On the Discrimination of Sockeye and Chinook Salmon in the Kenai River Based on Target Strength Determined with 420 kHz Dual-Beam Sonar

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ABSTRACT: The feasibility of using target strength to discriminate between upstream migrating salmon was examined by computer simulation of the expected sampling distribution of mean target strength for a variety of sampling regimes and mixed populations of Kenai River sockeye *Oncorhynchus nerka* and chinook *O. tshawytscha* salmon. The simulations were based on empirically derived parameters for underlying Rayleigh probability distribution for square root of the backscattering cross section and length-frequency distributions observed for Kenai River sockeye and chinook salmon. Computer simulation experiments were conducted to examine (1) the effect of target-strength measurement rate on ability to discriminate fish, (2) whether it was possible to discriminate sockeye and chinook salmon species or age classes of chinook salmon, and (3) the consistency of model predictions and observed target-strength distributions of migrating salmon in the Kenai River. Simulated target-strength distributions were consistent with observed target-strength distributions. Although with high sampling rates it was possible to discriminate certain mixed populations of sockeye and chinook salmon, it was not possible to discriminate between sockeye and chinook salmon with the sampling rates achieved in the Kenai River. Because of high within-fish variability in target strength and low between-fish differences in mean target strength, target strength cannot be used by itself to discriminate between fish in the Kenai River.

INTRODUCTION

The Alaska Department of Fish and Game uses target strength to routinely discriminate between upstream migrating large chinook salmon *Oncorhynchus tshawytscha* and sockeye salmon *O. nerka* in the Kenai River of Cook Inlet. This use of target strength rests primarily on an unpublished report (P.A. Skvorc and D. Burwin, Alaska Department of Fish and Game, draft 92-5001) claiming that a -28.5 dB threshold can be used to discriminate age-1.3 and older chinook salmon (roughly >75 cm) from sockeye salmon and age-1.2 chinook salmon (roughly <75 cm).

Ehrenberg (1984) suggested that it might be possible to discriminate different size categories of upstream migrating salmon in a riverine setting but cautioned that a very high number of target-strength measurements for individual fish would be required because there is considerable within-fish or ping-to-ping variability in target strength (Dawson and Karp 1987; Ehrenberg 1984; Ehrenberg et al. 1981; Dahl and Mathisen 1982). This variability is due to a stochastic nature of the reflectance of sound by the fish as effected by orientation, movement, behavior, tissue type, etc.

Dahl and Mathisen (1982) examined the within-fish variability of target strength of anesthetized, live rainbow *Oncorhynchus mykiss* and cutthroat *O. clarki* trout (40–61 cm in length) in controlled experiments using 420 kHz sonar. Under these conditions target-strength measurements were very accurate; i.e., coefficient of variation for digital output reference was 2%. However, the movement of the anesthetized fish was highly constrained. Under these idealized laboratory conditions, target-strength measurements from individual fish were highly variable; the range and standard deviation of side-aspect target strength from a single fish were approximately 30 dB and 5 dB, respectively (Dahl and Mathisen 1982).

In addition to the fundamental stochastic nature of sound reflectance by fish, other physical factors, such as noise level, changes in fish orientation, system threshold, and errors in system calibration, all contribute to a lack of precision (i.e., variability and bias) in the estimation of fish target strength. In view of this imprecision, the reliability of using target strength to discriminate between chinook and sockeye salmon in the Kenai River was examined by computer simulation using the expected sampling distribution

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of target strength for a variety of mixed populations of sockeye and chinook salmon. The computer simulations were based on (1) the ambient length frequency distributions of sockeye and chinook salmon in the Kenai River, (2) a well-known relationship between mean target strength and fish length (Love 1969), and (3) the theoretical probability distribution of side-aspect target strength for an individual fish at 420 kHz provided by Dahl and Mathisen (1982).

METHODS

A computer simulation model was used to estimate the expected sampling distribution of target strength from a population of mixed Kenai River sockeye and chinook salmon. The mean target strength for individual fish was estimated based on relationship between target strength and mean length. Fish lengths were simulated based on the respective species' ambient length-frequency distributions provided in Eggers et al. (*in press*). The simulated target-strength distributions were compared to those estimated from the Kenai River in 1987 and 1992 (Eggers et al. *in press*). In addition, the model was used to examine the number of target-strength measurements of individual fish (i.e., number of echoes examined for target strength per fish) required to discriminate between sockeye and chinook salmon.

The theoretical basis for the probability distribution of side-aspect target strength from an individual fish of a given size was based on Dahl and Mathisen (1982). Their work is recapitulated below.

The usual target-strength relationship,

$$TS = 10\log(\sigma_{bs}) \; . \qquad (1)$$

where TS = target strength in dB and σ_{bs} = fish backscattering cross section (m^2), was maintained throughout. The backscattering cross section is a random variable and any realization of σ_{bs} is governed by the joint probability distribution of a target's physical characteristics and target orientation or aspect in the sonar beam. The Rayleigh distribution has been found to fit empirical distributions of the square root of the backscattering cross section (i.e., $[\sigma_{bs}]^{1/2}$) for a variety of fish species, including large salmonids (Ehrenberg et al. 1981; Dahl and Mathisen 1982). It fits best for situations where the ratio of fish length (L) to acoustical wave length (λ) is >50. Note that for Kenai River salmon and at 420 kHz sonar, L/λ ranges from 175 to 350.

The Rayleigh probability density function (pdf) is

$$f_z(z) = \left(\frac{z}{\alpha}\right) e^{-\frac{z^2}{2\alpha}} \; , \qquad (2)$$

where z = the square root of σ_{bs} and α = the Rayleigh parameter or the mean square root of the backscattering cross section.

It is well known from various empirical studies (Love 1969, 1971; Buerkle 1987) that the acoustical backscattering cross section of fish is approximately proportional to the square of fish length and that target strength is proportional to the logarithm of fish length, such that

$$\overline{TS} = g(z) = A + B\log L \; . \qquad (3)$$

In many published studies on fish target strength (Love 1971; Buerkle 1987), the slope (i.e., B in equation 3) of the various empirically determined relationships has been very close to 20. The intercept parameter A in equation (3) was estimated by the least squares (holding B = 20) fit to mean side-aspect target-strength and length data given by Dahl and Mathisen (1982; Figure 1). To be consistent with length measurement of the ambient length-frequency distributions, fork lengths (FL; Dahl and Mathisen 1982) were converted to mid-eye to fork-of-tail length (MEFT) based on the approximate relationship MEFT = 0.9 FL (from chum and sockeye salmon length data provided by J. Helle, National Marine Fisheries Service, Auke Bay Laboratory, Juneau).

$$\overline{TS} = -58.4 + 20\log L \; . \qquad (4)$$

Because target strength is a function of the square root of the backscattering cross section random variable (z), which has a Rayleigh distribution, the mean or expected value of target strength is found using the relation

$$\overline{TS} = E\left[g(z)\right] = \int_Z g(z) f(z) dz \; . \qquad (5)$$

Dahl and Mathisen (1992) provide the following solution to equation (5):

$$\overline{TS} = E(t) = 4.3429\ln\alpha - 10.4888 \; . \qquad (6)$$

In the computer simulation the realization of target strength from an individual fish of length *L* was based on the Rayleigh distribution with parameter (α). Mean target strength was calculated from fish length based on equation (4). Alpha, as a function of mean target strength, was found by inverting equation (6):

$$\hat{\alpha} = exp\left[\frac{TS + 10.4888}{4.3429}\right]. \qquad (7)$$

A stochastic computer simulation model was used to generate the sampling distribution of mean target strength for a mixed population of Kenai River sockeye and chinook salmon. Simulations were conducted using FORTRAN with numerical routines for random number generation provided by Press et al. (1989). Stochastic simulations were conducted in the domain of square root of backscattering cross section (z). Realizations of z were based on simulated, uniform random variables that were converted to z based on the inverse Rayleigh pdf. Realizations of z were converted to target strength based on equation (1).

As a reality check on the model performance, means and standard deviations of target strength were estimated for simulated target-strength distributions for individual fish lengths in the range of those observed for sockeye and chinook salmon in the Kenai River (i.e., 34–126 cm). The simulated mean target strengths (Figure 2) under the model were virtually identical to those based on equation (6). The standard deviations of the simulated distributions of target strength for individual fish ranged from 5.2 to 6.0 dB and were consistent with those reported by Dahl and Mathisen (1982).

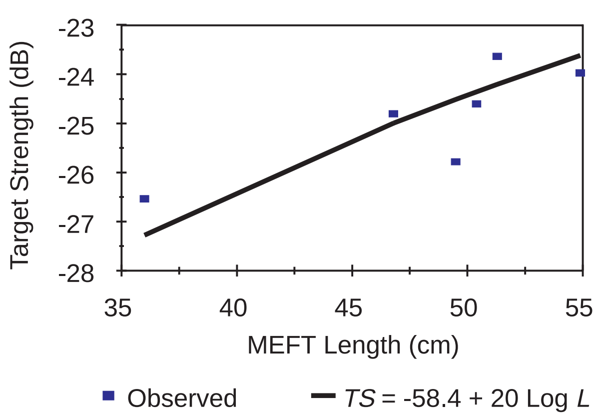

Figure 1. Estimated relationships between mean target strength and fish length based on data from Dahl (1982); TS = -58.4 + 20 log L.

Three computer simulation experiments were conducted. The first experiment examined the effect of target-strength measurement rate on ability to discriminate fish. The sampling distributions of target strength were generated using the 1986 observed ambient length-frequency distribution for Kenai River chinook and sockeye populations (Eggers et al. *in press*). Here, the sampling distribution for mean target strength was simulated under various target-strength measurement rates (i.e., 1, 5, 10, 20, and 50 pings per fish) and various mixtures of sockeye and chinook salmon (i.e., 0, 10, 50, and 100% sockeye salmon). The sampling distribution for mean target strength was estimated from 5,000 sets of individual fish target-strength measurements simulated under each combination of species mixture and target-strength measurement rate.

The second experiment examined whether it was possible to discriminate between sockeye and chinook salmon species or age classes of chinook salmon using mean target strength. Here, realizations of target strength were made assuming the same scenario of ambient length-frequency distributions and sockeye-chinook mixtures used in the first experiment; however, the number of target-strength measurements made per fish followed the distribution of target-strength measurements per fish observed in 1987 and 1993 (Figure 3). Again, the sampling distribution for mean target strength was estimated from 5,000 individual fish realizations for each scenario of species mixture.

The third experiment examined the consistency of model predictions and the target-strength distribution observed in 1987 and 1992. The model predictions excluded targets <-28.5 dB, which was consistent with the mode of operation for the Kenai River chinook sonar project. Here, the system threshold for narrow-beam voltage was a level that would exclude targets <-28.5 dB target strength from being sampled. The simulated sampling distribution for mean target strength simulated under the 4 scenarios of sockeye/chinook population mixtures were compared to the 1987 and 1992 observed mean target-strength distributions. The respective year ambient length distributions for the chinook and sockeye salmon populations (Eggers et al. 1994) and the observed distribution of pings per fish (Figure 3) were used to generate the simulated mean target-strength distribution.

RESULTS

The sampling distributions of mean target strength per fish were simulated for 4 populations of mixed sockeye and chinook salmon. Sampling distributions for each population were simulated assuming 5 scenarios (1, 5, 10, 20, and 50) for number of target-strength measurements made per fish. The populations included 100% sockeye salmon (Figure 4), 50% sockeye/50% chinook salmon (Figure 5), 10% sockeye/90% chinook salmon (Figure 6), and 100% chinook salmon (Figure 7). In all scenarios of number of target-strength measurements made per fish and species mixtures, there was no bimodality in the simulated sampling distribution for target-strength distribution, except for situations of equal mixtures of sockeye and chinook salmon and a very high number of target-strength measurements per fish. Therefore, it would not be possible to discriminate between sockeye and chinook salmon based on target strength, except for the situation of equal mixtures of chinook and sockeye salmon and a very high target-strength measurement rate of 20 or greater interrogations per fish.

The sampling distribution for mean target strength per fish using the 1987 (Figure 8) and 1993 (Figure 9) observed distribution of target-strength measurements made per fish (i.e., pings per fish; Figure 3) were estimated for populations of 100% sockeye salmon, 50% sockeye/50% chinook salmon, 10% sockeye/90% chinook salmon, and 100% chinook salmon. In the 1987 operations of the dual-beam sonar project, most of the fish were interrogated with 4 or less pings where target strength could be estimated (Figure 3). Under the low target-strength measurement rate observed in 1987, it was not possible to discriminate between

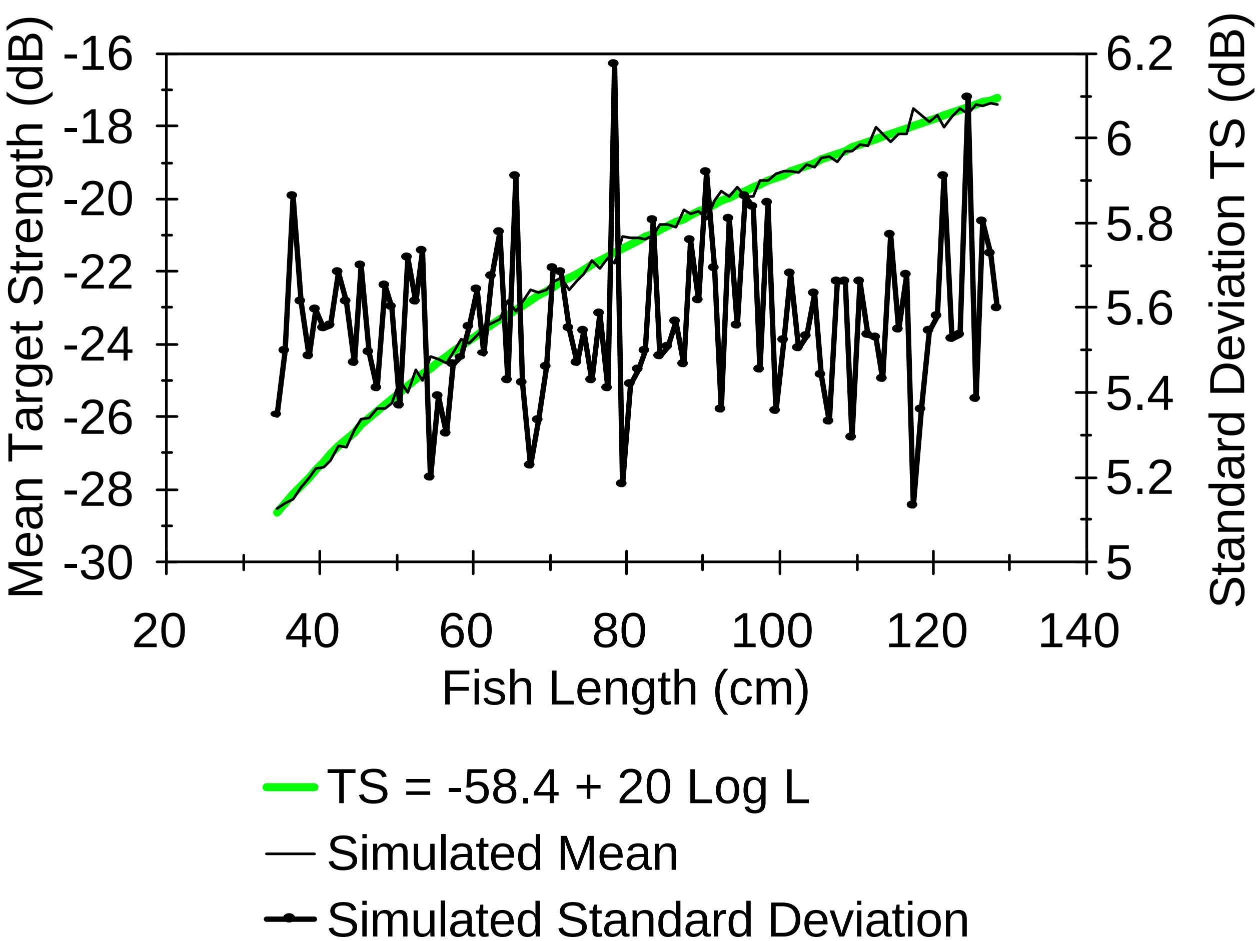

Figure 2. Mean (light solid) and standard deviation (heavy solid) of within-fish target strength estimated from simulated target-strength distributions for a range of fish lengths and the mean target strength (medium solid) based on relationship *TS* = -58.4 + 20 log *L*.

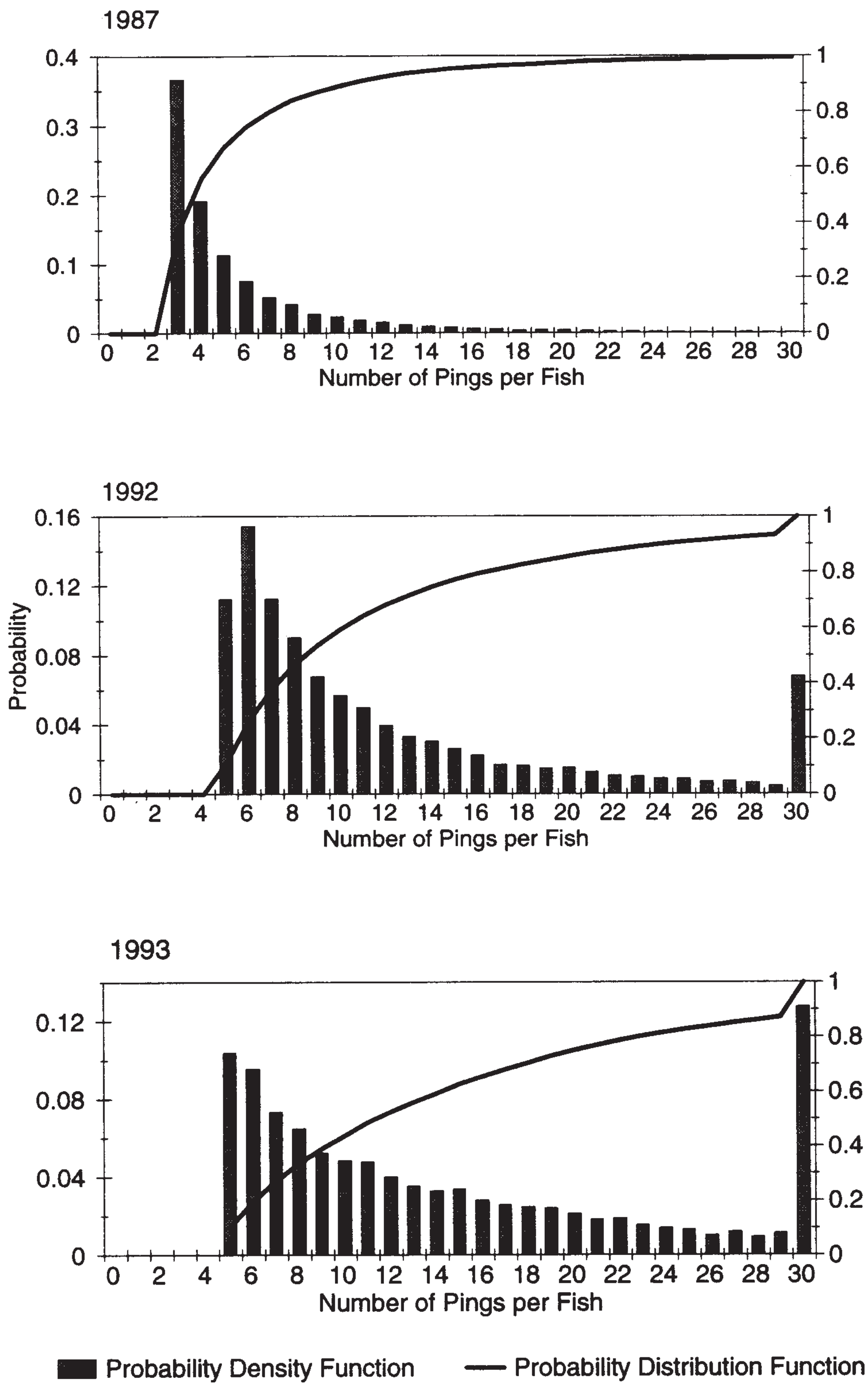

Figure 3. Frequency (solid bars) and cumulative frequency (solid line) distributions for number of pings per fish used to estimate mean target strength for salmonids in the 1987 (upper), 1992 (middle), and 1993 (lower) operations of the Kenai River chinook sonar project.

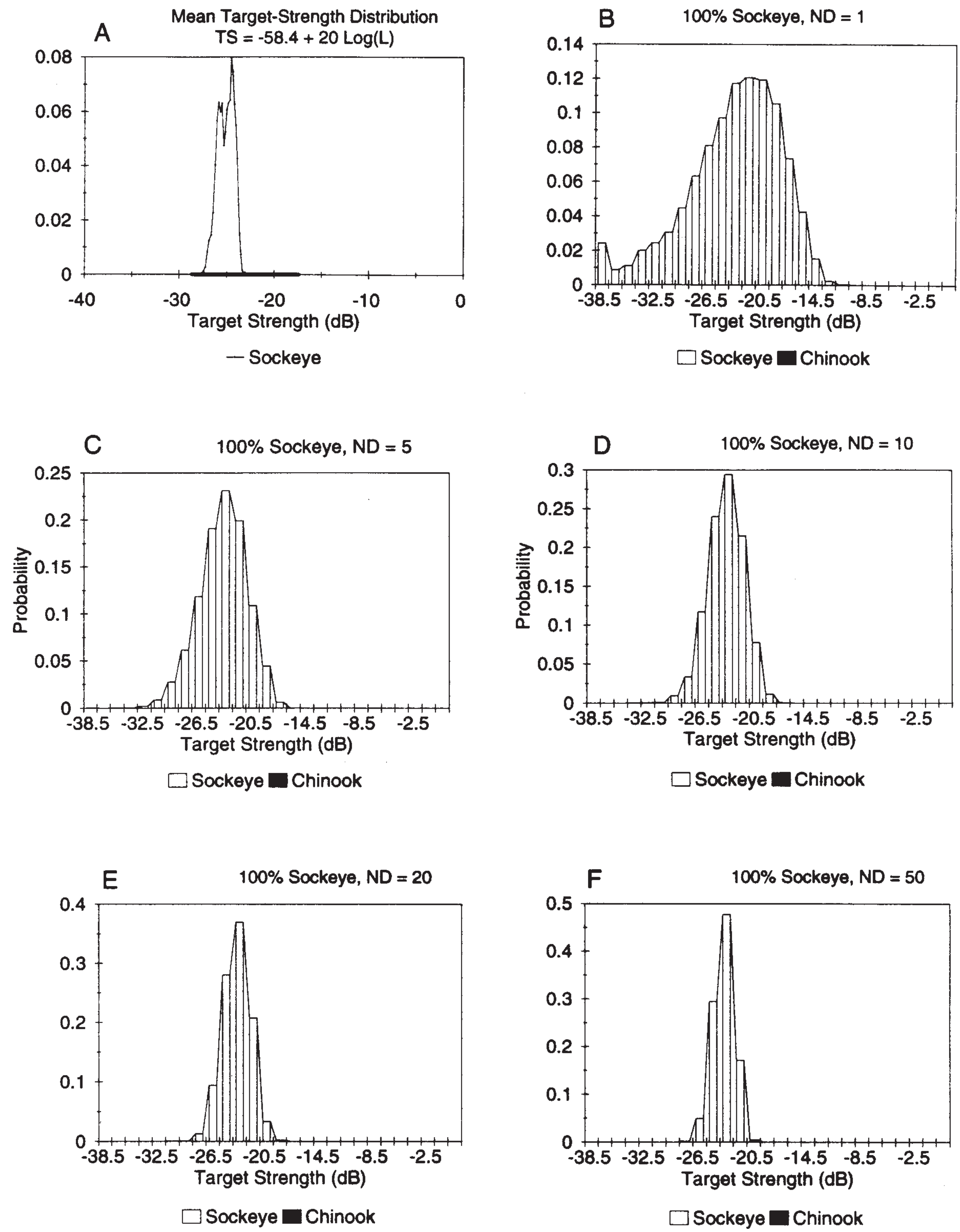

Figure 4. (A): Population mean target-strength distribution for a population of 100% sockeye salmon based on 1986 ambient length-frequency distributions. (B) – (F): Simulated sampling distribution for mean target strength given the population mean target-strength distribution in (A) and assuming interrogation rate (ND) of 1 (B), 5 (C), 10 (D), 20 (E), and 50 (F) pings per fish.

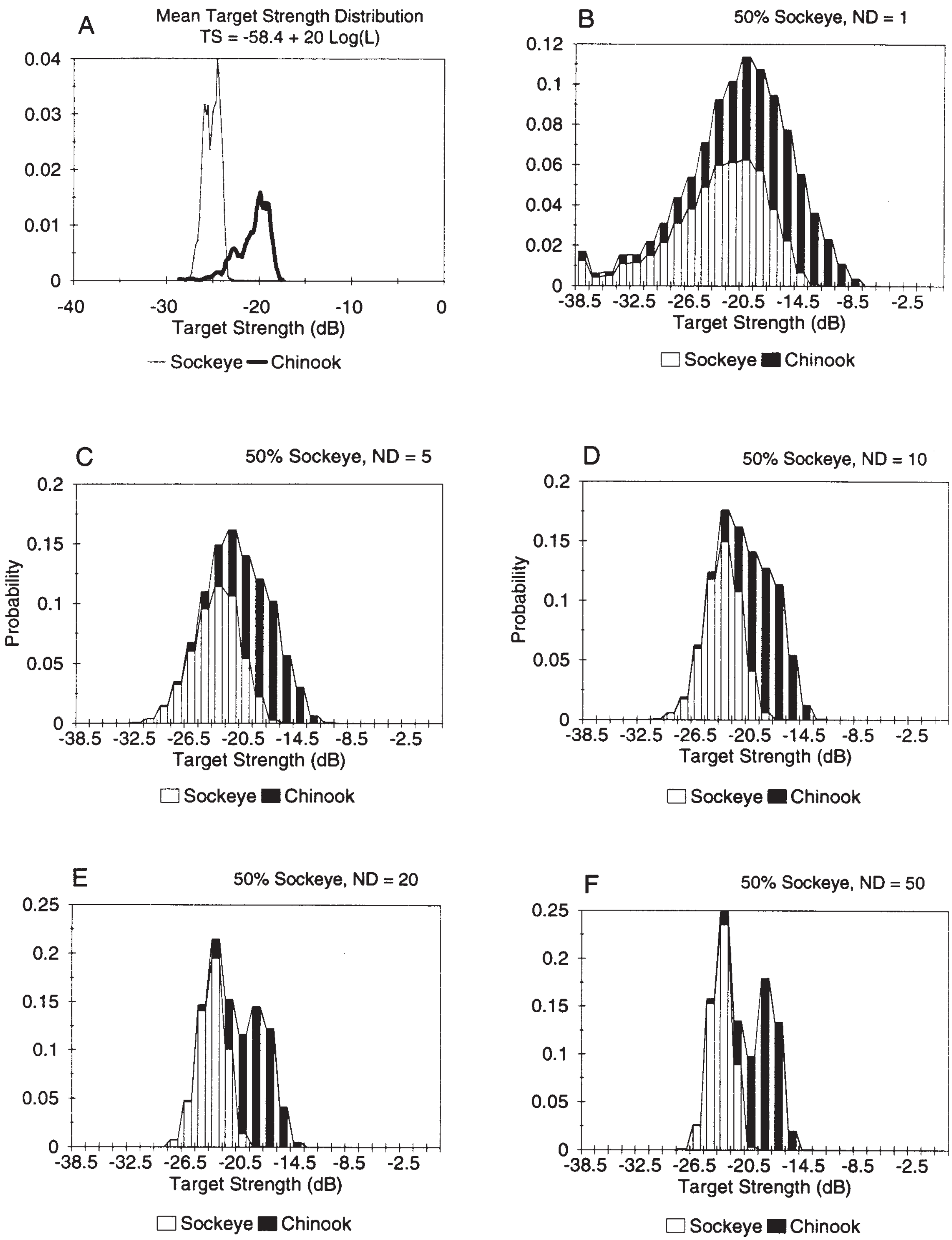

Figure 5. (A): Population mean target-strength distribution for a population of 50% sockeye and 50% chinook salmon, based on 1986 ambient length-frequency distributions. (B) – (F): Simulated sampling distribution for mean target strength given the population mean target-strength distribution in (A) and assuming interrogation rate (ND) of 1 (B), 5 (C), 10 (D), 20 (E), and 50 (F) pings per fish.

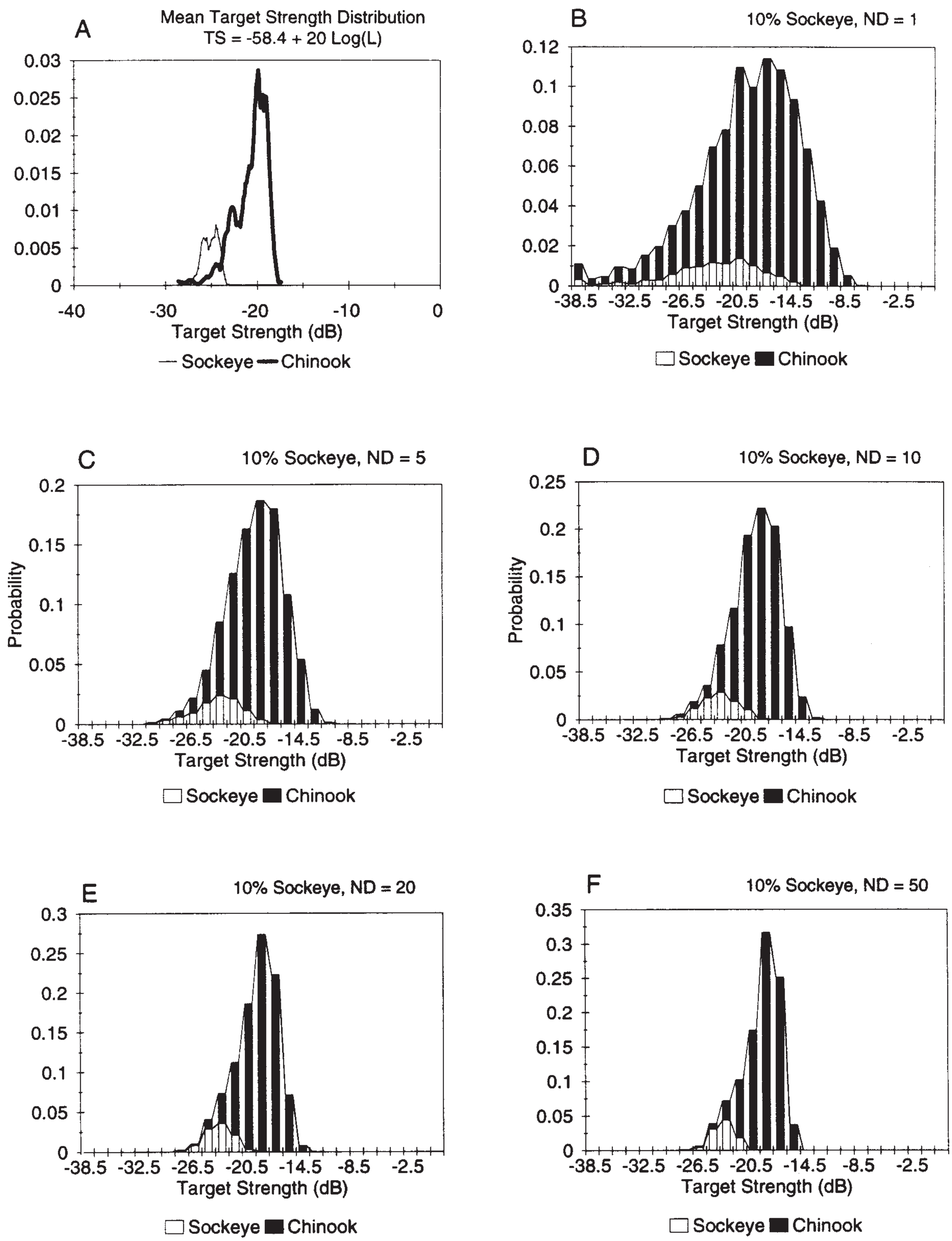

Figure 6. (A): Population mean target-strength distribution for a population of 10% sockeye and 90% chinook salmon, based on 1986 ambient length-frequency distributions. (B) – (F): Simulated sampling distribution for mean target strength given the population mean target-strength distribution in (A) and assuming interrogation rate (ND) of 1 (B), 5 (C), 10 (D), 20 (E), and 50 (F) pings per fish.

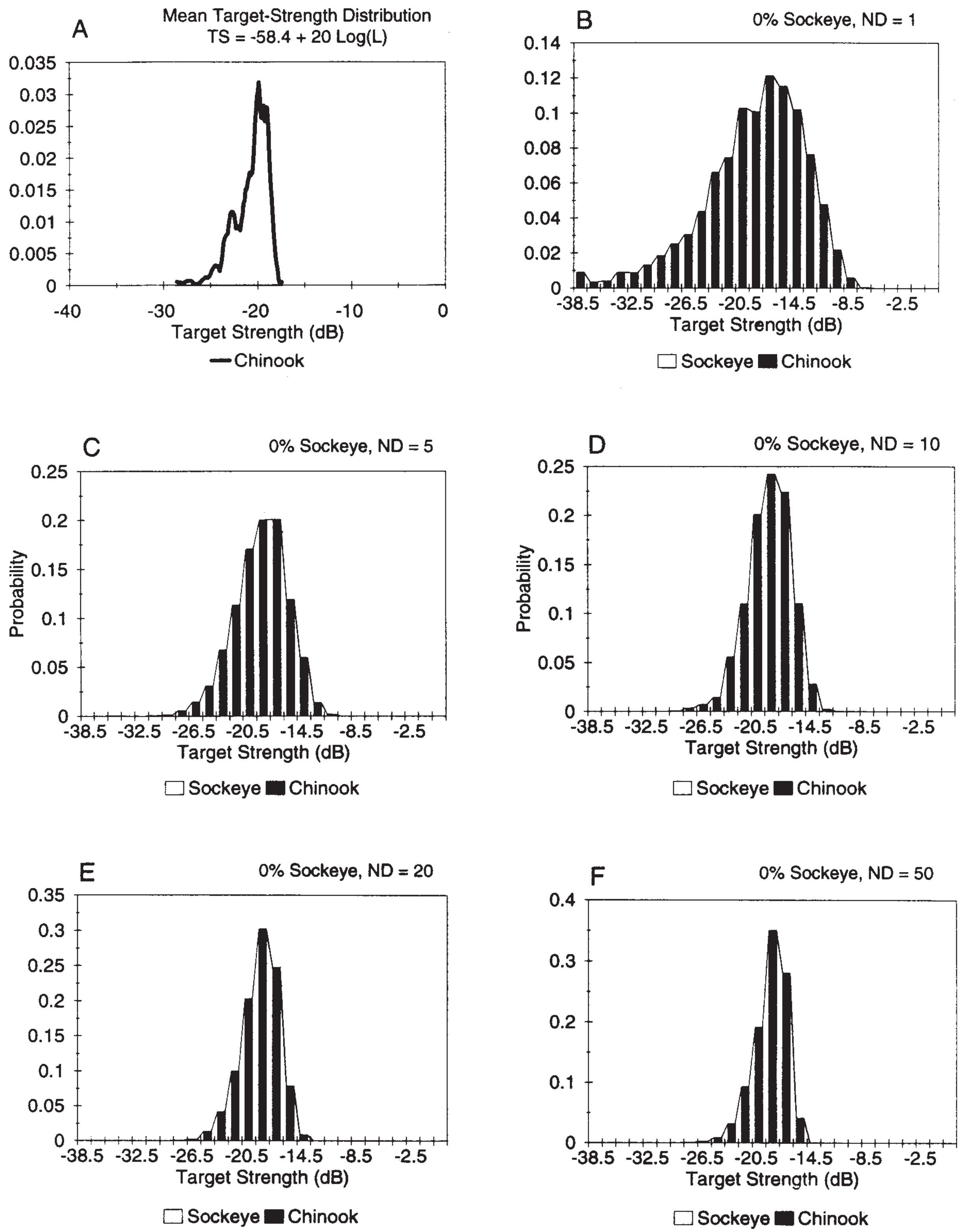

Figure 7. (A): Population mean target-strength distribution for a population of 100% chinook salmon based on 1986 ambient length-frequency distributions. (B) – (F): Simulated sampling distribution for mean target strength given the population mean target-strength distribution in (A) and assuming interrogation rate (ND) of 1 (B), 5 (C), 10 (D), 20 (E), and 50 (F) pings per fish.

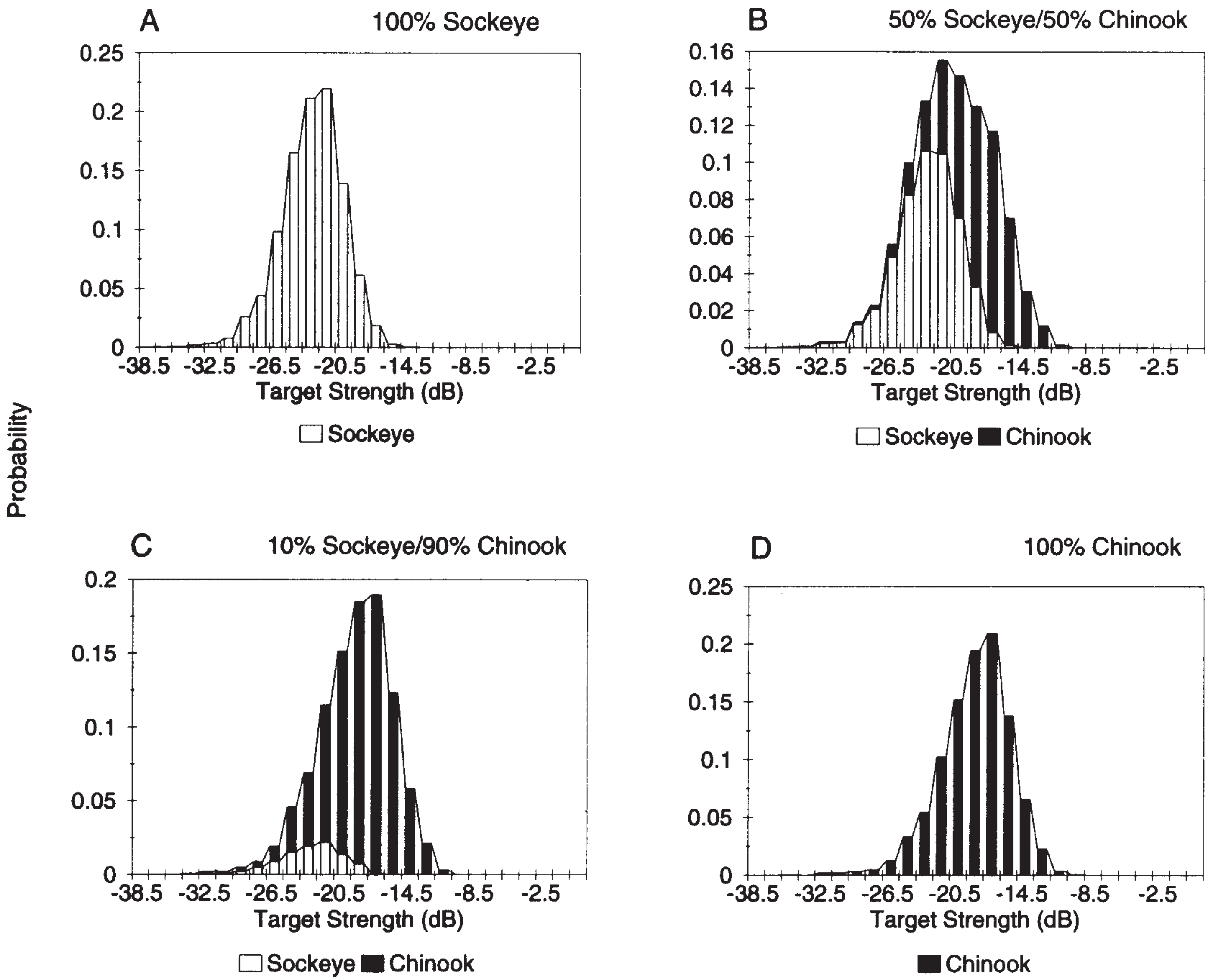

Figure 8. Simulated sampling distribution for mean target strength given the population mean target-strength distribution in Figures 4A, 5A, 6A, and 7A for 100% sockeye salmon (A), 50% sockeye and 50% chinook salmon (B), 10% sockeye and 90% chinook salmon (C), and 100% chinook salmon (D). Assumes target-strength measurement-rate distribution observed for 1987 (Figure 3).

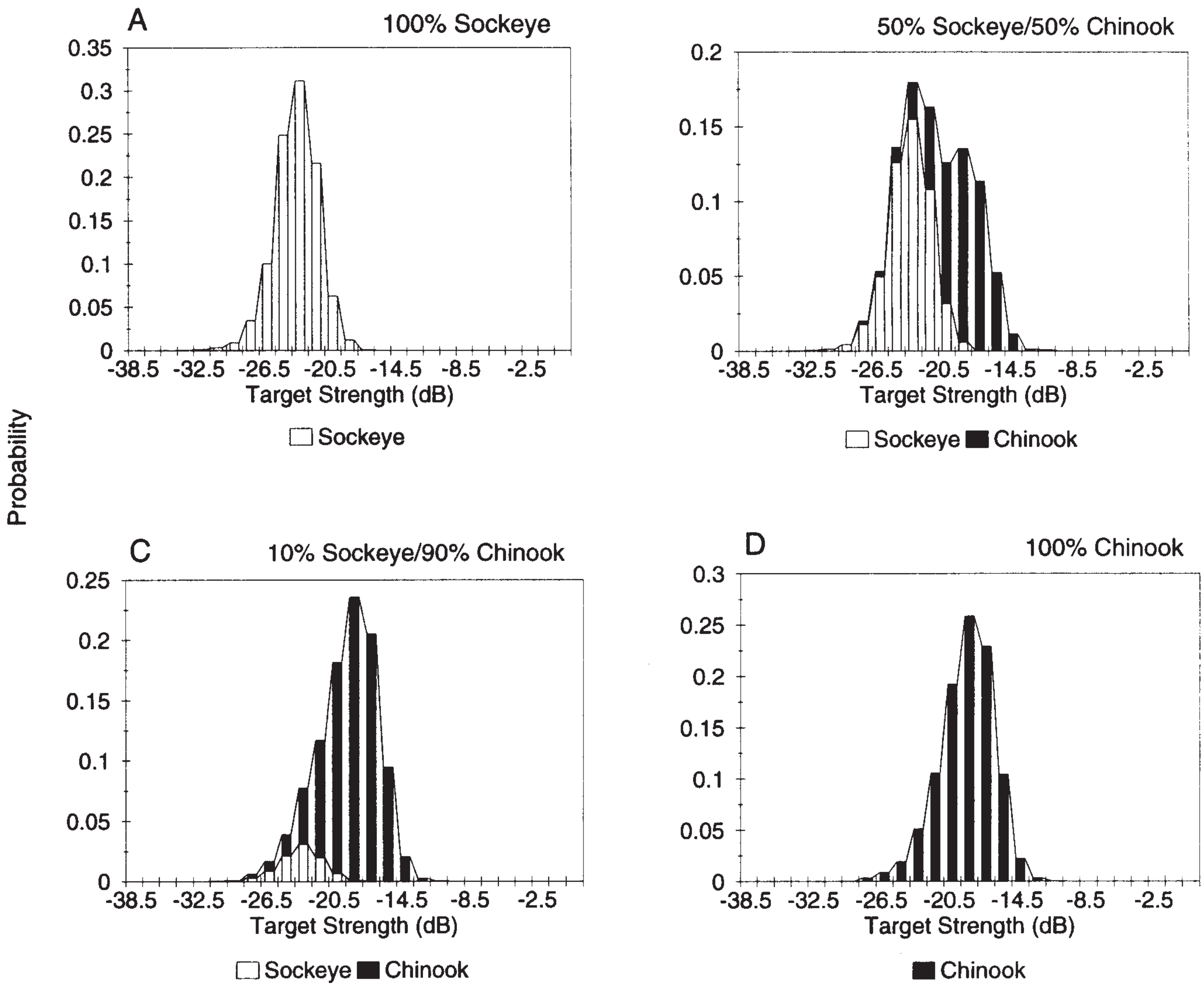

Figure 9. Simulated sampling distribution for mean target strength given the population mean target-strength distribution in Figures 4A, 5A, 6A, and 7A for 100% sockeye salmon (A), 50% sockeye and 50% chinook salmon (B), 10% sockeye and 90% chinook salmon (C), and 100% chinook salmon (D). Assumes target-strength measurement-rate distribution observed for 1993 (Figure 3).

sockeye and chinook salmon based on target strength under all scenarios of species mixture examined (Figure 8). Under the higher target-strength measurement rate observed in 1993, a bimodal sampling distribution for mean target strength was predicted for the 50% sockeye/50% chinook salmon population (Figure 9). Therefore, it might be possible to discriminate between sockeye and chinook salmon populations when the 2 species are similar in abundance (Figure 9).

The simulated sampling distributions for mean target strength per fish under the 4 scenarios of mixed sockeye and chinook salmon populations were compared to the observed distribution of mean target strength for 1987 (Figure 10) and 1992 (Figure 11). For both 1987 and 1992, the simulated sampling distributions for the various mixtures were quite similar. For 1987 the mode of the observed mean target-strength distribution was within the range of modes for the simulated sampling distributions (Figure 10). For 1992 the mode of the observed mean target-strength distribution was 4 to 10 dB higher than the modes of the simulated sampling distributions for mean target strength (Figure 11). This suggests that differences in system calibrations exist between years which would be manifest in between-year variability in the A parameter in equation (3).

DISCUSSION

The assumed probability-density function of target strength for individual fish used in the computer simulation model was based on empirical models derived under laboratory conditions. The standard deviation of the simulated, side-aspect target strengths ranged from 4.1 to 5.0 dB and was consistent with those reported for a 40-cm (4.7 dB) and 51-cm (5.1 dB) salmonid (Dahl and Mathisen 1982). The stochastic computer simulation model used to predict target strength was assumed to be conservative with respect to variation in target strength among echoes from individual fish because it did not account for variation in fish aspect or effects of noise.

The standard deviation of target-strength measurements from individual fish in the Kenai River is not readily available because the standard deviation of within-fish target strengths was not computed in tracking procedures to estimate mean target strength. Vaught and Skvorc (1993) reanalyzed data from 332 tracked fish collected during the 1993 operations in the Kenai River and found the standard deviation of within-fish target strength to be 5.31 dB. However, this data was collected with a -28.5 dB threshold, and estimates of within-fish target-strength variability would be expected to be less than the true within-fish target-strength variability because of significant truncation of the target-strength distribution for the smaller fish in the population at this threshold.

Some indications of the *in situ* within-fish standard deviation of target strength from the Kenai River can be determined from analysis of the between-fish mean target-strength data collected in the Kenai River during 1987 and 1993. This data set consisted of over 24,000 individual mean target-strength measurements in 1987 and over 10,000 in 1993. The mean target-strength data were grouped from 3 to 20, the number of target-strength measurements taken per fish. Standard deviation for the mean target strength was calculated for each interrogation rate (Figure 12A). As expected, based on the statistical independence of individual target-strength measurements, the standard deviation of the mean decreased with the square root of the interrogation rate. The standard deviation for between-fish, individual-echo target strength is the slope of the regression line between mean target strength and the inverse square root of target-strength measurement rate (Figure 12B). The estimated between-fish standard deviation was equal to 8.28 dB in 1987 and 9.52 dB in 1993.

Because of variation in fish lengths and its effect on target strength, the estimate of standard deviation for between-fish, individual-echo target strength would be expected to be greater than the within-fish target strength. However, the decrease in target-strength variation due to the -28.5 dB threshold would tend to compensate for the increase in target-strength variation due to length variation.

The data used to estimate the A parameter in the relationship between mean target strength and fish length were very limited. The estimate of the A parameter was based on target-strength measurements taken from 6 fish of MEFT lengths ranging from 35 to 55 cm. There is very little published information on mean side-aspect target strength and fish length for large salmonids. Simulated target-strength distributions based on the -28.5 dB threshold and the 1987 ambient conditions were generally consistent with the observed mean target-strength relationships (Figure 10) and suggested that the value of the A parameter, based on Dahl and Mathisen's (1982) data, was reasonable. Note that variability in system calibration would be manifested in uncertainty of A parameter in equation (4). This uncertainty would

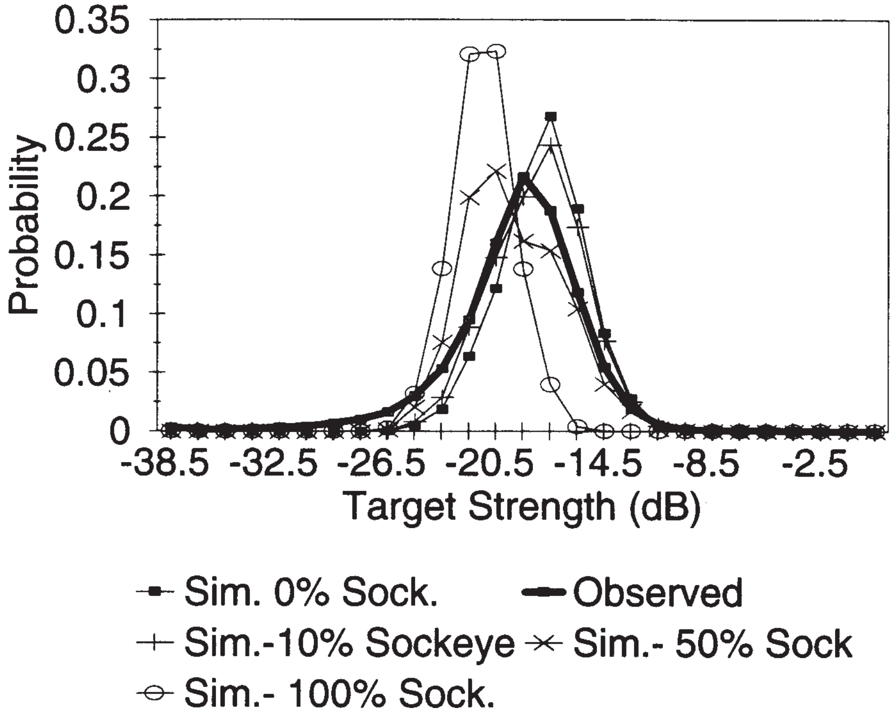

Figure 10. Simulated mean target-strength distribution for various scenarios of sockeye and chinook salmon mixtures and observed mean target-strength distribution for 1987. Simulations were made assuming 1987 ambient length-frequency distribution, 1987 observed target-strength measurement rates, and -28.5 dB target-strength threshold.

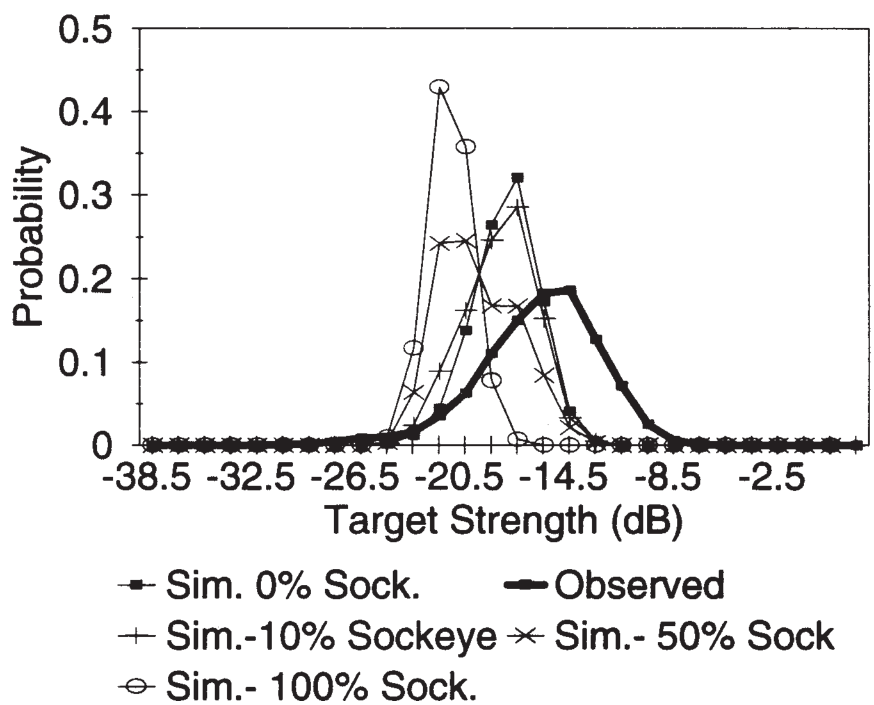

Figure 11. Simulated mean target-strength distribution for various scenarios of sockeye and chinook salmon mixtures and observed mean target-strength distribution for 1992. Simulations were made assuming 1992 ambient length-frequency distribution, 1992 observed target-strength measurement rates, and -28.5 dB target-strength threshold.

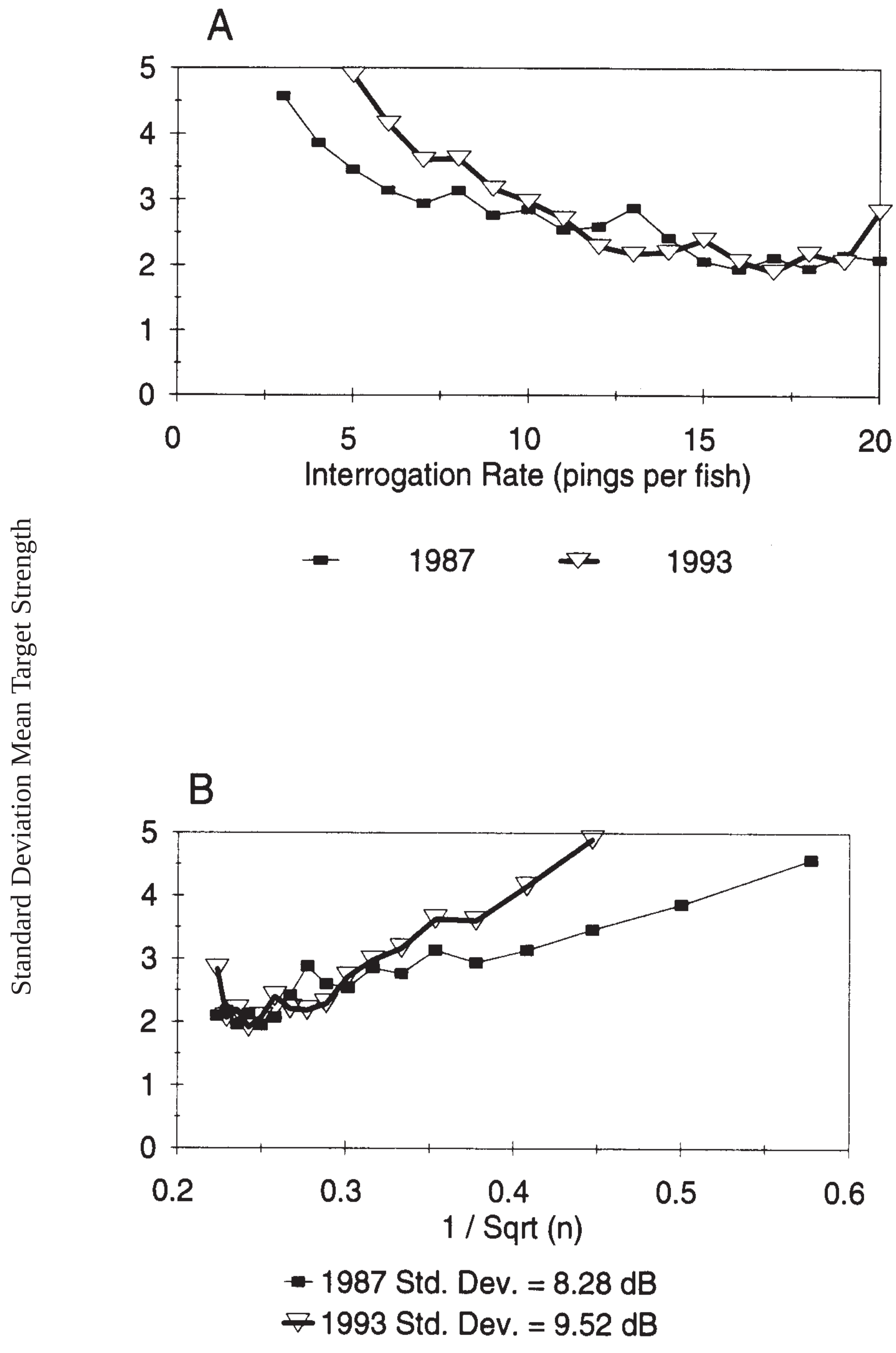

Figure 12. (A): Relationship between standard deviation of mean target strength and interrogation rate observed in 1987 and 1993. (B): Relationship between standard deviation of mean target strength and inverse square root of interrogation rate for 1987 and 1993. Note the slope of the regression line is the estimated standard deviation of ping-to-ping target strength and was equal to 8.28 dB in 1987 and 9.52 dB in 1993.

shift the mean of simulated mean target-strength distributions. Interannual differences in system calibration could easily account for a several-dB shift in observed distribution of mean target strength. The differences in the 1992 simulated and observed target-strength distributions (Figure 11) were consistent with interannual variability in system calibration.

Uncertainty in the *A* parameter would not effect the spread (i.e., variance) of the simulated distributions. The latter would be determined by the 20 log L transform based on a fundamental nature of sound reflectance by fish at high L/λ. Based on this analysis, the ability to discriminate chinook salmon from sockeye salmon based on target strength would not be sensitive to errors in the *A* parameter of the implicit relationship between target strength and fish length.

This information suggests that the standard deviation of target strength from individual fish collected *in situ* was substantially greater than that observed by Dahl and Mathisen (1982). Even with the conservative estimates of ping-by-ping variation in target strength, it is not possible to discriminate between sockeye and chinook salmon in the Kenai River based on target strength. Skvorc (Alaska Department of Fish and Game, Anchorage, personal communication; Skvorc, P.A. and D. Burwin, Alaska Department of Fish and Game, unpublished report, draft 92-5001) have claimed that it was possible to discriminate age-1.3 from age-1.4 and older chinook salmon in the Kenai River based on a target-strength threshold of -28.5 dB. The presence of these 2 age class groupings is manifested as a slight bimodality in the 1986 ambient chinook salmon length-frequency distribution (Eggers et al. *in press*) as well as the theoretical mean target-strength distribution for chinook salmon (Figure 8A). However, such modes did not occur in the simulated sampling distribution of mean target strength at high (50 interrogations per fish) target-strength measurement rates (Figure 8F). In view of the high ping-by-ping variation in target strength and low target-strength measurement rates achieved in the Kenai River chinook sonar project, I conclude that it is not feasible to discriminate sockeye and age-1.2 chinook salmon from age-1.3 and older chinook salmon.

Variability in system calibration (i.e., uncertainty in the *A* parameter in equation 4), uncertain applicability of the theoretical (i.e., the Rayleigh distribution) model of within-fish variability in target strength to *in situ* conditions, and the bias due to the high system threshold effectively eliminate inferences that can be drawn from comparisons of simulated and observed mean target-strength distributions (Figures 10, 11). Given the uncertainty in these quantities, the simulated mean target-strength distribution for any of the species mixtures could be consistent with the observed target-strength distribution.

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