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## USE OF SCALE PATTERNS TO IDENTIFY THE ORIGINS OF SOCKEYE SALMON (*Oncorhynchus nerka*) IN THE FISHERY OF NUSHAGAK BAY, ALASKA

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## ABSTRACT

The use of scale patterns to identify the stocks of sockeye salmon *(Oncorhynchus nerka)* harvested in Nushagak Bay, Alaska was examined using data collected during 1977 through 1980. Overall classification accuracies for three-way Wood, Igushik, Nuyakuk River models ranged from 54% to 66% with approximate 90% confidence intervals of ±.52 to ±.24. Two-way classification models of Wood and Nuyakuk River runs had average classification accuracies ranging from 69% to 76% with approximate 90% confidence intervals of ±.28 to ±.19. Between and within-run variability of scale variables is large because of the complexity of the rearing environments and the multi-population composition of the runs. Significant differences were present in the means of scale variables by sex and date and location of capture. Nearest neighbor analysis tended to yield higher classification accuracies and lower confidence coefficients than linear discriminant function analysis since variables were not always normally distributed.

# INTRODUCTION

The Nushagak Bay sockeye salmon *(Oncorhynchus nerka)* fishery is one of the largest and most valuable salmon fisheries in Alaska. The 21 year (1961-1981) average annual harvest of sockeye salmon for the Nushagak District is 2.107 million fish with a current value to the fishermen of over $37 million.

The Nushagak Bay fishery harvests sockeye salmon destined primarily for the Wood, Igushik, and Nuyakuk Rivers (Figure 1). Previous studies indicate that considerable mixing of these runs occurs within the Nushagak District (Straty 1975; Pennoyer and Nelson 1967; Krasnowski and Bethe 1978). The Nushagak Bay sockeye salmon fishery is managed on an individual run basis. Escapement goals for each river system are established and management involves opening and closing the commercial fishery to maximize the commercial catch while still attempting to meet the desired escapement goals. In order to develop optimal harvest strategies for this "mixed run" fishery, managers must have reliable estimates of the run composition of the salmon subject to the harvest. Estimates of the total return by brood year are also needed to model spawner-recruit relationships for estimating optimum escapements and forecasting run size.

In this paper I report on the application of scale pattern analysis for identification of Wood, Igushik, and Nuyakuk River runs of sockeye salmon in the Nushagak Bay sockeye salmon fishery. This study is based on 4 years (1977-1980) of scale samples from these component runs. Two statistical techniques, linear discriminant function analysis (LDF) and k nearest neighbor analysis[1] (KNN), were tested to determine the best statistic to discriminate the stocks.

Classification models were constructed to examine the accuracy and its approximate confidence interval for a Wood-Igushik-Nuyakuk model and a Wood-Nuyakuk model. Tagging studies had indicated that most sockeye salmon tagged along the Eastern and Northern parts of Nushagak District were of Wood and Nuyakuk River origin (Straty 1975). A two-way Wood-Nuyakuk model might, therefore, be applicable in classifying fish caught in the Northern and Eastern parts of Nushagak District.

This research is part of a larger project designed to evaluate different catch allocation techniques for Bristol Bay fisheries by comparing each methods relative accuracy and cost. The different catch allocation techniques to be eventually evaluated include: (1) the age composition method currently used (Meacham and Nelson 1980), (2) a maximum likelihood method (Gnanadesikan 1977), (3) a migratory time density function method (Hornberger and Mathisen 1981), and (4) scale pattern analysis. Overall classification accuracies and approximate confidence intervals will be determined for each method. The most accurate and cost effective method will then be used for allocating catches.

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[1] k = 1,3,4,5,6,7,8,9, or 10. A case is classified to the category which is represented most often in the k-closest patterns to the pattern being classified. When two or more categories are equally represented, a case is classified to the category which has the smallest sum-of-distances.

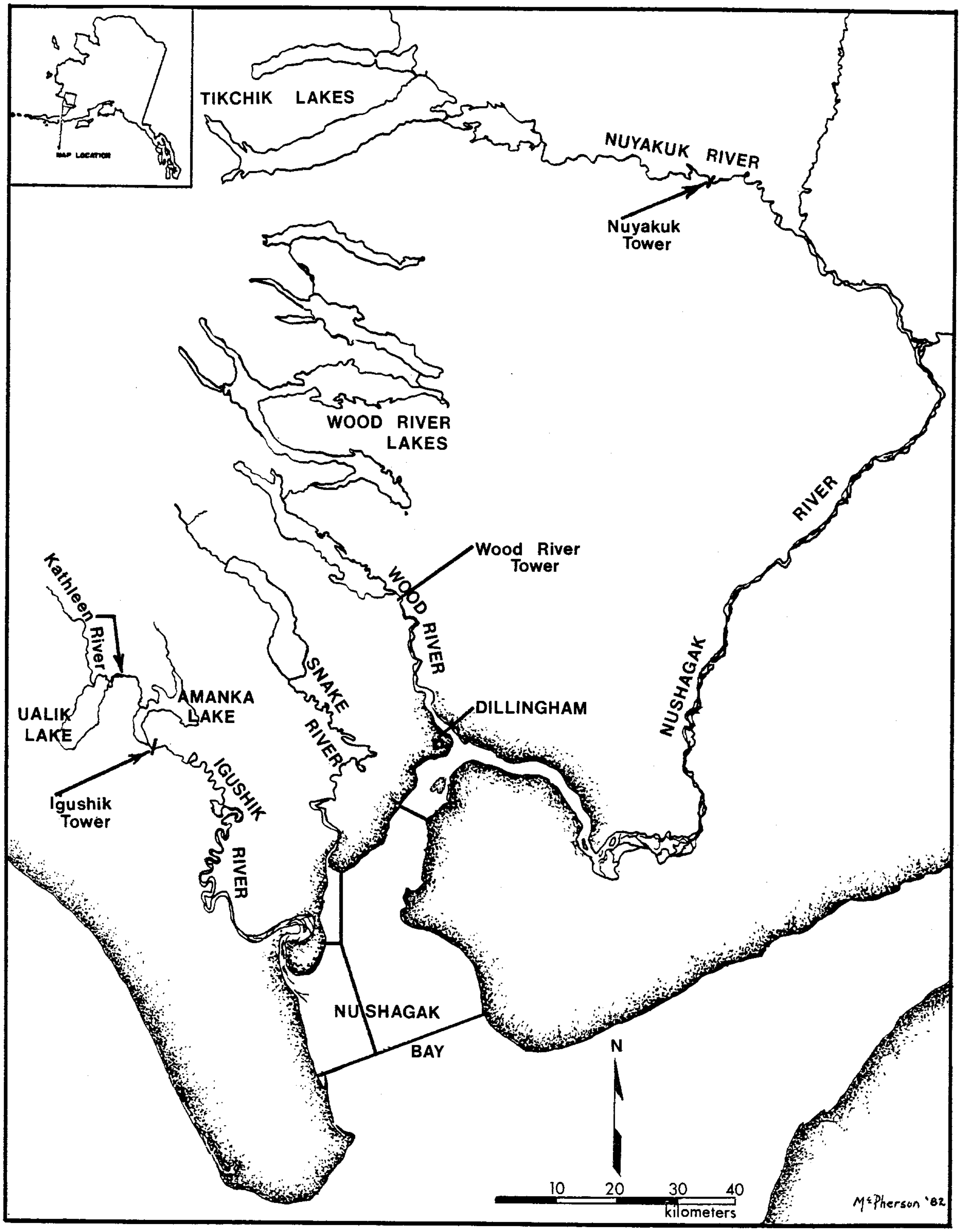


Figure 1. Map of Nushagak Bay and drainages.

The specific objectives of the scale pattern study were as follows:

1) Calculate the accuracy which can be expected in using scale pattern analysis to discriminate between the principal Nushagak Bay sockeye salmon stocks;

2) Examine within-run variability of scale patterns because of sex, date, and location of capture differences and relate this variability to the application of scale pattern analysis; and

3) Compare the performance of the LDF and KNN classification methods with Nushagak Bay sockeye salmon stocks.

## METHODS AND MATERIALS

### Scale Character Data Collection

Scale data from sockeye salmon that returned to Nushagak Bay in 1977, 1978, 1979, and 1980 are included in the scale pattern analysis. All analyses in this report are limited to age $5_2$[2] sockeye salmon since they are the dominant age class, comprising between 43% and 74% of the return to Nushagak Bay for the years of this study. Approximately 50 age $5_2$ scales were measured from each quarter of the run, yielding a total sample size of 200 fish per year. The methods used to collect the scale samples and measure the scales are described below.

Sample Collection:

The sockeye salmon escapements into Wood, Igushik, and Nuyakuk Rivers were sampled by beach seine near the headwaters of each river. In 1980, additional scale samples were collected from spawning sockeye salmon in Ualik Lake, Kathleen River, and Amanka Lake in the Igushik River system. Ocean age of these fish was obtained from otoliths since resorption of scale margins in spawning sockeye salmon makes age determination unreliable.

Scales were collected from the preferred area on the left side of the fish approximately two rows above the lateral line in the diagonal scale row downward from the posterior insertion of the dorsal fin (I.N.P.F.C. 1961). Scales were mounted on gummed cards and impressions made in cellulose acetate (Clutter and Whitese 1956). Ages were recorded in Gilbert-Rich notation. The sex and mid-eye to fork length were recorded for each fish.

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[2] Gilbert-Rich formula: Total years of life at maturity (superscript) - year of life at emigration from freshwater (subscript).

Scale Examination and Data Processing:

Scale images were projected at 100X magnification onto a table surface using equipment similar to that described by Bilton (1970) and later modified by Ryan and Christie (1976). Scale data were recorded onto computer diskettes from a digitizer tablet under the control of a FORTRAN program executing on a microcomputer. A detailed description of the scale measurement procedure is given by Krasnowski and Bethe (1978).

Scale variable measurements were the number of circuli (NC) and incremental distance (ID) within certain scale zones (Figure 2). The following scale zones measured from the 1978, 1979, and 1980 samples were: zone 1 - focus to end of the first summer; zone 2 - beginning to end of freshwater winter growth; zone 3 - beginning to end of plus growth; zone 4 - beginning to end of first summer marine growth, and zone 5 - beginning to end of first winter marine growth. The scale zones measured from the 1977 samples were: zone 1 - focus to end of first winter; zone 2 - beginning of second summer to end of second winter; zone 3 - beginning of third summer to end of third winter; zone 4 - beginning of fourth summer to end of fourth winter, and zone 5 - beginning of fifth summer to edge of scale (Figure 3).

Fourteen new characters were calculated for the 1978, 1979, and 1980 data bases on transformations of the original characters. These character transformations were designated T1 to T4 and their formulas are listed in Table 1. No transformations were calculated for the 1977 data base. These transformations were not based on biological theory but were an attempt to determine if combinations of the original variables would better discriminate between stocks.

## Statistical Techniques

The method used for scale pattern analysis in this study involved selecting the scale characters which best discriminated between the runs, building and testing pattern recognition models from selected scale character data sets, and computing classification accuracies and approximate 90% confidence intervals. The within-run distribution of measured scale variables by sex, date, and location of capture was also examined.

Within-Run Variability:

Variability of scale characteristics within the major runs was examined to better understand the classification model results. I used analysis of variance to test for differences in scale characteristics by sex, time, and location of capture for each major run. The means of measured scale variables by sex and by run were examined for the years 1978, 1979, and 1980. Differences in scale patterns from fish sampled during different segments of the run were examined for four time periods and for the years 1978, 1979, and 1980. Stock variability of scale patterns by location of capture was examined for three locations within the Igushik River system, using the 1980 Ualik Lake, Kathleen River, and Amanka Lake samples. Linear discriminant function analysis was performed to evaluate the ability to identify the fish sampled in these areas.

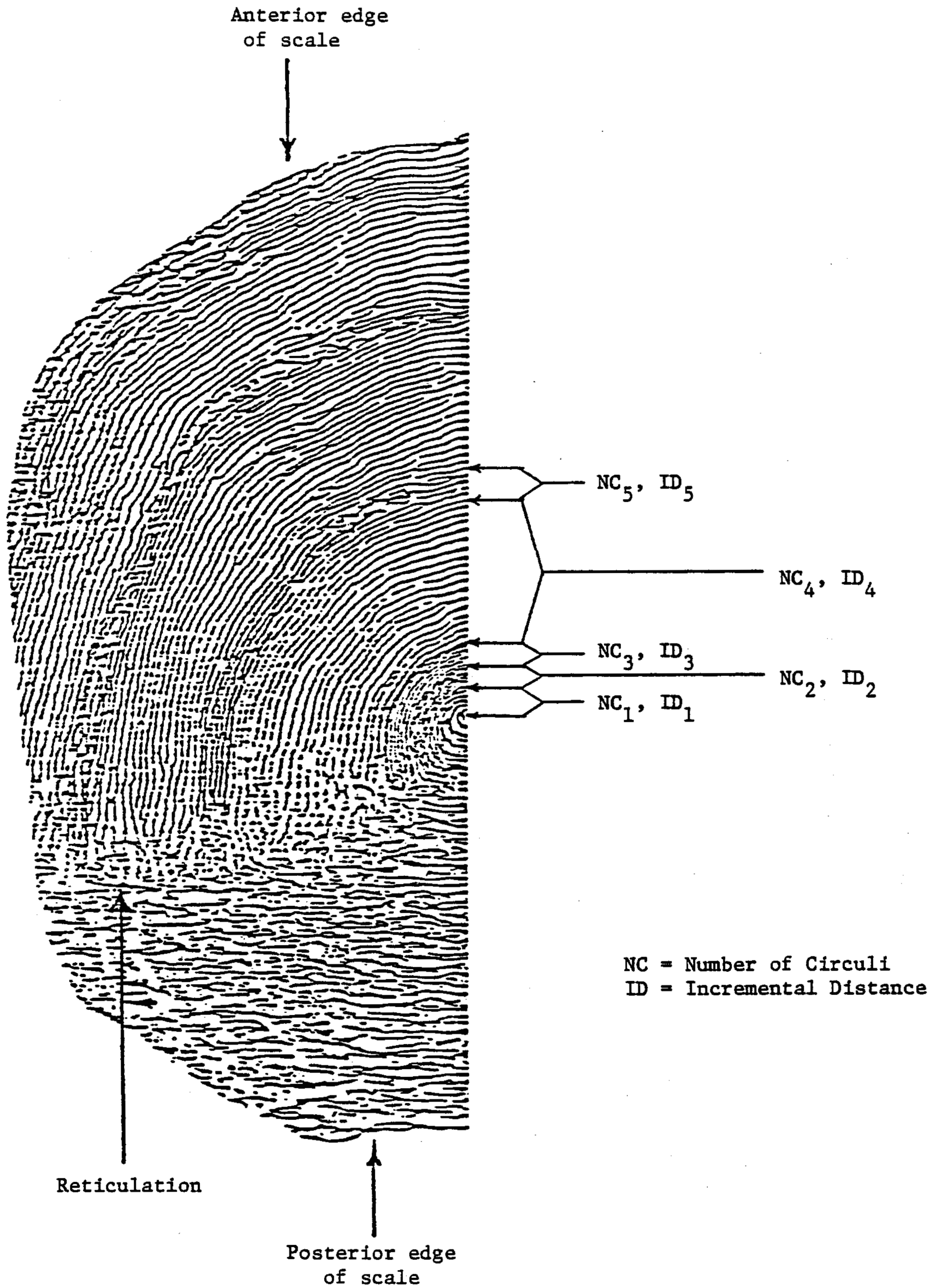


Figure 2. Diagram of scale variables measured, 1978 to 1980.

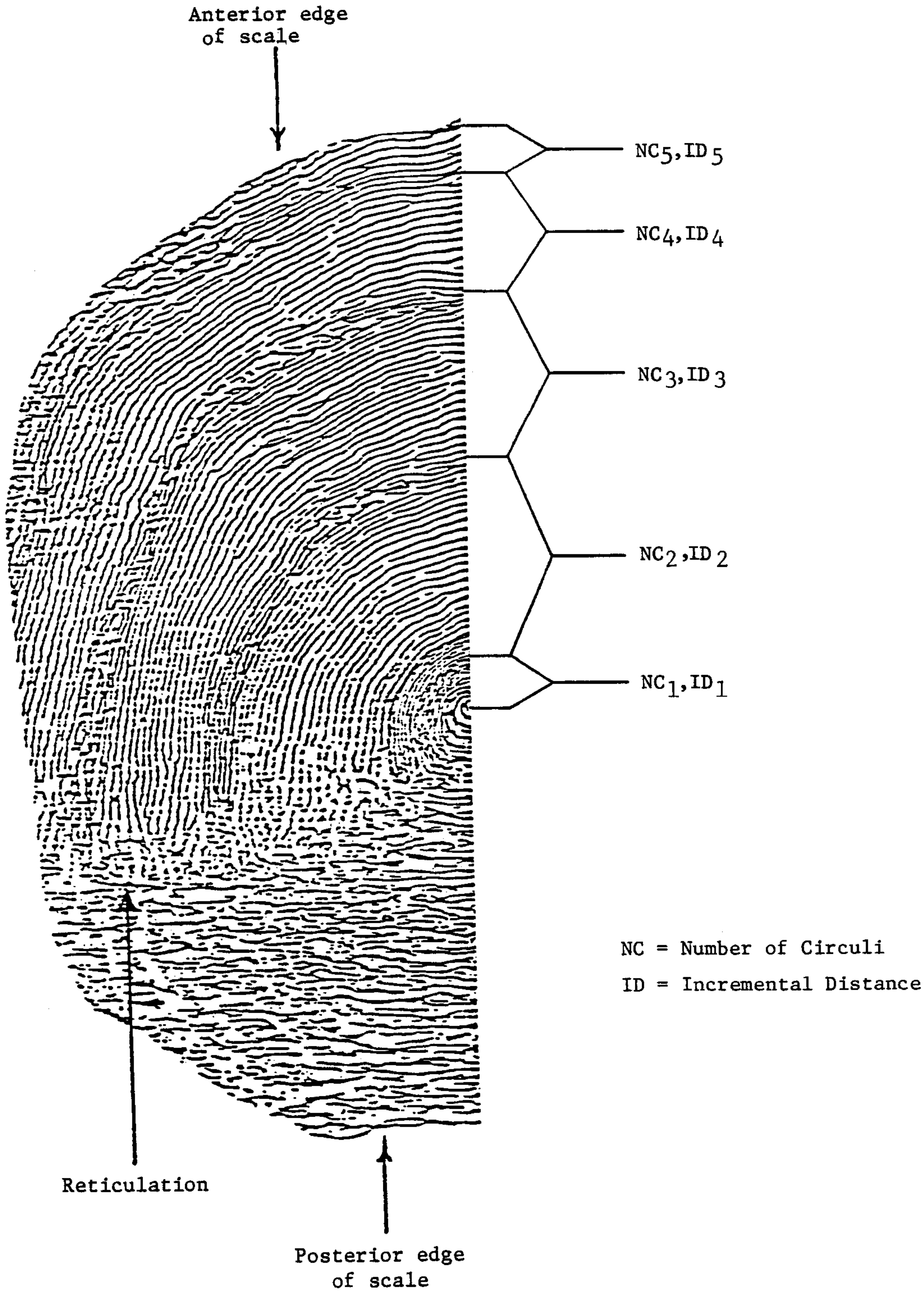


Figure 3. Diagram of scale variables measured, 1977.

Table 1. Transformation formulas of scale characters calculated for the 1978, 1979, and 1980 Wood, Igushik, and Nuyakuk River data bases[1].

$$T1 = (ID_1 \times NC_1)/((ID_2 \times NC_2) + (ID_3 \times NC_3))$$

$$T2 = ID_1/ID_2$$

$$T3 = ID_2/(ID_1 + ID_2)$$

$$T4 = ID_1/(ID_2 + ID_3)$$

$$T5 = ID_2/(ID_1 + ID_3)$$

$$T6 = (ID_2 \times NC_2)/((ID_1 \times NC_1) + (ID_2 \times NC_2))$$

$$T7 = ID_1/(ID_1 + ID_2 + ID_3)$$

$$T8 = (ID_1 + ID_2 + ID_3 + ID_4 + ID_5)/(NC_1 + NC_2 + NC_3)$$

$$T9 = (ID_1 + ID_2 + ID_3)/(ID_4 + ID_5)$$

$$T10 = NC_4 + NC_5$$

$$T11 = ID_4 + ID_5$$

$$T12 = ID_1/(ID_1 + ID_2 + ID_3 + ID_4 + ID_5)$$

$$T13 = ID_2 + ID_3$$

$$T14 = (ID_2 \times NC_2) + (ID_5 \times NC_5)$$

[1] Refer to Figure 2 for variable identification.

Scale Character Selection:

A stepwise procedure was used to select scale variables or transformed variables for inclusion in the classification models. The variables and transformed variables from each year were first normalized to have a mean of 0 and a standard deviation of 1. This makes all variables approximately equal in magnitude without destroying separation information (Duewer, Kokinen, and Kowalski 1975).

The "select" routine in the ARTHUR pattern recognition computer program package (Duewer, Kokinen, and Kowalski 1975) was used to select the variables for inclusion into the classification models. This routine is a stepwise procedure which selects the variables with the best linear discriminating ability first, removes linear correlations between it and all other variables, weights it in terms of its discriminating power between groups, then recomputes Fisher weights on the remaining variables, and selects the "next" best variable for inclusion into the model. This procedure continues until all variables have been selected and ranked in order of their power to discriminate between runs. The top ranked variables were then used to build the classification models. The weighted values for each variable were graphed to aid in selecting the variables which contribute most to discriminating the stocks. The ratio between number of variables included in the model and number of cases in each group was kept less than 1:10.

Classification Models:

Classification models with both parametric (LDF) and non-parametric (KNN) assumptions were examined to determine which model was best able to identify the component runs. Linear discriminant function analysis has been used extensively for identifying racial origin of fish (Mason 1966; Anas and Murai 1969; Krasnowski and Bethe 1978; Bethe and Krasnowski 1979; and Cross et al. 1981). The LDF method assumes that the data sets be multivariate normal and have common variance-covariance matrices. It is, however, fairly robust to violations of these assumptions when sample sizes are large (Issacson 1954). Analysis of the LDF method was performed using the BMDP program BMDP7M (Dixon 1977).

Nearest neighbor analysis classifies a data case to the group membership of the nearest (measured in multivariate space) known data case (Cover and Hart 1967); no population parameters are estimated. The computational routines of ARTHUR, a pattern recognition computer program (Duewer, Kokinen, and Kowalski 1975) were used for the nearest neighbor analysis.

Classification Error Estimation and Variance Calculation:

The accuracy of the LDF model was estimated by classifying a second test set of data obtained from fish of known origin. Splitting the available samples of known origins into learning and test groups provides an independent and unbiased estimates of accuracy. I therefore randomly selected one-half of the known samples as the learning sample to construct the model and the other half was used as a test sample to estimate the classification accuracy.

The KNN technique does not require that different samples be used to construct and test the model because the data obtained from each fish is classified using the data collected from all other fish. Therefore, all the data were used simultaneously.

Expected confidence limits were computed for the classification models by a modification of a method used to correct the classification of unknown samples. The procedure for making this correction was first presented for a two-class problem by Worlund and Fredin (1962), and expanded to n-classes by Cook and Lord (1978). The variance and confidence interval for the corrected estimate are calculated by the procedure described by Pella and Robertson (1979). Pella and Robertston's $\theta$ estimation formula was used for this study because simulation studies indicate that this estimator has the smallest bias and the smallest variance of the estimators studied. This estimation procedure considers the following two sources of error in estimating the variance of the corrected estimates: (1) the sampling variation in obtaining estimates for the unknown sample, and (2) the sampling variation in obtaining a test sample.

With three unknown groups approximately 100 fish are required in the unknown sample and 50 fish are necessary in each group of the test sample in order to achieve reasonable estimates of variance.

In this study no actual mixed stock samples (unknowns) were classified. In order to obtain confidence intervals for the classification models unknown samples were simulated with the following assumptions: (1) the unknown sample contained data from 99 cases for the three-way model and 100 cases for the two-way model, and (2) the unknown sample is assumed to contain equal proportions of each run.

## RESULTS

### Principal Run Separability

Linear discriminant function analysis and KNN analysis were used to construct two and three-way models for classifying Wood, Igushik, and Nuyakuk River sockeye salmon runs. Ninety percent confidence intervals were computed around these classifications. The between-run variability of measured scale variables was also examined.

Wood-Igushik-Nuyakuk Model:

Differences were present in classification accuracies for the three-way models between runs, years, and classification methods. Tables 2 through 5 show the classification results for both the KNN and IDF methods from 1977 through 1980 and Table 6 summarizes the results for all years. The average classification accuracies for the KNN analysis ranged from .540 in 1979 to .630 in 1980. Average classification accuracies for LDF analysis ranged from .535 in 1977 to .657 in 1980. Misclassifications were approximately balanced between runs. Classification accuracies from KNN or LDF analysis did not tend to be better for any particular run, Wood, Igushik, or Nuyakuk, for the years of this study.

The best discriminating variables were those associated with the freshwater growth phase, especially the first summers growth measurements, $NC_1$ and $ID_1$. The variables selected for building these classification models were different each year (Tables 2 to 5). Only the top variables which contributed most to discriminating the runs were used to build the classification models (Figure 4).

Table 2. Test classification matrices for nearest neighbor (KNN) and linear discriminant function (LDF) analysis of Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1977.

| Actual Group of Origin | Sample Size | KNN Classified Group of Origin (Variables = $ID_2, NC_2, ID_1, NC_1$, K=7) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 87 | <u>.609</u> | .149 | .241 |
| Igushik | 87 | .184 | <u>.517</u> | .299 |
| Nuyakuk | 87 | .149 | .264 | <u>.586</u> |
| | | Average correctly classified = .571 | | |

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = $ID_2, NC_2, ID_1, NC_1$) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 62 | <u>.548</u> | .290 | .161 |
| Igushik | 52 | .211 | <u>.615</u> | .173 |
| Nuyakuk | 43 | .139 | .419 | <u>.442</u> |
| | | Average correctly classified = .535 | | |

Table 3. Test classification matrices for nearest neighbor (KNN) and linear discriminant function (LDF) analysis of Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1978.

| Actual Group of Origin | Sample Size | KNN Classified Group of Origin (Variables = $NC_1$,T11,$ID_2$,T6,T10, K=8) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 203 | .606 | .286 | .108 |
| Igushik | 211 | .275 | .569 | .156 |
| Nuyakuk | 216 | .176 | .208 | .616 |
| | | Average correctly classified = .597 | | |

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = $NC_1$,T11,$ID_2$,T6,T10) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 100 | .490 | .360 | .150 |
| Igushik | 99 | .323 | .525 | .151 |
| Nuyakuk | 101 | .228 | .178 | .594 |
| | | Average correctly classified = .536 | | |

Table 4. Test classification matrices for nearest neighbor (KNN) and linear discriminant function (LDF) analysis of Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1979.

| Actual Group of Origin | Sample Size | KNN Classified Group of Origin (Variables = T12, $ID_5$, $ID_4$, T6 , K=10) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 173 | .433 | .358 | .208 |
| Igushik | 173 | .237 | .601 | .162 |
| Nuyakuk | 169 | .142 | .272 | .586 |
| | | Average correctly classified = .540 | | |

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = T12, $ID_5$, $ID_4$, T6) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 87 | .529 | .276 | .195 |
| Igushik | 91 | .341 | .484 | .176 |
| Nuyakuk | 80 | .200 | .162 | .637 |
| | | Average correctly classified = .550 | | |

Table 5. Test classification matrices for nearest neighbor (KNN) and linear discriminant function (LDF) analysis of Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1980.

| Actual Group of Origin | Sample Size | KNN Classified Group of Origin (Variables = $ID_1$,T7,T9, K=10) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 200 | .675 | .110 | .215 |
| Igushik | 201 | .144 | .627 | .229 |
| Nuyakuk | 211 | .199 | .213 | .588 |

Average correctly classified = .630

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = $ID_1$,T7,T9) | | |
|---|---|---|---|---|
| | | Wood | Igushik | Nuyakuk |
| Wood | 98 | .663 | .102 | .235 |
| Igushik | 99 | .182 | .667 | .151 |
| Nuyakuk | 114 | .167 | .193 | .640 |

Average correctly classified = .657

Table 6. Approximate 90% confidence intervals for three-way nearest neighbor (KNN) and linear discriminant function (LDF) models classifying Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon for the years 1977, 1978, 1979, and 1980.

| Year | Method | 90% Confidence Interval Wood | Igushik | Nuyakuk | Average 90% Confidence Interval | Average Correctly Classified |
|---|---|---|---|---|---|---|
| 1977 | KNN | ±0.266 | ±0.412 | ±0.398 | ±0.345 | 0.571 |
| | LDF | ±0.386 | ±0.638 | ±0.562 | ±0.523 | 0.535 |
| 1978 | KNN | ±0.308 | ±0.349 | ±0.227 | ±0.295 | 0.597 |
| | LDF | ±0.639 | ±0.611 | ±0.259 | ±0.503 | 0.536 |
| 1979 | KNN | ±0.513 | ±0.457 | ±0.260 | ±0.420 | 0.540 |
| | LDF | ±0.551 | ±0.534 | ±0.260 | ±0.448 | 0.550 |
| 1980 | KNN | ±0.219 | ±0.245 | ±0.298 | ±0.254 | 0.630 |
| | LDF | ±0.231 | ±0.219 | ±0.254 | ±0.235 | 0.657 |

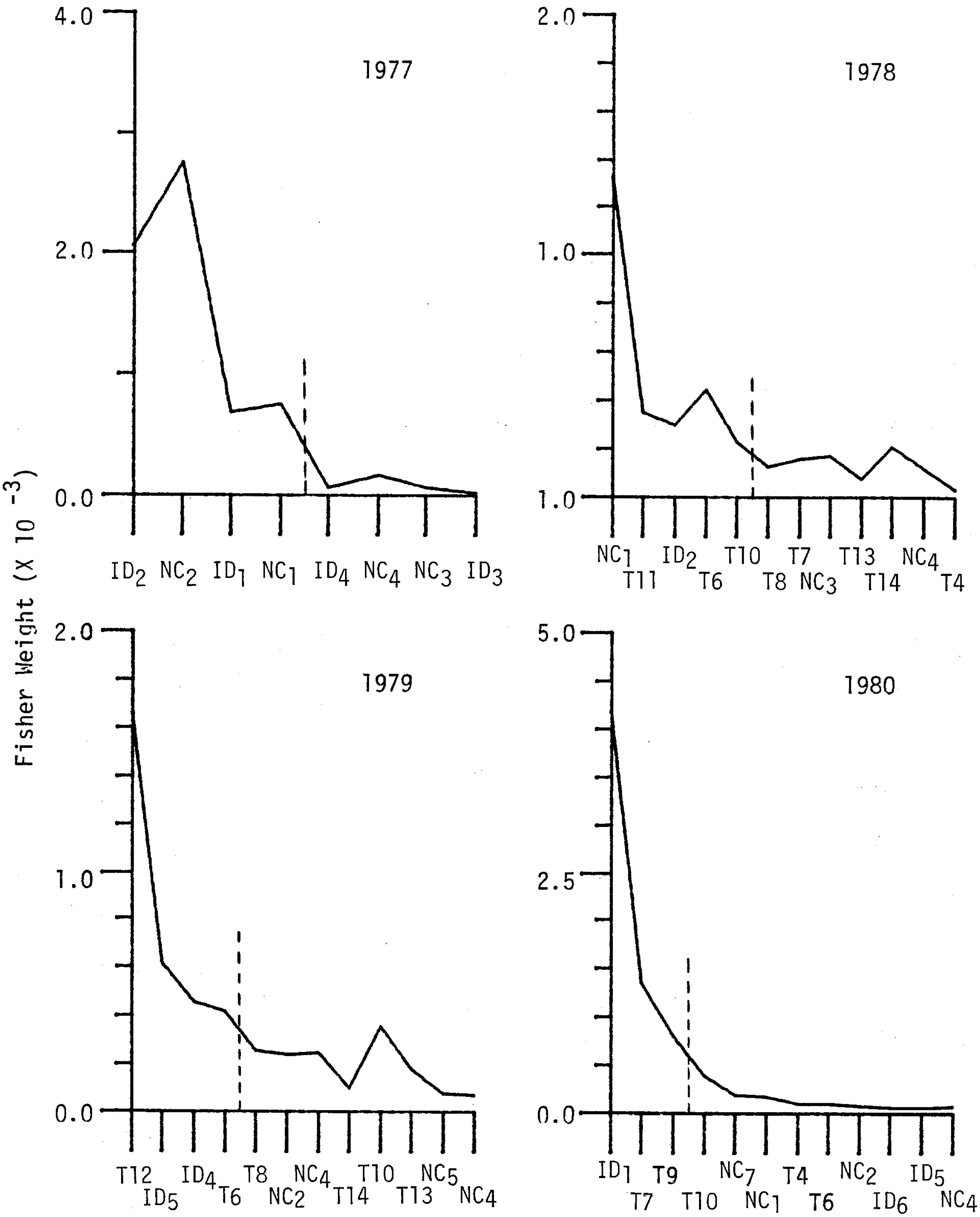


Figure 4. Weighted values of the top ranked variables for 1977, 1978, 1979, and 1980 Wood, Igushik, and Nuyakuk analysis. The variables to the left of the dashed line were those selected to build the classification models.

Transformed variables (Table 1) were among the top selected variables. The same variables and order of entry were used to construct both KNN and LDF models.

Approximate 90% confidence intervals were computed for both KNN and LDF models (Table 6). Average 90% confidence intervals for the KNN model ranged from ±.25 to ±.42 and for the LDF model ranged from ±.24 to ±.52. The confidence intervals tended to be smallest for Nuyakuk and largest for Igushik for both models.

The KNN models tended to have higher average classification accuracies and smaller confidence intervals than the LDF models. The non-parametric KNN method yielded shorter average confidence intervals for 1977, 1978, and 1979 and slightly longer average confidence intervals for 1980 (Table 6). To accurately compare the relative accuracy of the KNN and LDF models the sample sizes for each model would need to be the same. Since the LDF analysis involved dividing the knowns into two groups, learning and test, the sample sizes of the LDF model were approximately half those in the KNN model. It is possible that the confidence intervals are larger for the LDF analysis primarily because the sample sizes were smaller.

Wood-Nuyakuk Model:

Linear discriminant function analysis was used to construct two-way models for classifying Wood and Nuyakuk River sockeye salmon. The overall classification accuracies for the Wood-Nuyakuk model ranged from .760 in 1980 to .687 in 1978 (Tables 7-10). Confidence interval lengths ranged from ±.19 in 1980 to ±.28 in 1977 (Table 11). The variables and variable transformations used to build each LDF model are listed in Tables 7 to 10 and are the same as those variables selected for the three-way model. Misclassifications were approximately balanced between runs.

Distribution of Scale Variables by Run:

The distribution of scale variables by run was examined using one-way analysis of variance. The means, standard deviations, F value, and probabilities for the measured scale variables for the years 1977, 1978, 1979, and 1980 are presented in Appendix Tables 1, 2, 3, and 4. Measurements from the freshwater portion of the scales tended to have the greatest differences between stocks. The fewest number of significant differences were present between the three runs in 1977 (5 insignificant at the 95% confidence level). Scale measurements for the years 1978, 1979, and 1980 showed significant differences in either all or all but one of the scale measurements. There was considerable overlap in the distribution of scale variables between runs. Variable $ID_1$ for Igushik and Nuyakuk in 1978 was bimodal and variable $ID_3$ for all stocks and years was negatively skewed (Figures 5, 6, and 7).

There tended to be little difference in variance of the measured scale variables between runs. The following freshwater scale variables, however, did have substantially larger standard deviations for a particular run; variable $ID_2$ for Wood River in 1977; variable $ID_1$ for Nuyakuk River in 1978; variable $ID_2$ for Wood River in 1979; and variable $ID_3$ for Wood River in 1980. Years 1977 and 1978 tended to have the widest variability of scale measurements from the fresh-

Table 7. Test classification matrices for linear discriminant function analysis of Wood and Nuyakuk River age $5_2$ sockeye salmon, 1977.

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = $ID_2, NC_2, ID_1, NC_1$) | |
|---|---|---|---|
| | | Wood | Nuyakuk |
| Wood | 62 | .677 | .323 |
| Nuyakuk | 43 | .279 | .721 |
| | | Average correctly classified = .699 | |

Table 8. Test classification matrices for linear discriminant function analysis of Wood and Nuyakuk River age $5_2$ sockeye salmon, 1978.

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = $NC_1$,T11,$ID_2$,T6,T10) | |
|---|---|---|---|
| | | Wood | Nuyakuk |
| Wood | 100 | .740 | .260 |
| Nuyakuk | 101 | .366 | .634 |
| | | Average correctly classified = .687 | |

Table 9. Test classification matrices for linear discriminant function analysis of Wood and Nuyakuk River age $5_2$ sockeye salmon, 1979.

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = T12, $ID_5$, $ID_4$, T6) | |
|---|---|---|---|
| | | Wood | Nuyakuk |
| Wood | 87 | .770 | .230 |
| Nuyakuk | 80 | .312 | .687 |
| | | Average correctly classified = .729 | |

Table 10. Test classification matrices for linear discriminant function analysis of Wood and Nuyakuk River age $5_2$ sockeye salmon, 1980.

| Actual Group of Origin | Sample Size | LDF Classified Group of Origin (Variables = $ID_1$,T7,T9) | |
|---|---|---|---|
| | | Wood | Nuyakuk |
| Wood | 98 | .704 | .296 |
| Nuyakuk | 114 | .184 | .816 |
| | | Average correctly classified = .760 | |

Table 11. Approximate 90% confidence intervals for two-way LDF models classifying Wood and Nuyakuk River age $5_2$ sockeye salmon for the years 1977, 1978, 1979, and 1980.

| Year | 90% Confidence Intervals for Wood and Nuyakuk | Average Correctly Classified |
|---|---|---|
| 1977 | $\pm$0.277 | 0.699 |
| 1978 | $\pm$0.268 | 0.687 |
| 1979 | $\pm$0.221 | 0.729 |
| 1980 | $\pm$0.187 | 0.760 |

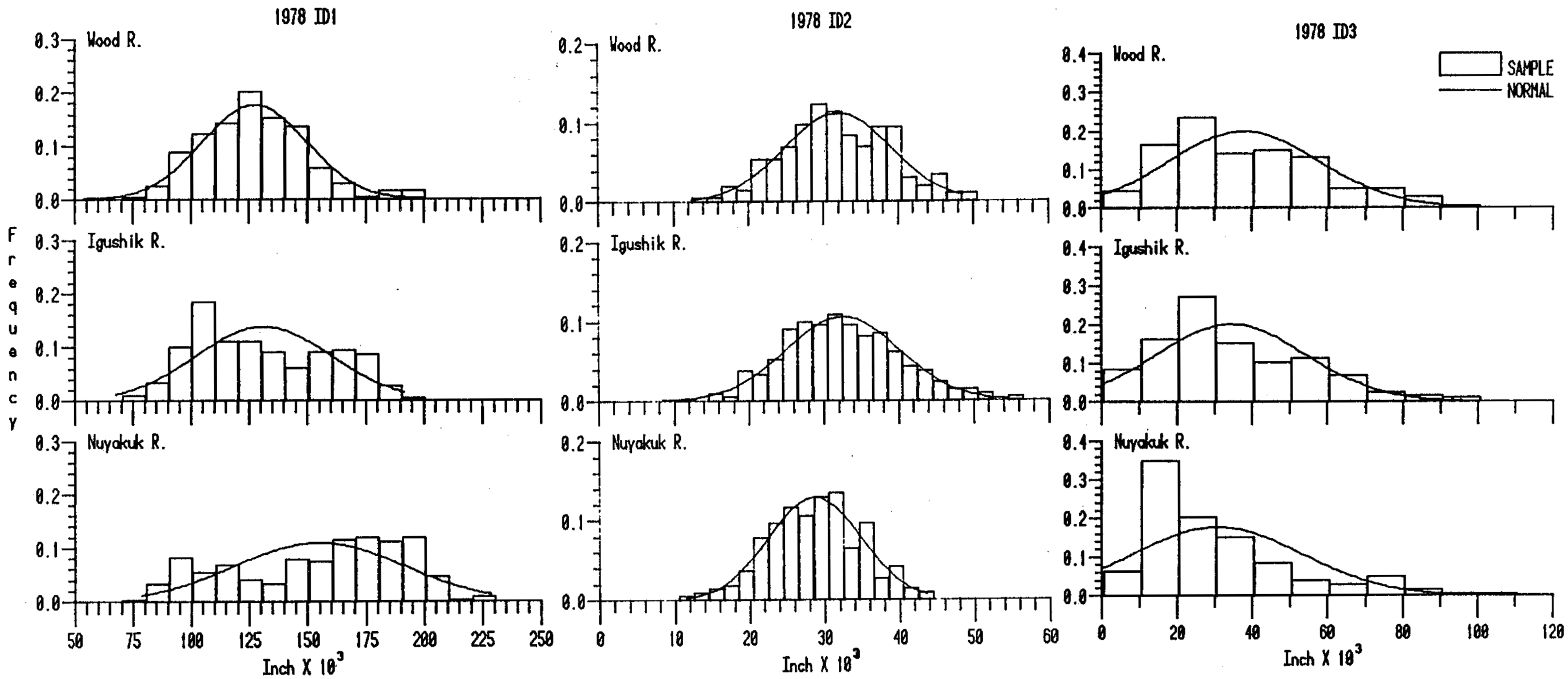


Figure 5. Frequency distributions of scale variables $ID_1$, $ID_2$, and $ID_3$ from Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1978.

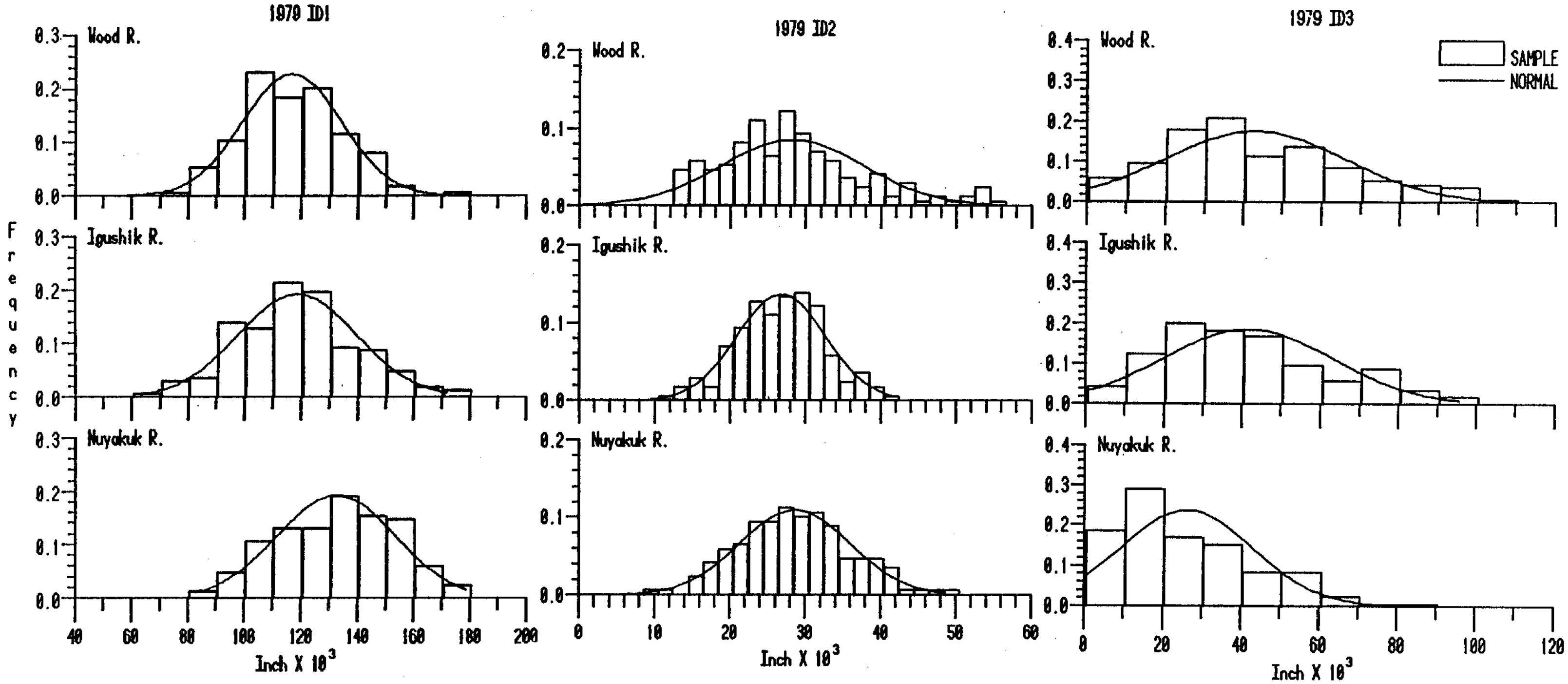


Figure 6. Frequency distributions of scale variables $ID_1$, $ID_2$, and $ID_3$ from Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1979.

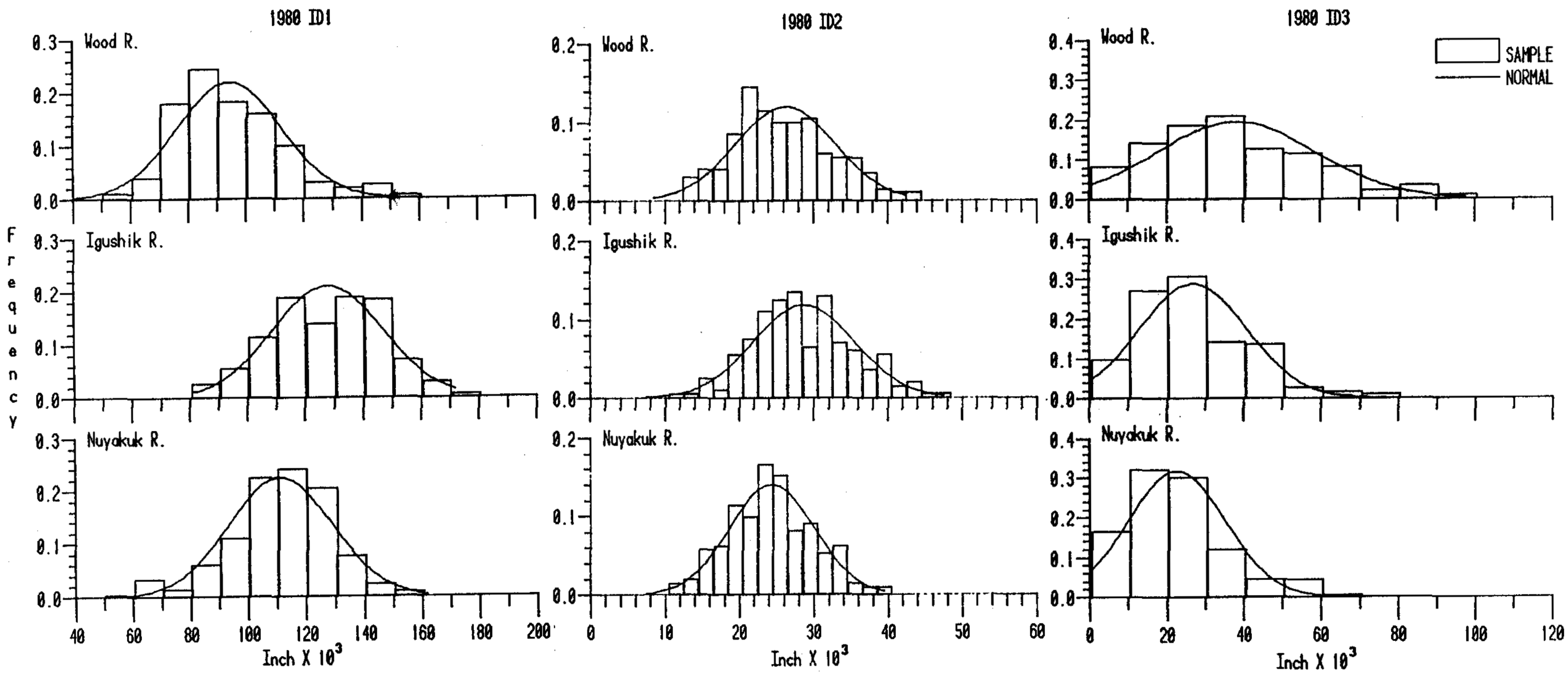


Figure 7. Frequency distributions of scale variables $ID_1$, $ID_2$, and $ID_3$ from Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1980.

water zone, particularly for variable $ID_2$ in 1977 and variable $ID_1$ in 1978. Large differences are seen in the means, standard deviations and F values of variables between years. This suggests large between year fluctuations in the growth environment of the Nushagak Bay sockeye salmon.

Within-Run Variance

Variability of scale characteristics within Wood, Igushik, and Nuyakuk River systems was examined to better understand the results of the classification models. The within-run variability in scale patterns by sex, date, and location of capture was tested using one-way analysis of variance for the years 1978, 1979, and 1980.

Distribution of Scale Variables by Sex:

Significant differences ($P<.05$) were detected between males and females in the means of some measured scale variables (Appendix Tables 5 to 7). Significant differences were present in some runs and years for all scale zones 1 to 5, but no consistent pattern was discernible.

Distribution of Scale Variables by Time:

Significant differences were detected in the means of some scale variables from fish sampled during different quarters of the run (Appendix Tables 8 to 10). Wood River shows consistent differences in zone 2 (all years), zone 3 (2 of 3 years), zone 5 (all years). Igushik River shows consistent differences in zone 1 (2 of 3 years) and zone 5 (3 of 3 years). Nuyakuk River was more stable but significant differences were present in zone 1 (2 of 3 years) and in zones 3 and 4 in 1980.

Distribution of Scale Variables by Sampling Location:

Scales from spawning sockeye salmon sampled in 1980 from three areas of the Igushik Lake system: Ualik Lake, Kathleen River, and Amanka Lake (Figure 1), were analyzed to see if their scale patterns were similar. One-way analysis of variance testing detected significant differences ($P<.05$, df = 2,186) between areas in the means of the freshwater zone scale variables (Appendix Table 11). The $NC_1$, $NC_2$, $ID_1$, and $ID_2$ scale measurements for Ualik Lake fish are larger than in Kathleen River and Amanka Lake fish. Variable $ID_3$ (plus growth) was largest for Amanka Lake ($P<.10$).

A three-way discriminant function model was constructed with Wood, Igushik, and Nuyakuk River 1980 scale data and tested with the Igushik stock component divided into Ualik Lake, Kathleen River, and Amanka Lake samples (Appendix Table 12). Differences were present in the classification accuracies for the three Igushik system samples. Sockeye salmon from Ualik Lake were classified correctly .852 of the time compared to .778 for Kathleen River and .556 for Amanka Lake. Amanka Lake fish were misclassified most frequently as Nuyakuk fish (.270). Results from both the one-way analysis of variance and LDF analysis indicates measurable differences in sub-populations of sockeye salmon in the Igushik system.

## DISCUSSION

### Feasibility of Scale Pattern Analysis

The scale pattern analysis technique for discriminating Nushagak Bay sockeye salmon stocks worked better in some years than others. In general, the three-way and two-way classification models had low classification accuracies and wide confidence intervals for the years studied. This indicates that the within-run (system) variability was similar to the between system variability.

There are measurable differences in scale patterns of sockeye salmon from different areas of the Wood River system (Burgner 1962; Marshall 1980) and Igushik River system (this report). The Wood, Igushik, and Nuyakuk systems are all composed of multiple lake basins. Differences in the rearing environment within each system's lakes and rivers contributes to this within-run variability of scale patterns.

The Nushagak Bay drainages are roughly similar in terms of morphology, hydrology, limnology, geography, and climatic conditions. The major lakes are all oligotrophic lakes and have similar resident and anadromous fish populations. There are no environmental conditions which I would expect to result in consistent large measurable differences in scale patterns between the stocks.

Differences in freshwater growth of sockeye salmon is primarily a factor of differences in the fry rearing density between systems. Burgner (1962) and Rogers (1973) found evidence of density dependent growth for sockeye salmon fry in the Wood River lakes system, the growth of fry being faster in years of low fry abundance than in years of high fry abundance. Newcombe (1976) found evidence of density dependent growth in the Igushik lake system where fry in the less densely populated Ualik Lake grew faster than fry in the more populated Amanka Lake. The scale pattern analysis technique would then be best in years where there are large differences in the fry rearing density between systems.

The applicability of scale pattern analysis in identifying Nushagak Bay stocks might be reduced by differences in scale patterns between sexes. It is advisable to restrict the variables in scale pattern analysis to those which are independent of sex if there are differences in the sex composition between catch samples and escapement samples. For the years of this study there were significant differences ($P<.05$) in the sex composition of the catch and escapement samples (1977 $X^2 = 62.96$, 1978 $X^2 = 13.26$, 1979 $X^2 = 33.66$, 1980 $X^2 = 6.79$). This indicates differences between gear types (gill net and beach seine) in sex selectivity. Classification models built with sexes combined will have reduced accuracy from increased within-run variability. It would be best, therefore, to build separate models for males and females if the highest possible classification accuracy is desired. This will require larger sample sizes and cost more in terms of sampling, processing, and computing time.

Differences in the means of scale variables from fish sampled during different quarters of the run are likely the result of differences in run timing of the component populations of fish comprising the run. The between date variability information was especially significant for the Wood and Igushik River runs which are composed of multiple stocks. Most significant differences in means of scale variables by date were with variables from the freshwater zones 1, 2, and 3, which suggests differences in freshwater rearing environments of the sub-populations within each system. These differences in means of scale variables by date reduces the applicability of in-season classification models since the scale patterns of early-run fish are different from that of late-run fish. In-season models constructed from fish sampled early in the run will be least accurate for classifying late returning fish. Post-season classification models should consist of scale data from fish sampled in proportion to the escapement.

Sockeye salmon scales from the Nushagak Bay drainages are relatively difficult to read because of poor definition of the beginning and ends of scale zones. The first marine winter check is particularly hard to distinguish. A 1978 study in the Stock Separation lab on that years Wood, Igushik, and Nuyakuk River data base revealed differences between readers in the means of scale variables (Appendix Table 13). For this reason one scale reader read all scales analyzed in this report. In-season catch allocation of Nushagak Bay stocks would require at least two scale readers for timely reading of catch and escapement scales. Scale reading assignments would have to be distributed between readers to eliminate reader bias.

### Recommended Statistical Technique

The KNN method tended to yield higher classification accuracies and lower confidence intervals than the LDF method, however, the 1980 LDF three-way model yielded the best classification matrix. I conclude that in years when non-normal distribution of scale variables is suspected, then KNN is the superior method. In years that scale variables are normally distributed then the LDF method is best since classification accuracies and confidence intervals are at least as good as the KNN models, and LDF analysis is faster, requires less data manipulation, less computer processing time making it easier and less expensive than KNN analysis.

## CONCLUSIONS

Current catch allocation methodology for Nushagak Bay stocks involves comparing the age and sex composition of the catch samples with the escapement samples from the contributing river systems (Meacham and Nelson 1980). Confidence intervals have not been computed for these catch allocations. The simplicity and low cost by which these catch allocations are derived warrants their continued used unless an alternate method produces estimates with an acceptable level of accuracy at an acceptable cost.

The generally low accuracies and correspondingly high anticipated confidence intervals obtained with scale pattern analysis do not warrant an intensive scale pattern analysis based catch allocation program for Nushagak Bay. As mentioned in the introduction of this paper this study is part of a larger project designed to evaluate the relative accuracy and costs of different catch allocation techniques, scale pattern analysis being only one of the methods.

Development of an in-season scale pattern analysis model is not recommended because of the likelihood of obtaining unacceptable classification accuracies. An in-season catch allocation program would be logistically difficult to set up because of the short duration of the run. Eighty percent of the Nushagak District run usually passes within a 10-day period. It would be difficult to sample, age, read, and analyze samples quickly enough for management purposes.

If scale pattern analysis is found to be the most accurate method for post-season allocation of Nushagak Bay catches it can be implemented relatively easily. There would be a limited need for special samples since sampling catch and escapement is part of the regular management program. More intensive catch sampling would be desired, however, if scale pattern analysis is used for entry pattern analysis.

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# APPENDICES

Appendix Table 1. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for equality of group means for measured scale variables between age $5_2$ sockeye salmon sampled from Wood, Igushik, and Nuyakuk Rivers, 1977.

| Variable | Wood | Igushik | Nuyakuk | F value | Probability |
|---|---|---|---|---|---|
| $NC_1$ | 12.6<br>(2.7) | 12.3<br>(2.7) | 11.9<br>(3.0) | 1.6099 | 0.2016 |
| $ID_1$ | 99.5<br>(18.3) | 94.3<br>(17.9) | 97.3<br>(17.6) | 2.3888 | 0.0934 |
| $NC_2$ | 25.6<br>(4.7) | 26.5<br>(3.2) | 24.6<br>(2.5) | 5.8184 | 0.0033 |
| $ID_2$ | 240.9<br>(43.5) | 269.1<br>(26.6) | 253.3<br>(26.3) | 19.2522 | 0.0000 |
| $NC_3$ | 23.3<br>(2.8) | 21.8<br>(2.4) | 22.3<br>(2.7) | 8.9992 | 0.0002 |
| $ID_3$ | 210.3<br>(27.0) | 208.5<br>(23.2) | 215.9<br>(27.9) | 2.0814 | 0.1265 |
| $NC_4$ | 16.6<br>(2.4) | 16.5<br>(2.4) | 16.6<br>(2.7) | 0.1149 | 0.8915 |
| $ID_4$ | 161.0<br>(26.7) | 163.0<br>(28.7) | 165.5<br>(26.2) | 0.6901 | 0.5023 |
| $NC_5$ | 4.5<br>(1.3) | 3.4<br>(1.3) | 3.6<br>(1.5) | 22.1622 | 0.0000 |
| $ID_5$ | 50.8<br>(15.2) | 35.3<br>(15.1) | 39.6<br>(16.4) | 30.6698 | 0.0000 |
| Sample Size | 124 | 105 | 87 | | |

Appendix Table 2. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for equality of group means for measured scale variables between age $5_2$ sockeye salmon sampled from Wood, Igushik, and Nuyakuk Rivers, 1978.

| Variable | Wood | Igushik | Nuyakuk | F value | Probability |
|---|---|---|---|---|---|
| $NC_1$ | 9.3 (1.8) | 9.5 (2.3) | 11.8 (3.1) | 66.6873 | 0.0000 |
| $ID_1$ | 127.2 (22.3) | 131.0 (28.8) | 154.7 (36.2) | 53.1598 | 0.0000 |
| $NC_2$ | 4.0 (0.9) | 3.9 (1.0) | 3.6 (0.8) | 12.3840 | 0.0000 |
| $ID_2$ | 32.0 (7.1) | 32.5 (7.5) | 28.7 (6.2) | 18.8767 | 0.0000 |
| $NC_3$ | 3.6 (1.9) | 2.9 (1.8) | 2.5 (2.1) | 15.2831 | 0.0000 |
| $ID_3$ | 37.2 (20.3) | 33.3 (20.2) | 29.2 (22.7) | 7.5297 | 0.0006 |
| $NC_4$ | 14.9 (2.5) | 15.2 (2.5) | 14.3 (1.9) | 8.5297 | 0.0002 |
| $ID_4$ | 269.3 (39.9) | 286.8 (42.0) | 272.6 (34.3) | 12.0364 | 0.0000 |
| $NC_5$ | 6.9 (1.0) | 6.9 (1.2) | 6.6 (1.1) | 5.0471 | 0.0067 |
| $ID_5$ | 102.6 (13.5) | 103.1 (14.8) | 97.7 (14.1) | 9.7491 | 0.0001 |
| Sample Size | 203 | 211 | 216 | | |

Appendix Table 3. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for equality of group means for measured scale variables between age $5_2$ sockeye salmon sampled from Wood, Igushik, and Nuyakuk Rivers, 1979.

| Variable | Wood | Igushik | Nuyakuk | F value | Probability |
|---|---|---|---|---|---|
| $NC_1$ | 9.1<br>(1.7) | 9.2<br>(1.7) | 9.9<br>(1.7) | 12.4690 | 0.0000 |
| $ID_1$ | 116.7<br>(17.2) | 118.7<br>(20.6) | 132.6<br>(20.5) | 33.6243 | 0.0000 |
| $NC_2$ | 3.3<br>(1.1) | 3.2<br>(0.8) | 3.5<br>(0.9) | 4.8754 | 0.0080 |
| $ID_2$ | 28.1<br>(9.4) | 26.7<br>(5.8) | 28.7<br>(7.3) | 2.8433 | 0.0592 |
| $NC_3$ | 4.0<br>(2.1) | 3.9<br>(2.0) | 2.5<br>(1.5) | 34.2922 | 0.0000 |
| $ID_3$ | 42.2<br>(23.1) | 41.2<br>(21.6) | 25.7<br>(16.8) | 33.9459 | 0.0000 |
| $NC_4$ | 14.7<br>(2.3) | 15.4<br>(2.4) | 14.7<br>(2.0) | 5.3996 | 0.0048 |
| $ID_4$ | 282.8<br>(39.5) | 304.9<br>(38.7) | 295.1<br>(36.9) | 14.2812 | 0.0000 |
| $NC_5$ | 6.0<br>(1.2) | 5.8<br>(0.8) | 5.4<br>(0.9) | 13.7273 | 0.0000 |
| $ID_5$ | 91.0<br>(15.8) | 89.4<br>(10.9) | 81.1<br>(12.2) | 28.1085 | 0.0000 |
| Sample Size | 173 | 173 | 169 | | |

Appendix Table 4. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for equality of group means for measured scale variables between age $5_2$ sockeye salmon sampled from Wood, Igushik, and Nuyakuk Rivers, 1980.

| Variable | Wood | Igushik | Nuyakuk | F value | Probability |
|---|---|---|---|---|---|
| $NC_1$ | 7.8<br>(1.8) | 9.9<br>(1.5) | 8.6<br>(1.3) | 89.7622 | 0.0000 |
| $ID_1$ | 94.3<br>(17.9) | 127.8<br>(18.8) | 111.0<br>(17.6) | 172.2436 | 0.0000 |
| $NC_2$ | 3.4<br>(0.9) | 3.6<br>(0.8) | 3.1<br>(0.8) | 15.9929 | 0.0080 |
| $ID_2$ | 26.2<br>(6.6) | 28.7<br>(6.8) | 24.3<br>(5.7) | 23.9531 | 0.0000 |
| $NC_3$ | 3.7<br>(1.9) | 2.5<br>(1.3) | 2.1<br>(1.2) | 66.6374 | 0.0000 |
| $ID_3$ | 37.9<br>(20.5) | 26.4<br>(13.9) | 22.0<br>(12.6) | 53.9700 | 0.0000 |
| $NC_4$ | 16.4<br>(2.2) | 16.5<br>(1.5) | 16.4<br>(1.6) | 0.5473 | 0.5846 |
| $ID_4$ | 294.4<br>(34.0) | 323.8<br>(29.8) | 307.9<br>(29.7) | 44.4444 | 0.0000 |
| $NC_5$ | 5.8<br>(1.0) | 5.7<br>(0.9) | 5.3<br>(0.8) | 19.3377 | 0.0000 |
| $ID_5$ | 72.9<br>(14.2) | 79.0<br>(13.2) | 72.4<br>(11.2) | 18.6583 | 0.0000 |
| Sample Size | 200 | 201 | 211 | | |

Appendix Table 5. Group means, and standard deviations (in parenthesis), and one-way analysis of variance F test and probability for differences in group means of measured scale variables by sex for Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1978.

| Stock | Variable | Females | Males | F value | Probability |
|---|---|---|---|---|---|
| Wood R. | NC1 | 9.4 (1.9) | 9.1 (1.7) | 1.3457 | 0.2474 |
| | ID1 | 128.6 (23.6) | 125.8 (20.9) | 0.8107 | 0.3690 |
| | NC2 | 4.0 (0.9) | 4.0 (0.9) | 0.2101 | 0.6471 |
| | ID2 | 31.5 (7.2) | 32.4 (7.0) | 0.8547 | 0.3563 |
| | NC3 | 3.5 (1.9) | 3.6 (2.0) | 0.2143 | 0.6439 |
| | ID3 | 36.8 (19.6) | 37.7 (21.1) | 0.1042 | 0.7472 |
| | NC4 | 14.9 (2.5) | 14.9 (2.4) | 0.0098 | 0.9213 |
| | ID4 | 276.9 (39.0) | 270.8 (41.0) | 0.2632 | 0.6085 |
| | NC5 | 6.8 (13.4) | 7.0 (13.5) | 2.3231 | 0.1290 |
| | ID5 | 103.0 (13.4) | 102.2 (13.5) | 0.1844 | 0.6681 |
| | Sample Size | 105 | 98 | | |
| Igushik R. | NC1 | 9.4 (2.3) | 9.7 (2.4) | 0.7534 | 0.3864 |
| | ID1 | 129.8 (29.0) | 132.6 (28.5) | 0.4894 | 0.4850 |
| | NC2 | 3.9 (1.0) | 4.0 (1.0) | 0.0257 | 0.8729 |
| | ID2 | 32.2 (7.3) | 32.8 (7.9) | 0.2431 | 0.6225 |
| | NC3 | 2.9 (1.8) | 2.9 (1.8) | 0.0505 | 0.8225 |
| | ID3 | 33.4 (20.5) | 33.2 (20.1) | 0.0064 | 0.9364 |
| | NC4 | 15.3 (2.5) | 15.2 (2.6) | 0.0911 | 0.7630 |
| | ID4 | 286.2 (44.2) | 287.7 (38.9) | 0.0643 | 0.8001 |
| | NC5 | 6.9 (1.1) | 6.9 (1.3) | 0.0108 | 0.9175 |
| | ID5 | 103.2 (14.4) | 102.9 (15.3) | 0.0179 | 0.8939 |
| | Sample Size | 123 | 88 | | |
| Nuyakuk R. | NC1 | 11.8 (3.2) | 11.9 (3.0) | 0.0815 | 0.7755 |
| | ID1 | 154.5 (37.2) | 155.2 (34.2) | 0.0164 | 0.8981 |
| | NC2 | 3.6 (0.8) | 3.6 (0.8) | 0.5283 | 0.4681 |
| | ID2 | 28.7 (6.3) | 28.6 (5.8) | 0.0010 | 0.9744 |
| | NC3 | 2.6 (2.2) | 2.3 (1.8) | 0.7929 | 0.3742 |
| | ID3 | 30.5 (24.4) | 26.4 (18.3) | 1.5271 | 0.2179 |
| | NC4 | 14.3 (1.9) | 14.4 (2.0) | 0.1246 | 0.7244 |
| | ID4 | 272.4 (33.9) | 272.9 (35.2) | 0.0088 | 0.9254 |
| | NC5 | 6.6 (1.1) | 6.7 (1.0) | 0.9976 | 0.3190 |
| | ID5 | 96.5 (14.2) | 100.0 (13.4) | 2.9471 | 0.0875 |
| | Sample Size | 147 | 69 | | |

Appendix Table 6. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for differences in group means of meaasured scale variables by sex for Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1979.

| Stock | Variable | Females | Males | F value | Probability |
|---|---|---|---|---|---|
| Wood R. | NC1 | 9.2 (1.8) | 8.9 (1.5) | 0.9451 | 0.3324 |
| | ID1 | 117.4 (17.0) | 115.6 (17.7) | 0.4352 | 0.5104 |
| | NC2 | 3.1 (1.0) | 3.7 (1.1) | 12.9845 | 0.0004 |
| | ID2 | 26.7 (9.2) | 30.5 (9.5) | 6.8466 | 0.0097 |
| | NC3 | 4.0 (2.0) | 4.1 (2.3) | 0.0573 | 0.8111 |
| | ID3 | 41.6 (22.2) | 43.3 (24.7) | 0.2010 | 0.6545 |
| | NC4 | 14.6 (2.3) | 14.9 (2.3) | 0.5751 | 0.4493 |
| | ID4 | 281.1 (39.4) | 285.7 (39.8) | 0.5431 | 0.4622 |
| | NC5 | 5.9 (1.3) | 6.1 (1.0) | 0.9585 | 0.3289 |
| | ID5 | 90.2 (16.6) | 92.5 (14.4) | 0.8854 | 0.3481 |
| | Sample Size | 108 | 65 | | |
| Igushik R. | NC1 | 9.4 (1.7) | 8.9 (1.7) | 3.9762 | 0.0477 |
| | ID1 | 121.5 (19.8) | 115.3 (21.1) | 5.2375 | 0.0233 |
| | NC2 | 3.2 (0.7) | 3.3 (0.8) | 1.9611 | 0.1632 |
| | ID2 | 26.3 (6.2) | 27.4 (5.1) | 1.4842 | 0.2248 |
| | NC3 | 3.6 (1.8) | 4.3 (2.2) | 4.7754 | 0.0302 |
| | ID3 | 38.5 (19.6) | 45.4 (23.9) | 4.2698 | 0.0403 |
| | NC4 | 15.3 (2.3) | 15.6 (2.6) | 0.4124 | 0.5216 |
| | ID4 | 303.7 (38.6) | 306.6 (39.0) | 0.2263 | 0.6349 |
| | NC5 | 5.8 (0.8) | 5.8 (0.8) | 0.2849 | 0.5942 |
| | ID5 | 89.7 (11.2) | 89.0 (10.5) | 0.1467 | 0.7022 |
| | Sample Size | 105 | 68 | | |
| Nuyakuk R. | NC1 | 9.9 (1.7) | 10.0 (1.8) | 0.0069 | 0.9339 |
| | ID1 | 131.9 (20.2) | 133.9 (21.2) | 0.3893 | 0.5335 |
| | NC2 | 3.6 (0.9) | 3.4 (10.0) | 1.1083 | 0.2940 |
| | ID2 | 29.1 (7.0) | 27.8 (7.8) | 1.1805 | 0.1805 |
| | NC3 | 2.5 (1.6) | 2.4 (1.4) | 0.2971 | 0.5865 |
| | ID3 | 26.4 (17.6) | 24.6 (15.4) | 0.4557 | 0.5006 |
| | NC4 | 14.5 (1.9) | 15.1 (2.1) | 2.9675 | 0.0868 |
| | ID4 | 288.7 (34.7) | 306.5 (38.3) | 9.5175 | 0.0024 |
| | NC5 | 5.5 (1.0) | 5.4 (0.8) | 0.3669 | 0.5455 |
| | ID5 | 80.6 (12.5) | 82.0 (11.9) | 0.4958 | 0.4823 |
| | Sample Size | 108 | 61 | | |

Appendix Table 7. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for differences in group means of meaasured scale variables by sex for Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1980.

| Stock | Variable | Females | Males | F value | Probability |
|---|---|---|---|---|---|
| Wood R. | NC1 | 7.8 (1.7) | 7.8 (1.8) | 0.0622 | 0.8033 |
| | ID1 | 93.1 (16.7) | 95.9 (19.3) | 1.2317 | 0.2684 |
| | NC2 | 3.4 (0.9) | 3.3 (0.8) | 1.0999 | 0.2956 |
| | ID2 | 26.4 (6.6) | 26.1 (6.7) | 0.0963 | 0.7567 |
| | NC3 | 3.7 (2.0) | 3.8 (1.7) | 0.2097 | 0.6475 |
| | ID3 | 37.4 (22.1) | 38.6 (18.3) | 0.1585 | 0.6909 |
| | NC4 | 16.4 (2.3) | 16.4 (1.9) | 0.0066 | 0.9354 |
| | ID4 | 293.4 (35.2) | 295.7 (32.5) | 0.2326 | 0.6301 |
| | NC5 | 5.8 (1.0) | 5.8 (1.0) | 0.0372 | 0.8472 |
| | ID5 | 79.4 (14.2) | 78.9 (14.1) | 0.0540 | 0.8164 |
| | Sample Size | 113 | 87 | | |
| Igushik R. | NC1 | 9.8 (1.3) | 9.9 (1.8) | 0.5238 | 0.4701 |
| | ID1 | 127.3 (18.7) | 128.5 (18.9) | 0.2151 | 0.6433 |
| | NC2 | 3.6 (0.8) | 3.6 (0.8) | 0.0001 | 0.9915 |
| | ID2 | 28.4 (6.9) | 29.1 (6.5) | 0.4728 | 0.4925 |
| | NC3 | 2.3 (1.2) | 2.7 (1.3) | 4.6826 | 0.0317 |
| | ID3 | 25.0 (13.4) | 28.2 (14.5) | 2.5473 | 0.1121 |
| | NC4 | 16.5 (1.4) | 16.6 (1.6) | 0.0813 | 0.7759 |
| | ID4 | 321.6 (30.5) | 326.9 (28.8) | 1.5575 | .21355 |
| | NC5 | 5.8 (0.9) | 5.7 (0.9) | 0.0304 | 0.8619 |
| | ID5 | 78.7 (13.0) | 79.5 (13.4) | 0.1709 | 0.6798 |
| | Sample Size | 117 | 84 | | |
| Nuyakuk R. | NC1 | 8.7 (1.2) | 8.6 (1.5) | 0.4047 | 0.5254 |
| | ID1 | 111.7 (16.9) | 109.6 (19.1) | 0.6295 | 0.4284 |
| | NC2 | 3.1 (0.8) | 3.2 (0.8) | 1.0971 | 0.2961 |
| | ID2 | 23.9 (5.4) | 25.3 (6.2) | 3.0068 | 0.0844 |
| | NC3 | 2.0 (1.1) | 2.4 (1.3) | 4.4422 | 0.0363 |
| | ID3 | 21.2 (11.9) | 23.9 (13.9) | 2.0396 | 0.1547 |
| | NC4 | 16.5 (1.6) | 16.1 (1.6) | 1.8592 | 0.1742 |
| | ID4 | 309.3 (30.1) | 304.6 (28.7) | 1.1000 | 0.2955 |
| | NC5 | 5.2 (0.8) | 5.4 (0.8) | 0.9929 | 0.3202 |
| | ID5 | 72.5 (11.1) | 72.3 (11.6) | 0.0097 | 0.9216 |
| | Sample Size | 147 | 64 | | |

Appendix Table 8. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for differences in group means of measured scale variables by date of capture for Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1978.

| Stock | Variable | 6/25-6/30 | 7/1-7/2 | 7/3-7/4 | 7/5-7/13 | F value | Probability |
|---|---|---|---|---|---|---|---|
| | | | Dates | | | | |
| Wood R. | NC1 | 9.2 | 9.3 | 9.0 | 9.5 | 0.8439 | 0.4713 |
| | | (2.0) | (1.7) | (1.7) | (1.8) | | |
| | ID1 | 123.6 | 131.0 | 124.2 | 130.2 | 1.5756 | 0.1965 |
| | | (24.3) | (21.3) | (20.0) | (22.9) | | |
| | NC2 | 4.2 | 3.7 | 4.0 | 4.0 | 2.7087 | 0.0463 |
| | | (0.9) | (0.9) | (0.9) | (0.9) | | |
| | ID2 | 34.5 | 30.4 | 31.3 | 31.6 | 3.3992 | 0.0188 |
| | | (7.9) | (6.9) | (7.0) | (6.0) | | |
| | NC3 | 4.1 | 3.1 | 3.8 | 3.2 | 2.8168 | 0.0403 |
| | | (2.3) | (1.5) | (1.9) | (1.9) | | |
| | ID3 | 42.7 | 32.9 | 39.6 | 33.4 | 2.9425 | 0.0342 |
| | | (22.8) | (17.5) | (21.2) | (17.5) | | |
| | NC4 | 14.5 | 15.1 | 14.8 | 15.4 | 1.4498 | 0.2295 |
| | | (2.2) | (2.5) | (2.5) | (2.7) | | |
| | ID4 | 264.0 | 266.4 | 268.8 | 278.1 | 1.2273 | 0.3009 |
| | | (36.7) | (39.9) | (39.8) | (42.9) | | |
| | NC5 | 7.1 | 6.9 | 6.9 | 6.6 | 2.3584 | 0.0729 |
| | | (0.9) | (1.0) | (1.0) | (1.0) | | |
| | ID5 | 104.6 | 98.8 | 106.6 | 100.4 | 3.7643 | 0.0117 |
| | | (14.2) | (14.0) | (13.8) | (10.4) | | |
| | Sample Size | 52 | 50 | 50 | 51 | | |
| | Dates | 6/23-7/2 | 7/3-7/4 | 7/5-7/6 | 7/7-7/16 | | |
| Igushik R. | NC1 | 9.2 | 9.1 | 10.1 | 9.8 | 2.5900 | 0.0539 |
| | | (2.1) | (2.3) | (2.7) | (2.3) | | |
| | ID1 | 126.1 | 125.6 | 137.5 | 136.0 | 2.6265 | 0.0514 |
| | | (26.0) | (28.4) | (30.8) | (28.9) | | |
| | NC2 | 3.9 | 3.9 | 3.9 | 4.1 | 0.5929 | 0.6203 |
| | | (1.1) | (1.0) | (0.9) | (1.0) | | |
| | ID2 | 31.7 | 32.8 | 32.3 | 33.3 | 0.4311 | 0.7309 |
| | | (8.2) | (7.6) | (6.5) | (7.8) | | |
| | NC3 | 3.1 | 3.1 | 2.9 | 2.5 | 1.3019 | 0.2749 |
| | | (2.0) | (1.7) | (2.0) | (1.4) | | |
| | ID3 | 36.0 | 35.2 | 32.4 | 28.9 | 1.2988 | 0.2759 |
| | | (22.4) | (19.4) | (21.2) | (16.7) | | |
| | NC4 | 15.2 | 14.8 | 15.5 | 15.4 | 0.6994 | 0.5534 |
| | | (2.6) | (2.2) | (2.6) | (2.6) | | |
| | ID4 | 283.5 | 280.3 | 293.6 | 290.7 | 1.1140 | 0.3444 |
| | | (42.7) | (38.4) | (41.9) | (44.7) | | |
| | NC5 | 6.8 | 7.3 | 6.8 | 6.8 | 2.1596 | 0.0939 |
| | | (1.1) | (1.2) | (1.3) | (1.2) | | |
| | ID5 | 99.5 | 109.1 | 100.5 | 104.1 | 4.8963 | 0.0026 |
| | | (12.0) | (15.8) | (15.3) | (14.5) | | |
| | Sample Size | 61 | 51 | 52 | 47 | | |
| | Dates | 7/1-7/4 | 7/5-7/6 | 7/7-7/9 | 7/10-7/26 | | |
| Nuyakuk R. | NC1 | 12.1 | 11.1 | 12.3 | 11.7 | 1.3251 | 0.2672 |
| | | (3.0) | (3.6) | (2.8) | (3.6) | | |
| | ID1 | 160.8 | 147.2 | 158.3 | 152.2 | 1.5503 | 0.2026 |
| | | (38.3) | (38.9) | (32.6) | (34.1) | | |
| | NC2 | 3.5 | 3.6 | 3.4 | 3.7 | 1.3535 | 0.2581 |
| | | (0.8) | (0.9) | (0.8) | (0.8) | | |
| | ID2 | 28.6 | 28.7 | 27.4 | 30.0 | 1.6582 | 0.1771 |
| | | (5.3) | (6.0) | (7.1) | (6.0) | | |
| | NC3 | 2.2 | 2.7 | 2.4 | 2.8 | 0.9965 | 0.3954 |
| | | (2.0) | (2.2) | (1.8) | (2.3) | | |
| | ID3 | 25.4 | 31.1 | 27.4 | 33.1 | 1.3217 | 0.2683 |
| | | (21.2) | (24.4) | (18.2) | (25.9) | | |
| | NC4 | 14.2 | 14.5 | 14.3 | 14.3 | 0.2265 | 0.8779 |
| | | (2.0) | (1.9) | (1.8) | (1.9) | | |
| | ID4 | 276.4 | 278.5 | 269.0 | 266.5 | 1.5247 | 0.2091 |
| | | (35.3) | (35.2) | (32.3) | (33.5) | | |
| | NC5 | 6.6 | 6.5 | 6.7 | 6.6 | 0.4319 | 0.7304 |
| | | (1.2) | (1.1) | (1.0) | (1.0) | | |
| | ID5 | 98.9 | 96.9 | 99.6 | 95.0 | 1.2003 | 0.3107 |
| | | (15.3) | (14.4) | (13.4) | (13.0) | | |
| | Sample Size | 56 | 52 | 54 | 54 | | |

Appendix Table 9. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for differences in group means of measured scale variables by date of capture for Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1979.

| Stock | Variable | Dates 6/22-6/25 | 6/26-6/28 | 6/29-7/1 | 7/2-7/10 | F value | Probability |
|---|---|---|---|---|---|---|---|
| Wood R. | NC1 | 9.0 (1.9) | 9.5 (1.6) | 9.0 (1.6) | 9.0 (1.6) | 1.0103 | 0.3896 |
| | ID1 | 118.4 (17.8) | 120.9 (17.6) | 113.0 (17.6) | 114.9 (15.3) | 1.8616 | 0.1380 |
| | NC2 | 4.4 (1.0) | 3.2 (0.8) | 2.9 (0.7) | 2.9 (0.9) | 31.2824 | 0.0000 |
| | ID2 | 38.6 (9.6) | 26.3 (7.1) | 24.1 (5.7) | 24.3 (7.0) | 35.6228 | 0.0000 |
| | NC3 | 3.4 (1.9) | 3.7 (2.1) | 4.2 (2.2) | 4.7 (2.1) | 3.2551 | 0.0231 |
| | ID3 | 35.7 (21.8) | 38.9 (22.9) | 44.0 (22.7) | 49.7 (23.3) | 3.1384 | 0.0269 |
| | NC4 | 14.4 (2.5) | 14.7 (2.2) | 15.2 (2.2) | 14.4 (2.2) | 1.2674 | 0.2873 |
| | ID4 | 276.1 (38.6) | 284.1 (41.7) | 288.8 (39.1) | 282.0 (39.0) | 0.7390 | 0.5302 |
| | NC5 | 6.9 (1.4) | 5.9 (1.1) | 5.5 (1.0) | 5.8 (0.9) | 14.3535 | 0.0000 |
| | ID5 | 105.3 (14.2) | 88.2 (14.0) | 84.2 (13.8) | 87.4 (10.4) | 19.8728 | 0.0000 |
| | Sample Size | 41 | 44 | 43 | 45 | | |
| | Dates | 6/21-6/28 | 6/29-7/1 | 7/2-7/5 | 7/6-7/16 | | |
| Igushik R. | NC1 | 9.7 (1.6) | 9.3 (1.8) | 9.2 (1.5) | 8.4 (1.8) | 4.4215 | 0.0051 |
| | ID1 | 127.6 (18.5) | 119.7 (18.0) | 118.7 (18.7) | 108.0 (22.8) | 17.1787 | 0.0001 |
| | NC2 | 3.2 (0.8) | 3.2 (0.7) | 3.3 (0.7) | 3.2 (0.8) | 0.0605 | 0.9805 |
| | ID2 | 27.7 (5.8) | 27.2 (5.7) | 26.9 (6.1) | 25.0 (5.6) | 1.7151 | 0.1658 |
| | NC3 | 3.7 (1.7) | 3.7 (1.9) | 3.6 (1.9) | 4.6 (2.2) | 2.2833 | 0.0809 |
| | ID3 | 39.1 (18.5) | 38.6 (19.2) | 38.8 (22.6) | 48.8 (24.9) | 2.2723 | 0.0820 |
| | NC4 | 15.1 (2.2) | 15.4 (2.4) | 15.6 (2.6) | 15.6 (2.5) | 0.3681 | 0.7761 |
| | ID4 | 305.9 (38.7) | 298.2 (35.3) | 308.1 (41.5) | 307.3 (39.5) | 0.5937 | 0.6200 |
| | NC5 | 5.8 (0.7) | 6.1 (0.8) | 5.9 (0.8) | 5.4 (0.8) | 4.8845 | 0.0028 |
| | ID5 | 89.2 (10.7) | 90.0 (9.5) | 91.2 (11.3) | 87.2 (11.9) | 0.9998 | 0.3944 |
| | Sample Size | 44 | 44 | 44 | 41 | | |
| | Dates | 7/2-7/4 | 7/5-7/7 | 7/8-7/9 | 7/10-7/13 | | |
| Nuyakuk R. | NC1 | 10.2 (1.6) | 9.5 (1.7) | 9.5 (1.9) | 10.3 (1.5) | 2.5116 | 0.0605 |
| | ID1 | 135.9 (19.5) | 127.7 (20.5) | 128.4 (23.2) | 136.1 (18.5) | 2.0672 | 0.1066 |
| | NC2 | 3.6 (0.9) | 3.4 (1.0) | 3.5 (1.0) | 3.6 (0.9) | 0.6409 | 0.5897 |
| | ID2 | 29.3 (6.9) | 27.5 (7.2) | 28.1 (7.0) | 29.3 (8.4) | 0.6208 | 0.6025 |
| | NC3 | 2.3 (1.5) | 2.4 (1.2) | 2.8 (1.7) | 2.4 (1.7) | 0.9319 | 0.4267 |
| | ID3 | 23.9 (16.4) | 25.1 (13.9) | 29.9 (18.9) | 25.8 (18.1) | 0.9746 | 0.4062 |
| | NC4 | 14.5 (1.9) | 15.1 (2.0) | 14.9 (2.4) | 14.4 (1.7) | 1.0561 | 0.3694 |
| | ID4 | 290.3 (33.4) | 295.9 (34.0) | 299.3 (45.8) | 299.2 (36.8) | 0.6512 | 0.5833 |
| | NC5 | 5.6 (0.9) | 5.1 (0.6) | 5.5 (1.0) | 5.4 (1.1) | 2.0671 | 0.1066 |
| | ID5 | 80.4 (13.0) | 78.8 (10.4) | 83.4 (12.5) | 82.5 (12.3) | 1.0820 | 0.5837 |
| | Sample Size | 65 | 36 | 35 | 33 | | |

Appendix Table 10. Group means, standard deviations (in parenthesis), and one-way analysis of variance F test and probability for differences in group means of measured scale variables by date of capture for Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon, 1980.

| Stock | Variable | Dates 6/29-7/2 | 7/3-7/4 | 7/5-7/8 | 7/9-7/17 | F value | Probability |
|---|---|---|---|---|---|---|---|
| Wood R. | NC1 | 8.2 (1.9) | 7.6 (1.8) | 7.8 (1.9) | 7.6 (1.4) | 1.2851 | 0.2807 |
| | ID1 | 99.7 (19.1) | 92.3 (17.7) | 93.9 (19.9) | 90.9 (13.3) | 2.5310 | 0.0584 |
| | NC2 | 3.5 (0.8) | 3.7 (0.8) | 3.2 (1.0) | 3.2 (0.8) | 3.8710 | 0.0102 |
| | ID2 | 27.0 (5.9) | 29.1 (6.8) | 25.1 (7.2) | 36.6 (5.3) | 6.9269 | 0.0002 |
| | NC3 | 4.1 (2.1) | 3.6 (1.7) | 3.4 (1.7) | 3.7 (1.9) | 1.1193 | 0.3113 |
| | ID3 | 42.1 (23.9) | 36.6 (19.2) | 35.0 (16.6) | 37.5 (20.8) | 1.1165 | 0.3435 |
| | NC4 | 15.8 (2.0) | 16.0 (2.0) | 16.9 (2.3) | 17.0 (2.2) | 3.8468 | 0.0105 |
| | ID4 | 284.8 (35.5) | 292.0 (29.8) | 298.6 (37.4) | 303.3 (31.2) | 3.0007 | 0.0317 |
| | NC5 | 6.0 (1.0) | 6.0 (1.0) | 5.6 (1.1) | 5.6 (1.1) | 2.3371 | 0.0749 |
| | ID5 | 80.8 (12.9) | 84.9 (12.0) | 78.8 (16.0) | 75.8 (13.7) | 5.6804 | 0.0009 |
| | Sample Size | 54 | 50 | 45 | 51 | | |
| | Dates | 6/23-7/6 | 7/7-7/9 | 7/10-7/13 | 7/14-7/21 | | |
| Igushik R. | NC1 | 9.8 (1.4) | 10.1 (1.8) | 9.7 (1.6) | 9.7 (1.3) | 0.1826 | 0.4883 |
| | ID1 | 126.6 (17.7) | 130.7 (21.3) | 126.6 (17.1) | 127.4 (18.9) | 0.5529 | 0.6468 |
| | NC2 | 3.6 (0.8) | 3.5 (0.6) | 3.6 (0.8) | 3.6 (0.9) | 0.4558 | 0.7135 |
| | ID2 | 28.7 (7.3) | 27.7 (4.7) | 29.2 (6.6) | 29.1 (8.1) | 0.5128 | 0.6739 |
| | NC3 | 2.4 (1.3) | 2.6 (1.5) | 2.5 (1.2) | 2.5 (1.1) | 0.1647 | 0.9201 |
| | ID3 | 26.1 (14.8) | 27.5 (16.6) | 25.9 (12.6) | 25.9 (11.6) | 0.1462 | 0.9320 |
| | NC4 | 16.4 (1.2) | 16.6 (1.8) | 16.6 (1.5) | 16.6 (1.6) | 0.2537 | 0.8586 |
| | ID4 | 317.2 (27.7) | 319.2 (32.3) | 327.9 (30.2) | 331.0 (27.6) | 2.5801 | 0.0548 |
| | NC5 | 6.0 (0.9) | 6.0 (0.7) | 5.4 (0.8) | 5.6 (1.0) | 5.6831 | 0.0009 |
| | ID5 | 83.3 (12.6) | 80.7 (12.4) | 72.8 (11.9) | 79.1 (13.8) | 6.1660 | 0.0005 |
| | Sample Size | 51 | 50 | 49 | 51 | | |
| | Dates | 7/6-7/9 | 7/10-7/13 | 7/14-7/16 | 7/17-7/24 | | |
| Nuyakuk R. | NC1 | 8.6 (1.3) | 8.6 (1.3) | 9.0 (1.4) | 8.3 (1.2) | 1.9522 | 0.1223 |
| | ID1 | 113.2 (18.2) | 112.9 (17.5) | 112.7 (16.9) | 105.2 (16.9) | 2.5966 | 0.0535 |
| | NC2 | 3.1 (0.9) | 3.1 (0.7) | 3.1 (0.7) | 3.3 (0.8) | 1.1177 | 0.3429 |
| | ID2 | 24.5 (5.9) | 23.9 (5.3) | 23.7 (5.0) | 25.2 (6.4) | 0.6796 | 0.5654 |
| | NC3 | 2.3 (1.2) | 2.1 (1.0) | 1.8 (1.1) | 2.2 (1.3) | 2.0050 | 0.1144 |
| | ID3 | 25.5 (12.9) | 21.1 (11.4) | 18.7 (11.9) | 22.6 (13.4) | 2.7725 | 0.0425 |
| | NC4 | 16.1 (1.8) | 16.0 (1.4) | 17.0 (1.8) | 16.4 (1.4) | 4.5428 | 0.0042 |
| | ID4 | 304.4 (32.6) | 300.4 (26.0) | 318.4 (31.5) | 308.6 (26.0) | 3.6860 | 0.0129 |
| | NC5 | 5.2 (0.8) | 5.3 (0.7) | 5.4 (1.0) | 5.3 (0.8) | 0.7558 | 0.5201 |
| | ID5 | 71.5 (11.7) | 72.9 (9.9) | 72.4 (12.0) | 72.8 (11.3) | 0.1823 | 0.9083 |
| | Sample Size | 54 | 53 | 52 | 52 | | |

Appendix Table 11. Group means, standard deviations (in parenthesis), and one-way analysis of variance F-test and probability for equality of group means for measured scale variables between age $5_2$ sockeye salmon sampled from Ualik Lake, Kathleen River, and Amanka Lake, 1980.

| Variable | Ualik | Kathleen | Amanka | F value | Probability |
|---|---|---|---|---|---|
| $NC_1$ | 10.0<br>(1.3) | 9.9<br>(1.5) | 9.3<br>(1.8) | 3.3600 | 0.0369 |
| $ID_1$ | 131.7<br>(15.7) | 127.9<br>(20.0) | 115.5<br>(19.1) | 13.2493 | 0.0000 |
| $NC_2$ | 3.6<br>(0.8) | 3.2<br>(0.7) | 3.1<br>(0.7) | 7.0282 | 0.0011 |
| $ID_2$ | 28.6<br>(6.2) | 26.2<br>(5.8) | 26.4<br>(5.3) | 3.4152 | 0.0350 |
| $NC_3$ | 2.2<br>(1.0) | 2.6<br>(1.5) | 2.7<br>(1.9) | 2.2637 | 0.1069 |
| $ID_3$ | 22.9<br>(10.8) | 25.4<br>(15.9) | 29.3<br>(18.6) | 2.7009 | 0.0698 |
| $NC_4$ | 17.0<br>(1.6) | 17.4<br>(1.9) | 16.9<br>(2.0) | 1.3928 | 0.2510 |
| $ID_4$ | 325.4<br>(26.6) | 323.5<br>(36.0) | 321.2<br>(36.3) | 0.2450 | 0.7829 |
| $NC_5$ | 5.0<br>(1.1) | 5.2<br>(0.9) | 5.0<br>(0.8) | 0.7605 | 0.4689 |
| $ID_5$ | 66.9<br>(13.4) | 67.4<br>(11.2) | 69.5<br>(10.4) | 0.9004 | 0.4082 |
| Sample Size | 61 | 63 | 63 | | |

Appendix Table 12. Linear discriminant function test classification matrix classifying Ualik Lake, Kathleen River, and Amanka Lake[1] age $5_2$ sockeye salmon with a three-way Wood, Igushik, Nuyakuk River model, 1980.

| Actual Group of Origin | Sample Size | Classified Group of Origin (Variables selected = $ID_1, NC_3, NC_4$, Length, $ID_5, ID_2$) | | |
|---|---|---|---|---|
| | | Igushik | Wood | Nuyakuk |
| Ualik | 61 | .852 | .033 | .115 |
| Kathleen | 63 | .778 | .111 | .111 |
| Amanka | 63 | .556 | .175 | .270 |
| Wood | 100 | .070 | .710 | .220 |
| Nuyakuk | 105 | .267 | .124 | .609 |
| | | Average correctly classified = .701 | | |

[1] Ualik Lake, Kathleen River, and Amanka Lake are part of the Igushik Lake system. Ualik Lake flows into Amanka Lake via the Kathleen River.

Appendix Table 13. Comparisons of means and standard deviations for 1978 Wood, Igushik, and Nuyakuk River age $5_2$ sockeye salmon scale variables read by three different readers[1].

| System | Reader Number | Sample Size | $ID_1$ | | $ID_2$ | | $ID_3$ | | $ID_4$ | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | $\bar{X}$ | S | $\bar{X}$ | S | $\bar{X}$ | S | $\bar{X}$ | S |
| Wood R. | 1 | 100 | 82.6 | 14.2 | 18.7 | 4.6 | 23.4 | 14.8 | 170.1 | 28.7 |
| | 2 | 98 | 76.4 | 10.5 | 18.5 | 5.4 | 19.2 | 12.2 | 167.1 | 25.6 |
| Igushik R. | 2 | 54 | 82.1 | 14.3 | 23.0 | 6.2 | 12.1 | 15.7 | 187.1 | 21.8 |
| | 3 | 51 | 94.3 | 20.5 | 17.3 | 4.8 | 14.6 | 13.8 | 176.6 | 24.5 |
| Nuyakuk R. | 1 | 104 | 105.7 | 22.7 | 19.1 | 4.0 | 21.6 | 10.9 | 168.6 | 27.0 |
| | 3 | 112 | 102.5 | 24.7 | 18.2 | 6.0 | 13.5 | 7.4 | 176.9 | 25.3 |

[1] Scales were magnified 100X and measurements recorded using a linear digitizer and encoder manufactured by Glenayre Electronics Ltd., refer to Krasnowski and Bethe (1978) for description of equipment and procedure.