of the study was to enumerate the late-run sockeye salmon population in this area. Data gathered during each of four surveys were processed at an analysis facility in Seattle, with preliminary quantitative results provided to the Pacific Salmon Commission within several days following each survey.

Subsequently, in 1990 Levy Research Services was contracted to synthesize the 1986 hydroacoustic results, conduct additional analyses of the hydroacoustic data set, and prepare a technical report summarizing the hydroacoustic results. Specific objectives of the present report are to: 1) estimate the numerical abundance of sockeye salmon in the Strait of Georgia during four discrete survey periods, 2) compare the acoustically-derived population estimates with estimates made using run-reconstruction methodologies, 3) describe the horizontal and vertical distribution of sockeye salmon within the Strait of Georgia and 4) evaluate the utility of the approach and make recommendations for future improvements.

STUDY AREA

The study area consisted of a major portion (920 km^2) of the southern Strait of Georgia between Vancouver Island and the British Columbia mainland (Figure 1). Maximum depth of the Strait is over 400 m, with average depths greater than 100 m. There are extensive, shallow tidal flats adjacent to the diked areas of the Fraser Delta (immediately east of Area B on Figure 2). The Strait of Georgia is an important commercial and recreational fishing area for Fraser River salmon stocks and also supports numerous commercial non-salmonid fish populations. A 1982 symposium (Parsons 1983) was convened to summarize physical (LeBlond 1983), geological (Luternauer et al. 1983), biological (Harrison et al. 1983; Levings et al. 1983), fisheries (Ketchen et al. 1983), and pollution studies of the Strait of Georgia (Waldichuk 1983). Additionally, there is a published bibliography concerning ecological aspects of biological oceanography within the Strait (Harrison et al. 1984).

The study area was separated into two main sub-areas (Figure 2): Area A, consisting of the entire pelagic zone between the Gulf Islands and the Fraser Delta; and Area B, the pelagic portion of the Strait of Georgia adjacent to the Fraser Delta. Area B was nested within Area A. Area B was further divided into Area C and Area E, which were nested within Area B (Figure 3). Area D, northwest of the main study area, was also sampled during one of the surveys to extend coverage to this portion of the Strait. Table 1 provides the surface areas for the respective sampling areas. Acoustic transects followed a zig-zag pattern across the Strait (Figure 3).

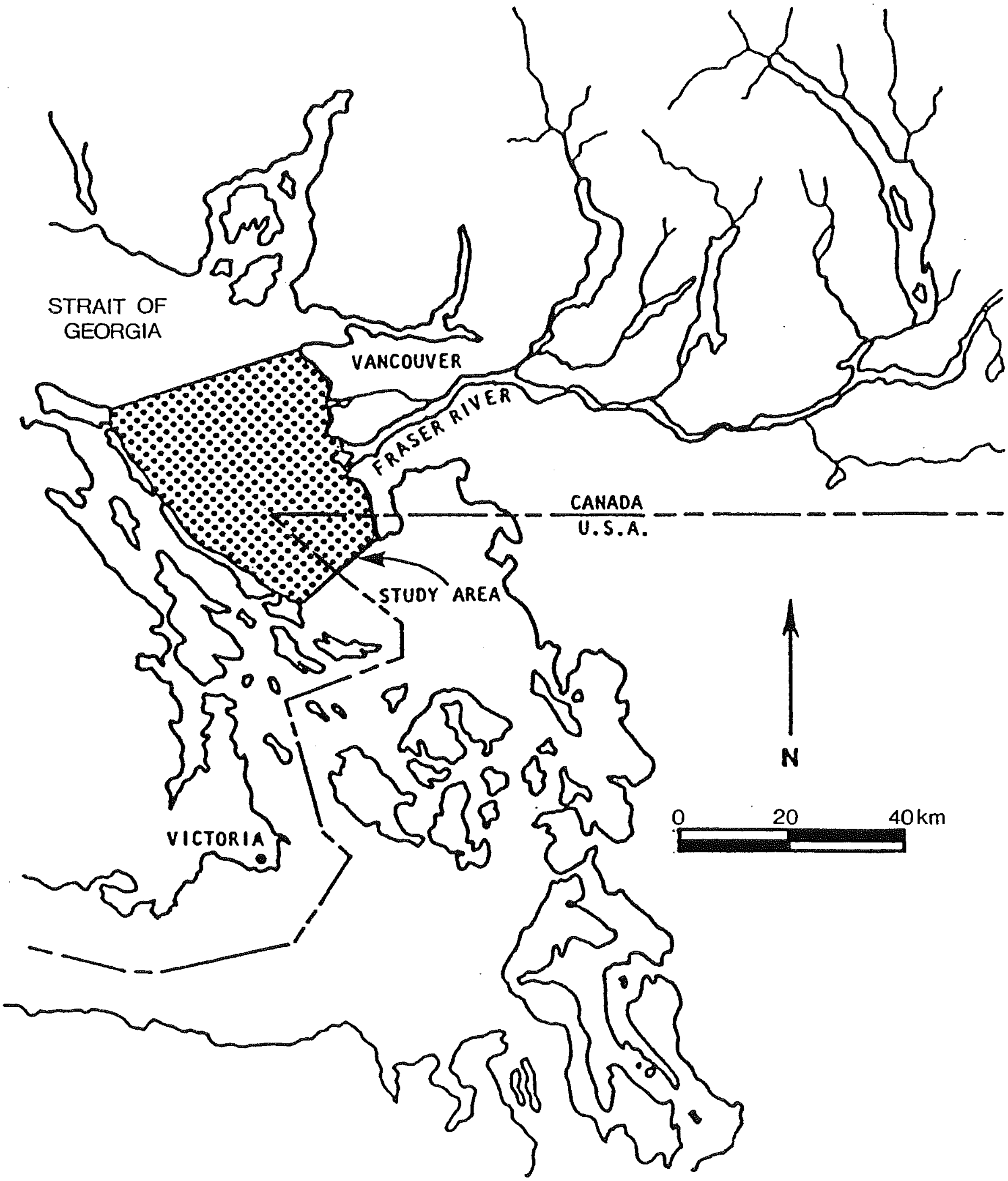

Figure 1. Location of the Strait of Georgia study area on the coast of British Columbia.

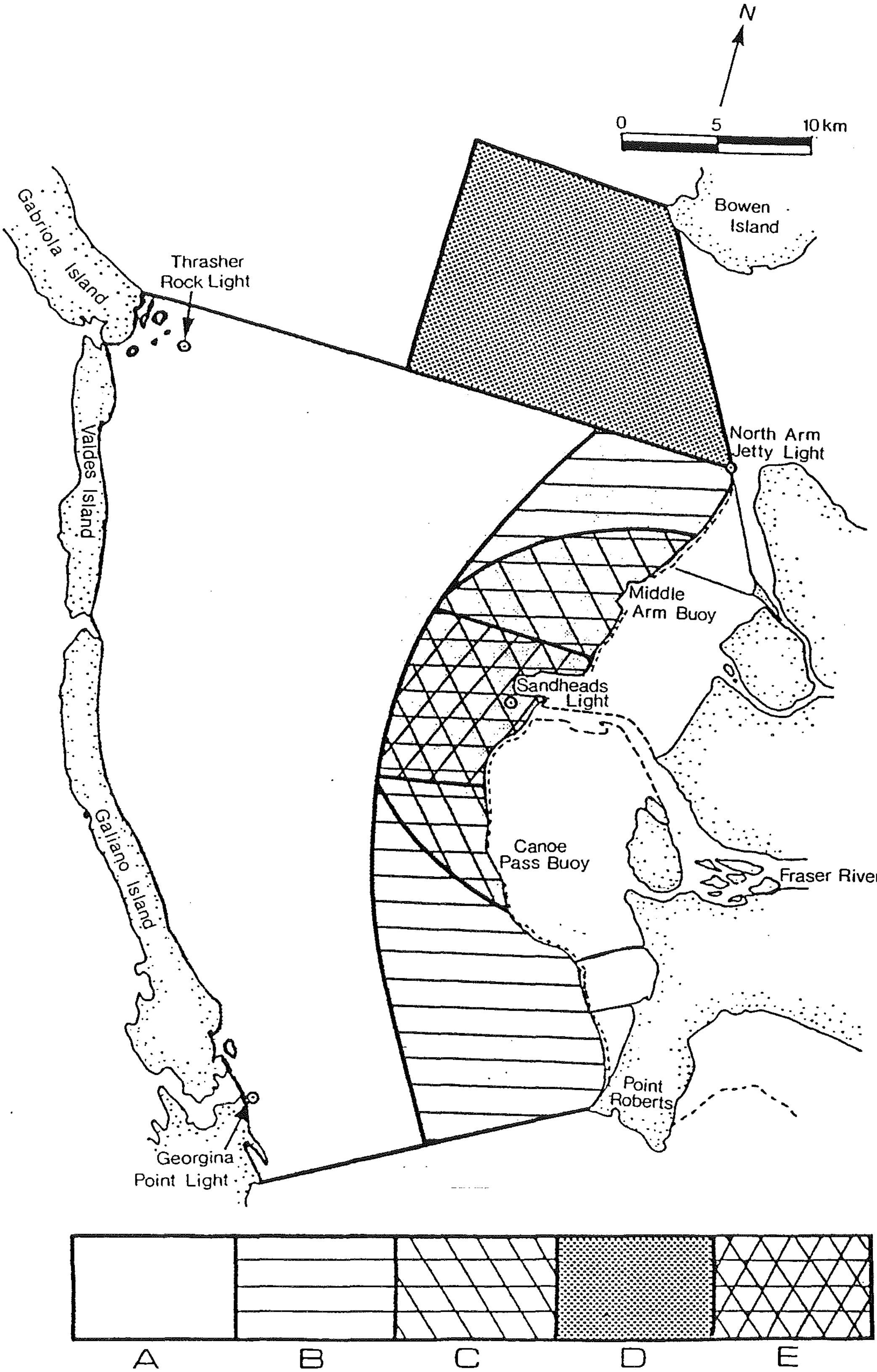

Figure 2. Survey areas in the Strait of Georgia. Area E is nested in Area C; Areas C and E in Area B; and Areas B, C and E in Area A.

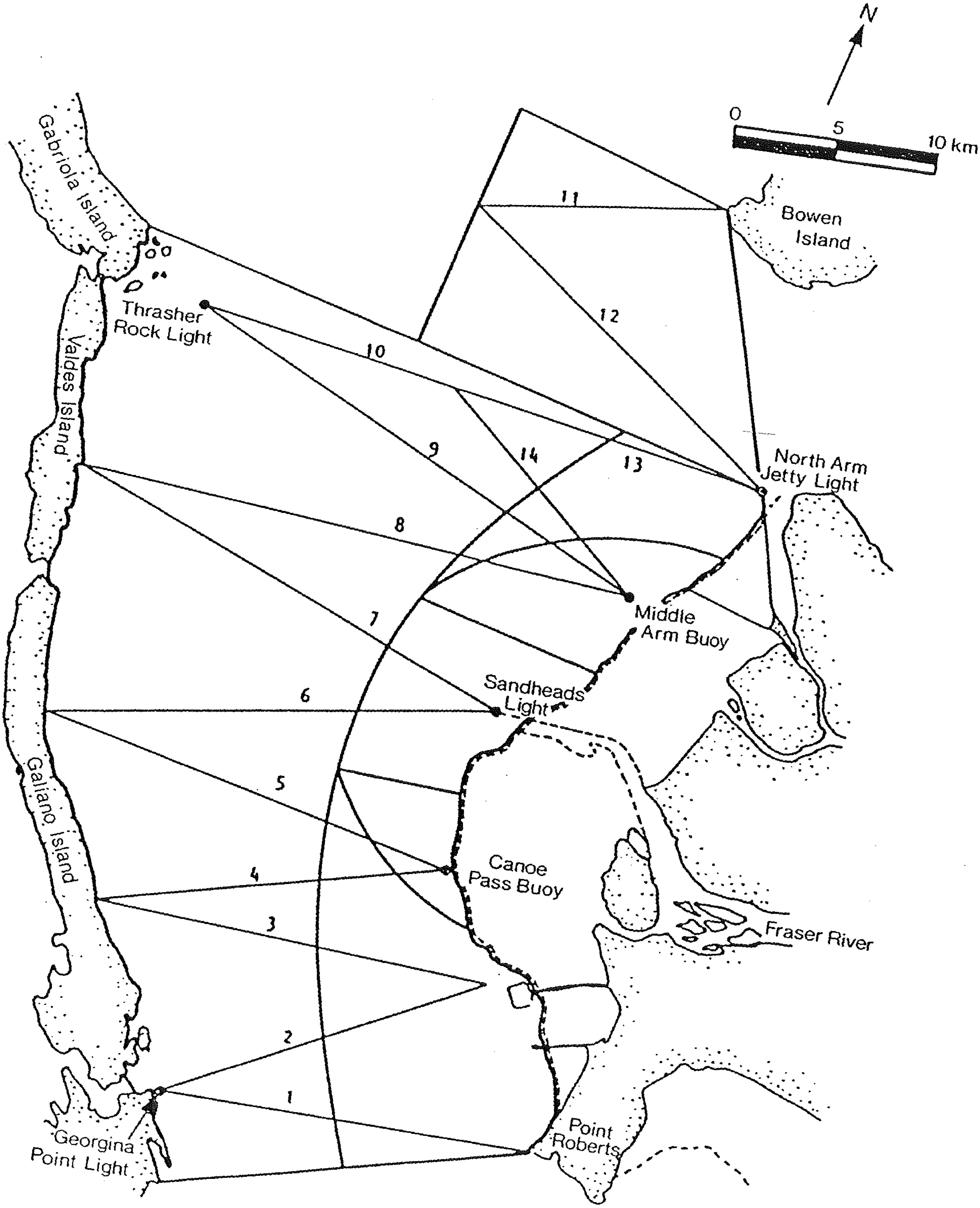

Figure 3. Approximate transect locations in the study area in the Strait of Georgia, British Columbia.

Table 1. Estimated surface areas (km^2) for the nested survey areas.

Area	Surface Area (m^2)	Surveys Sampled
A	9.187×10^8	1,2,3
B	3.018×10^8	1,2,3,4
C	1.543×10^8	1,2,3,4
D	1.723×10^8	3
E	7.717×10^7	1,2,3,4

METHODS

HYDROACOUSTICS

Field data collection

Hydroacoustic observations were undertaken aboard two commercial gillnet fishing boats (10 m), each containing a BioSonics dual-beam echo-sounder and recording system. One of the survey boats deployed its transducers within a towed body, 2 m below the surface, in a standard downlooking mode of operation (Figure 4). The second boat deployed its transducers from a specially designed, double V-fin, paravane towed vehicle (Figure 4) which dove to a depth of about 30 m below the surface and 30 m to the side of the boat, when operated at transect speed (8 knots). Transducers within the paravane system were oriented vertically upwards towards the surface, such that the system sampled shallow depth strata in a mobile, uplooking mode of operation. Due to the conical beam dimensions of the transducers and boat avoidance behavior by fish in shallow depths, the latter system was adopted in an attempt to increase acoustic sampling power within shallow depths, where adult sockeye were anticipated to concentrate.

Hydroacoustic equipment aboard each survey vessel included a 200 kHz BioSonics Model 105 dual channel echo-sounder, a Model 171 tape recorder interface, a Sony beta-format video cassette recorder (VCR) and pulse code modulator (PCM) device, a Model 115 (or Model 111) chart recorder, a dual channel oscilloscope, transducer cables (50 m and 122 m for the downlooking and uplooking systems, respectively), and dual beam transducers (6°/15°) housed within fiberglass towed bodies. Power on each vessel was supplied by a gasoline generator.

Pulse width during data collection was 0.4 msec and pulse repetition rates were 6.5 pulses per second for the uplooking system and either 3.5 (survey 1) or 2.5 (surveys 2-4) pulses per second for downlooking system. Acoustic returns were amplified at both 20 Log R (where R = distance from transducer) and 40 Log R, time-varied gain, and multiplexed onto the VCR tape. This procedure permitted simultaneous data collection for echo integration (20 Log R) and dual-beam processing (40 Log R) purposes in subsequent data analyses.

Due to the different transducer deployments, echograms obtained from the two systems required different interpretation (Figure 5). Downlooking echograms covered the entire water column from the surface to the bottom and showed a strong signal produced by the bottom echo. In contrast, uplooking echograms showed a reversed vertical orientation, such that the surface echo was situated at the bottom portion of the chart (Figure 5). Fish targets from both systems showed up as distinct marks on the echograms (Figure 5) or discrete voltage pulses when observed on the oscilloscope.

In general, the paravane towed-body performed well, providing a stable platform for the uplooking transducers, even in relatively rough seas. The angle of the tow cable indicated a satisfactory lateral deflection of the device away from the path of the survey vessel. During survey 2, however, the towed body became unstable at depth, generating a spiral motion (detected on the oscilloscope by a regularly-intermittent bottom signal) which severely twisted the transducer cables and caused premature termination of the survey.

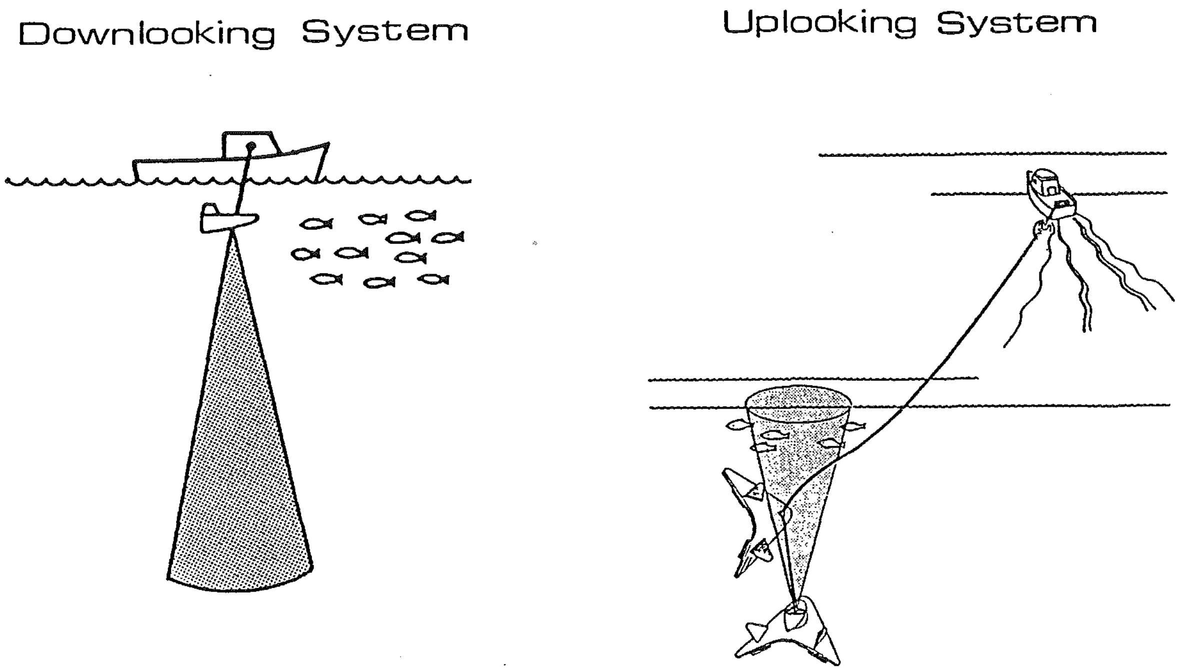

Figure 4. Orientation of towed-bodies and acoustic sample volumes for downlooking and uplooking acoustic systems, as operated in the Strait of Georgia during 1986.

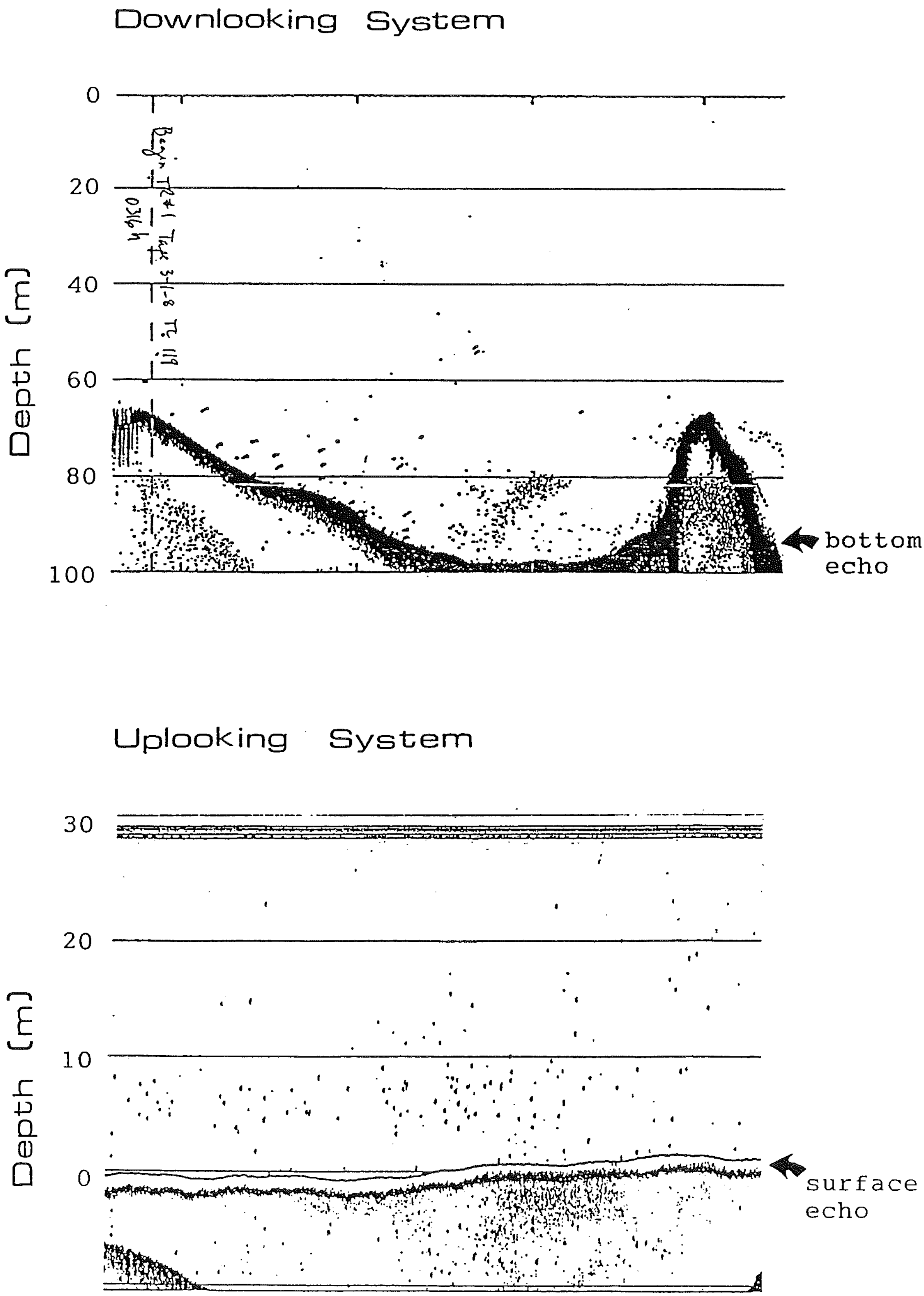

Figure 5. Sample echograms produced by the downlooking and uplooking acoustic systems (survey 3, transect 1).

Survey design

Four acoustic surveys were scheduled during mid August to mid September of 1986, a time period when late-run sockeye salmon delay their upstream migration in the Strait of Georgia for a 2-6 week period (Gilhousen 1960). Surveys were undertaken at night, when the nocturnal dispersion of fish schools is advantageous during quantitative acoustic assessments. Surveys were scheduled during periods of fishery closures (to avoid interference with fishing vessels) on the following dates:

Survey	1st night	2nd night	3rd night
1	August 19-20	20-21	21-22
2	August 28-29	29-30	30-31
3	September 4-5	5-6	---
4	September 9-10	10-11	---

A zig-zag transect scheme was adopted during Surveys 1-3 (Figure 3), in order to effectively cover the entire study area. During Survey 4, different transects contained within Area B (Figure 2) were adopted to intensify acoustic sampling adjacent to the Fraser Delta. Actual transect paths followed during the four surveys are given in the results.

Acoustic tape processing

Abundance estimates for each survey were derived by echo integration (Burczynski 1982; Thorne 1983A). The echo integrator results were scaled by an estimate of fish target strength within the study area, as derived by the dual beam system (Traynor and Ehrenberg 1979; Ehrenberg 1983). Similar methods have recently been adopted during quantitative surveys of diverse aquatic organisms (Burczynski and Johnson 1986; Jefferts et al. 1987; Greene et al. 1988).

Voltage thresholds were established by examining the VCR tapes visually with an oscilloscope prior to analysis and setting threshold levels at approximately twice the observed background noise level. Echo integration of the 20 Log R - amplified returns was undertaken with a Model 121 BioSonics Echo Integrator connected to a microcomputer. The integrator was programmed to output results for 0.25 nautical mile transect distances and produced 20-60 numerical outputs (sequences) per transect. Depth strata for analysis purposes were defined as 2.5 and 5 m for the uplooking and downlooking systems, respectively. The numerical integrator outputs were saved on computer disk. Prior to further analysis, the integrator data files were manually edited in order to reduce errors produced by false bottoms or electrical noise.

Dual-beam processing of the 40 Log R - amplified data (both narrow-beam and wide-beam) was undertaken with a BioSonics Model 181 Dual Beam Processor connected to microcomputer. The recommended pulse duration and amplitude criteria (BioSonics 1985) were adopted in order to filter out multiple fish targets. Data files containing the peak voltage returns for individual fish targets from both narrow-beam and wide-beam transducer elements, together with their corresponding depth value and ping number, were saved to computer disk. These data files were then analyzed with the BioSonics "TS" program (BioSonics 1985) to compute average target strengths (measured in decibels) per individual fish.

Acoustic data analysis

Due to the diverse fish assemblage within the pelagic zone of the Strait of Georgia, the echo integrator data were scaled to units of fish biomass. Acoustic estimates of biomass are less sensitive to changes in fish size than direct estimates of fish numbers. It was anticipated that adult sockeye would comprise a high proportion of the fish biomass during the Strait of Georgia acoustic surveys (but not necessarily a high proportion of the total fish numbers), making biomass estimates potentially more accurate than direct numerical estimates.

The following procedure was adopted to convert the estimated target strength values per individual fish, to target strength estimates per kg of biomass. First, the measured target strength (*TS*) per fish was converted to a "predicted" fish length with literature relationships reported by Love (1977):

$$TS_{dorsal} = 18.4 \text{ Log } L - 1.6 \text{ Log } f - 62.14$$

$$TS_{ventral} = 19.0 \text{ Log } L - \text{Log } f - 66.0$$

where TS_{dorsal} and $TS_{ventral}$ are the dorsal- and ventral-aspect target strengths, L is the fish length in cm, and f is the frequency of the acoustic system in kHz. Next, the predicted fish length was converted to target strength per unit biomass using relationships reported by Thorne (1983B) and shown in Figure 6. Lastly, the estimated target strength per unit biomass was converted to its arithmetic equivalent, the acoustic back-scattering cross-section. This latter parameter was then used to scale the integrator outputs and produce a fish biomass estimate for Georgia Straits in kg/m^3. This estimate was expanded to the study area of interest by direct multiplication with the surface area estimates (Table 1). Thus:

$$B_{tot} = \left(\sum_{i=1}^{m} b_i \, M \right) A$$

where B_{tot} is the total fish biomass in kg, i is the depth interval number, M is the number of meters per depth interval, m is total number of depth intervals, b_i is the biomass per m^3 in depth interval i, and A is the areal expansion factor in m^2. Variance estimates were calculated from values in the sequential, 0.25 nautical mile integrator outputs and provided the basis for estimating 95% confidence intervals.

Calculations of fish biomass were undertaken with the BioSonics "CRUNCH" program (BioSonics 1985). This program averages the integrator outputs, scales the values by the proportion of each depth strata within the sample, and produces an absolute biomass estimate based on system parameters, calibration data, and estimated target strength. The fish biomass estimate was then scaled by the proportion of sockeye biomass within the study area (as determined within purse seine samples) to obtain a sockeye biomass estimate. The latter estimate was then converted to adult sockeye numbers by division with the average sockeye weight (as determined from purse seine samples).

To assess sockeye distribution qualitatively within the Strait of Georgia water column, voltage isopleths were fit to the echo integrator data for individual transects. The orientation (E-W) of each transect was confirmed from LORAN readings in the field logs. Each integrator output was assigned a number, corresponding to its horizontal position across the transect. Figure 7 is an example of voltage isopleths fit through downlooking and uplooking integrator data files. Fish vertical distribution was also analyzed quantitatively by generating density profiles for individual surveys in both downlooking and uplooking data sets.

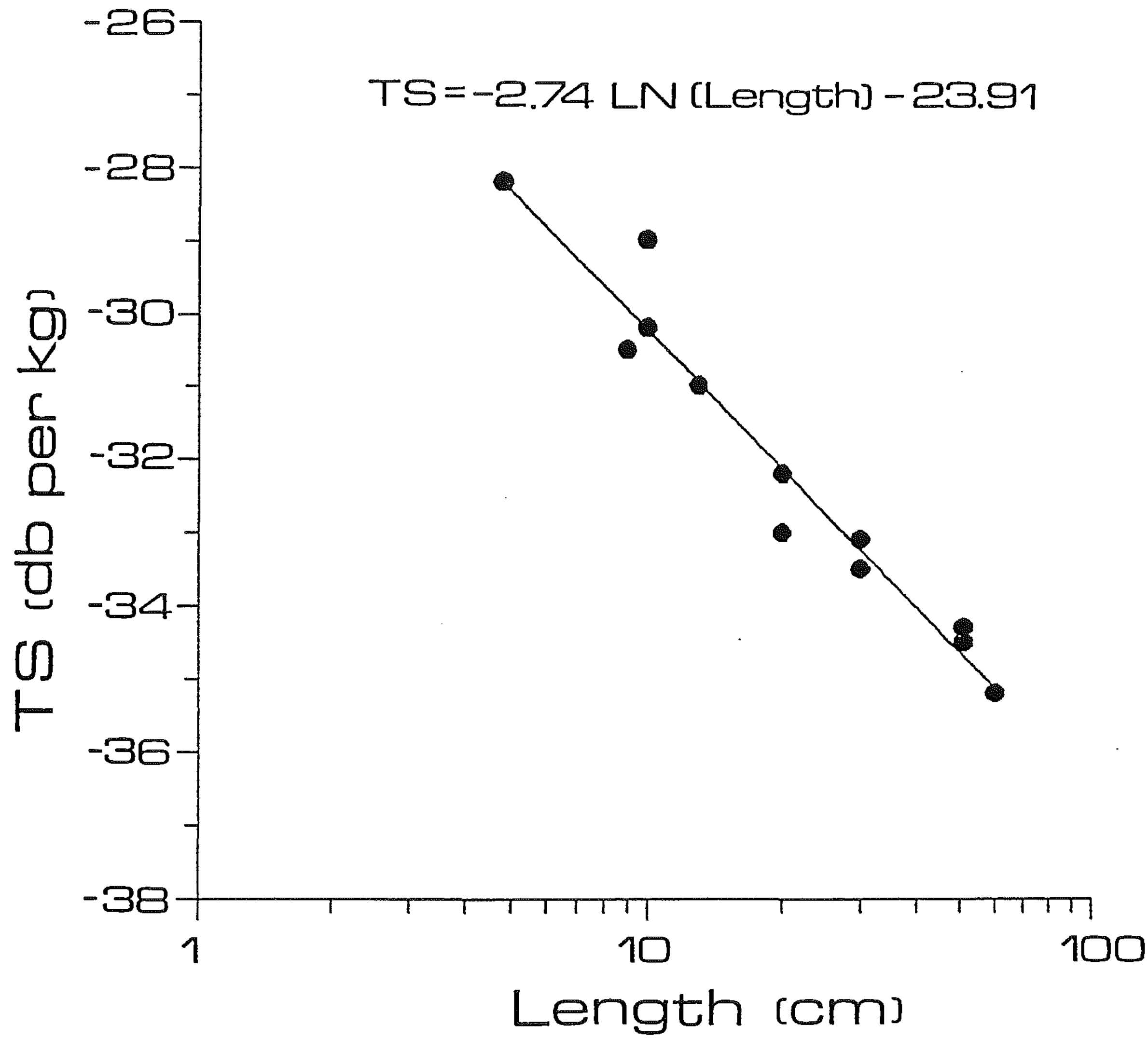

Figure 6. Relationships between fish length and target strength (TS) per kg fish biomass. Redrawn from data in Thorne (1983B).

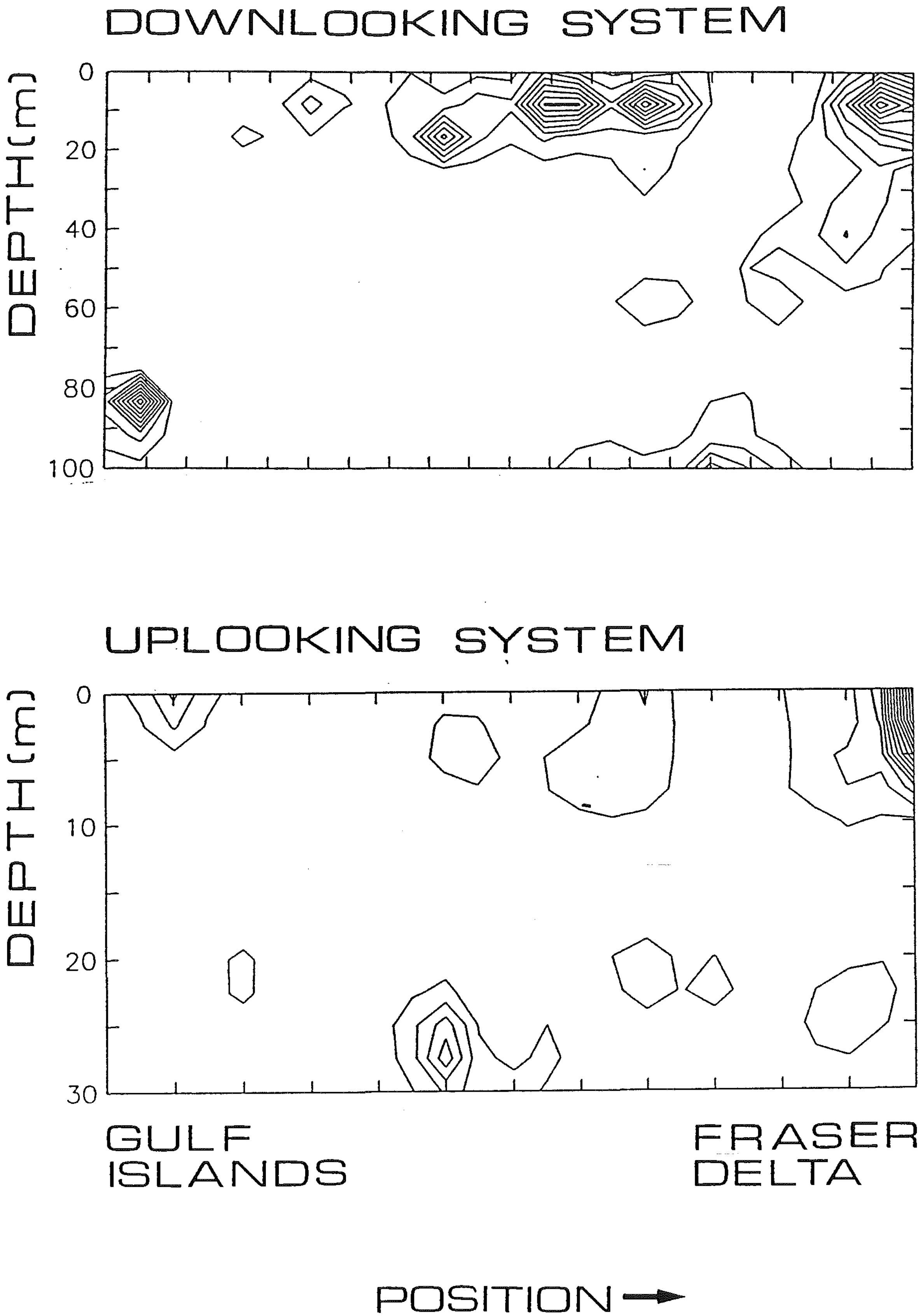

Figure 7. Results of survey 3, transect 1, with isopleths fitted to integrator voltage^2 values for downlooking and uplooking acoustic systems. Note different depth scales.

PURSE SEINE SAMPLING

Fish species composition within the study area was estimated during surveys 2-4 by analyzing the catches of a chartered purse seine vessel outfitted with a "herring seine". The seine dimensions were 500 m wide by 60 m deep, with 3.2 cm stretch mesh web material. Sets were undertaken at night adjacent to hydroacoustic transect locations. A bathythermograph recording was taken to record vertical temperature profiles adjacent to seine set locations or acoustic transects and are shown in Figure 8. Catches were identified and enumerated aboard the seine vessel. Lengths and weights of all fish captured were measured and recorded. Purse seine set locations are shown in Figures 9-11.

SOCKEYE RUN RECONSTRUCTION

Hydroacoustic estimates of sockeye abundance were compared to post-season estimates of reconstructed abundance by day. The timing-abundance profile of sockeye entering the hydroacoustic study area was estimated by a forward simulation model. This model calculates normally distributed abundances of individual sockeye stocks, sequentially moves the fish through the fishery areas, and removes catch according to imposed fishery regulations (Cave and Gazey in press). The Starr and Hilborn (1988) method of backwards reconstruction was not used because late-run sockeye violate the "order of movement" assumption of that method. For the 1986 Strait of Georgia sockeye reconstruction, the actual 1986 fishing regulations were simulated in the model along with post-season estimates of total run sizes, migration timing and rate of diversion through Johnstone Strait. The Strait of Georgia escapement profiles were calculated separately for the northern (Johnstone Strait) and southern (Juan de Fuca Strait) approaches and summed together to estimate daily escapements to the Strait of Georgia. Daily abundances in the Strait for each hydroacoustic survey date were obtained using these estimates of daily escapement minus fishery catches in the Strait and lower Fraser River, and escapement upstream past the acoustic monitoring site at Mission, B.C. These abundance estimates were scaled to final (post-season) estimates of escapement and catch of the particular stocks which contributed fish to the Strait of Georgia population during the survey period.

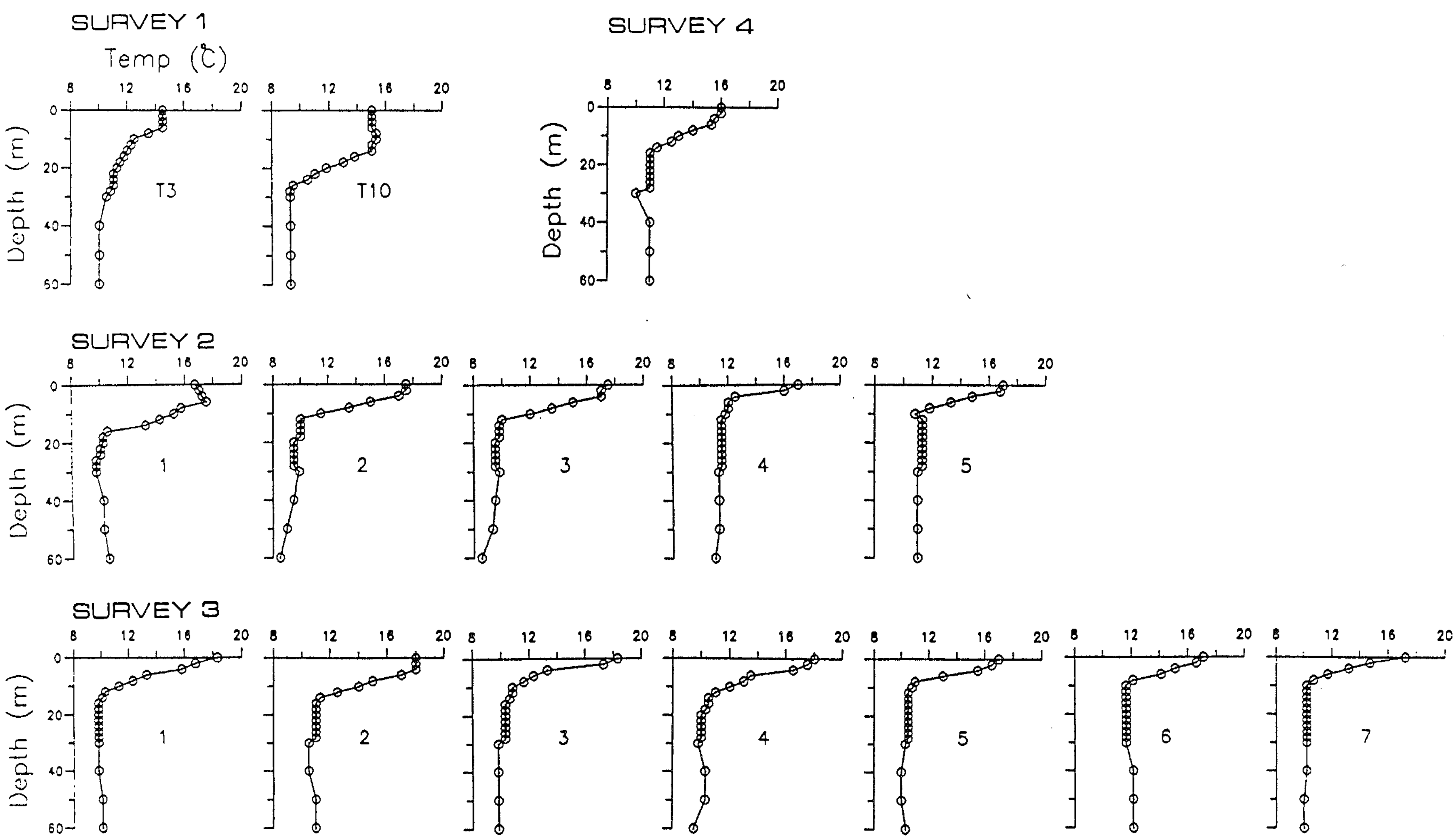

Figure 8. Temperature profiles obtained by bathythermograph recorder adjacent to seine set locations (surveys 2 and 3) or hydroacoustic transect locations (survey 1). The temperature profile location for survey 4 was not recorded.

RESULTS

PURSE SEINE RESULTS

Purse seine catch results for surveys 2-4 are summarized in Figures 9-11, respectively. Adult sockeye comprised a small percentage (10%) of the total number of fish captured during survey 2, but a major percentage (74%) of the biomass within the catch (Figure 9). During the latter two surveys (Figures 10-11), sockeye comprised a major percentage of the total fish numbers (> 50%) and almost the entire fish biomass within the catches (>97%). In these two surveys, even when sockeye were extremely numerous within the study area, there was substantial variation in the number and proportion of sockeye captured in individual seine sets (Table 2). Fish size characteristics and corresponding predicted target strengths based on empirically derived regressions (Love 1977) are shown in Table 3.

HYDROACOUSTIC ESTIMATES OF SOCKEYE ABUNDANCE

Hydroacoustic estimates of fish abundance are sensitive to variations in target strength; estimated densities are directly proportional to differences in acoustic back scattering cross-section (Thorne 1983B), the arithmetic form of target strength. Therefore, it was necessary to consider spatial and temporal variation in target strength.

Target strength estimates did not differ greatly between sampling areas (Figure 12). Moreover, when target strength estimates were combined for the different survey dates, there was only minor variation in target strength estimates for different depth strata (Figure 13). Because of the observed homogeneity in the estimated target strengths, the average measured target strength values shown in Figure 14 were used in the sockeye abundance calculations. Sample sizes used to compute the mean target strength values in Figures 12-14, are shown in Table 4.

Measured target strength values during all four surveys were substantially lower than predicted values (Figure 14) based on fish size measurements (Table 3). The discrepancy between measured and predicted target strength was largest (8 db) for the ventral aspect target strength during survey 2. During surveys 3 and 4, discrepancies between measured and predicted target strengths were 2-5 db (Figure 14).

The measured target strength values were used for the sockeye abundance calculations. Sockeye abundance estimates for the four surveys are shown in Table 5. These estimates are combined for the uplooking and downlooking systems, with uplooking results for depth strata 0-10 m, and downlooking results for depth strata 10-60 m. Printouts of the echo integrator data files used to derive the estimates for the different survey areas are shown in Appendix C of an earlier report (Ransom and Burczynski MS 1986). Highest numbers of sockeye occurred during surveys 3 and 4, when a total of 2,015,000 (Areas A and D) and 1,610,000 (Area B) sockeye were estimated, respectively (Table 5).

The sockeye abundance estimates derived by the uplooking and downlooking systems, as well as the combined results as described above, are compared in Figure 15. During surveys 1-3, sockeye abundance estimates were considerably lower in the uplooking data set, resulting in only a minor impact of including the uplooking data in the combined abundance estimate (Figure 15). In contrast, the number of sockeye estimated by the uplooking system was double that obtained by the downlooking system during survey 4 (Figure 15). Inclusion of the uplooking data had a large effect on the combined sockeye abundance estimate on this particular survey date.

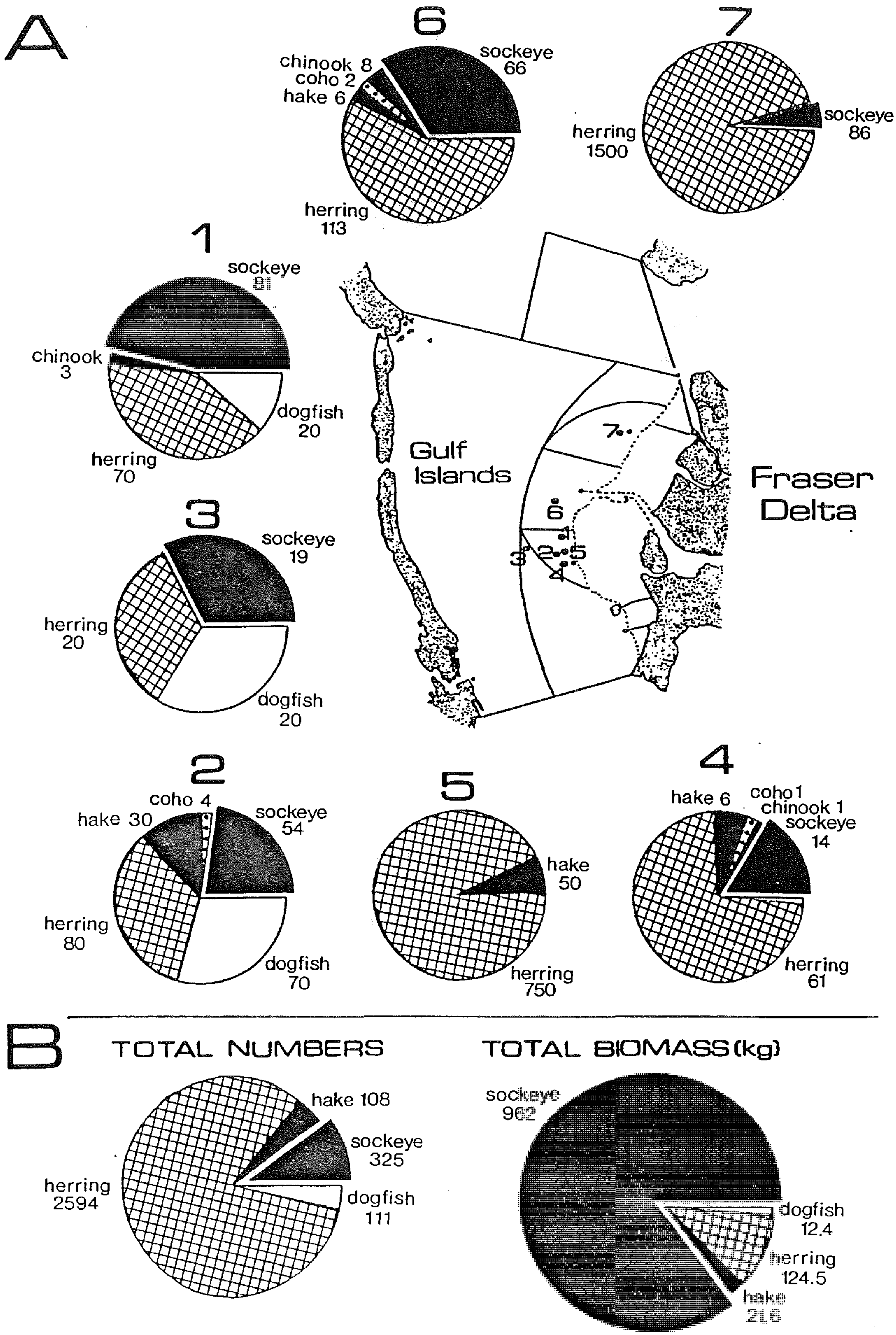

Figure 9. Purse seine set locations and catch results during survey 2.

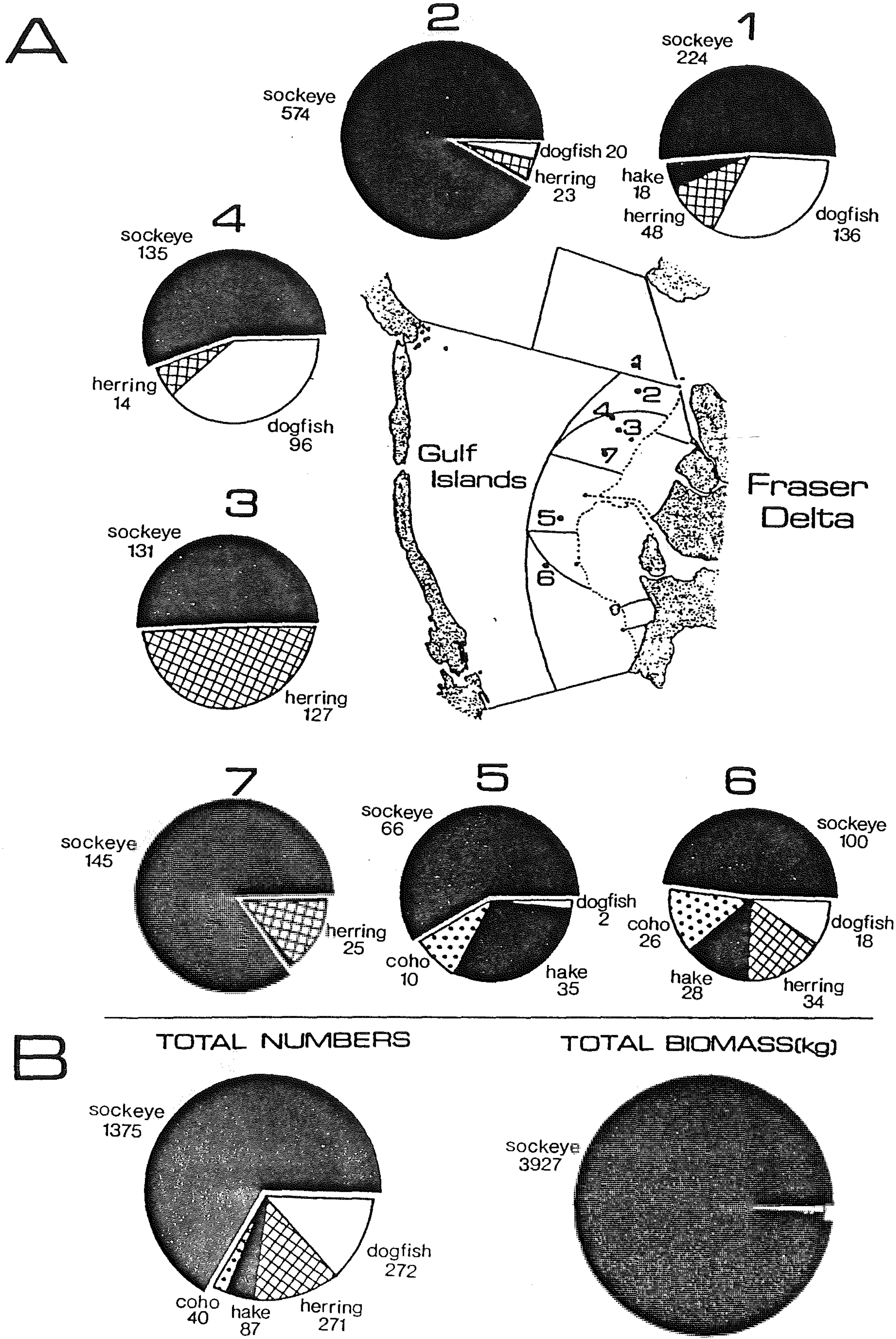

Figure 10. Purse seine set locations and catch results during survey 3.

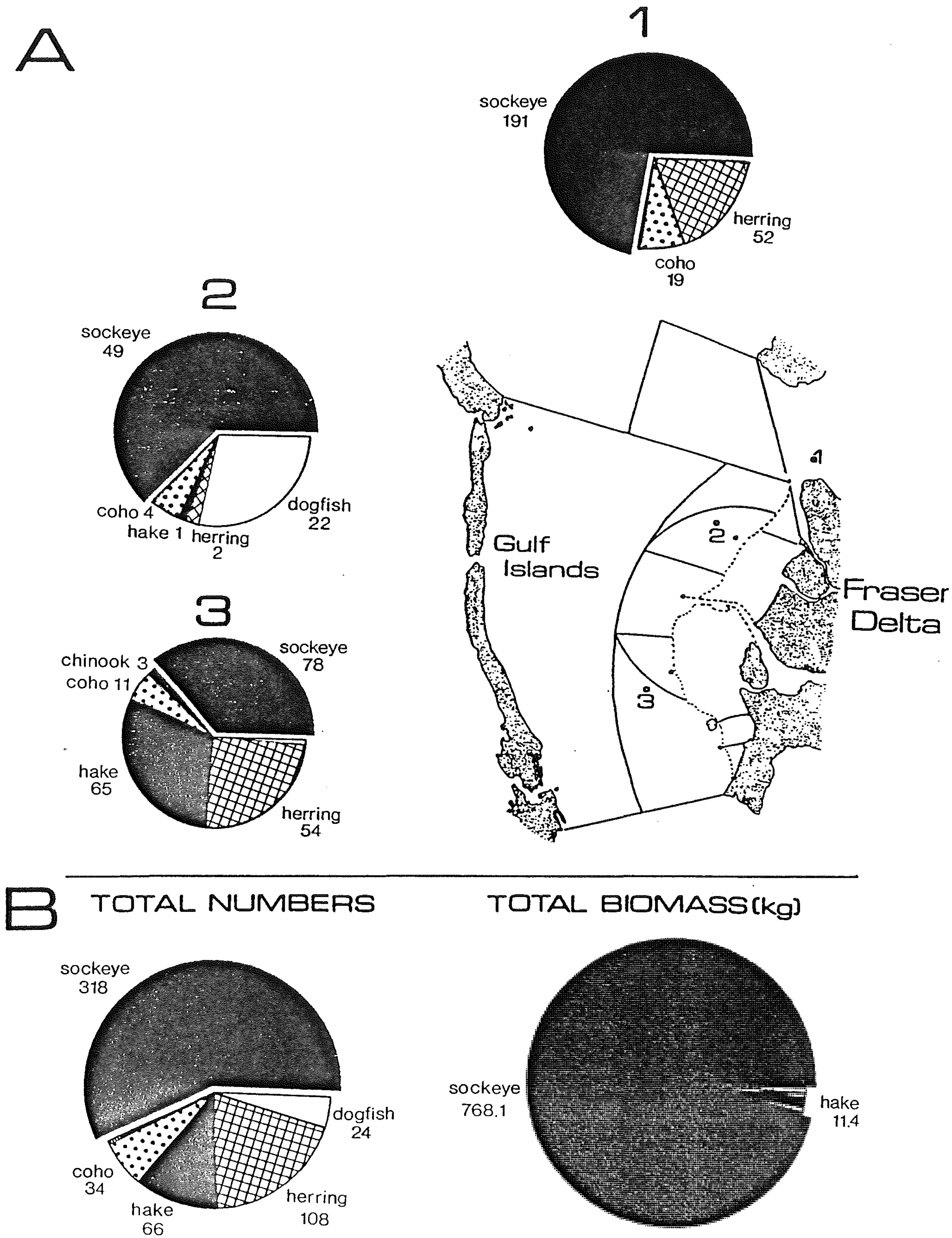

Figure 11. Purse seine set locations and catch results during survey 4.

Table 2. Fish catch results in purse seine sets.

Survey	Set	No. Sockeye	Prop. Sockeye	No. Chinook	No. Coho	No. Hake	No. Herring	No. Dogfish
2	1	81	0.46	3	1	0	70	20
	2	54	0.23	0	4	30	80	70
	3	19	0.32	0	0	0	20	20
	4	14	0.17	1	1	6	61	1
	5	5	0.01	2	0	50	750	0
	6	66	0.34	8	2	6	113	0
	7	86	0.05	3	0	0	1500	0
	Mean	46	0.22	2	1	13	371	16
	S.D.	33		3	1	19	560	26
3	1	224	0.52	0	4	18	48	136
	2	574	0.92	0	0	5	23	20
	3	131	0.51	0	0	0	127	0
	4	135	0.55	0	0	0	14	96
	5	66	0.58	0	10	35	0	2
	6	100	0.49	0	26	28	34	18
	7	145	0.84	1	0	1	25	0
	Mean	196	0.63	0	6	12	39	39
	S.D.	173		0	10	15	42	55
4	1	191	0.73	1	19	0	52	0
	2	49	0.63	0	4	1	2	22
	3	78	0.37	3	11	65	54	2
	Mean	106	0.58	1	11	22	36	8
	S.D.	75		2	8	37	29	12

Table 3. Measured fish size characteristics in purse seine sets, and predicted target strengths based on Love (1977) equations.

	Sockeye	Chinook	Coho	Herring	Hake	Dogfish	Weighted Average
Survey 2							
Number	325	17	8	2594	108	111	
% of total	10.3	0.5	0.3	82.0	3.4	3.5	
Biomass (kg)	649.2	1.9	1.7	124.5	21.6	12.4	
% of total	74.0	0.3	0.1	23.0	1.7	1.2	
Length (cm)	54.8	21.8	20.4	19.8	26.4	28.7	
TS_{dorsal} (db)[1]	-33.8	-41.2	-41.7	-41.9	-39.6	-39.0	-40.9
$TS_{ventral}$ (db)[2]	-33.0	-40.6	-41.1	-41.4	-39.0	-38.3	-40.3
Survey 3							
Number	1375	1	40	271	87	272	
% of total	67.2	0	2.0	13.2	4.3	13.3	
Biomass (kg)	3927.0	0.6	12.8	16.4	12.5	38.4	
% of total	98.0	0	0.3	0.4	0.3	1.0	
Length (cm)	54.7	35.5	21.6	14.6	23.0	29.6	
TS_{dorsal} (db)[1]	-33.8	-37.7	-41.2	-44.4	-40.7	-38.7	-36.3
$TS_{ventral}$ (db)[2]	-33.0	-36.5	-40.6	-43.9	-40.1	-38.0	-35.6
Survey 4							
Number	318	4	34	108	66	24	
% of total	57.4	0.7	6.1	19.5	11.9	4.3	
Biomass (kg)	768.1	2.1	4.3	5.7	11.4	4.2	
% of total	96.5	0.3	0.5	0.7	1.4	0.5	
Length (cm)	54.6	39.9	18.0	19.1	25.4	31.7	
TS_{dorsal} (db)[1]	-33.8	-36.3	-42.7	-42.2	-40.0	-38.2	-36.9
$TS_{ventral}$ (db)[2]	-33.0	-35.6	-42.2	-41.7	-39.3	-37.5	-36.2

[1] $TS_{dorsal} = 18.4 \text{ Log } L - 1.6 \text{ Log } f - 62.14$

[2] $TS_{ventral} = 19.0 \text{ Log } L - \text{Log } f - 66.0$

where TS_{dorsal} and $TS_{ventral}$ are the dorsal- and ventral-aspect target strengths in db, L is the fish length in cm, and f is the frequency of the hydroacoustic system in kHz.

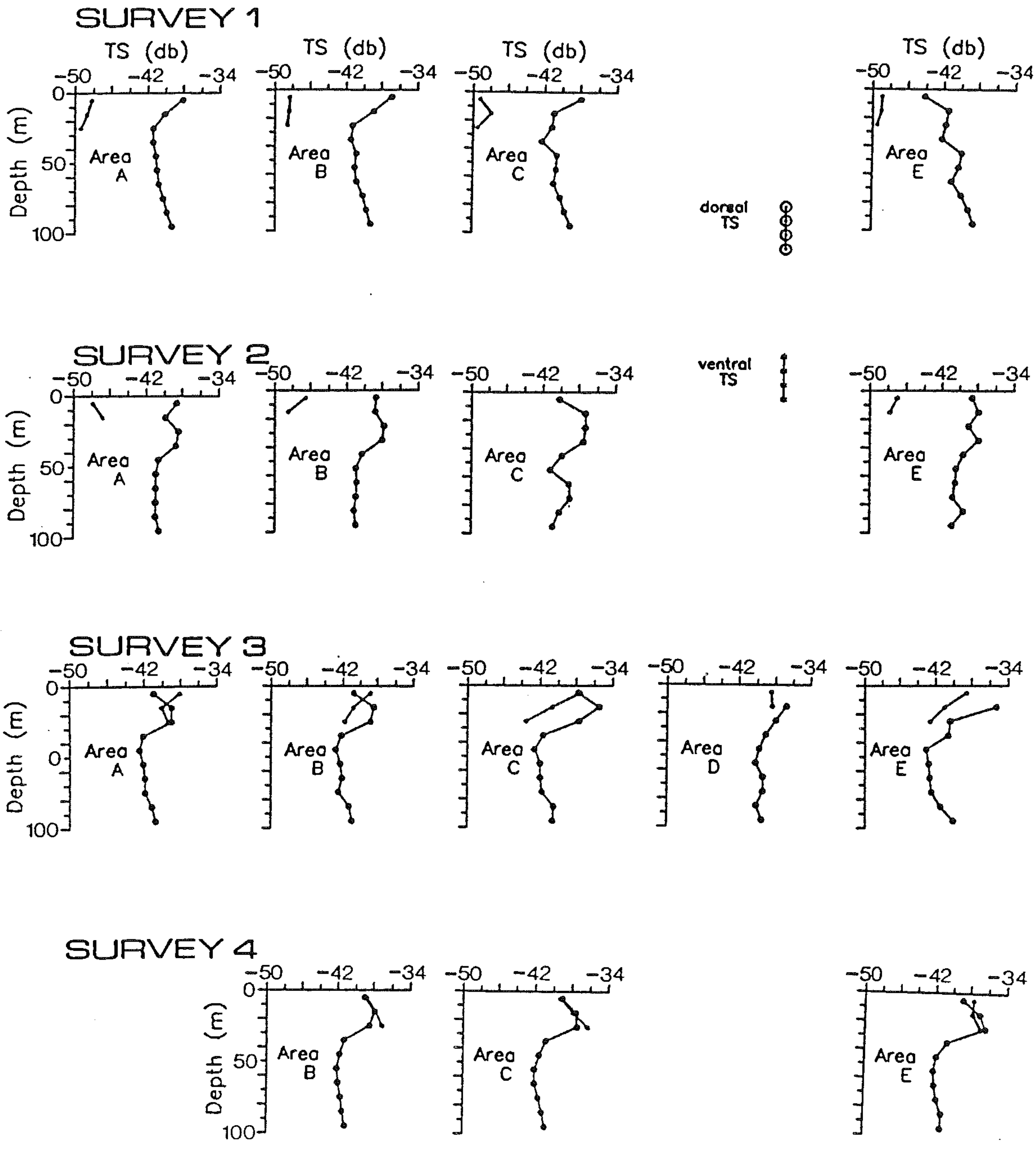

Figure 12. Measured target strength depth profiles, stratified by sampling area.

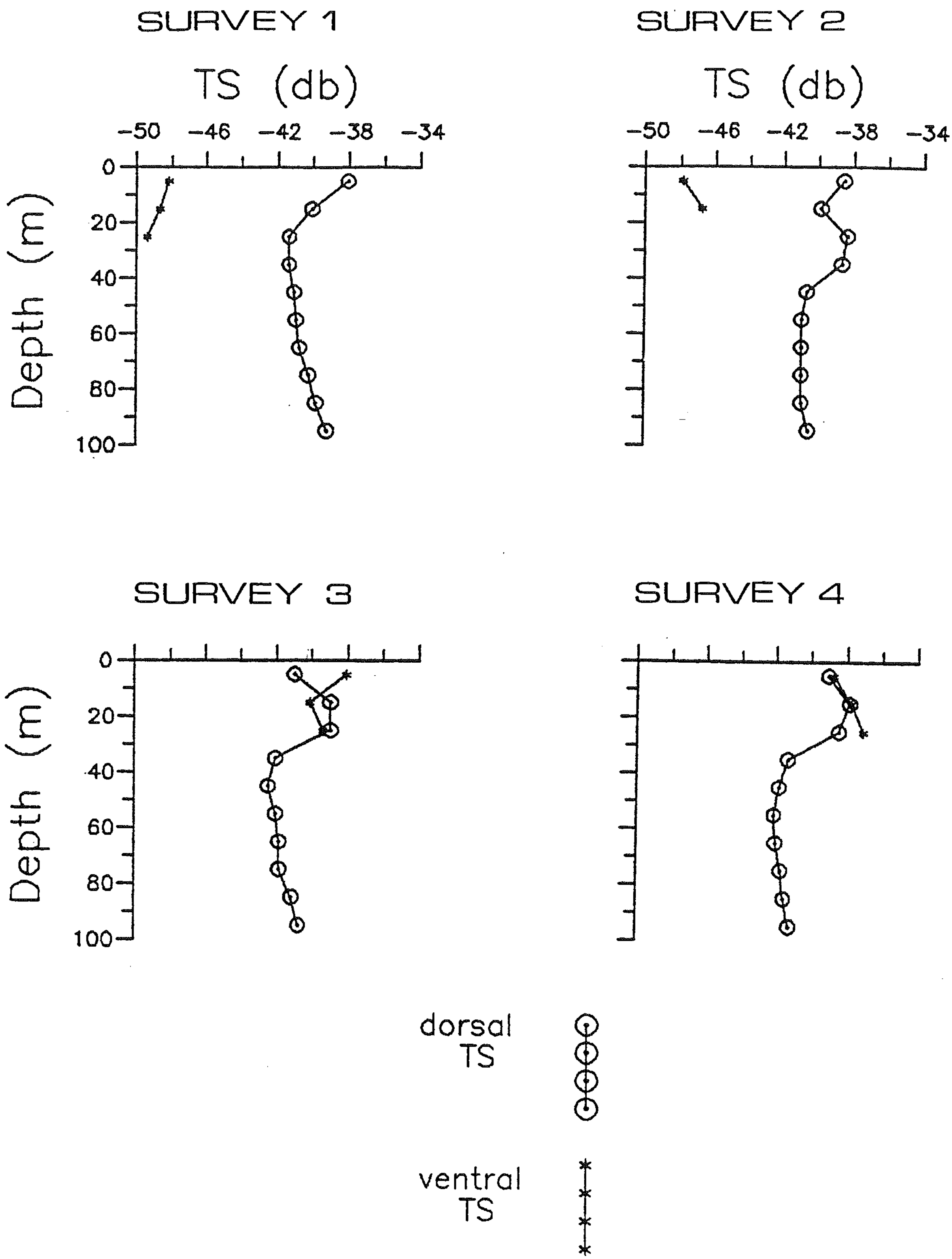

Figure 13. Combined target strength depth profiles for the four survey dates.

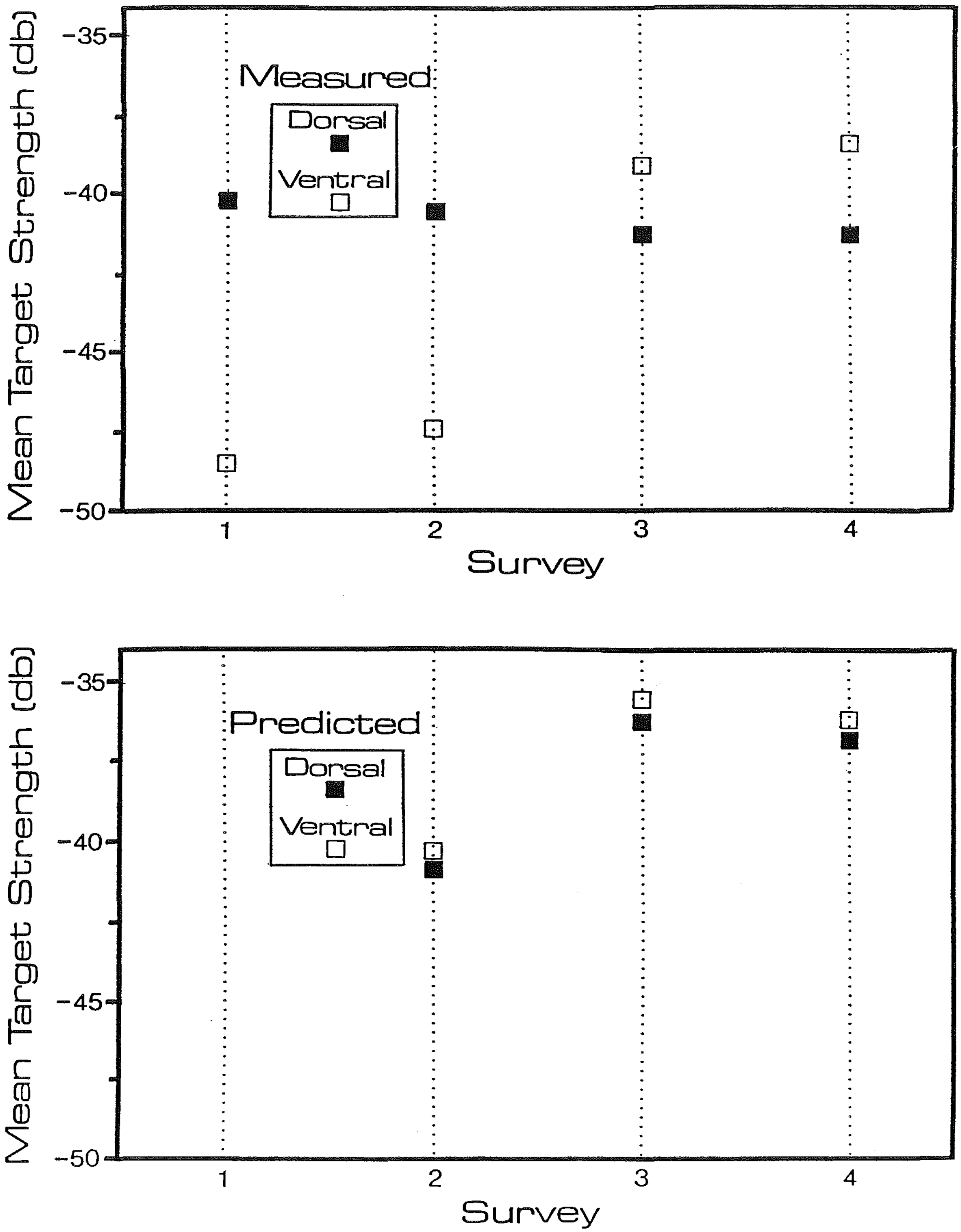

Figure 14. Target strength estimates measured by the dual-beam system and predicted values based on fish size characteristics in purse seine samples (Table 3).

Table 4. Sample sizes for mean target strengths shown in Figures 11-13.

	Area A		Area B		Area C		Area D		Area E	
	Down	Up	Down	Up	Down	Up	Down	Up	Down	Up
Survey 1										
Depth (m)										
5	29	147	18	70	5	39			3	18
15	326	123	185	59	51	21			34	8
25	658	6	294	3	90	2			60	2
35	725		306		63				37	
45	616		285		83				33	
55	1020		466		146				69	
65	1963		897		291				132	
75	2980		1417		478				238	
85	3329		1432		417				265	
95	2775		1021		490				357	
Total	14421	276	6321	132	2114	62			1228	28
Survey 2										
Depth (m)										
5	20	30	10	47	5				4	70
15	212	26	144	13	47				29	28
25	340		156		105				40	
35	296		172		76				68	
45	496		286		114				129	
55	832		510		188				212	
65	1227		613		189				281	
75	1667		691		284				476	
85	2348		892		392				548	
95	3697		1042		370				269	
Total	11315	56	4516	60	1770	0			2056	98
Survey 3										
Depth (m)										
5	20	592	13	308	3	180	0	120	0	77
15	207	368	134	163	43	76	14	51	113	60
25	277	63	213	33	53	7	31		49	9
35	244		180		45		31		49	
45	393		310		78		39		72	
55	534		371		172		136		146	
65	631		400		243		222		298	
75	793		427		246		222		530	
85	1010		457		328		253		502	
95	1065		426		261		235		138	
Total	5174	1023	2931	504	1472	263	1183	171	1897	146
Survey 4										
Depth (m)										
5			129	1500	32	1036			25	1021
15			352	479	252	381			199	330
25			613	75	471	60			383	43
35			415		290				223	
45			507		358				262	
55			865		675				564	
65			1481		1113				880	
75			1812		1309				1012	
85			2048		1416				990	
95			1682		1123				825	
Total			9904	2054	7039	1477			5363	1394

Table 5. Sockeye abundance estimates during surveys 1-4, broken down by study area.

Area	Total Biomass (kg)	Prop.[a] Sockeye Biomass	Mean Sockeye Biomass (kg)	Sockeye Weight[a] (kg)	Number Sockeye	95% CI (%)
Survey 1						
A	4185000	0.25[b]	1046000	2.96[c]	353000	39
B	2164000	0.25	541000	2.96	183000	51
C	623000	0.25	156000	2.96	53000	56
E	308000	0.25	77000	2.96	26000	71
Survey 2						
A	2396000	0.74	1773000	2.96	599000	35
B	1305000	0.74	966000	2.96	326000	44
C	959000	0.74	710000	2.96	240000	55
E	401000	0.74	297000	2.96	100000	95
Survey 3						
A	4703000	0.98	4610000	2.83	1629000	36
B	2170000	0.98	2126000	2.83	751000	45
C	1227000	0.98	1202000	2.83	425000	67
D	1116000	0.98	1093000	2.83	386000	62
E	956000	0.98	937000	2.83	331000	73
Survey 4						
B	4054000	0.97	3912000	2.43	1610000	31
C	2161000	0.97	2085000	2.43	858000	37
E	1283000	0.97	1238000	2.43	509000	49

a Estimated from measured fish weights in seine catches (Table 3).

b Sockeye biomass proportion assumed as 1/3 of the survey 2 value, since no seine samples were taken during survey 1.

c Survey 2 value used for calculation.

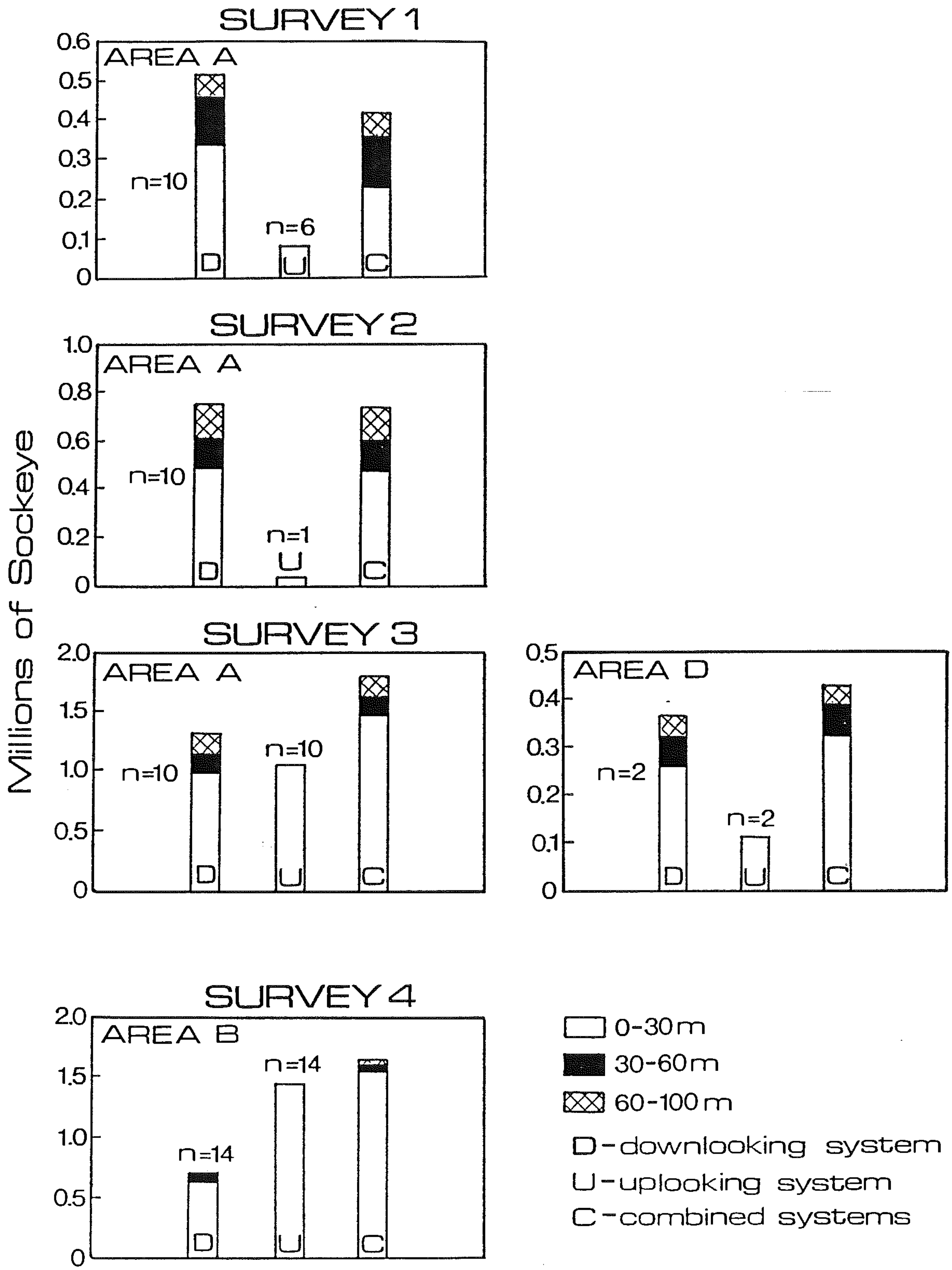

Figure 15. Sockeye abundance estimates during surveys 1-4, as determined by downlooking, uplooking, and combined systems (uplooking data for 0-10 m, downlooking data for 10-100 m). Number of transects per survey shown by "n".

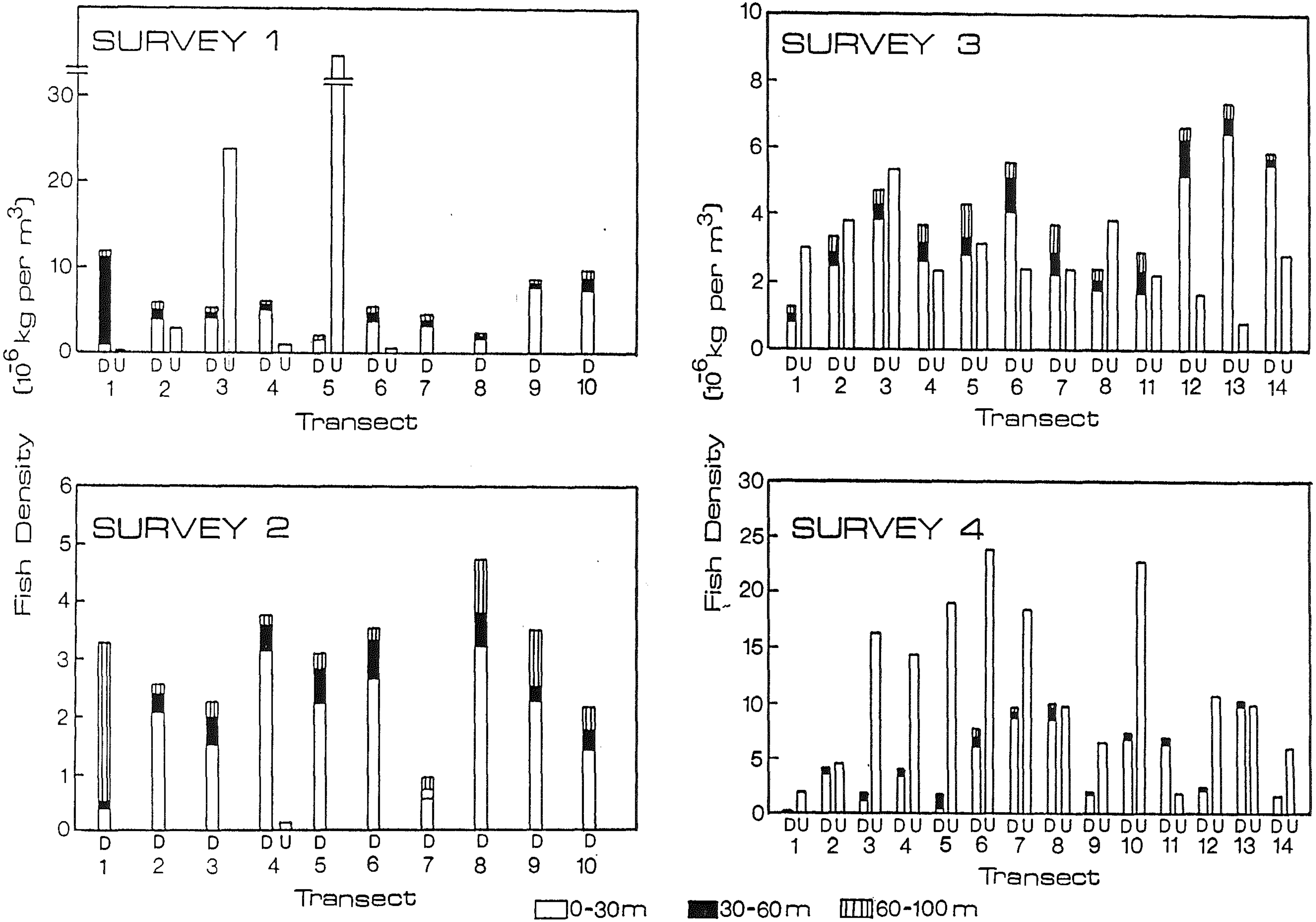

Figure 16. Estimated fish densities for individual transects in downlooking (D) and uplooking (U) data sets, during surveys 1-4.

Downlooking and uplooking results were further compared by analyzing results obtained for individual transects (Figure 16). The high density recorded by the uplooking system on transect 5 during survey 1 may be an artifact due to inadvertent echo integration of the surface echo. During survey 3, the downlooking system estimated higher densities (0-30 m depth interval) than the uplooking system on five out of twelve transects. By contrast, during survey 4, the uplooking results were higher than the downlooking estimates on most of the transects (Figure 16).

STRAIT OF GEORGIA SOCKEYE SALMON RUN RECONSTRUCTION

The reconstructed sockeye abundance profile for the Strait of Georgia is shown in Figure 17. The reconstructed abundances include Canada Department of Fisheries and Oceans spawning escapement estimates derived by mark-recapture spawning ground enumerations of late-run sockeye populations (Adams River, Lower Shuswap River, Weaver Creek), weir counts (Cultus Lake), and visual population counts (Harrison River and Portage Creek) as well as catches in the Strait of Georgia and lower Fraser River. The mark-recapture estimates of escapement are precise (Woodey 1984) and considered to be reasonably accurate. Peak numbers for the Strait of Georgia, estimated by reconstruction (Figure 17), were about 4 million sockeye in mid September, 1986. Sockeye numbers derived by hydroacoustic surveys were considerably lower than those estimated by the reconstruction (Figure 17, Table 5). Assuming that the reconstruction profile is accurate, the hydroacoustic surveys seriously underestimated the adult sockeye population in the Strait of Georgia during 1986.

SOCKEYE SALMON DISTRIBUTION WITHIN THE STRAIT OF GEORGIA

To assess fish distribution within the study area, isopleths were fit to the integrator (V^2) output data (Figure 7). The integrator value is proportional to fish biomass (Burczynski 1982); thus, both fish target strength (proportional to fish size) and fish density (numbers) contribute to the numerical value produced by the integrator.

The following observations can be made from the isopleth diagrams shown in Figures 18-21. First, the distribution of fish was irregular (patchy) across the horizontal plane, both in the downlooking and uplooking data sets. Second, there was little correspondence between the uplooking and downlooking isopleths and concentrations of fish were detected at different positions across the transects. This suggests that intra-transect variation (the uplooking and downlooking survey vessels did not follow identical transect paths) affected the results to the same extent as inter-transect variation. Third, there were distinct fish aggregations which appeared as diamond-shaped isopleth patterns on the diagrams (e.g., Transect 3, downlooking, on Figure 19). These features may be a consequence of sockeye aggregation behavior (schooling) within the study area. Fourth, there was a marked tendency for fish to concentrate along the Fraser Delta side of the Strait of Georgia, particularly on survey 3 (Figure 20). This may reflect a progressive concentration and delay pattern of adult sockeye off the mouth of the Fraser River. Lastly, there were distinct concentrations of fish present at approximately 20 m depth during survey 3 (downlooking transects 12, 13 and 14 on Figure 20) and 15 m depth during survey 4 (downlooking transects 10, 11, 12 and 13 on Figure 21). These observed patterns are probably a result of fish holding behavior prior to freshwater migration, causing relatively high sockeye densities in this depth zone and vicinity of the Strait of Georgia.

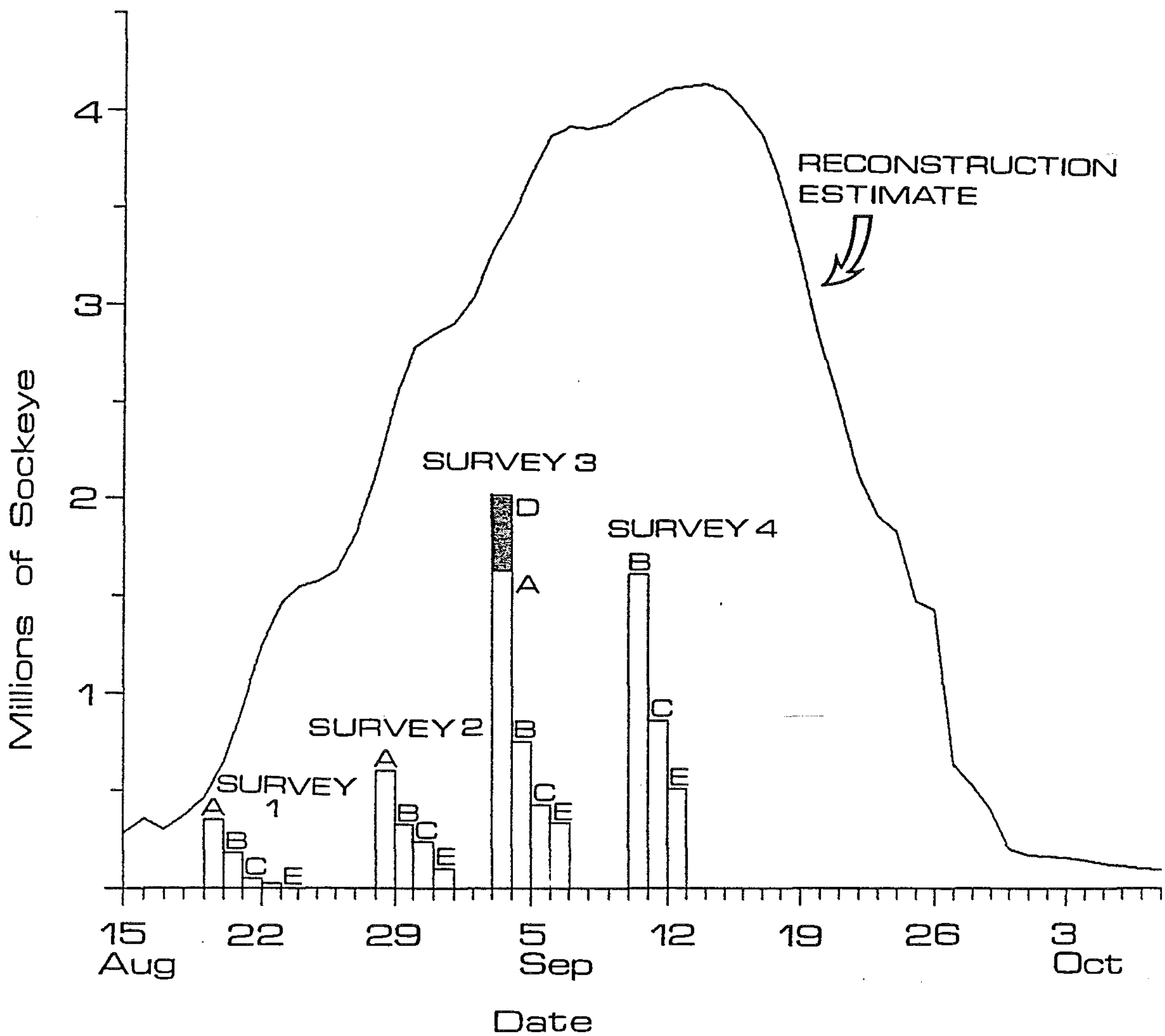

Figure 17. Reconstructed sockeye abundance curve in the Strait of Georgia during August and September, 1986, compared to acoustic survey estimates for Areas A-E (Areas B, C and E are nested within Area A).

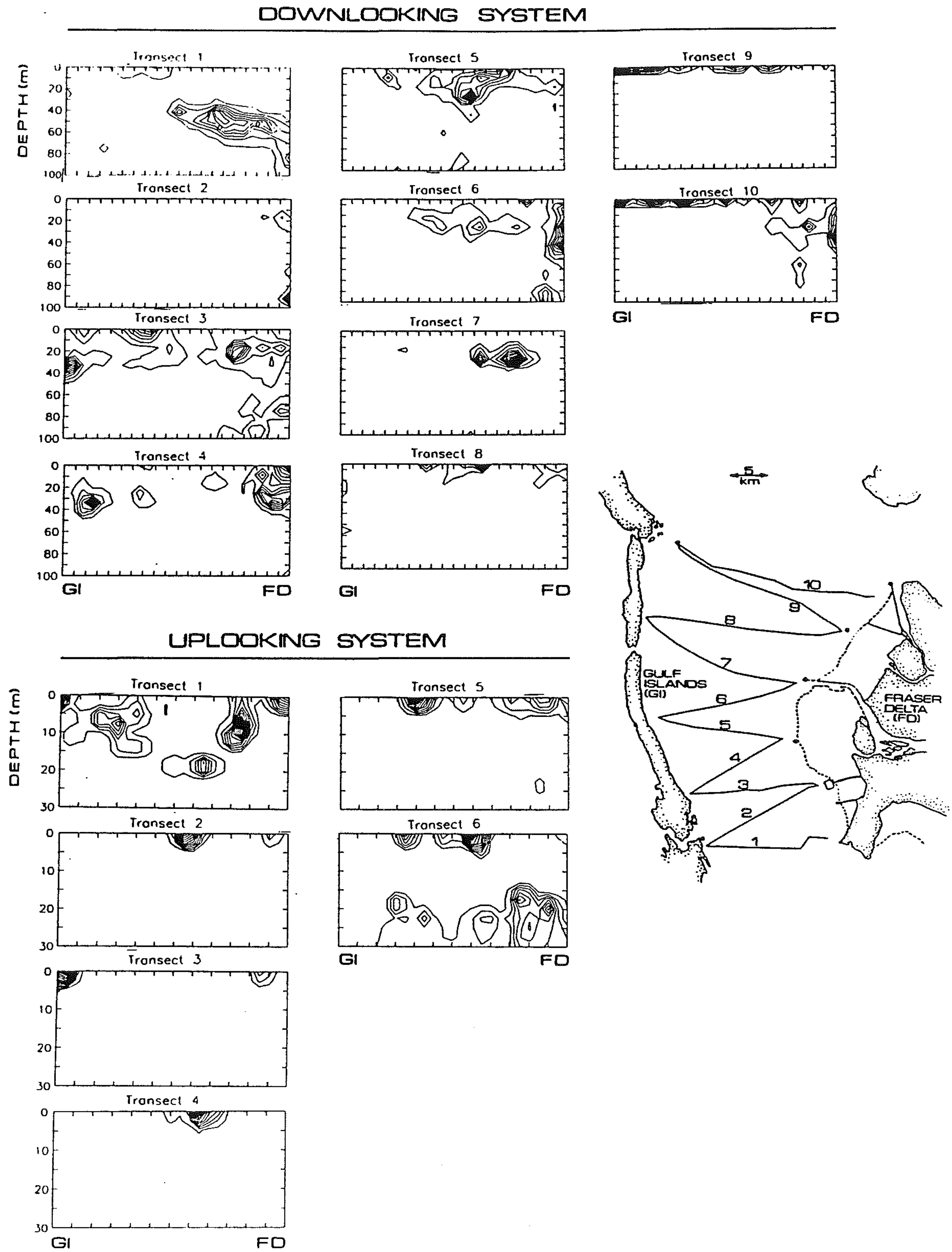

Figure 18. Voltage isopleths for integrator data obtained during survey 1.

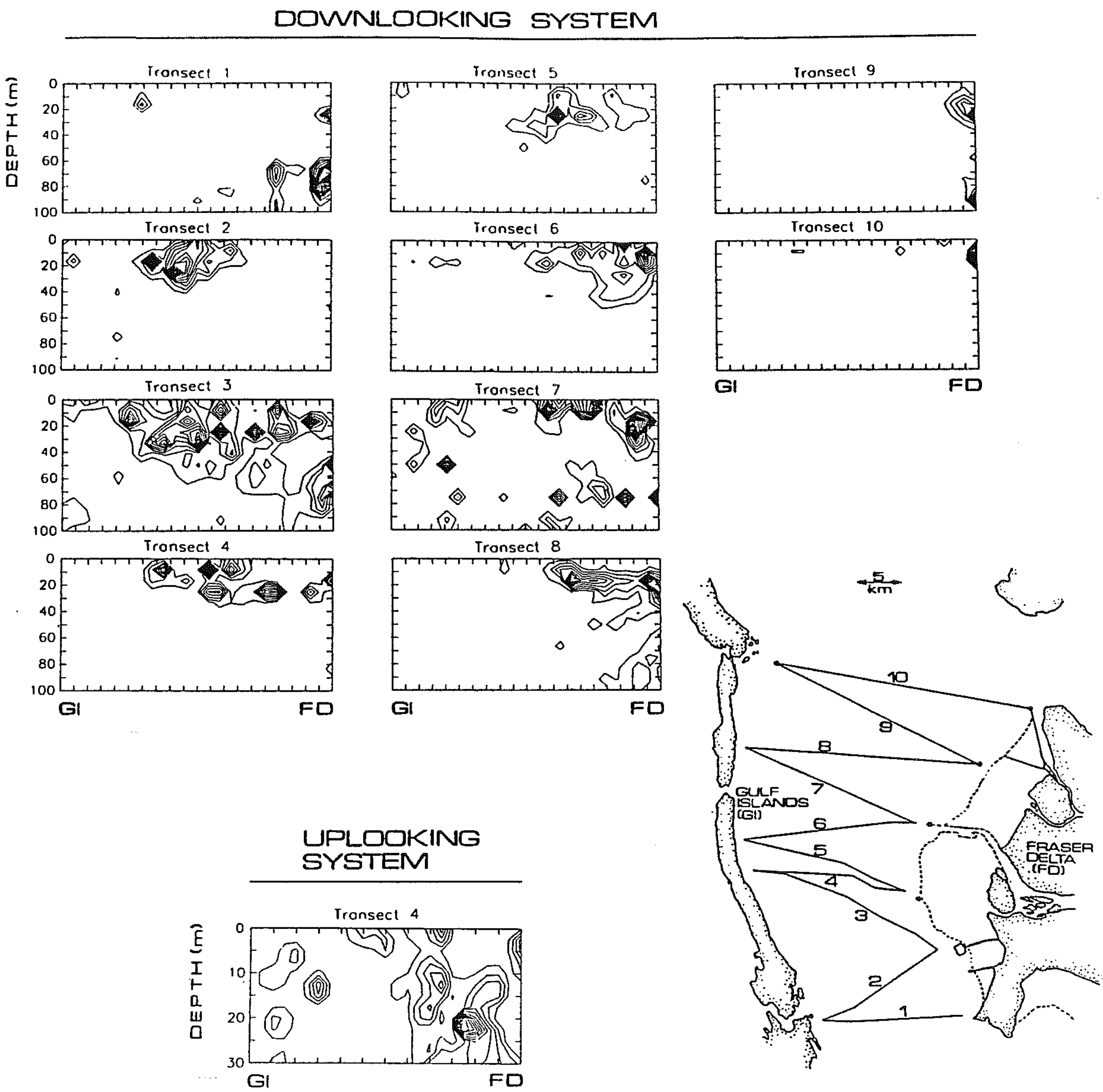

Figure 19. Voltage isopleths for integrator data obtained during survey 2.

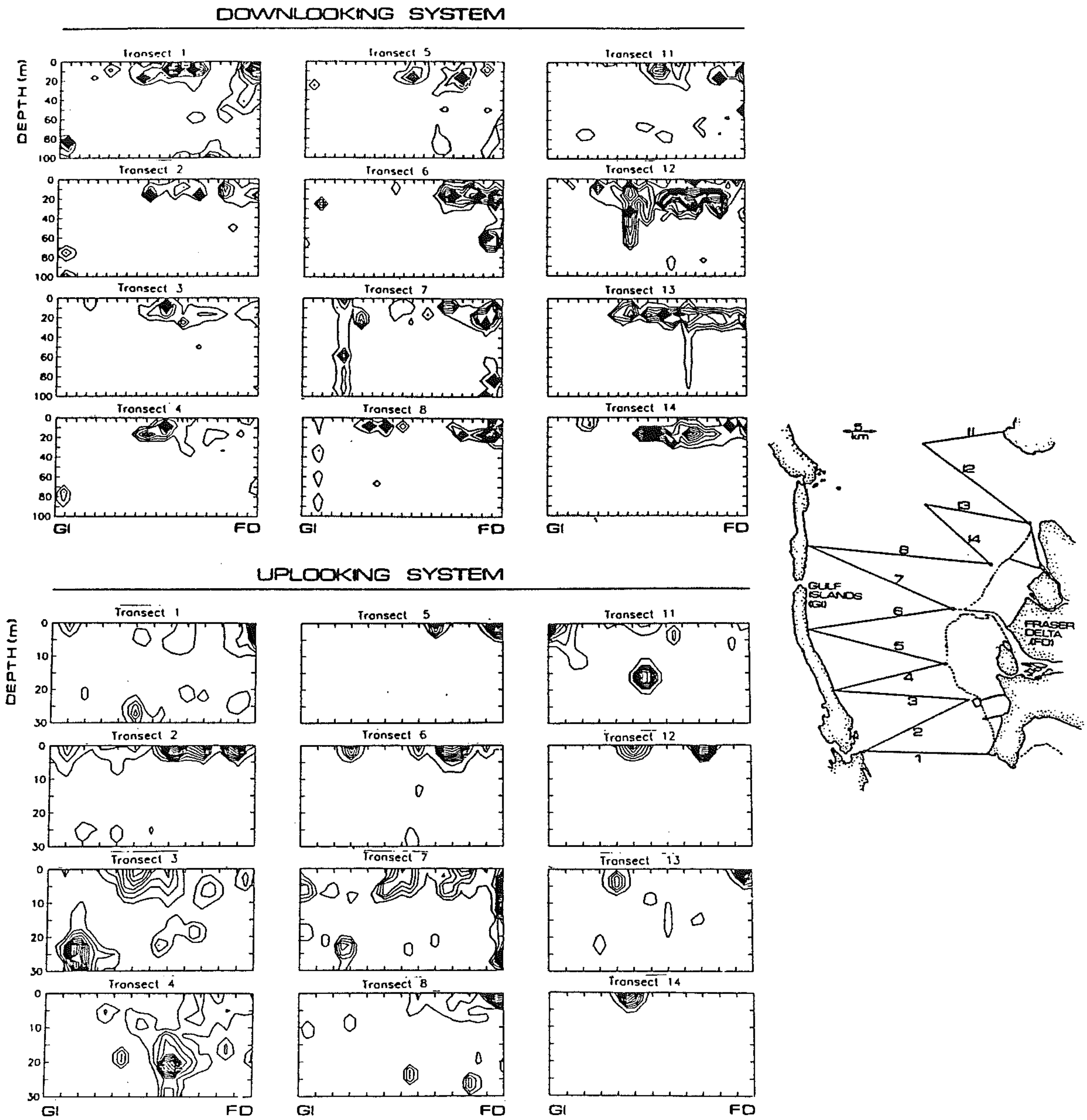

Figure 20. Voltage isopleths for integrator data obtained during survey 3.

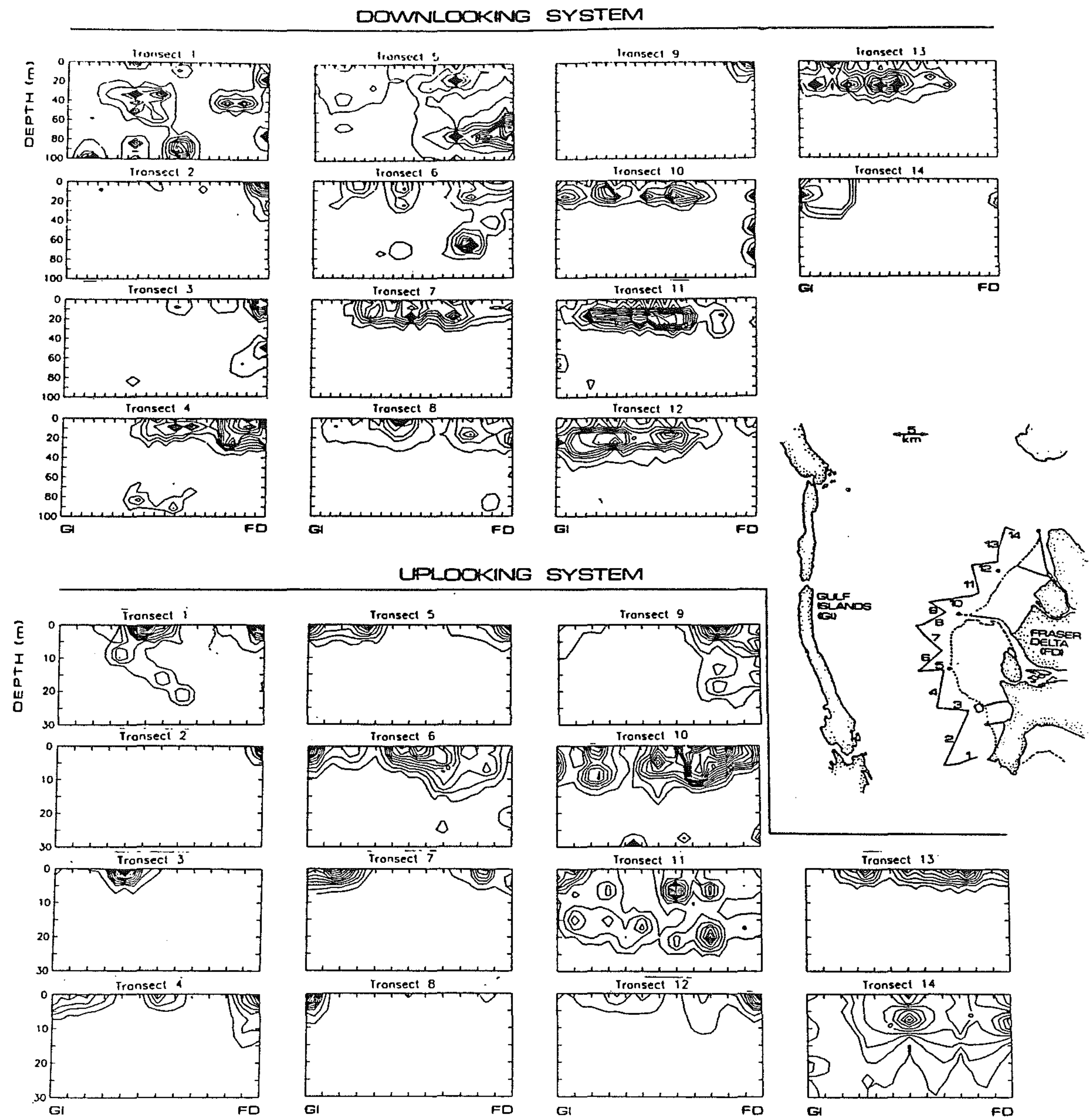

Figure 21. Voltage isopleths for integrator data obtained during survey 4.

The uplooking system appeared to enumerate fish effectively in relatively shallow water, and many of the isopleths occurred in water depths of 5 m or shallower (uplooking data sets on Figures 20 and 21). These depths were not effectively sampled by the downlooking system and corresponding concentrations of fish were largely absent from the downlooking data sets.

The vertical distribution of fish during the four surveys was quantified and plotted in vertical profile (Figure 22). Maximum densities for the downlooking data sets corresponded to depths of 25 m, 20 m, 15 m and 18 m during surveys 1-4, respectively (Figure 22). The uplooking system produced smaller density peaks at depths 20 m and 22 m during surveys 2 (n=1 transect) and 3 (n=12 transects), respectively. Highest densities detected by the uplooking system were in the very shallowest strata during surveys 3 and 4 (Figure 22).

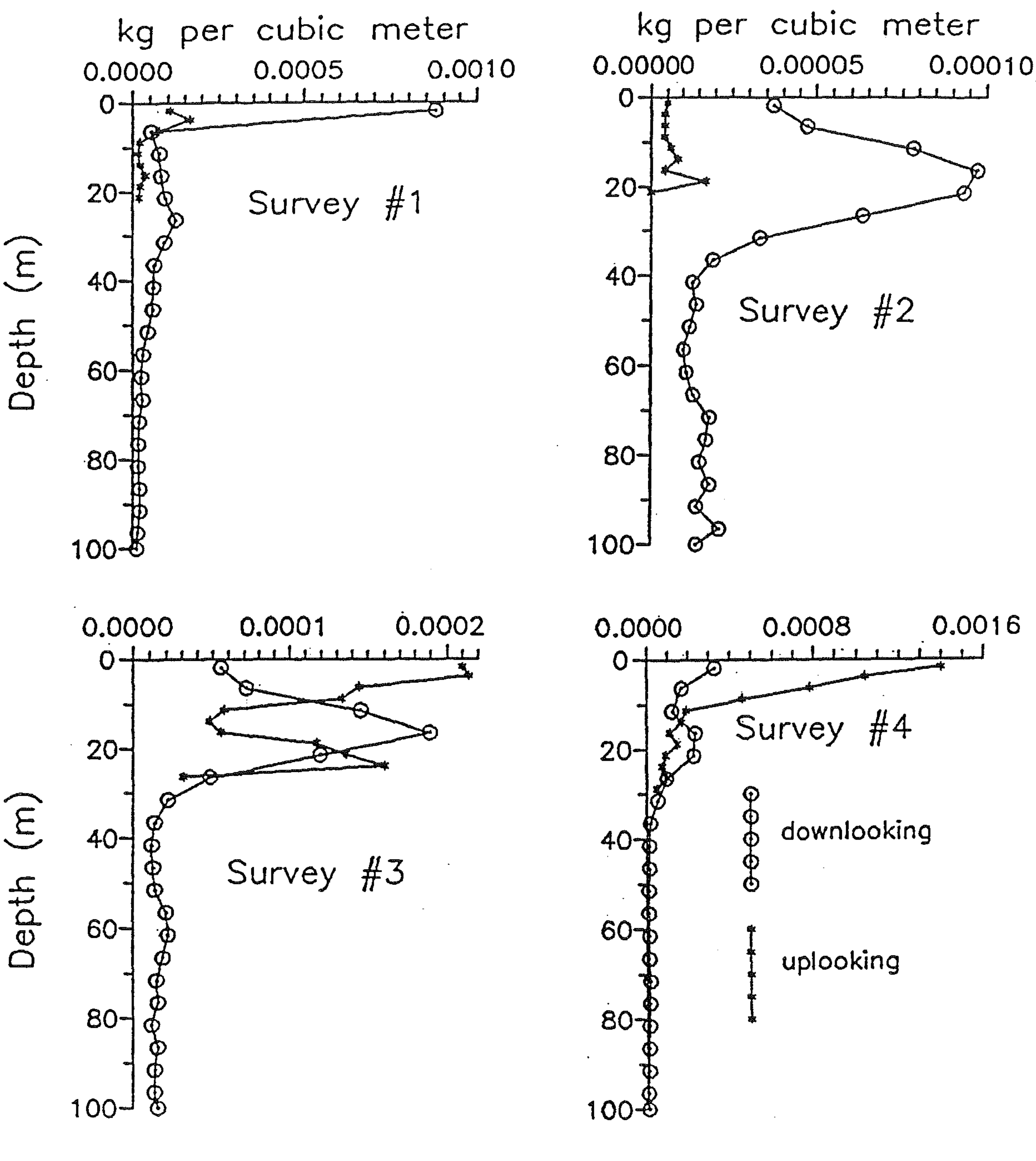

Figure 22. Fish density profiles during surveys 1-4.

DISCUSSION

Adams River sockeye delay their upstream migration in the Strait of Georgia for about a month prior to moving into the Fraser River. The delay has been described by Gilhousen (1960, p.42): *"The delay period of Adams River sockeye of the dominant run is spent in slow wandering movements in southern Georgia Strait apparently within the area where Fraser River discharge is present in the form of a distinct brackish layer at the surface. These sockeye do not approach the Fraser River mouth closely when they arrive off the Fraser Delta. At first they keep to the deeper, clearer waters beyond the edge of the tidal flats. The wide distribution at this time is shown by catches made by gill nets as far north of the delta as Gibsons Landing, as far west and south as the Gulf Islands which stretch from Gabriola Island near Nanaimo to Saturna Island at Boundary Pass, and as far east as the Point Roberts area."* The migratory delay of Adams River sockeye makes the Strait of Georgia a strategic location for stock assessment. An accurate and timely estimate of run size to the Strait of Georgia would be extremely useful for in-season management and could help to forecast the Adams River spawning escapement.

The area of the Strait of Georgia where sockeye concentrate (described above) covers about 1000 km^2 and the magnitude of stock size is millions of fish. Assuming an unknown non-random sockeye distribution and the presence of numerous fish species within the pelagic water column (e.g., Kieser 1983), an accurate estimate of Adams River stock size within the Strait of Georgia is a challenging assessment task. The advantages and limitations of hydroacoustics for fish stock assessment have been described by Thorne (1983A). These include the following advantages: (1) independence from fishery catch statistics, (2) favourable time scale, (3) relatively low operational costs, (4) low variance, and (5) potential for absolute population estimation. Limitations include: (1) poor species discrimination, (2) little or no sampling capability near bottom and surface, (3) relatively high complexity, (4) high initial investment, (5) lack of biological samples, and (6) potential bias associated with target strength and calibration.

During the present study, attempts were made to minimize adverse impacts from the known hydroacoustic limitations. These include the use of target strength per kg for scaling the echo integrator results to minimize the influence of other (smaller) fish species on the sockeye abundance estimate; use of an uplooking transducer to improve the near surface estimates; seine sampling to estimate fish species composition; and use of the dual beam system for *in situ* target strength estimation. In spite of these attempts, it was evident (Figure 17) that the hydroacoustic method underestimated the adult sockeye salmon population within the Strait of Georgia. The best result was obtained in survey 3, in which the estimated abundance in the study area (Areas A and D) was about 2 million sockeye, compared to the post-season run-reconstruction estimate of 4 million sockeye in the Strait of Georgia.

Previous studies within Lake Washington (Thorne and Dawson 1974; Thorne 1979) and Long Lake (Mulligan and Kieser 1986) have compared acoustically-derived sockeye population estimates from mobile surveys of lakes and riverine weir counts, with favourable results. It is imperative that the discrepancy in the Strait of Georgia sockeye population size estimates derived by hydroacoustic and reconstruction methods be resolved, if mobile hydroacoustic surveys are to provide reliable information for in-season sockeye salmon management.

Possible reasons for a hydroacoustic underestimate include: 1) the survey design was inadequate to cover the entire distribution of adult sockeye and 2) errors in the estimated target strength. Any substantial concentration of sockeye on the Fraser delta tidal flats (Figure 2) would have caused an underestimate in adult sockeye stock size. Gilhousen (1960) reports that Adams

River sockeye move onto the Fraser tidal flats close to the time of river entry. Because the uplooking system required water depths of at least 50 m for unimpeded operation, shallow depth strata adjacent to, and on top of, the tidal flats were not sampled. Since sockeye were evidently concentrated along the Fraser delta shoreline (Figure 20), the lack of inter-tidal and shallow sub-tidal sampling may have biased the acoustic population estimate. In future surveys, it would be desirable to operate shallow draft vessels on the tidal flats for both hydroacoustic sampling and net sampling to establish the sockeye population sizes within these relatively shallow areas.

During three of the four surveys, inclusion of uplooking data for sockeye population estimation had only a minor influence on the abundance values (Figure 15). During the final survey, when the sockeye were evidently more surface-oriented (Figure 22), inclusion of the uplooking data set had a strong influence on the abundance estimate (Figure 15). Given the expense of operating two vessels (both downlooking and uplooking), it may be possible to derive an abundance estimate based on downlooking echo-sounding alone, provided the surveys are conducted prior to mid September when sockeye concentrate in shallow water. Maximum values for fish density occurred in depth strata 25, 20 and 15 m during surveys 1-3, respectively (Figure 22). These are favourable depths for downlooking echo-sounding.

Several sources of variation may have contributed to the discrepancy in results between the downward- and upward-looking acoustic systems. The poor agreement in sockeye distribution patterns observed by the two systems (Figures 18-21) may reflect intra-transect variation since the two survey vessels followed slightly different transect paths and did not execute transects in a coordinated fashion. In future, this source of variation could be eliminated by deploying downlooking and uplooking transducers from the same survey vessel. Also, the observed shift of sockeye into shallower depth strata over time (as described above) resulted in a higher rate of detection of fish by the uplooking system than the downlooking system (0-30 m depth strata).

The measured target strength estimates departed considerably from predicted values (Figure 14) based on the measured fish sizes. Mulligan and Kieser (1986) obtained target strength estimates of -30.7 to -25.3 db/fish for 2.9 kg adult sockeye within Long Lake, considerably higher than the values obtained within Georgia Strait (Figure 14). Use of the predicted target strengths would greatly diminish the present sockeye population estimates, since hydroacoustic population estimates are inversely proportional to target strength. (A 3 db error in target strength will cause a 100% error in the abundance estimate). The cause of the relatively low values for measured target strength is unknown. If small-bodied fish species (e.g., herring, juvenile salmon) were under-represented in the pelagic water column by purse seine sampling, this would cause a discrepancy between measured and predicted target strengths in the observed direction. During future surveys, it would be desirable to estimate the target strength of known standards (e.g., a ping pong ball or a tungsten-carbide sphere) during each survey, so that the accuracy of the dual-beam system can be determined.

For a given survey design, the patchiness in fish distribution will influence the precision of hydroacoustic estimates. Within the Strait of Georgia, a contagious fish distribution (Figures 18-21) probably contributed to the wide confidence interval (31-95 % of estimated population size; Table 5) for the sockeye abundance estimates. The precision of the estimates could probably be increased by using a more intensive survey grid (i.e., increase the number of transects in stratified areas where sockeye concentrate). However, this refinement is recommended only after the inaccuracy in hydroacoustic population estimation (Figure 17) is resolved.

Procedures for determining variance estimates from hydroacoustic samples are controversial at present, in part because of the serial correlation which is usually present within hydroacoustic data sets (Williamson 1982; MacLennan and MacKenzie 1988; Traynor et al. in press). Recently, Jolly and Hampton (in press) criticized many commonly adopted statistical procedures in hydroacoustics, including the definition of elementary sampling units, and the use of zig-zag transects. The survey approach proposed by Jolly and Hampton (in press), using a stratified random sample of parallel transects (in which each transect within pre-determined strata serves as an independent sampling unit), has important statistical advantages over traditional acoustic survey designs. Moreover, a stratified random survey design was effectively implemented by Jolly and Hampton (1990) during an acoustic survey of anchovy *(Engraulis capensis)* covering 10^5 km^2 on the South African continental shelf. The main advantage of the approach is that sampling effort (i.e., transects) is allocated according to the actual fish density within the survey area (determined during previous surveys or during the initial phase of an acoustic survey). Thus, areas containing high fish densities receive more intensive acoustic sampling effort (higher numbers of transects) than low density areas. Since transects within sub-areas are allocated at random, the variance estimates based on individual transects are theoretically preferable to variance estimates based on intra-transect observations along a fixed survey path (Jolly and Hampton in press), and no assumptions are required regarding serial correlations of densities along a transect.

The method of fitting isopleths to integrator voltages (Figures 18-21) is convenient for depicting fish distribution during acoustic surveys. The diagrams can be scaled for any length of acoustic transect and provide a useful qualitative summary of fish distribution during acoustic surveys. The high fish biomass observed in the vicinity of 20 m depth during survey 3 (downlooking transects 12, 13, and 14 on Figure 20) and 15 m depth during survey 4 (downlooking transects 10, 11, 12, and 13 on Figure 21) probably resulted from dense concentrations of sockeye in this vicinity of the Strait of Georgia during this time period of 1986. Interestingly, this area corresponds closely to the zone where numerous sport fishermen concentrated their angling efforts on adult sockeye during 1990 (D.A.Levy, personal observation).

The depth distribution of adult sockeye in the southern Strait of Georgia was analyzed by Quinn and terHart (1987) using ultrasonically-tagged individuals. Results of daytime fish tracks (Figure 23) suggest that adult sockeye would be in a depth zone amenable to standard downlooking echo-sounding (below 5 m) for approximately 80% of the time (Figure 23B). It may, therefore, be feasible to undertake daytime hydroacoustic surveys (provided the sockeye are not tightly aggregated), particularly if a method can be devised to develop a correction factor to account for the proportion of sockeye present in shallow water (0-5 m) and inaccessible to a surface-deployed system.

Accurate documentation of sockeye diel vertical distribution in the Strait of Georgia is important for future acoustic survey design purposes. The ultrasonic-tagging approach described by Quinn and terHart (1987) could provide useful information if tagged fish are continually tracked over the diel cycle. (Data collected by Quinn and terHart (1987) pertain to hours of daylight only). Systematic replication of acoustic transects over the diel cycle would provide a means to rapidly document diel shifts in sockeye depth distribution. Such information would be extremely useful for survey design purposes.

Clearly, it is premature to rely on results from mobile hydroacoustic surveys to provide accurate information on sockeye stock size for in-season sockeye management. As an alternative to deriving absolute sockeye population estimates, it may be feasible to derive a relative index of

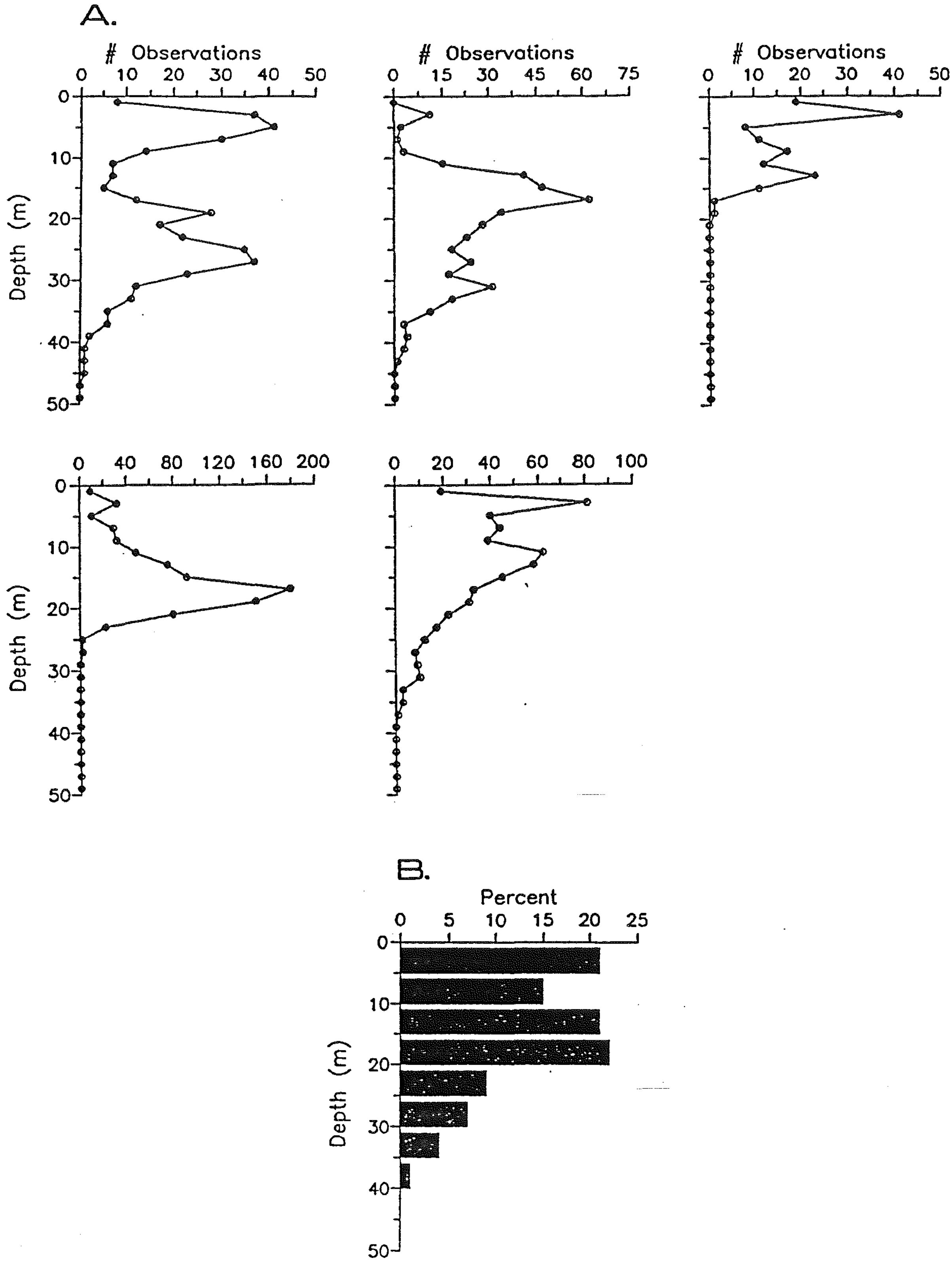

Figure 23. A) Daytime depth distribution of five ultrasonically-tagged sockeye in the Strait of Georgia during 1985, and B) mean percent of daytime depth observations in different depth strata. Redrawn from Quinn and terHart (1987).

sockeye abundance based on acoustic surveys within a fixed sub-area of the Strait of Georgia. For example, intensive acoustic monitoring of known areas of sockeye concentration (e.g., vicinity of transects 12-14 during survey 3, Figure 20) may provide a useful predictor of sockeye spawning escapements for large Fraser sockeye populations. Such an approach would be analogous to a test fishing index of salmon stock abundance, with the added advantage of intensive pelagic sampling power. A drawback of this approach is that the intra- and inter-annual variability in the timing and location of sockeye concentrations in the Strait is largely unknown, and a large number of annual observations would be required before the approach could be evaluated statistically.

Lastly, the costs and benefits of different methods of stock enumeration should be carefully considered prior to undertaking additional hydroacoustic surveys of sockeye salmon in the Strait of Georgia. Additional hydroacoustic surveys would require data collection and processing equipment currently valued at approximately $100,000, plus annual operating costs of about $50,000/year. In particular, the usefulness of hydroacoustic methods of enumeration should be compared with the performance of existing indirect (catch per unit effort) methods of sockeye stock assessment.

RECOMMENDATIONS

1. Additional development work will be required to develop an estimator of sockeye population size within the Strait of Georgia, based on mobile hydroacoustic surveys. Hydroacoustic survey programs to estimate sockeye abundance in the Strait of Georgia should be viewed as experimental, until the discrepancies between the estimates from acoustic and run reconstruction methods can be resolved.

2. Future hydroacoustic surveys of sockeye salmon within the southern Strait of Georgia should be extended to include all portions of available habitat including shallow sub-tidal areas adjacent to the Fraser Delta, inter-tidal areas, and sub-tidal river channels.

3. Diel and seasonal shifts in sockeye depth distribution should be documented so that hydroacoustic sampling strategies can be refined. The possibility of conducting daytime hydroacoustic surveys should be evaluated. If feasible, surveys should be scheduled when the fish are favourably distributed for enumeration by standard, downlooking echo-sounding methods.

4. Future hydroacoustic investigations should include echo-sounding on standard targets of known target strength on each survey date, in order to test the accuracy of the dual-beam system.

5. Future hydroacoustic surveys should adopt a stratified random transect design (Jolly and Hampton 1990) with a flexible allocation of transects between sub-areas. Hydroacoustic sampling effort should be expended in proportion to the observed sockeye densities within the Strait of Georgia study area. Thus, over the 4-6 week period when Adams River sockeye occur within the Strait, survey effort would shift progressively closer to the Fraser Delta, in parallel with seasonal distribution changes of sockeye within the Strait.

6. Sampling areas during future surveys should be uniquely defined (no nesting) so as to permit parametric statistical testing of acoustic results.

7. Allocation of purse seine sampling effort for fish species identification purposes should extend over the entire hydroacoustic sampling area.

8. A hydroacoustic index of sockeye population size should be developed by intensive surveys of a discrete sub-area of the Strait of Georgia where sockeye concentrate. This area should be surveyed frequently (e.g., daily) for the period that Adams River sockeye are present.

ACKNOWLEDGEMENTS

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