CRI1
red fox
Kodiak

Outer Continental Shelf Environmental Assessment Program

Final Reports of Principal Investigators

Volume 63 August 1989

U.S. DEPARTMENT OF COMMERCE
National Oceanic and Atmospheric Administration
National Ocean Service
Office of Oceanography and Marine Assessment
Ocean Assessments Division
Alaska Office

U.S. DEPARTMENT OF THE INTERIOR
Minerals Management Service
Alaska OCS Region
OCS Study, MMS 89-0071

"Outer Continental Shelf Environmental Assessment Program Final Reports of Principal Investigators" ("OCSEAP Final Reports") continues the series entitled "Environmental Assessment of the Alaskan Continental Shelf Final Reports of Principal Investigators."

It is suggested that reports in this volume be cited as follows:

Craig, P. C., and P. Skvorc. 1982. Fish resources of the Chukchi Sea: status of existing information and field program design. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 63 (1989): 1–62.

Everett, R. J., and R. L. Wilmot. 1987. Population genetic structure of Arctic char (*Salvelinus alpinus*) from rivers of the North Slope of Alaska. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 63 (1989): 63–121.

Martin, D. J., C. K. Whitmus, L. E. Hachmeister, E. C. Volk, and S. L. Schroder. 1987. Distribution and seasonal abundance of juvenile salmon and other fishes in the Yukon Delta. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 63 (1989): 123–277.

McGurk, M. D. 1989. Early life history of Pacific herring in Auke Bay, Alaska: relationships of growth and suvival to environmental conditions. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 63 (1989): 279–421.

Rice, S. D., M. M. Babcock, C. C. Brodersen, M. G. Carls, J. A. Gharrett, S. Korn, A. Moles, and J. W. Short. 1986. Lethal and sublethal effects of the water-soluble fraction of Cook Inlet crude oil on Pacific herring (*Clupea harengus pallasi*) reproduction. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 63 (1989): 423–490.

Schmidt, D. R., R. O. McMillan, and B. J. Gallaway. 1983. Nearshore fish surveys in the western Beaufort Sea: Harrison Bay to Elson Lagoon. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 63 (1989): 491–552.

Wilmot, R. L., R. J. Everett, and W. A. Gellman. 1989. Genetic stock identification of sockeye and chum salmon from Bristol Bay, Alaska. U.S. Dep. Commer., NOAA, OCSEAP Final Rep. 63 (1989): 553–599.

OCSEAP Final Reports are published by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Ocean Service, Ocean Assessments Division, Alaska Office, Anchorage, and primarily funded by the Minerals Management Service, U.S. Department of the Interior, through interagency agreement.

Requests for receipt of OCSEAP Final Reports
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Anchorage, Alaska

The facts, conclusions, and issues appearing in these reports are based on research results of the Outer Continental Shelf Environmental Assessment Program (OCSEAP), which is managed by the National Oceanic and Atmospheric Administration, U.S. Department of Commerce, and funded (wholly or in part) by the Minerals Management Service, U.S. Department of the Interior, through an Interagency Agreement.

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Outer Continental Shelf Environmental Assessment Program

Final Reports of Principal Investigators

VOLUME 63 AUGUST 1989

CONTENTS

FISH RESOURCES OF THE CHUKCHI SEA: STATUS OF EXISTING INFORMATION AND FIELD PROGRAM DESIGN

by

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Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 618

May 1982

ACKNOWLEDGMENTS

We wish to thank the people who have helped our project. Dave Norton and Benny Gallaway provided administrative support and direction. Aaron Sekerak, Bill Griffiths, Nell Stallard and Jill Peterson provided editorial assistance and helped with report production. The individuals listed below provided fisheries information for the study area.

University of Alaska

Howard Feder, Richard Nelson

Alaska Department of Fish and Game

Terry Bendock, Ken Alt, Lloyd Lowry, Sverre Pedersen, Glen Seaman, Larry Moulton, Chris Bowden, Lynn Swartz

National Marine Fisheries Service

Robert Wolotira, Robert Otto, Rick MacIntosh

North Slope Borough

Lester Suvlu, Shehla Anjum, Ray Dronenberg

LGL Alaska

Dave Roseneau

Barrow

Edward Hopson, Othniel Oomituk, Tom Albert, Eugene Brower, Jr.

Wainwright

Jacob Kagak, Billy Patakok, Jim Allen Aveoganna, Frank Bester, Waldo Bodfish, Simon Simpson, Rossman Peetook, Peter Panik, Roy Tharp

Point Lay

Amos Agnassagga, Donald Neakok, Willie Tuknook

Point Hope

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ABSTRACT

Existing data sources describing fish resources in the Chukchi Sea are reviewed and annotated. The purpose of this review is to evaluate (rather than summarize) the status of available fisheries data in terms of the kinds of information needed to assess environmental impacts. Although a moderate amount of fisheries research has been conducted in southern regions of the Chukchi Sea, few data are available for northern regions, particularly the 'Barrow Arch Sale No. 85' oil and gas lease sale area. While it is tempting to draw upon the relatively greater data bases available for coastal regions adjacent to the 'Sale No. 85' area, there are reasons to suspect that such biological extrapolation may not be valid. These include differences in oceanography, fish populations and presumed fish use of coastal habitats. Several testable hypotheses regarding fish use of the 'Sale No. 85' area are discussed and a field research plan is formulated.

TABLE OF CONTENTS

INTRODUCTION

The forthcoming oil and gas lease sale in the northeast Chukchi Sea (Barrow Arch Sale No. 85) has prompted a review of the fisheries information currently available for this region. In recent overviews of biological resources of the northeastern Chukchi Sea, Moulton and Bowden (1981) and Morris (1981) found that marine fishes have been the subject of only a few studies, and anadromous fish are even more poorly known. Both of these reports list a variety of fisheries and habitat data gaps for this region. The present report examines the status of available literature in detail and formulates a research program to address data deficiencies. This report is not intended to serve as a resource document describing the environmental setting for Chukchi fish resources, since this would be a duplication of the existing reviews.

The specific objectives of the present study are to:

1. compile, evaluate and annotate a bibliography and analyze the state of knowledge of nearshore fish resources of the Chukchi Sea, particularly in the 'Sale No. 85' region,
2. evaluate the usefulness of fisheries data obtained in conjunction with subsistence fisheries, and
3. design a preliminary interdisciplinary research program to investigate the composition, movements and trophic relationships of nearshore anadromous and marine forage fishes.

The area covered by this study includes the Chukchi Sea with emphasis on the Alaskan coastal zone between Point Hope and Barrow (Fig. 1). In addition, Alaskan streams which flow into the Chukchi Sea have been included since they are used by anadromous fishes, and some streams play an important role in local fisheries.

Background Information

Although fisheries data are limited for the Chukchi Sea in general, and the lease sale area in particular, the available information has been recently summarized by Morris (1981), Moulton and Bowden (1981) and Bowden and Moulton (1981). The following brief introduction to the fish resources of the northeastern Chukchi Sea is from Morris (1981).

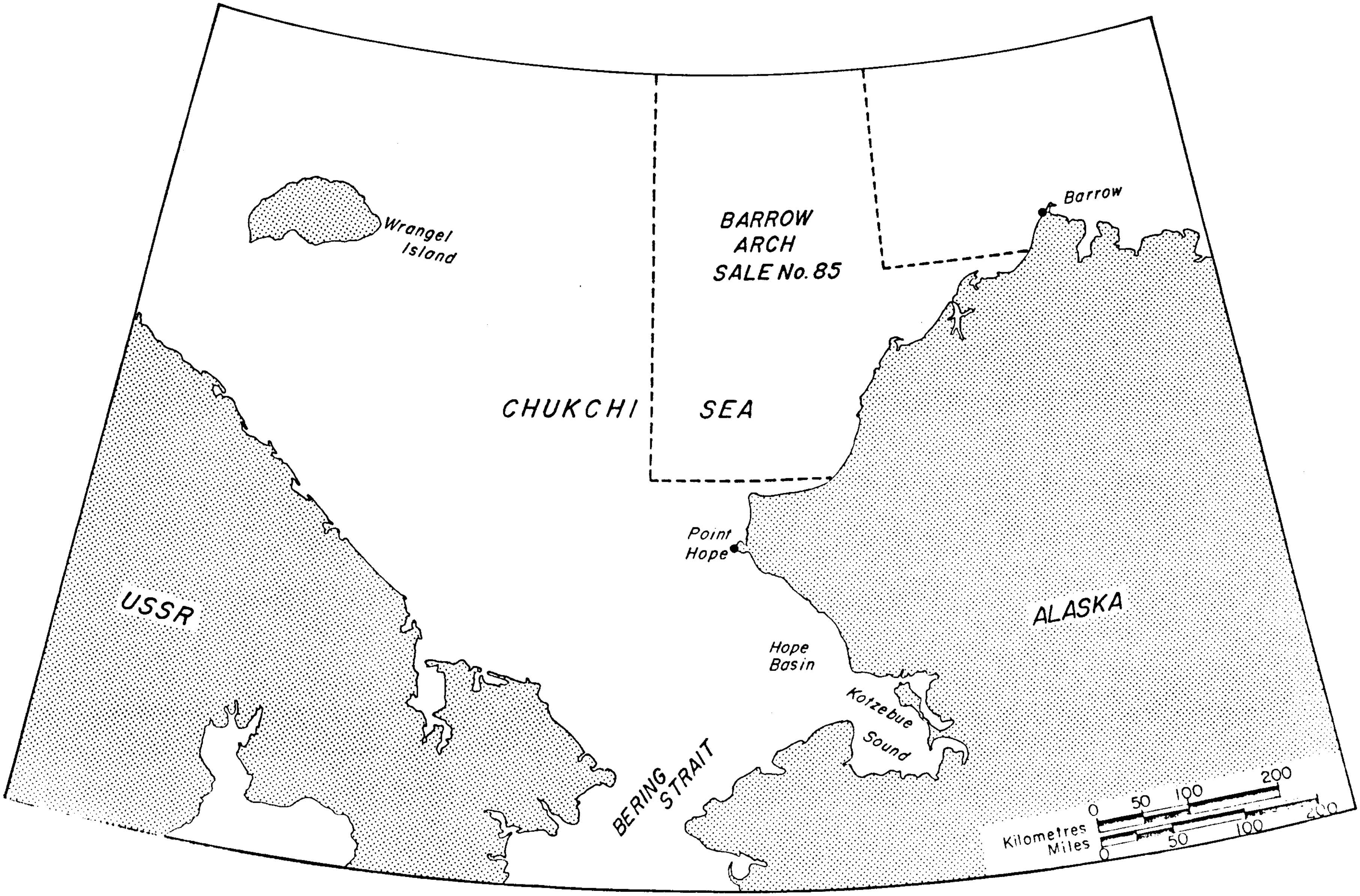

Figure 1. Location of the 'Barrow Arch Sale No. 85' area in relation to the primary study area between Barrow and Point Hope.

In terms of both species diversity and abundance, the fish fauna of the Chukchi Sea is sparse compared to that in the Bering Sea but greater than that in the Beaufort Sea. Based on limited sampling, the species composition in the Chukchi Sea consists of 41 marine species and 13 anadromous species. Abundant marine species are arctic cod, starry flounder, Pacific halibut, saffron cod, Pacific herring, capelin and sculpins. The majority of the marine fish fauna are demersal as adults; relatively few marine species are pelagic (arctic cod, Pacific herring, smelt, capelin and sand lance). Many of the marine fish in the Chukchi are believed to maintain their populations by recruitment of eggs and larvae transported north from the Bering Sea (Pruter and Alverson 1962). Fish that probably maintain their populations by resident breeding stocks include arctic and saffron cod, sand lance, capelin and some flounders (Walters 1955). Marine fishes are important prey of marine mammals and seabirds along the Chukchi coast.

Important anadromous species include pink and chum salmon, arctic char, ciscoes, whitefishes and smelt. Small runs of salmon occur in the larger rivers along the northeast coast: Kugrua, Utukok, Kokolik, Kukpowruk, and Pitmegea rivers. Sockeye and king salmon are also caught in coastal waters but they reach their northern spawning limit at Cape Lisburne. Larger runs of salmon occur in rivers along the southeast coast, especially near Kotzebue. There are no commercial fisheries for salmon north of Kotzebue Sound. Available data indicate that population densities of commercially valuable fish resources in the northeastern Chukchi Sea are low, but subsistence fishing, especially for salmon, whitefish and smelt, is important to some residents of villages along the coastline.

METHODS

It was recognized at the outset of this study that few fisheries studies had been conducted in the northeastern Chukchi Sea, and the data base for the 'Sale No. 85' region would likely be limited. Thus, our search for information was broadened to include the entire Chukchi Sea. Most information was obtained through a standard literature search as described below. In addition, we conducted interviews with agency personnel and subsistence users in the study area to insure that potential data sources were not overlooked.

Literature Search

Efforts were made to collect all pertinent information, including published reports, unpublished government file data and subsistence information. Foreign sources (Russian and Japanese) were also reviewed. Initial efforts to locate information began at the University of Alaska, Fairbanks, with a computer search of three data files maintained by Dialog Information Services, Inc. These were:

1. aquatic sciences and fisheries abstracts (1978, the starting date, to November 1981),
2. BIOSIS previews (1969 to November 1981), and
3. aquaculture (1970 to November 1981).

Russian translations of the key words used in these searches were included.

To insure coverage of unpublished information and reports with limited circulation, libraries at the North Slope Borough (Barrow), University of Alaska (Fairbanks), Arctic Project Office NOAA/OCSEAP (Fairbanks), Arctic Environmental Information and Data Center (Anchorage), University of Washington (Seattle), and National Marine Fisheries Service (Seattle) were searched.

The individuals contacted during the course of this study are listed in the Acknowledgments.

All sources of data gathered during this study were evaluated and pertinent information annotated and included in Appendix 1. We wish to emphasize that only information describing Chukchi fishes was annotated. Pertinent reports that were not obtained in time to be annotated are also listed in Appendix 1.

Subsistence Survey

Because information about subsistence fishing can often be obtained only by discussions with the fishermen themselves, we visited the coastal villages of Point Hope, Point Lay, Wainwright and Barrow during 19-29 March 1982. A primary objective was to gain insight about winter fish distributions through location and timing of the subsistence fishery and to document the extent of winter fishing. Where possible, fish samples were purchased to confirm species identification, and retained for future life history analyses.

RESULTS

The following material examines the status of available fisheries information. This includes an identification of data sources and an evaluation of the scope of the available data base which was annotated in Appendix 1. Available information was evaluated in relation to four basic questions.

1. To what extent does the total data base provide geographical coverage of the study area?
2. Have fish populations and their habitat uses been examined over an annual cycle?
3. Is the biology of important fish species reasonably well known?
4. Are subsistence fisheries adequately documented?

Status of Information

Data Sources

Research funded by the Outer Continental Shelf Environmental Assessment Program (OCSEAP) has provided the majority of information for the eastern Chukchi Sea (Barton 1977; Spring and Roseneau 1977, 1978; Feder and Jewett 1978; Wolotira *et al.* 1979; Jewett 1981). However, while it is true that these reports are a substantial source of information, there are few studies whose primary purpose was collecting fishery data in the area from Point Hope to Point Barrow. Many of the above reports provide fishery data which were gathered incidentally or in conjunction with studies of marine mammals, birds or invertebrates. Barton (1977) and Wolotira *et al.* (1979) describe fisheries investigations south of the area of interest.

Fisheries libraries at the University of Washington (Seattle) and National Marine Fisheries Service (Seattle) are outstanding sources of information, but they did not contain any additional information on the Chukchi Sea in general or the area covered by the 'Barrow Arch Sale No. 85' than was available from the University of Alaska library.

The Alaska Department of Fish and Game (ADF&G) has performed many studies in the Chukchi Sea, most of which deal with commercially valuable species in the area from Bering Strait to Point Hope (Geiger 1966; Winslow 1969; Lebida 1970; Hurd 1971; Yanagawa 1971; Alt 1971, 1973, 1979; Bendock

1979; Bendock and Burr 1980). Results of these studies are obtainable from ADF&G offices. These reports are often presented as annual progress reports of field work.

An important objective of the computer literature search was to locate Soviet and Japanese literature. It had been suggested that a substantial amount of information about fishes of the Chukchi Sea was available from these sources. However, it was found that Soviet literature pertaining to the study area is not abundant and what does exist is frequently 25-50 years old. Soviet literature is further limited because of its generalities. For example, older papers frequently discuss fish life histories using common non-specific names such as "cod" (which may be an artifact of translation from the Russian to English language) so that the particular species being referred to is not known (e.g., Moiseev 1953)*. The main value of the Russian literature is that it provides comparisons of life-history information for species common to both sides of the Chukchi Sea (e.g., Andriyashev 1954); for the most part, these reports are not included in Appendix 1. Pertinent Japanese information also appears to be limited. Only two reports describing cruises of Japanese research vessels in the Chukchi Sea were identified but not received in time for inclusion in this report (FFHU 1967, 1968).

Geographic Coverage

An initial view of geographic locations where studies have been conducted suggests a rather broad coverage for the eastern Chukchi Sea (Fig. 2). However, the impression is deceptive because of the limited fisheries content of many studies, particularly those in the region of the 'Barrow Arch Sale No. 85'. Without question, the region south of Point Hope has received the most study. A summary of the regional data coverage is as follows:

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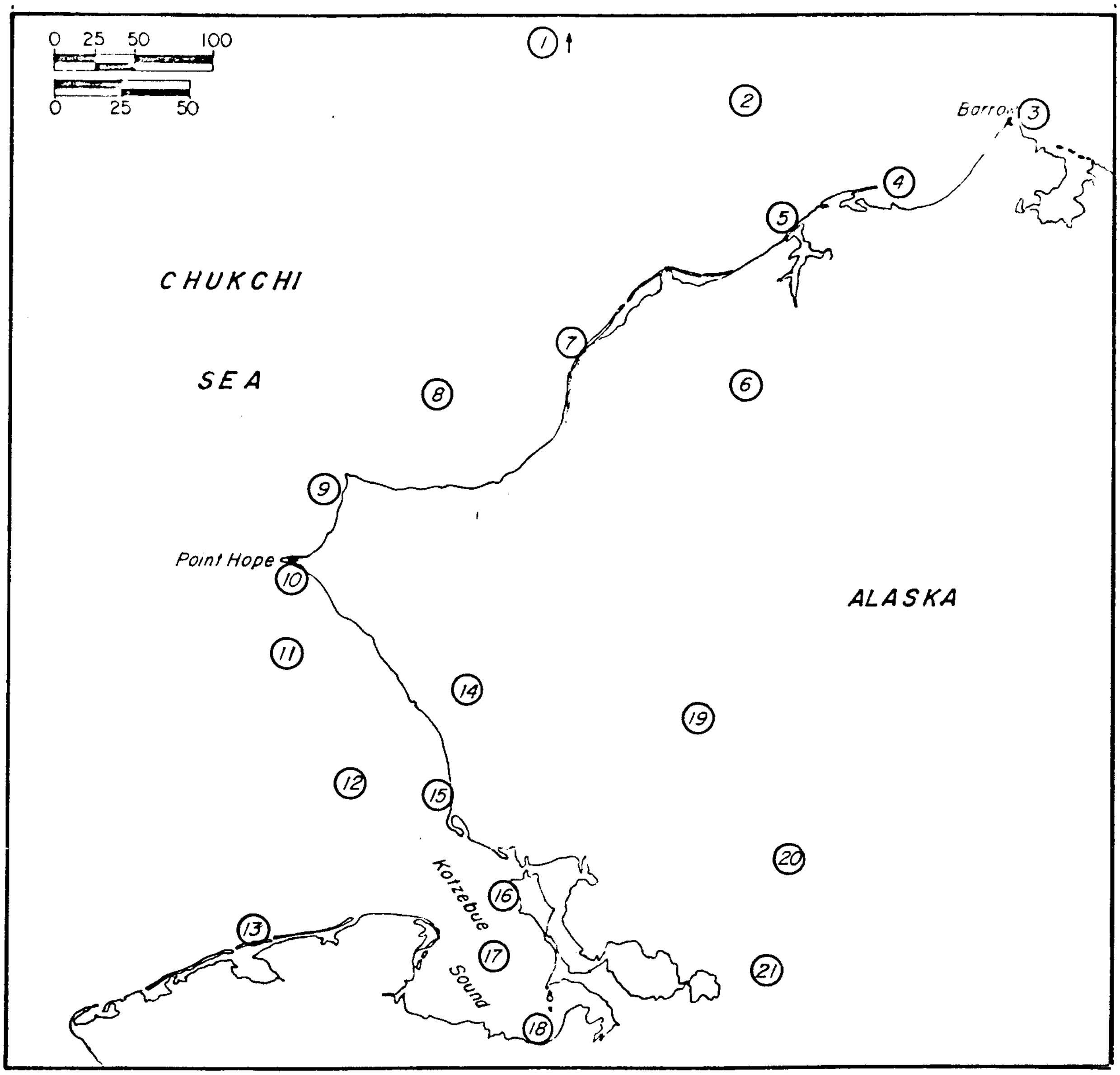
* Moiseev, P. 1953. Cod and flounders of far eastern waters. Fish. Res. Board Can., Translation Ser. No. 119.



1 Walters 1961 (winter fish 400 km NW Barrow)
2 Frost et al. 1978; Frost & Lowry 1981; Lowry & Frost 1981; Frost 1981 (offshore cod)
3 Murdoch 1884, 1885; MacGinitie 1955; Willmovsky 1956; Pedersen et al. 1979; Skvorc 1982 (subsistence general)
Cohen 1954; Wohlschlag 1956 (whitefish ecol.)
McPhail 1966 (cisco taxonomy)
4 Mohr et al. 1957 (kelp bed fishes)
5 Ivie & Schneider 1979 (subsistence)
Craig & Schmidt 1982 (survey, subsistence)
6 Bendock 1979; Hablett 1979 (stream & lake survey)
Bendock & Burr 1980
7 Schneider & Bennett 1979 (subsistence
Craig & Schmidt 1982 (survey, subsistence)
8 Quast 1972, 1974 (offshore survey)
9 Swartz 1966; Springer & Roseneau 1978, 1979; Springer et al. 1982 (seabird diets)
10 Pedersen 1979; Skvorc 1982 (subsistence)
Lowry et al. 1980 (seal diets)
Seaman & Burns 1980 (belukha diets)
11 Pruter & Alverson 1962 (flounder ecology)
Alverson & Willmovsky 1966 (marine fish)
12 Pereyra et al. 1977; Wolotira et al. 1979 (marine fish)
Feder & Jewett 1978; Jewett & Feder 1980 (flounder ecology)
13 Raleigh 1958; Mattson 1962 (salmon)
14 Saario & Kessel 1966 (subsistence)
Winslow 1969; Roguski & Winslow 1970; Alt 1978 (salmon)
15 Smith et al. 1966 (salmon)
16 Craig & Haldorson 1981 (saffron cod, subsis.)
Geiger 1966 (salmon)
17 Lebida 1970; Hurd 1971; Yanagawa 1971; Barton 1977 (salmon, whitefish)
18 Cunningham 1976 (salmon)
19 AEIDC 1975a (inventory)
20 Alt 1971, 1973, 1979 (whitefish, subsistence)
21 AEIDC 1975b (inventory)

Figure 2. Approximate locations of fisheries-related studies conducted in the eastern Chukchi Sea.

		Relative fisheries coverage	
Zone	Fish species	South of Pt. Hope	North of Pt. Hope
Offshore	marine	high	low
Coastal	anadromous, marine	high	low
Inland	anadromous	moderate	low

Salmon and offshore fishes south of Point Hope in Kotzebue Sound have been the subject of several sizable research programs: Project Chariot near Cape Thompson (Pruter and Alverson 1962; Alverson and Wilmovsky 1966; Smith *et al.* 1966), ADF&G (Lebida 1970; Hurd 1971; Yanagawa 1971; Alt 1971, 1973, 1979; Cunningham 1976) and OCSEAP (Barton 1977; Pereyra *et al.* 1977; Feder and Jewett 1978; Springer and Roseneau 1978, 1979; Wolotira *et al.* 1979; Jewett and Feder 1980; Springer *et al.* 1982). Additional information has been gathered by USF&W (Raleigh 1957; Mattson 1962) and AEIDC (1975a, b). These studies provide considerable background information for both offshore and coastal fish populations and, because of interest in the commercial salmon fisheries, the major rivers have been surveyed from Cape Prince of Wales to Point Hope.

Fisheries data north of Point Hope are sparse. The data base for offshore waters is limited to trawl surveys in Ledyard Bay (Alverson and Wilmovsky 1966; Quast 1972, 1974) and near Barrow (Frost *et al.* 1978). Coastal information consists of species caught at Wainwright and Point Lay (Craig and Schmidt 1982) and in a kelp bed at Peard Bay (Mohr 1957). Similarly, information on anadromous fishes in rivers flowing into the northern Chukchi Sea is limited to brief surveys (Hablett 1979; Bendock 1979; Bendock and Burr 1980). Incidental fisheries data are available for the Barrow region (Murdoch 1884, 1885; Cohen 1954; MacGinitie 1955; Wohlschlag 1956; McPhail 1966) and an under-ice location 400 km northwest of Barrow (Walters 1961). Additional information can be derived from papers describing subsistence fishing patterns at coastal villages (Wilmovsky 1956; Ivie and Schneider 1979; Schneider and Bennett 1979; Pedersen 1979; Pedersen *et al.* 1979) and the feeding habits of seabirds at Cape Lisburne (Schwartz 1966; Springer and Roseneau 1978, 1979; Springer *et al.* 1982).

Seasonal Coverage

Virtually all fisheries data available for the Chukchi Sea have been gathered during the open-water season. The exceptions are winter data collected in 1959-1960 at a floating ice station located 400 km northwest of Barrow (Walters 1961) and a pot pourri of information about subsistence fishing, including some winter information (Murdoch 1884, 1885; Wilimovsky 1956; Saario and Kessel 1966; Ivie and Schneider 1979; Schneider and Bennett 1979; Craig and Haldorson 1981; Craig and Schmidt 1982).

Biological Information

Because of the greater sampling effort in the southeast Chukchi Sea, there is a useful body of information describing the fish fauna of this region. Studies in offshore waters (e.g., Alverson and Wilimovsky 1966; Wolotira *et al.* 1979) and an interest in salmon and whitefish resources in Kotzebue Sound have provided some basic information regarding species composition, distribution, abundance and life history characteristics.

In contrast, the northeast region of the Chukchi Sea has received relatively little study and, consequently, a potential understanding of fish communities in this area is largely based on extrapolation of data gathered elsewhere, principally from Kotzebue Sound, Beaufort Sea and Russian arctic waters (e.g., Andriyashev 1954).

The status of biological information for anadromous and marine fishes specifically in the 'Barrow Arch Sale No. 85' region has recently been reviewed by Morris (1981). We concur with his evaluation of the existing data base which follows in summary form (not a direct quotation):

1. Anadromous Fish. Knowledge of the anadromous fish resource is poor. Among the 13 anadromous species reported in these waters are arctic char, whitefish, ciscoes and salmon. The coastal distribution and abundance of these species between Point Hope and Barrow is largely undefined, and little is known of the location of their spawning areas in rivers along the northeast Chukchi coast.
2. Marine Fish. The marine fishes of the northeastern Chukchi Sea have received little attention in the past. From data provided by limited trawl surveys, the number of marine fishes reported for the Chukchi Sea is 41 species, but very little is known about the life history, population dynamics, or ecological relationships of most of these species. Even information about the relative abundance of marine fishes is derived mainly from south of Point

Hope. Little is known about forage species (arctic cod, sand lance, capelin, herring) which are important prey of marine mammals and seabirds in this area.

Subsistence Information

Subsistence fishing has been an important activity to the people living in villages along the Chukchi coastline. Some historical information describing past fishing practices is available (e.g., Murdoch 1884; Wilimovsky 1956), and more recent reports provide an adequate basis for understanding the general use of fish resources at each coastal village (Saario and Kessel 1976; Pedersen 1979; Pedersen *et al.* 1979; Schneider and Bennett 1979; Craig and Schmidt 1982; Skvorc 1982). Within the northern portion of the study area, it appears that residents of Wainwright and Point Hope are presently most active in subsistence fishing. Subsistence patterns are changing as villagers adopt a cash-based economy (Skvorc 1982); however, quantitative information regarding fish harvests is lacking. Consequently such changes, or changes resulting from future developments in the 'Sale No. 85' area, cannot be precisely determined.

Summary

Although a moderate amount of fisheries research has been conducted in the Chukchi Sea, it is apparent that most attention to date has been directed towards fishes in Hope Basin and Kotzebue Sound. Little information exists for the 520 km coastal region north of Point Hope and, consequently, little is known about marine or anadromous fish distribution, habitat dependencies, life histories or trophic interactions with other organisms in the 'Sale No. 85' area. Fish are known, however, to occupy an important position in foodwebs of this region. Marine fish are a vital component in the diets of many marine mammals and seabirds. Marine and anadromous fish are important to residents of the area since they are harvested in subsistence fisheries at or adjacent to several coastal villages.

The present situation is in direct contrast to that existing at the time of oil and gas lease sales in the Beaufort Sea. A feature common to both Chukchi and Beaufort lease areas is that very little was known about coastal resources or sensitivities prior to interest in offshore exploration. However, by the time the Beaufort Sea Joint State/Federal lease sale occurred

(December 1979), over four years of biological research had been conducted. Studies included both broad-scale surveys of marine organisms and an extensive process-oriented research program in coastal waters adjacent to the lease area. Consequently, the numerous scientists, agency personnel and industry representatives involved in Beaufort Sea studies were able to convene their first interdisciplinary workshop two years prior to the lease sale in order to:

1. provide a synthesis of existing knowledge about the Beaufort Sea as it related to the proposed leasing of the outer continental shelf,
2. assess likely impacts of petroleum developments, and
3. review the adequacy of on-going projects.

In addition, subsequent field research programs provided the basis for additional synthesis meetings and a re-evaluation of Federal/State Lease Sale Stipulations prior to the lease sale.

It is already too late to meet an equivalent timetable for environmental input into the Chukchi Sea 'Sale No. 85', since it is scheduled for January 1985. A substantial research effort is needed immediately to provide the fundamentals of biological understanding which scientists had already processed at the time of the first Beaufort Sea synthesis.

FIELD PROGRAM DESIGN

Rationale for New Studies

Recent reviews of fish resources in the northeast Chukchi Sea indicate that anadromous species play an important role in subsistence fisheries of several coastal communities and that marine species are an integral component of marine food webs in this region (Bowden and Moulton 1981; Morris 1981; Moulton and Bowden 1981). Despite this trophic linkage, it is apparent from the first section of this report that very few data describing fish resources in the study area currently exist. It is, therefore, tempting to draw upon the relatively greater data bases available for coastal regions adjacent to the study area. As previously described, knowledge of Chukchi Sea fish resources south of Point Hope is considerably better than for north of Point Hope. Similarly, years of fisheries research in the Beaufort Sea near Prudhoe Bay have produced a reasonable level of insight into fish use of coastal waters. While some cautious extrapolation of information from one area to another is not unreasonable, there are reasons to suggest that such extrapolation should not extend beyond the stage of establishing preliminary hypotheses to test with field studies in the study area. Several lines of reasoning, which point to the distinctiveness of the northeast Chukchi Sea, are discussed below.

Distinctiveness of the NE Chukchi Sea

While the coastal environment of the NE Chukchi Sea shares many physical and biological characteristics with both the SE Chukchi and Beaufort seas, there are also notable dissimilarities in oceanography, fish populations and presumed fish use of coastal habitats.

Comparisons with SE Chukchi Sea

The biological productivity of the SE Chukchi Sea, and the rivers which flow into it, appears to be considerably greater than that of the NE Chukchi Sea. For example, there are much larger runs of anadromous fish in the rivers to the south. Many thousands of pink and chum salmon from the Noatak and Kobuk rivers and arctic char from the Wulik and Kivilina rivers enter coastal waters and support extensive subsistence harvests and a commercial fishery. The Noatak and Kobuk rivers are, in fact, the most northerly streams supporting major salmon runs. It has been hypothesized that water temperatures in more northern streams are prohibitively cold for the freshwater stages of some salmon species (Salonius 1973).

Two hydrologic features contribute to the apparent productivity of the SE Chukchi Sea. First, the water mass is more directly influenced by the relatively warm marine waters which flow northward from the Bering Sea. Pruter and Alverson (1962) have suggested that stocks of some marine species in the southern Chukchi Sea are maintained by recruitment from the Bering Sea. Second, there is a large freshwater input from several rivers flowing into Hope Basin and Kotzebue Sound. Consequently, the SE Chukchi Sea, particularly Kotzebue Sound, is warmer (Fig. 3), less saline and perhaps less nutrient limited than waters north of Point Hope.

Comparisons with the Beaufort Sea

There are fundamental oceanographic differences between the Chukchi and Beaufort seas. They differ in depth, productivity, circulation patterns and source of water. The Chukchi Sea is a relatively shallow basin which is heavily influenced by the northward flow of warm waters from the Bering Sea. In comparison, the Beaufort Sea is deeper and its coastal waters are part of the colder, westward-flowing Beaufort Sea gyre in the Arctic Ocean. The progressive cooling of waters from south to north is illustrated in Figure 3.

Such basic differences between these two water masses are reflected in their fish communities. The Chukchi Sea supports a more diverse fish fauna which includes salmon and forage species such as arctic and saffron cod, sand lance and herring which occur in vast numbers. These fish in turn support large populations of fish-eating seabirds and marine mammals, several coastal subsistence fisheries, and a commercial fishery in southern waters. On all of these accounts, there are smaller harvests of fish populations in the Beaufort Sea.

Fish use of coastal habitats in the two seas may likewise be very different. In Beaufort Sea coastal waters, studies have shown that the distribution of important anadromous species (char, ciscoes, whitefishes) is associated with a narrow band of relatively warm and brackish water which

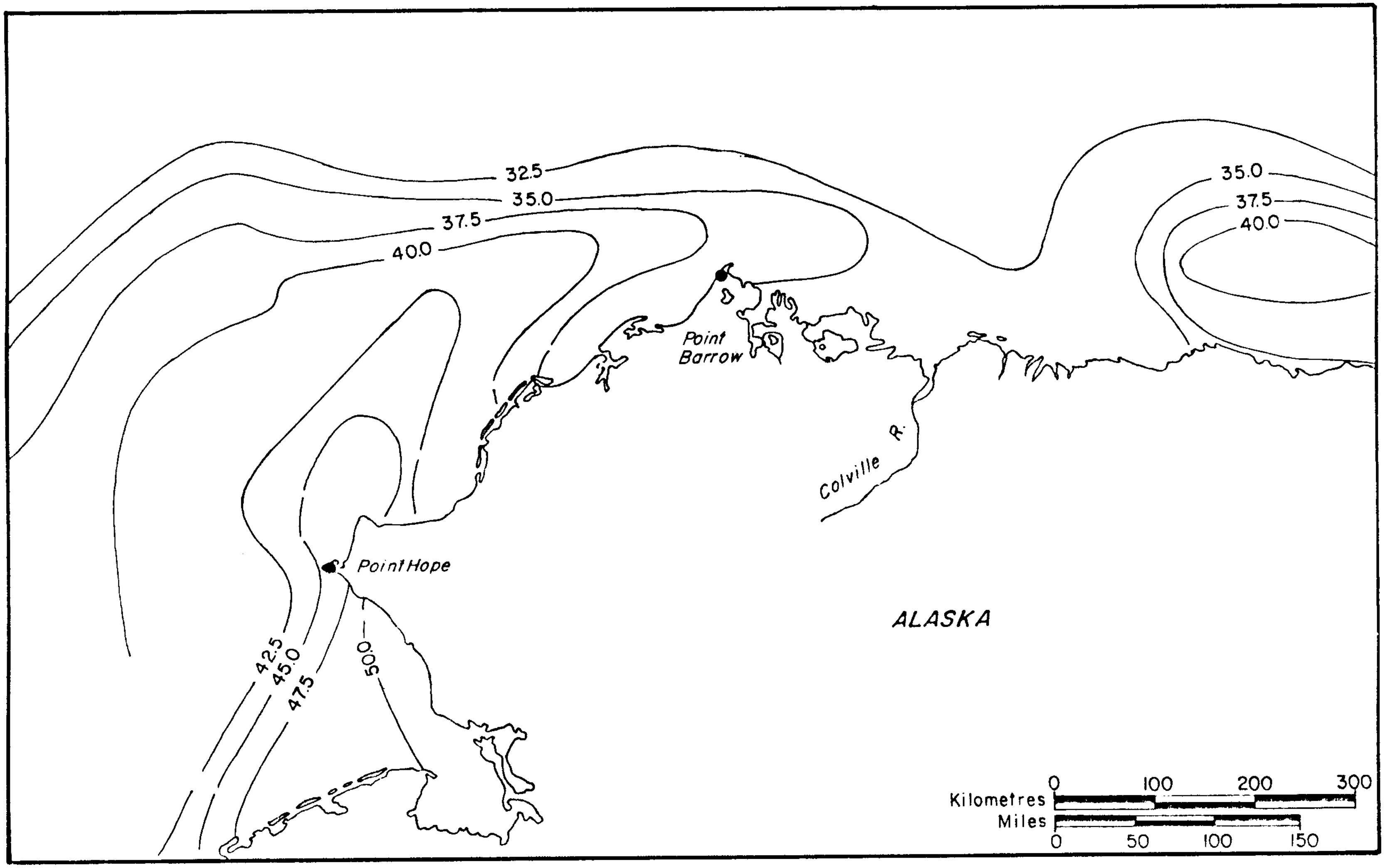


Figure 3. Average surface temperatures (°F in August) for the Chukchi and Beaufort seas. Source: U.S. Navy Hydrographic Office, 1958 (reprint 1968); Oceanographic Atlas of the Polar Seas. Part II Arctic.

flows along the coast with prevailing westward currents. The width of this band of water is usually 1-4 km depending on coastal features such as barrier islands and freshwater plumes of the larger North Slope rivers. In comparison to offshore ocean waters of the Beaufort Sea, the nearshore waters are warm, periodically attaining temperatures up to 10 to 12°C as compared to levels generally well below 5°C in offshore waters. Recent OCSEAP research indicates that there are physiological advantages, and probably requirements, for anadromous species to remain in these nearshore waters (Fechhelm *et al.* 1982)*.

The situation in the Chukchi may not be analogous to that in the Beaufort. Based on very limited data, there does not appear to be a similar, characteristic band of warmer and brackish water along the northeast Chukchi coastline. This may be due to a combination of meteorological, hydrological and topographical features. Surface waters of the Chukchi Sea are warmer than in the Beaufort Sea due to the northward-moving current of warmer water from southern regions. At the same time, nearshore currents or the discharge of fresh water from streams along the northeast coast may be inadequate to establish a narrow and significantly distinct body of even warmer and brackish water along the shoreline, except in enclosed areas such as Wainwright Inlet or Kasegaluk Lagoon (Fig. 4). Consequently, we might predict one of two very different patterns of fish distribution and habitat use in the 'Sale No. 85' area.

1. Anadromous fish may range farther offshore (as occurs with salmon) since temperature and/or salinity gradients between nearshore and offshore waters are not great. It has already been hypothesizes that arctic char may range offshore in the Chukchi Sea (Alt, pers. comm. 1981, cited in Bowden and Moulton 1981).
2. Anadromous fish may congregate in the few protected coastal areas where coastal waters are warmest and brackish (i.e., Wainwright Inlet and Kasegaluk Lagoon).

Distinguishing between these two hypotheses is essential because each leads to a very different concept of the sensitivities of coastal habitats in the northeast Chukchi Sea.

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*Fechhelm, R., W. Neill and B. Gallaway. 1982. Temperature preference of arctic cisco, *Coregonus autumnalis*. Rep. by LGL Ecological Research Associates (Bryan, Texas) for BLM/NOAA/OCSEAP, Arctic Project Office.

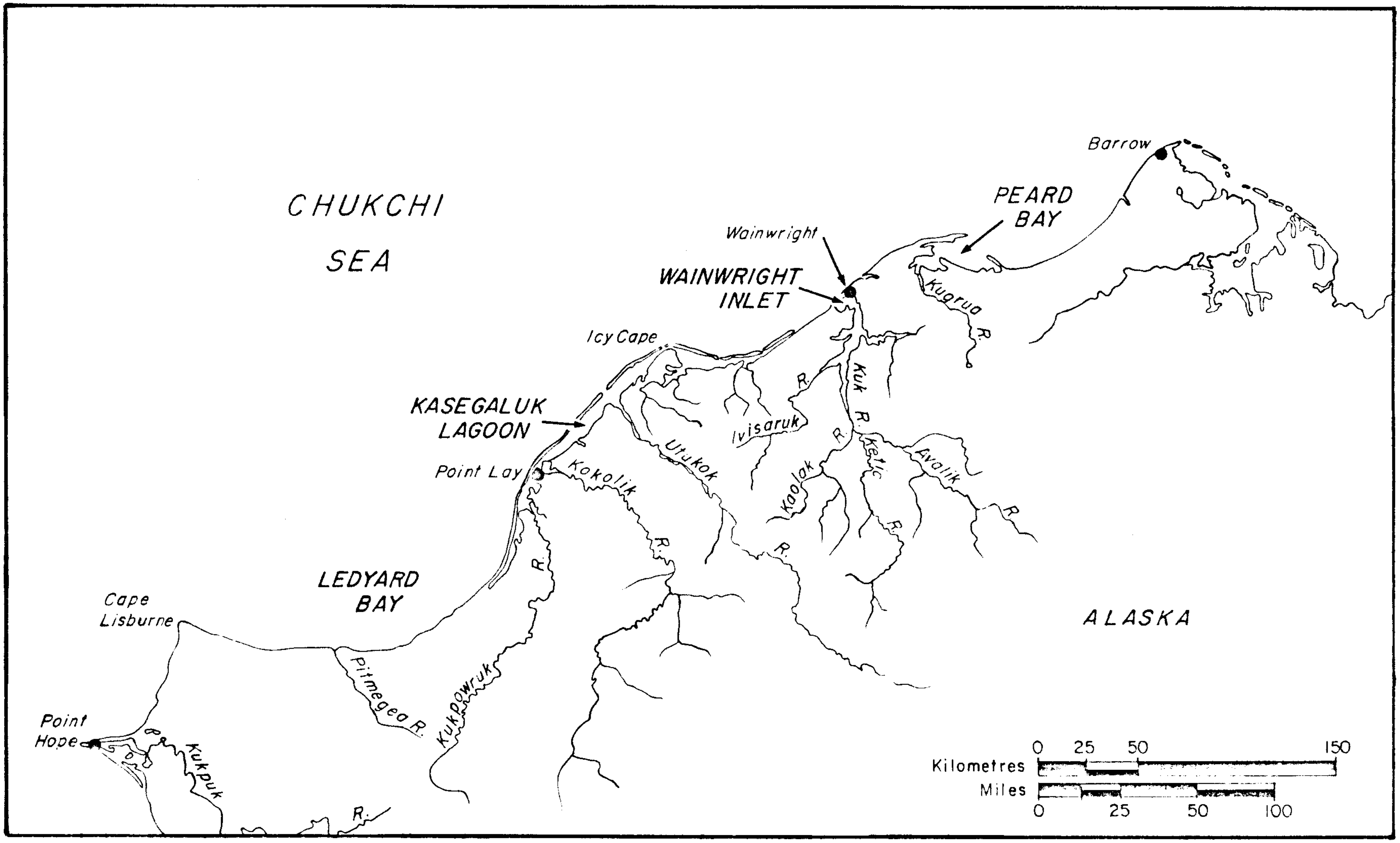

Figure 4. Major coastal features of the northeast Chukchi coast.

Other Distinctive Features

Kasegaluk Lagoon is a prominent feature of the study area that is unparalleled in size by the smaller lagoons along the Beaufort Sea coast. Kasegaluk Lagoon is a long and shallow body of water which extends along 180 km (110 mi) of coastline, forming an enclosed estuarine habitat. As previously described, the brackish waters of this lagoon may provide an important feeding area for anadromous and marine fishes. The lagoon is also an important subsistence hunting area for belukha.

Two sites of marine upwelling in the 'Sale No. 85' area may also affect aquatic productivity and distribution of fish. Morris (1981) states that a weak but apparently persistent anticyclonic gyre occurs northeast of Cape Lisburne, resulting in local upwelling and an increase in biological producitivity in this area. Another anticyclonic eddy reportedly occurs near Peard Bay where Mohr *et al.* (1957) found the unusual occurrence of a kelp community on a rocky substrate.

Finally, results of the literature and information analyses suggest that the rivers which flow into the northeast Chukchi Sea appear to be less, not more, productive than Beaufort Sea drainages. Anadromous and resident freshwater fish in streams of the study area are extremely sparse in both species and numbers of fish. An ecological explanation for the paucity of anadromous fishes will be an important objective of this fisheries study. Population sizes of North Slope (Beaufort) fishes are considered to be limited by the extent of available overwintering habitat, not by food. This finding has had important ramifications for the oil industry, as regulatory agencies have consistently required protection of overwintering stream habitats. Possibly, the extent of overwintering areas along the Chukchi Sea coast is even more severely limiting to anadromous fish populations than in the Beaufort, as has been hypothesized by state fisheries biologists. Should this be the case, the apparently abundant anadromous fish in coastal waters of the northeast Chukchi Sea (compared to the Beaufort Sea) may well be a result of northward immigration of fishes originating from streams draining into the southern Chukchi Sea.

Agency Recommendations

Responses of state and federal regulatory agencies to the need for baseline information for the lease sale area have been direct. The Alaska Department of Fish and Game identified the following issues requiring additional information (Moulton and Bowden 1981):

> "Knowledge of the offshore and coastal circulation patterns in the Chukchi Basin is presently inadequate to develop an oil spill trajectory model for all seasons. Similarly, aside from a few critical habitats, there is a paucity of data relating to shoreline sensitivity. These issues should be addressed prior to the lease sale.... The importance of the nearshore region, Kasegaluk Lagoon in particular, to anadromous fish should be investigated prior to leasing; there is a significant lack of information on this species group."

Study recommendations from the National Marine Fisheries Service are similar. The fisheries portion of their list is as follows (Morris 1981):

> "3. Prior to the exploration phase, studies should be conducted and completed in sufficient detail to provide information on the following subjects:
>
> (b) The location of *critical habitats* and the key ecological parameters that characterize these habitats in the northeast Chukchi Sea for:
>
> 4. Winter under-ice habitat utilization by fish and invertebrates, especially in relation to the life history of key prey species such as Arctic cod, saffron cod, and shrimp.
>
> 5. Locations of concentration areas and movements of anadromous fish along the coast, in bays, lagoons, and river mouths, in both summer and winter seasons.
>
> (d) Offshore demersal *fish and shellfish resource surveys* similar to NMFS surveys conducted in Hope Basin should extend northward to improve on the very inadequate resource information that presently exists for the northeast Chukchi Sea."

Study Plan

The following material describes a basic research program to examine fish resources in the northeast Chukchi Sea prior to the scheduled 'Barrow Arch Sale No. 85' in January 1985. The initial phase of an intensive two-year fisheries study is outlined. It is anticipated that the results obtained during the first summer and winter will determine the objectives of further work.

Objectives

The objectives of the fisheries investigations are to:

1. assess fish population dynamics during open-water and winter periods, habitat dependencies and trophic relationships in the northeast Chukchi Sea. Emphasis shall be placed upon subsistence-harvested and trophically important forage fishes in the coastal region between Point Hope and Barrow,
2. compare patterns of fish habitat use in the northern Chukchi Sea with those occurring in nearshore and offshore regions of the Beaufort Sea and southern Chukchi Sea,
3. analyze the degree to which physical and biological parameters are limiting determinants of the northern Chukchi Sea ichthyofauna, and
4. estimate harvest of subsistence-caught fish.

Methods

Approach

The general approach of first year studies should combine elements of both survey- and hypothesis-oriented studies. Some survey efforts are desirable because fish resources of the study area are so poorly known. In areas where fish resources are better known, research can progress to the stage where important hypotheses are generated and tested with field studies. Clearly the hypothesis-oriented approach is preferred, but to be productive it requires that there is already a basic understanding of the resources in the area to be examined. We are not yet at that point in the Chukchi program.

For the first year in the Chukchi program, we do not recommend sampling the entire coastline at frequent intervals since an inventory approach frequently results in little more than species distribution maps. Nor do we recommend concentrating all efforts at one location because we would not know whether these findings are applicable to different coastal areas. Rather, it seems prudent to sample several of the considerably different habitat types which occur along the northeastern Chukchi coastline, and at each of these sites conduct studies sufficiently intensive to allow general comparisons of habit use by fishes in the various segments of the Chukchi coastline. Results from the first year of study would also provide some evidence to support or reject several of the hypotheses about fish use of the Chukchi Sea previously alluded to in this report. These include:

1. Fish use of nearshore and offshore waters in the Chukchi Sea is not analogous to that occurring in the Beaufort Sea; anadromous fish range farther offshore in the Chukchi Sea.
2. Kasegaluk Lagoon and Wainwright Inlet are of exceptional importance to anadromous fish.
3. The standing crop of fish food items (principally epibenthic invertebrates) is low in Kasegaluk Lagoon and Wainwright Inlet due to a limited water exchange with offshore marine waters.

Additional hypotheses for subsequent research are:

4. Subsistence-caught fish at villages within the study area are largely derived from streams south of Point Hope.
5. The low productivity of streams draining into the northeast Chukchi Sea is due to the limited availability of overwintering sites.
6. The productivity of ichthyofauna in the Chukchi Sea depends directly on the immigration of fish eggs, larvae and juveniles from the Bering Sea.

Study Area

The study area is the eastern Chukchi Sea with particular reference to the northern region between Point Hope and Point Barrow. This region appears to be a geographically distinct entity and it encompasses the 'Barrow Arch Sale No. 85' area (Fig. 1). The proposed area is defined as north of 69°N latitude, and south and west of a line that starts at a point where 71°N latitude intersects the coastline west of Barrow, thence west to 162°W longitude, thence north; the western boundary is at about 169°W at the U.S.-U.S.S.R. 1967 Convention Line (Morris 1981). This area encompasses approximately 28 million acres.

During the first year of study, emphasis should be directed towards the nearshore zone for several reasons. Subsistence fisheries are located in nearshore waters, and migratory pathways and feeding areas of important anadromous species are presumed to be located primarily in the nearshore zone. Also, it is likely that the petroleum industry will be technologically restricted to the nearshore zone during initial phases of exploration and development. The nearshore zone is broadly defined as coastal areas extending from the lower reaches of rivers to several miles offshore. This would include the variety of aquatic habitats known to be important to anadromous fish species for various life functions (e.g., feeding, overwintering) during different stages of their life cycle.

Although the northeastern Chukchi coastline is long (550 km, 340 mi) and varied, the study area can be divided into four coastal components, each of which may be characterized by distinctive patterns of fish usage. The four areas are:

Peard Bay
Wainwright Inlet
Kasegaluk Lagoon
Ledyard Bay

By coincidence, these locations are distributed evenly across the study area, thus providing some measure of geographic representation (Fig. 3).

Peard Bay is located in the northeast sector of the study area near Barrow where the Chukchi and Beaufort water masses mix. The general area includes an exposed coastline as well as Peard Bay proper which is a large body of water protected from direct ocean exposure by Point Franklin. As previously mentioned, upwelling of marine water may occur in this area, and the unusual occurrence of a kelp community on a rocky substrate has been reported. The region may, therefore, harbor (1) a presumed increase in biological productivity associated with coastal upwelling and a community of fishes associated with the kelp habitat, and (2) an assemblege of fishes associated with the northernmost extension of Chukchi waters and the mixture of these waters with the Beaufort Sea.

Wainwright Inlet is a large, inland body of brackish water utilized by anadromous fishes year-round. It is a summer feeding area and migratory pathway for a variety of species during the open-water season, and in winter it supports an important and well-known subsistence fishery for boreal smelt.

Kasegaluk Lagoon has been identified as a unique feature of the study area. This long and enclosed body of brackish water is distinctly different from adjacent aquatic habitats, and it may provide an important feeding area for anadromous and marine fishes.

Ledyard Bay forms the southern portion of the primary study area. Available biological evidence for the importance of Ledyard Bay is primarily related to the heavy use of the area by fish-eating seabirds and marine mammals. This in turn provides indirect evidence for the existence of large populations of forage fish. The physical processes that contribute to the biological productivity of Ledyard Bay are probably related to the northward movement of the Alaska coastal water mass, a body of water that moves north from the Bering Sea and promotes a large clockwise gyre in Ledyard Bay. The resultant upwelling is presumably a factor contributing to the productivity of the area.

Key Species

Field studies will focus on fish species which are harvested in local subsistence fisheries or are trophically important forage fish in this region. At present, six anadromous fish species or species groups and four marine species fall within these categories:

Fish	Subsistence harvest	Important forage fish
Anadromous species		
Chum salmon	x	
Pink salmon	x	
Arctic char	x	
Whitefishes	x	
Ciscoes	x	
Boreal smelt	x	
Marine species		
Arctic cod	x	x
Saffron cod	x	x
Pacific herring		x
Sand lance		x

This list will likely be refined after field studies document the relative abundance and harvest of these species.

Data Collection

Fish will be sampled during open-water *and winter periods* in each of four regions: Peard Bay, Wainwright Inlet, Kasegaluk Lagoon and Ledyard Bay. In each region, the primary objective will be to determine fish utilization of major habitat types (exposed coast, bay, lagoon, offshore, etc.). The sampling design will facilitate comparisons of fish use (1) among habitat types within a region, (2) among the four Chukchi regions, and also (3) between habitats in the Chukchi and Beaufort seas. Sampling gear will include gill nets, seines and fyke nets for capture of representative samples and for catch-per-unit-effort comparisons, and plankton nets for capture of larval stages. Concurrent with biological collections, useful physical and chemical data (surface-to-bottom profiles of water temperature, salinity, turbidity, etc.) will be collected.

Winter sampling will require under-ice gill and fyke nets. Because of difficulties in collecting fish in ice-covered waters, it is worthwhile to investigate whether co-ordination with winter subsistence fisheries is possible.

Fish will be collected for life history analyses and diet studies. Arctic and Bering cisco, which are similar in appearance, will be distinguished taxonomically since the study area is a region where these two species overlap in distribution.

Timing, extent and amount of subsistence harvests will be documented in greater detail than presently available. Although general subsistence patterns have already been described, additional quantitative information may be warranted.

Scheduling

In order to provide useful and timely input to the regulatory processes prior to the 'Barrow Arch Sale No. 85', the fisheries field program should be initiated as soon as possible. A biologically convenient schedule is to begin with the open-water phase (i.e., summer 1983), to identify important species and areas, and then to proceed with winter studies. However, due to the lateness of the program (in terms of the lease sale schedule), serious consideration should be given to a winter 1982-83 start-up whereby field sampling would begin in late winter (March 1983) prior to the summer program. The advantages of this schedule are that:

1. the distribution of free (unfrozen) water and fish overwintering sites (or potential sites) could be determined when winter ice had reached its maximum thickness,
2. liaison with Chukchi coastal villagers and subsistence fishermen could be initiated, and
3. the study team and sampling gear would be assembled at an early date to insure that sampling during the biologically active period in summer would not be jeopardized by delays.

Co-ordination with Other Programs

While this program focuses on fish resources, we recognize that an important reason for initiating fisheries investigations is the trophic significance of fish in the Chukchi food web. For example, a major source of mortality for several juvenile and adult marine fishes (arctic cod, sand lance, herring) is predation by marine mammals and seabirds. Swartz (1966) estimated that as many as 250 million arctic cod are consumed annually by bird populations at Cape Thompson. The proposed fisheries program must, for completeness, draw upon such interdisciplinary information, some of which may best be obtained through co-ordination with studies being conducted by other government agencies. The interdisciplinary information needed to meet the fisheries objectives is listed in Table 1.

It is strongly recommended that a pre-field season organization and logistics meeting be held at the earliest possible date to co-ordinate all studies scheduled for Chukchi waters. Interdisciplinary exchange and co-ordination will greatly enhance the quality of research conducted in the study area.

Table 1. Interdisciplinary information needed to meet fisheries objectives.

Subject	Information needed
Coastal processes	- nearshore circulation and temperature/ salinity patterns. - seasonal dynamics and influence of water from the Bering Sea on biological processes in study area. - historical warming trend of Chukchi waters. - flushing rate of Kasegaluk Lagoon.
Food sources	- distribution in time and space of fish food organisms (mysids, amphipods, etc.) - is the ultimate source of fish food marine primary production or terrestrially derived energy (modern or peat)?
Fish predation	- seasonal distributions and predation rates by marine mammals and seabirds.
Subsistence fisheries	- locations, seasons and harvests by coastal communities.

APPENDIX 1

Fisheries information for the Chukchi Sea: an annotated bibliography

AEIDC (Arctic Environmental Information and Data Center). 1975a. Anadromous fish inventory, Noatak National Arctic Range, Alaska, and associated area of ecological concern. Report by AEIDC, Univ. Alaska (Anchorage) for U.S. Fish Wildl. Serv. Vol. 6. 37 p. + 9 maps.

This is part of a 10-volume set of reports which inventories streams and lakes important to anadromous fish in Alaska. Volume 6 describes the Noatak National Arctic Range which includes portions of the Noatak and Kobuk drainages and contains a list of anadromous and coastal-marine fishes of the locale.

Brief descriptions of subsistence, commercial and sport fisheries are provided. The extent and locations of habitat used by anadromous fishes are indicated for parts of the Noatuk and Kobuk rivers. Escapements, subsistence catches and commercial harvest are listed for the period 1963-1974. Chum salmon, followed by arctic char and inconnu, comprise most of subsistence and commercial catches.

This report identifies three requirements for further study: (1) a more thorough study of the upper Kobuk River, (2) more information about spawning areas for chum salmon, and (3) sport harvest data are needed in greater detail.

AEIDC (Arctic Environmental Information and Data Center). 1975b. Anadromous fish inventory, Selawik National Wildlife Refuge, Alaska, and associated area of ecological concern. Report by AEIDC, Univ. Alaska (Anchorage) for U.S. Fish Wildl. Serv. Vol. 7. 42 p. + 6 maps.

This is volume seven of a 10-volume set of reports which inventories streams and lakes important to anadromous fish in Alaska. This volume describes the area of the Selawik National Wildlife Refuge, which includes streams that drain into the Chukchi Sea in Kotzebue Sound. The major river of importance to salmon migration in this region is the Kobuk River.

Brief descriptions of subsistence, commercial and sport fisheries are provided. The extent and locations of habitat used by anadromous fishes are indicated. Escapements, subsistence catches and commercial harvests are listed for the period 1963-1974. A variety of species are caught but chum salmon are a major portion of the harvest.

This report identifies two data gaps: (1) a more thorough study of the upper Kobuk is required, and (2) sport harvest data are needed in greater detail.

AEIDC (Arctic Environmental Information and Data Center). 1975c. Chukchi Sea: Bering Strait-Icy Cape; physical and biological character of Alaskan coastal zone and marine environment. AEIDC Publication A75, Sea Grant No. 75-10. 63 p. + 31 maps.

This report consists of a 60-page bibliography and 31 maps which summarize known information (up to 1975) about physical and biological features of the region between the Bering Strait and Icy Cape. Each map contains a descriptive section based on data sources included in this report.

AEIDC (Arctic Environmental Information and Data Center). 1976. Profiles of the physical, biological and human environments of the Alaskan outer continental shelf lease areas. Unpubl. Rep. 54 p.

This report provides a state-wide overview (as of 1976) of Alaskan outer continental shelf oil and gas lease areas. The oceanography and biotic resources of the Chukchi Sea are summarized.

AEIDC (Arctic Environmental Information and Data Center). 1977. Bibliography of the environmental and engineering studies on the arctic coast and Beaufort and Chukchi Seas. Report by AEIDC, Univ. of Alaska (Anchorage).

This bibliography of 130 citations dealing with arctic coastal environmental and engineering studies was used in the present selection of annotated reports.

Alt, K. 1971. A life history study of sheefish and whitefish in Alaska. Alaska Dep. Fish and Game 12:1-31.

This report describes a variety of topics related to sheefish collected at various locations in Alaska. Sport and subsistence utilization in the Kobuk-Selawik area is briefly mentioned. During aerial surveys in 1968-1970, approximately 3000-5000 sheefish spawners were counted in the Kobuk River. The 1970 subsistence catch of sheefish in the Kobuk River was about 9000 fish. Additional sheefish were also caught in the Selawik drainage and Hotham Inlet in Kotzebue Sound.

Alt, K. 1973. Age and growth of the inconnu (*Stenodus leucichthys*) in Alaska. J. Fish. Res. Board Can. 30:457-459.

Age and growth characteristics are described for inconnu from several Alaskan drainages, including the Kobuk-Selawik rivers which flow into Kotzebue Sound. Inconnu from the Kobuk-Selawik system grew slower and lived longer than the other inconnu populations examined.

Alt, K. 1978. Inventory and cataloging of sport fish and sport fish waters of western Alaska - Wulik-Kivalina rivers study. Annual Report, Alaska Dep. Fish and Game 19:61-76.

The author's abstract follows:

> Information collected on various life history aspects of Wulik River and Kivalina River Arctic char, *Salvelinus alpinus* (Linnaeus), is presented. Major spawning grounds on both the Kivalina and Wulik rivers have been located and delineated. Overwintering areas are generally described. Information on migrations, size and structure of the spawning population, number and location of spawners, spawning behavior, and location of char fry is also presented. Approximately 3,200 Arctic char spawn in the Wulik-Kivalina system, with 60% spawning in the Kivalina River system. The sex ratio at spawning is approximately three females per male. Grayling Creek is the most important spawning area. The main utilization of these char is for subsistence with a few taken by sport anglers.

Alt, K.T. 1979. Contributions to the life history of the humpback whitefish in Alaska. Trans. Am. Fish. Soc. 108:156-160.

Life history aspects are described for humpback whitefish (*Coregonus pidschian*) from various areas throughout Alaska, including one Chukchi drainage (Kobuk River). The author states that test setting and observation of subsistence catches in the Kobuk River in 1967 indicate that, after overwintering in Hotham Inlet in Kotzebue Sound and in the lower reaches of the Kobuk River, the fish move upstream to feed and later to spawn. After spawning the fish move rapidly downstream.

Surveys in 1971 indicated residents of the five villages along the Kobuk River took 50,000 whitefish, of which over 60% were humpback whitefish.

Alverson, D.L., N.J. Wilimovsky and F. Wilke. 1960. Marine investigations of the Chukchi Sea. U.S. Atomic Energy Commission. Rep. PNE-479. 3 p.

This is a preliminary report on the first year (1959) of studies on Project Chariot (Alverson and Wilimovsky 1966). Information contained in this report is presented in greater detail by Alverson and Wilimovsky (1966).

Alverson, D.L. and N.J. Wilimovsky. 1966. Fishery investigations of the southeastern Chukchi Sea. Vol. 2, Chap. 31, Pages 843-860. *In*: N.J. Wilimovsky and J.N. Wolfe (eds.). Environment of the Cape Thompson Region, Alaska. U.S. Atomic Energy Commission, U.S. Dep. Commerce, Springfield, VA.

This report is part of Project Chariot, a comprehensive environmental study conducted in August 1959 in the Chukchi Sea, primarily south of Point Hope. The authors describe fishes caught in offshore waters by trawl, gill net and seine at 74 stations, only six of which were located north of Cape Lisburne.

Over 7000 fish of 52 species were collected. Although the species list was dominated by far northern types, the collection contained 12 fishes not previously known to occur north of the Bering Strait. For some species, distribution appeared related to water temperature and salinity.

Commercially important species were salmon, char, flatfish, herring and smelt. However, the authors note that these species were not found in sufficient abundance nor of an acceptable size to warrant a commercial interest.

Andriyashev, A.P. 1954. Ryby severnykh morei SSSR (Fish of northern Soviet Seas). Izdatel' stuo AN SSSR, Moscow. (Transl. by Israel Sci. Transl., 1964, 617 p., avail. U.S. Dep. Commerce, Nat. Tech. Inform. Serv., Springfield, VA, OTS63-11160).

This reference book contains extensive taxonomic, distributional and life history information for fishes of the northern seas of the Soviet Union.

Barton, L.H. 1977. Finfish resource surveys in Norton Sound and Kotzebue Sound. Pages 113-194. *In*: Environ. Assess. Alaskan Cont. Shelf, Ann. Rep. Prin. Invest. Vol. 7. BLM/NOAA, OCSEAP, Boulder, Colo.

This report contains considerable information on Pacific herring in the Bering Sea and the southeastern Chukchi Sea. Most information for the Chukchi portion of the study is confined to the area around Shishmaref. Herring are an important subsistence item to villagers at Shishmaref with the major fisheries effort completed by mid-August. At the villages of Deering, Buckland and Point Hope, dependence upon herring is lower because marine mammals are more important in filling subsistence needs.

Gillnetting conducted in the southern Chukchi Sea in fall (27 September through 9 October 1976) showed Pacific herring to be the most abundant species. Other species also taken included: king and pink salmon, and arctic char. Gill nets set near shorelines produced considerably greater catches than offshore sets.

Bendock, T.N. 1979. Inventory and cataloging of arctic area waters. Alaska Dep. Fish and Game, Sport Fish Division. Annual Performance Report, Study No. G-I. 20:1-64.

Although this report emphasizes fisheries information from the Colville River, the report includes data for three rivers which drain into the Chukchi Sea, the Kukpowruk, Kokolik and Utukok rivers. Surveys of the upper and middle reaches of these rivers were conducted 5-20 July 1978. Each river was sampled at 4-7 sites by seine and gill net (the level of effort was not specified).

All three rivers support small runs of pink salmon. Only single specimens of other anadromous species (chum salmon, arctic char and arctic cisco) were caught. Freshwater species present in low to moderate numbers were grayling, slimy sculpin and ninespine stickleback. [Additional information on fishes in the lower Kokolik is presented by Craig and Schmidt (1982)].

Bendock, T. and J. Burr. 1980. Index to North Slope stream and lake surveys. Rep. by Alaska Dep. Fish and Game (Fairbanks). 11 p.

This report is a list of fishes caught in North Slope streams and lakes, including several in the current study area. Accompanying text, specific sample locations and most data sources other than Alaska Department Fish and Game and U.S. Fish and Wildlife Service are not presented.

Bowden, C., and L. Moulton. 1981. Resource report for the proposed Hope Basin OCS oil and gas lease sale #86. Rep. by Alaska Dep. Fish and Game, Marine/Coastal Habitat Management. Anchorage, Alaska. 121 p.

This report provides a useful summary of the available information for marine and anadromous fishes in the Hope Basin lease sale #86 area. A comprehensive bibliography relevant to the southeastern Chukchi Sea is also provided.

Butorin, D.A. 1965. Areas of polar cod in the Arctic. Ryb. Khoz. 10(8).

(not seen)

Cohen, D.M. 1954. Age and growth studies on two species of whitefishes from Pt. Barrow, Alaska. Nat. Hist. Mus., Stanford Univ., Stanford Ichthyological Bull. Vol. 4(3):168-187.

This paper describes the age and growth characteristics of least cisco and broad whitefish near Barrow. Samples were collected in Ikroavik Lake and Elson Lagoon. Various growth patterns of least cisco were evident. The author concludes that fish in this region are few and slow growing. The possibility of a major commercial fishery seems improbable.

Craig, P.C. and L. Haldorson. 1981. Beaufort Sea barrier island-lagoon ecological process studies: Final report, Simpson Lagoon. Part 4. Fish. Pages 384-678. Res. Unit 467. *In*: Environ. Assess. Alaskan Cont. Shelf, OCS Biol. Sci. Final Rep. Prin. Invest. Vol. 7. BLM/NOAA, OCSEAP, Boulder, Colo.

Although this report describes Beaufort Sea fishes, incidental information is presented about a sample of saffron cod (*Eleginus gracilis*) collected in the Chukchi Sea. The authors state that these fish were part of a subsistence catch of "tomcod" jigged through the ice just offshore from the village of Kotzebue, southeast Chukchi Sea, on 15-30 November 1978.

The sample (n=33) consisted almost entirely of large, mature fish that were approaching a spawning condition. The average fork length was 238 mm and all but one of each sex were mature. Most were females (79%); egg diameters averaged 0.9 mm. Only three fish had empty stomachs; the rest had eaten fish (68% wet weight), mysids (18%) and decapods (13%).

Craig, P.C. and D. Schmidt. 1982. Fisheries surveys at potential dredging sites at North Slope villages: Wainwright, Point Lay, Atkasook, Nuiqsut and Kaktovik. Rep. by LGL Ltd. (Sidney) for the North Slope Borough, Barrow, Alaska.

The purpose of this investigation was to document the fisheries importance of potential dredging sites at five North Slope villages. The study includes some subsistence information and surveys of several coastal locations around two Chukchi communities, Wainwright and Point Lay. Fish were sampled by gill net and seine during 22-30 July 1981.

Sites sampled and species recorded at Wainwright were: Wainwright Inlet (least cisco, boreal smelt, arctic flounder, fourhorn sculpin), lower Sinaruruk River (fourhorn sculpin) and two nearby lakes (nil). Subsistence fishing along the village shoreline caught pink, chum and king salmon and fourhorn sculpin. Most subsistence fishing occurs at that location in summer and in Wainwright Inlet in winter.

Sites sampled and species recorded at Point Lay were: Kasegaluk Lagoon between the new and old village sites (pink salmon, arctic char, arctic and Bering cisco, boreal smelt, saffron cod, arctic flounder and fourhorn sculpin, lower Kokolik River (Pacific herring, boreal smelt, fourhorn sculpin), and several unnamed lakes (ninespine stickleback). A brackish water intrusion (17°/oo) from the lagoon extended 4 km into the Kokolik River at the time of sampling. Most subsistence fishing in summer occurs on both the ocean and lagoon sides of the barrier island at the old village site.

Cunningham, P. 1976. Deering experimental commercial salmon fishery. Alaska Dep. Fish and Game Spec. Rep. No. 9. 25 p.

This report discusses an experimental commercial salmon fishery in the Deering area of Kotzebue sound in 1974 and 1975. Results of this three year study indicate that the local stocks of pink and chum salmon in the vicinity of Deering are very limited and not capable of supporting harvests in excess of present subsistence needs. Furthermore, the Deering commercial fishery was dependent upon the interception of chum salmon bound for the Kotzebue/Noatak River area. For these reasons, continuation of the commercial fishery at Deering was not warranted.

Derjugin, K.M. 1937. Introduction to the investigations of the Chukchi and Bering seas. Issledovannia Morei SSSR 25:5-9. (In Russian and German, Translated from German by P. Skvorc.)

This is a preliminary report about the initiation of studies in the Bering and Chukchi seas by the new communist government. No scientific data are presented. Rather, the report extolls the virtues of the Red Army and its associated bureaucracies. The author describes the great strides in science that have been made since the revolution, and suggests that the economic reconstruction is being advanced by the scientists at the State Institute of Hydrology.

Derjugin, K.M. and A. Ivanov. 1937. Preliminary survey of studies on the benthos of the Bering and Chukchi seas. Issled. Morei. SSSR Vol. 25: 246-259.

No Chukchi data are presented in this preliminary report.

Feder, H.M., D.G. Shaw and A.S. Naidu. 1976. The arctic coastal environment of Alaska. Volume II: A compilation and review of scientific literature of the arctic marine environment. Univ. Alaska (Fairbanks), Instit. Mar. Sci. Rep. R76-5. 201 p.

This report provides a comprehensive bibliography of published literature and unpublished reports (up to 1976) on fish resources of arctic Alaska and Canada. Brief annotations are provided for each entry. The paucity of bibliographic entries for the Chukchi Sea region emphasizes the lack of information available for this area.

Feder, H. and S. Jewett. 1978. Survey of epifaunal invertebrates of Norton Sound, southeastern Chukchi Sea and Kotzebue Sound. Univ. Alaska (Fairbanks), Instit. Mar. Sci. Rep. R78-1. 124 p.

This report describes benthic invertebrates from the northeastern Bering Sea and southeastern Chukchi Sea. Information about starry flounders is also included (see Jewett and Feder 1980).

FFHU (Faculty of Fisheries, Hokkaido University). 1967. 1966 cruise of the 'Oshoro Maru' to the Bering and Chukchi seas. *In*: Data Record of Oceanographic Observations and Explorations Fish. Hokkaido Univ., Hakodate, Hokkaido, Japan. 10:126-215.

(not seen)

FFHU (Faculty of Fisheries, Hokkaido University). 1968. 1967 cruise of the 'Osmoro Maru' to the Chukchi Sea. *In*: Data Record of Oceanographic Observations and Explorations Fish. Hokkaido Univ., Hakodate, Hokkaido, Japan. 11:78-105.

(not seen)

Frost, K.J. 1981. Descriptive key to the otoliths of gadid fishes of the Bering, Chukchi and Beaufort seas. Arctic 34:55-59.

This report provides an illustrated key to the otoliths of fishes that are common food items of marine mammals of the northern seas, including the Chukchi Sea.

Frost, K.J. and L.F. Lowry. 1981. Trophic importance of some marine gadids in northern Alaska and their body-otolith size relationships. Fish. Bull. 79(1):187-192.

Marine fishes are important in the diets of marine mammals, seabirds and other fish. This report examines relationships between otolith length and fish length for three marine fishes in northern waters: walleye pollock, saffron cod, arctic cod. By using these relationships, it is possible to determine sizes of fish consumed by predators based on sizes of otoliths remaining in predator stomachs.

Frost, K.J., L.F. Lowry and J.J. Burns. 1978. Offshore demersal fishes and epibenthic invertebrates of the northeastern Chukchi and western Beaufort Seas. Pages 231-365. *In*: Environ. Assess. Alaskan Cont. Shelf, Annu. Rep. Prin. Invest., Vol. 1. BLM/NOAA, OCSEAP, Boulder, Colo.

This study provides some information on the abundance, distribution and life history characteristics of offshore demersal fishes in the northeastern Chukchi Sea. Ten otter trawl samples were collected between 2 August and 3 September 1977 in water depths ranging from 40 to 102 m. Ten species (or species groups) were identified, with the majority belonging to three families: Gadidae (cod), Cottidae (sculpin) and Zoarcidae (eel-blennies). In terms of both numbers and biomass, the arctic cod (*Boreogadus saida*) was the most abundant species collected. Information regarding the distribution, food habits and life history of abundant species is presented: arctic cod, Canadian eelpout (*Lycodes polaris*), fish doctor (*Gymnelis viridis*), arctic alligatorfish (*Aspidophoroides olriki*) and spatulate sculpin (*Icelus spatula*).

Geiger, M. 1966. Kotzebue chum salmon tagging project. Pages 78-98. *In*: Ayk area 1966 annual management report. Div. of Comm. Fish., Anchorage, AK.

This report provides limited data on the magnitude and timing of chum salmon runs in the Noatak and Kobuk rivers. It also provides limited data on subsistence and commercial catches in the area from 1962 through 1966.

Hablett, T. 1979. Fish inventories conducted within the National Petroleum Reserve on the North Slope of Alaska, 1977-78. Chap. 10, Pages 337-406. *In*: Studies of selected wildlife and fish and their use of habitats on and adjacent to NPRA 1977-1978, Vol. 2

The pertinent fisheries information in this report is the same as that provided by Bendock (1979).

Hurd, C. 1971. Kotzebue Sound sheefish investigations, 1971. Alaska Dep. Fish and Game, Arctic-Yukon-Kuskokwin Region. 17 p.

This report is a continuation of that by Lebida (1970) and provides limited age and length data for sheefish in the Kotzebue Sound area.

Ivie, P. and W. Schneider. 1979. Wainwright synopsis. Pages 75-87. *In*: Native livelihood and dependence. A study of land use values through time. U.S. Dep. Interior, National Petroleum Reserve in Alaska, 105(c) Field Study No. 1.

This report describes land use patterns by villagers at Wainwright. The study is based on interviews with Wainwright residents, and a brief amount of fisheries information is presented as it pertains to domestic fisheries.

Gill nets are set out in front of the village for salmon, "trout" and whitefish beginning in July and August. In fall, migrating fish are caught at camps along the Vtukok and Kuk rivers, and in winter smelt are caught in Wainwright Lagoon.

Jewett, S.C. and H.M. Feder. 1980. Autumn food of adult starry flounders, *Platichthys stellatus*, from the northeastern Bering Sea and the southeastern Chukchi Sea. J. Cons. Int. Explor. Mer 39(1):7-14.

Data describing starry flounder in this report were gathered during a larger study of benthic invertebrates described by Feder and Jewett (1978). This trawl survey was conducted 2-13 September 1976 in the northern Bering Sea and southern Chukchi Sea. Only 10% of the total fish sample were from the Chukchi Sea proper, and these sampling stations were located approximately 90 km north of Cape Prince of Wales. Dominant food items of the flounders included the brittle star, *Diamphiodia craterodmeta* and the protobranch clam, *Yoldia hyperborea*. The authors suggest that the northern movement of starry flounders may be restricted by temperature.

Lebida, R. 1970. Kotzebue Sound sheefish investigations, 1970. Alaska Dep. Fish and Game, Arctic-Yukon-Kuskokwin Region. 12 p.

This report, part of a several year management investigation of sheefish in the Kotzebue Sound area, presents tagging data from 1966 to 1970. Relative abundance and spawning dates for sheefish in the Kobuk River are also given.

Lindberg, G. 1937. On the classification and distribution of sand lances genus. East Branch Acad. Sci. USSR. Bull. 27:85-93.

(not seen)

Lowry, F.L., K.J. Frost and J.J. Burns. 1980. Variability in the diet of ringed seals, *Phoca hispida*, in Alaska. Can. J. Fish. Aquat. Sci. 37:2254-2261.

This report examines the diet of ringed seals which are the most abundant and widespread phocid in the northern hemisphere. Samples were collected in the Bering and Chukchi seas.

Fish are an important dietary item for ringed seals. Arctic cod were by far the major food eaten during winter months. The authors suggest that the abundance and distribution of ringed seals is directly related to the distribution of two marine fishes, arctic and saffron cod. A similar relationship has been described between ringed seals and arctic cod in some areas of the Siberian Arctic (Chapskii 1940*).

Lowry, L.F. and K.J. Frost. 1981. Distribution, growth and foods of Arctic cod (*Boreogadus saida*) in the Bering, Chukchi and Beaufort Seas. Canadian Field-Naturalist 95(2):186-191.

This study is based on a collection of fish in offshore arctic waters of the Beaufort, Chukchi and Bering seas. Bottom samples of fish were collected by otter trawl, 10 of which were located in the present study area. These samples were collected in the northeastern Chukchi Sea west of Pt. Barrow during late summer (2 August-3 September 1977). Although the Chukchi data are limited, this report nonetheless represents a significant portion of the fisheries data available for fish in the Chukchi Sea north of Pt. Hope.

Only one fish species, the arctic cod, is described in this report. It was presumably a dominant species in the trawl samples but the relative abundance of other species is not presented in this report. [A complete list of catch results is presented in another report by Frost *et al.* (1978).]

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*Chapskii, K.K. 1940. The ringed seal of western seas of the Soviet Arctic. Proc. Arctic Sci. Res. Inst., Leningrad, USSR. 145:1-72. (Transl. from Russian by Fish. Res. Board Can. Transl. Ser. No. 1665, 1971)

The author's abstract follows:

> Arctic Cod (*Boreogadus saida*) are abundant and ecologically important in arctic and subarctic marine ecosystems. Based on otter trawl collections made in the northern Bering and northeastern Chukchi and Beaufort seas, Arctic Cod were most abundant in the northeastern Bhukchi and western Beaufort seas. There was no relationship between water depth and abundance; however, in the Chukchi and Beaufort seas, small fishes were more common in water less than 100 m deep. Annual growth increments appear to be quite variable, which complicates interpretation of size at age data. Arctic Cod less than 4 yr were larger at a given age in the Bering Sea. In the Bering Sea gammarid amphipods were the main food with mysids, shrimps and hyperiid amphipods also eaten. In the northeastern Chukchi and Beaufort seas, calanoid copepods were by far the predominant prey with other crustaceans eaten much less frequently. Arctic Cod appear to be a very adaptable species, which may explain their overwhelming success in arctic marine waters.

MacGinitie, G.E. 1955. Distribution and ecology of the marine invertebrates of Point Barrow, Alaska. Smithsonian Misc. Coll. Vol. 128. No. 9.

Although fish were not within the scope of this project, the report provides a brief description of the fish fauna encountered during an invertebrate sampling program conducted in the Point Barrow area. The major species reported were: arctic cod, capelin and fourhorn sculpin.

Makarov, V.V. 1937. Data on the quantitative calculation of benthic fauna of the northern Bering Sea and the southern Chukchi Sea. Issled. Morei. USSR Vol. 25:260-291.

This report deals primarily with benthic invertebrates rather than fish.

Mattson, C.R. 1962. Chum salmon resources of Alaska from Bristol Bay to Point Hope. U.S. Fish Wildl. Serv., Special Scientific Rep. Fisheries No. 425. 22 p.

The author's abstract follows:

> A literature survey was conducted to determine the importance and utilization of chum salmon, *Oncorhynchus keta*, from Bristol Bay to Point Hope, Alaska. This species is the most abundant and economically important to the welfare of the local residents within this vast area, except for the Bristol Bay area where sockeye salmon, *Oncorhynchus nerka*, far outnumber chum salmon. The Yukon River system produces the greatest number of chum salmon of all the areas covered here, with catches ranging from 500,000 to nearly 1,000,000 fish annually. The Kuskokwim River system follows, with annual catches averaging over 500,000.

Ranking third in production is the Bristol Bay area where commercial catches range as high as 400,000. The rivers and streams entering Kotzebue Sound from the base of Seward Peninsula northwest to Point Hope rank fourth in importance, annual catches being estimated in excess of 264,000.

McPhail, J.D. 1966. The *Coregonus autumnalis* complex in Alaska and northwestern Canada. J. Fish. Res. Board Can. 23:141-148.

Whitefish common to the study area pose taxonomic uncertainties with some regularity. The relevance of this taxonomic study lies mainly in that some samples were obtained from areas of interest to this bibliography. This report indicates that the Chukchi Sea is an area of distributional overlap for arctic and Bering ciscoes. Since both the high gill raker form (arctic cisco) and low gill raker form (Bering cisco) occur along the arctic coast without intergrading, they are considered separate species.

Mohr, J.L., N.J. Wilimovsky and E.V. Dawson. 1957. An arctic Alaskan kelp bed. Arctic 10:45-52.

This paper reports the occurrence of a kelp bed near Peard Bay (70°51'30"N, 158°08'30"W), southwest of Barrow. The authors suggest that northern Alaska is poor in marine algae and such algal beds are not common in arctic waters. [This suggestion is supported by OCSEAP studies in the Beaufort Sea which located only a few such kelp beds on rocky substrates (i.e., the Boulder Patch in Stefansson Sound)]. Six species of fish were collected from this kelp bed: arctic cod (*Boreogadus saida*), an eelpout (*Gymnelis viridis*), and four species of sculpin (*Gymnocanthus tricuspis, Myoxocephalus scorpius, Artediellus scaber beringianus, Enophrys diceraus*). The arctic cod had eaten gammarid amphipods and numerous copepods. The sculpin (species combined) had eaten mainly gammarid and caprellid amphipods, with small amounts of crab, shrimp, polychaete, pteropod and plant material.

Morris, B. 1981. Living marine resources of the Chukchi Sea: A resource report for the Chukchi Sea oil and gas lease sale #85. Rep. by Nat. Mar. Fish. Serv. for Bureau of Land Management (Anchorage). 117 p.

In this synthesis, the author presents an overview of northeast Chukchi fishes, although he concludes that marine fishes of this region have received little attention in the past and knowledge of anadromous fish is poor.

From limited sampling in other studies, the number of marine fishes reported in the Chukchi Sea is 41 species representing 11 families. The Chukchi Sea has lower species diversity and biomass than the northern Bering Sea but greater than that in the Beaufort Sea. Dominant marine species are arctic cod, starry flounder, Pacific halibut, saffron cod, Pacific herring, sculpins and capelin. Of the 13 anadromous fishes reported in the Chukchi, the most abundant are pink and chum salmon, arctic char, ciscoes, whitefish and smelt. Along the northeast coast, the larger drainages support small runs of salmon. Population sizes of commercially valuable fish resources in the Chukchi Sea are low, but villages along the coastline rely heavily on subsistence hunting and fishing for food.

Moulton, L.L. and S. Bowden. 1981. Resource report for the proposed Chukchi Basin OCS oil and gas lease sale #85. Unpubl. Rep. by Alaska Dep. Fish and Game, Marine/Coastal Habitat Management. Anchorage, Alaska. 38 p.

This report summarizes available information and identifies major data gaps in the knowldge of anadromous and marine species in the Chukchi Basin lease sale #85 area located in the northeastern Chukchi Sea. Two resource maps provide some information on habitat use of abundant marine fishes (arctic cod, Pacific sand lance and capelin) and anadromous fishes (arctic char, ciscoes, pink and chum salmon). The report also contains a comprehensive bibliography relevant to the Chukchi Sea lease area.

Murdoch, J. 1884. Fish and fishing at Point Barrow, arctic Alaska. Trans. Am. Fish. Soc. 13:111-115.

Murdoch presents an interesting account of the fish and fishing practices of the "Esquimaux" at Point Barrow in 1882. Whitefish, burbot, arctic cod, and occasionally pink salmon and arctic char were the species of primary importance. Capelin and smelt were also present since the author relates that in the summer of 1882 he caught thousands of capelin, but local residents did not utilize them because they lacked nets small enough to catch them. Gill-netting and jigging through the ice were the primary means of fishing observed. It is also noted that while it was usually only the women and children who fish, many people were involved in fishing activities when seal hunting was poor and during times of low food supplies.

Murdoch, J. 1885. Fishes. Pages 129-132. *In*: P. Ray (ed.) Report on the International Polar Expedition to Pt. Barrow, Alaska 1882-3. Part 4, Sec. 3. U.S. Gov. Printing Office (Washington, D.C.).

This report provides interesting comments regarding 18 fish species caught in the Barrow area during 1881-1883. Of particular interest are the life history observations on the distribution of arctic cod. The importance of boreal smelt in Wainwright Inlet is also noted.

Namvedt, T., S. Parrish, N. Friese and W. Quirk. 1974. Pages 252-268. *In*: Alaska arctic coast-a background study of overall knowledge. Prep. for Dep. of the Army, Alaska Dist. Corps of Eng. Alaska Office.

(not seen)

Pedersen, S. 1979. Point Hope synopsis. Pages 141-149. *In*: Native livelihood and dependence. A study of land use values through time. U.S. Dep. Interior, National Petroleum Reserve in Alaska, 105(c) Field Study No. 1.

This report describes land use patterns by villagers at Point Hope. A brief amount of fisheries information is presented as it pertains to subsistence fishing. Marine and freshwater fish are listed as a primary subsistence resource. Ocean fishing occurs almost year round and freshwater fishing on the Kukpuk River occurs in late fall and winter.

Pedersen, S., D. Libbey, W. Schneider and C. Dementieff. 1979. Barrow-Atgasuk (Atkasook) synopsis. Pages 49-74. *In*: Native livelihood and dependence. A study of land use values through time. U.S. Dep. Interior, National Petroleum Reserve in Alaska, 105(c) Field Study No. 1.

This report describes land use patterns by villagers at Barrow and Atkasook. A brief amount of fisheries information is presented as it pertains to domestic fisheries. In the area of current interest, some fishing for salmon, char and whitefish occurs along the Chukchi coastline between Point Barrow and Ualiqpaa, located about 35 km to the southwest. There is also jigging for tomcod in winter although this resource "does not receive much attention these days".

Pereyra, W.T., R.J. Wolotira, Jr., T.M. Sample and M. Morin, Jr. 1977. Baseline studies of fish and shellfish resources of Norton Sound and the southeastern Chukchi Sea. Pages 229-287. *In*: Environ. Assess. Alaskan Cont. Shelf. Ann. Rep. Prin. Invest. Vol. 8. BLM/NOAA, OCSEAP, Boulder, Colo.

This study summarizes existing literature about fish resources of the southeastern Chukchi Sea and presents new data collected during September-October 1976. Gillnet samples and pelagic trawl hauls for near-surface fish were generally unproductive, with toothed smelt (*Osmerus mordax dentex*) and Pacific herring (*Clupea harengus pallasi*) being most common. Inshore sets usually caught more than those made in offshore waters.

Otter trawl catches of demersal fish were small. Fish commonly caught by this method were: Gadidae (arctic and saffron cod), Pleuronectidae (Alaska plaice), Osmeridae (rainbow smelt), Clupeidae (Pacific herring) and Cottidae (plain sculpin, shorthorn sculpin).

In a comparison of day/night otter trawl catches, most species were more abundant during the day.

Pfeifer, W.E. 1977. An annotated bibliography of the fishes of the Beaufort Sea and adjacent regions. Univ. Alaska, (Fairbanks), Biol. Pap. No. 17. 81 p.

This report is a useful compilation of approximately 500 references that describe fishes of the Beaufort Sea and adjacent regions. Coastal streams are also included because they are used by anadromous fishes of the study area. Several Russian references are included. Many of the references are briefly annotated.

Ponomarenko, V.P. 1968. Some data on the distribution and migration of polar cod in the seas of the Soviet Arctic. Rapp. Proc. Perm. Cons. Int. Explor. Mer 158:131-134.

The polar cod referred to in the title is *Boreogadus saida*. Very little of the information on distribution and life history was obtained from the Chukchi Sea. Because of the circumpolar distribution of *B. saida* and similarities in natural history between various stocks, the information from the western Soviet seas is helpful.

It is suggested that *B. saida* overwinters in the southern Chukchi and northern Bering seas and summers to the north and west. It is associated with the ice-edge and spawns in January and February. It may be locally abundant at any time along any part of its distribution. The author states that during late fall storms, 'one may see heaps 50-100 cm wide and 30-50 cm deep extending over hundreds of kilometers along the waters edge'.

Pruter, A., and D. Alverson. 1962. Abundance, distribution, and growth of flounders in the south-eastern Chukchi Sea. J. Cons. Perm. Int. Explor. Mer 27:81-99.

This report concentrates on the flounders collected during the August 1959 'Project Chariot' studies reported by Alverson and Wilimovsky (1966). Demersal fish were collected by otter trawl throughout the southeast Chukchi Sea and southern Ledyard Bay.

A total of 289 pleuronectids composed of six species was collected; most were *Hippoglossoides robustus*. Population densities were extremely low and sizes of all flounder species were smaller than accepted in commercial markets.

An important contribution of this paper is the discussion regarding physical properties of the Chukchi Sea which dictate the population dynamics of flounders found there. Recruitment is apparently dependent upon the transport of eggs, larvae and young fish into the Chukchi Sea by waters originating south in the Bering Sea. The authors hypothesize that population levels of these fish are kept low due to harsh winter mortalities.

Quast, J.C. 1972. Preliminary report on the fish collected on WEBSEC-70. Pages 203-206. *In*: WEBSEC-70, an ecological survey in the eastern Chukchi Sea. U.S. Coast Guard, Oceanographic Rep. No. 50. 206 p.

This data report consists of tables which list species of fish collected during the WEBSEC-70 cruise in Ledyard Bay. Twenty-six species were caught by trawl at 21 offshore stations during the period 25 September to 17 October 1970. The most widespread species caught were arctic cod and sand lance.

Quast, J.C. 1974. Density distribution of juvenile arctic cod, *Boreogadus saida*, in the eastern Chukchi Sea in the fall of 1970. Fish. Bull. 72:1094-1105.

This study presents information about the biomass and distribution of juvenile arctic cod (*Boreogadus saida*) in the Chukchi Sea. Samples were collected during September and October 1970 at 20 stations in Ledyard Bay. An Isaacs-Kidd mid-water trawl was used to collect fish at depths of 2-45 m in water that was 22-54 m deep.

The two most abundant species collected were arctic cod and Pacific sand lance (*Ammodytes hexapterus*). The average concentration of arctic cod juveniles was 28/1,000 m^3 and their average biomass was 0.7 metric ton/km^2 of ocean surface. Numbers of arctic cod increased with depth, and concentrations at different depths appeared to be negatively related to sunlight. The author suggests that the arctic cod originated in the northwestern Bering Sea off Siberia or within the Chukchi Sea.

Raleigh, R.J. 1957. Reconnaissance of salmon fisheries between Cape Newenham and Point Hope, Alaska, 1957. U.S. Dep. Commerce, NMFS Biological Lab., Auke Bay, Alaska. 27 p.

This report deals almost exclusively with the subsistence use of salmon by the people along the Bering Sea and southern Chukchi Sea coastlines. Historical data regarding people:dog ratios and the quantity of fish used for dog food are presented.

Roguski, E. and P. Winslow. 1970. Monitoring and evaluation of arctic waters with emphasis on the North Slope drainages. Annu. Rep. No. 15-C. Alaska Dep. Fish and Game 11:279-301.

This report is primarily concerned about Beaufort Sea drainages but presents incidental information about the Wulik River subsistence catch. The total catch of all fish caught by Kivalina villagers in the spring of 1969 was 8400 arctic char weighing 19,000 pounds. Age and maturity data are presented for 24 arctic char.

Romanov, V.V. 1959. Bibliography of literature relating to fish of the Far East 1923-1956. Akad. Sci. Moscow 1959. 290 p.

(translated copy not seen)

Saario, D.J. and B. Kessel. 1966. Human ecological investigations at Kivalina. Vol. 2, Chap. 35, Pages 969-1040. *In*: N.J. Wilimovsky and J.N. Wolfe (eds.) Environment of the Cape Thompson Region, Alaska. U.S. Atomic Energy Commission, U.S. Dep. Commerce, Springfield, VA.

This chapter documents subsistence patterns in the coastal village of Kivalina in the southern Chukchi Sea. The authors found that "fish play a vital part in the subsistence economy of the Kivalina people". The major portion of the catch consisted of Dolly Varden (*Salvelinus malma*) [currently called arctic char, *S. alpinus*], but whitefish and arctic cod were also taken. Seasonal fishing patterns, locations and methods are described. Most fishing occurred in the Wulik River in fall and Kivalina lagoon in winter. Fall catches totalled 98,000 lb in 1959 and 124,000 lb in 1960.

Salonius, P. 1973. Barriers to range extensions of Atlantic and Pacific salmon in arctic North America. Arctic 26:112-122.

This report suggests that the long arctic coastline between Alaskan salmon rivers and the Mackenzie River in Canada is a major barrier to the range extension of salmon because the rivers on these coastlines are not suitable for colonization. Salmon, particularly the juvenile life stages, have a marked intolerance to the low water temperatures (compared with other salmonids) occurring in these northern streams. The author suggests that this is the reason that chinook, sockeye and coho salmon are encountered only sporadically north of Norton Sound. Pink and chum salmon may have been able to colonize streams farther north because of their relative independence from freshwater life stages.

Schneider, W. and R. Bennett. 1979. Point Lay synopsis. Pages 107-119. *In*: Native livelihood and dependence. A study of land use values through time. U.S. Dep. Interior, National Petroleum Reserve in Alaska, 105(c) Field Study No. 1.

This report describes land use patterns by villagers at Point Lay. A brief amount of fisheries information is presented as it pertains to domestic fisheries. Gill nets are set, from early July through late September, at many places around Point Lay (i.e., river mouths, the lagoon, and the sea). Species caught include chum, pink and king salmon, flounder, smelt, herring, whitefish, sculpin and grayling. In late fall and winter, fishing in the Kukpowruk River yields large catches of grayling.

Seaman, G. and J. Burns. 1980. Preliminary results of recent studies on belukhas in Alaskan waters. Unpubl. Rep. by Alaska Dep. Fish and Game (Fairbanks). 31 p.

This report describes the trophic importance of marine fishes in the diet of white whales in Chukchi coastal waters:

> Belukhas taken during spring migration in the Chukchi Sea had eaten arctic cod, (*Boreogadus saida*), shrimps, and octopus. During late spring and summer, in the coastal zone, important prey included saffron cod (*Eleginus gracilis*), sculpins, herring, smelt, capelin, salmon, char (*Salvelinus malma*), shrimps, and octopus. In Norton Sound and southeastern Kotzebue Sound, saffron cod were the primary prey. It was presumed that arctic cod are the most important prey in more northerly regions.

Sekerak, A. 1982. Summary of the natural history and ecology of the arctic cod (*Boreogadus saida*). Species Account Report by LGL Limited for BLM/NOAA OCSEAP. 10 p.

This report provides a review of the world-wide distribution and life history information for arctic cod, a species of prime trophic importance for seabirds and marine mammals in the Arctic. The report is useful for comparative purposes since arctic cod are abundant in the Chukchi Sea.

Skvorc, P.A. 1982. Winter subsistence fishing at villages along the northeast Chukchi coastline. Unpubl. Field Rep. by LGL Limited.

This report describes winter subsistence fishing at the villages of Barrow, Wainwright, Point Lay and Point Hope. It is based upon conversations with villagers conducted during March 19-29, 1982, which were held in order to evaluate the extent that subsistence fisheries could serve as a source of fisheries data relevant to the 'Barrow Arch Sale No. 85' for oil and gas leases. The subsistence information gathered corroborates that related in previous reports (Ivie and Schneider 1979; Pedersen 1979; Pedersen *et al.* 1979; Schneider and Bennett 1979; Craig and Schmidt 1982).

There appears to be a general reduction in the level of winter fishing efforts as villagers adopt a cash-based economy. Time spent at a job is increasing as the villagers now pay for electric household appliances and electric heat. However, subsistence fishing remains important to the people of the villages along the Chukchi Sea coast, particularly at Wainwright. The fish caught here are often sent to Barrow and Point Lay through friends, relatives or barter. There is some winter fishing in Barrow and Point Hope and the people that participate rely on this source of food. In Point Lay, the fall fishing trip to the Kukpowruk River is an important social and subsistence activity.

Smith, H.D., A.H. Seymour and L.R. Donaldson. 1966. The salmon resource. Vol. 2, Chap. 31, pages 861-871. *In*: N.J. Wilimovsky and J.N. Wolfe (eds.). Environment of the Cape Thompson Region, Alaska. U.S. Atomic Energy Commission, U.S. Dep. Commerce, Springfield, VA.

This report describes salmon resources in Kotzebue Sound during 1959-1961. Data were gathered by coastal sampling near Cape Thompson, stream surveys, and discussions with local residents at Kotzebue, Kivalina and Point Hope.

The authors conclude that pink and chum salmon are the abundant species in this region, although all five salmon species range as far north as Cape Thompson. The number of salmon and their importance to the economy of the region dwindle north of Kotzebue Sound. Large catches of salmon are made in subsistence fisheries at Kotzebue, but very few salmon are taken at Point Hope and Kivalina. Some morphometric and meristic data are presented for salmon in the Kotzebue Sound region.

Springer, A.M. and D.G. Roseneau. 1978. Ecological studies of colonial seabirds at Cape Thompson and Cape Lisburne, Alaska. Pages 839-960. *In*: Environ. Assess. Alaskan Cont. Shelf. Annu. Rep. Prin. Invest. Vol. 2. BLM/NOAA, OCSEAP, Boulder, Colo.

This report concentrates on seabird studies, but also presents useful information about forage fishes in terms of the birds' feeding ecology. Information about the general distribution of fishes is derived from bird foraging patterns and fishes eaten. Principal fish species eaten by murres at Cape Thompson and Cape Lisburne were: arctic and saffron cod, sand lance, and sculpin. Yearly changes in seabird feeding patterns are discussed in terms of fish population dynamics.

Springer, A.M. and D.G. Roseneau. 1979. Ecological studies of colonial sea birds at Cape Thompson and Cape Lisburne, Alaska. Pages 517-574. *In*: Environ. Assess. Alaskan Cont. Shelf. Annu. Rep. Prin. Invest. Vol. 2. BLM/NOAA, OCSEAP, Boulder, Colo.

This report is similar to an earlier report by Springer and Roseneau (1978) and represents the data collection and analysis for 1978. More attention is given to feeding, flight patterns and feeding sites than previously, and less attention to stomach content analysis. It is noted that at Cape Thompson, murres and kittiwakes exploited Pacific herring, which had been absent from their diets in previous years. A major reason for fluctuations in bird distributions appears to be changes in prey (fish and zooplankton) abundance and diversity. The authors state:

> One of the most critical elements of kittiwake biology in the region appears to be sandlance. In certain years the fish school in dense shoals in shallow, nearshore waters and are easy prey for most seabirds, especially kittiwakes which are restricted to feeding in waters less than about one meter in depth. Sandlance have been seen to fluctuate in their abundance and in the time when they arrive near the bird colonies, fluctuations which have coincided with major changes in kittiwake reproductive success. Therefore, we believe that studies should be undertaken which would address questions concerning the natural history of sandlance. If sandlance populations were jeopardized by effects of resource development, the results might be disastrous to kittiwake populations in the eastern Chukchi Sea.
>
> Sandlance, however, are not the only food resources upon which seabirds depend. Murre food habits data suggest that other fish -- cod and sculpins -- and invertebrates are also important to the population. Our data also suggest that different food groups may be more abundant at some times during the summer than others. The success of the murre population, therefore, may depend upon a well-timed

sequence of events which assures that adequate food of some type will be available to the birds throughout the summer. Loss of any component could threaten the population.

Springer, A.M., E.C. Murphy, D.G. Roseneau, and M.I. Springer. 1982. Population status, reproductive ecology and trophic relationships of seabirds in northwestern Alaska. *In*: Environ. Assess. Alaskan Cont. Shelf. BLM/NOAA, OCSEAP, Boulder, Colo. 470 p. (in press)

(not seen)

Swartz, L.G. 1966. Sea cliff birds. Bol. 2, Chap. 23, Pages 611-678. *In*: N.J. Wilimovsky and J.N. Wolfe (eds.). Environment of the Cape Thompson region, Alaska. U.S. Atomic Energy Commission, U.S. Dep. Commerce, Springfield, VA.

This chapter of the Project Chariot report concentrates on seabirds, but contains useful information about fish of the area as a function of bird diets. The author suggests that the birds in the Cape Thompson region consume approximately 13 million kg of fish per 139 day breeding season, indicating that there is a very substantial population of forage fish in the area. Most of this biomass is made up of arctic cod, sand lance and fourhorn sculpin.

Walters, V. 1955. Fishes of western arctic America and eastern arctic Siberia. Bull. Am. Mus. Nat. Hist. 106:255-368.

This report provides a taxonomic key and annotated list of arctic fishes, and an extensive discussion of zoogeographic patterns of fishes since the last period of glaciation. While the breadth of information presented is considerable, almost 30 years' worth of more recent information has accumulated.

Walters, V. 1961. Winter abundance of *Arctogadus glacialis* in the Polar Basin. Copeia 2:236-237.

In recognizing the sparsity of fisheries information available for the Polar Basin, the author briefly presents some data regarding fishes caught in 1959-1960 by seismic blasting and dredging from Station Charlie, a floating ice station northwest of Barrow. The polar cod, *Arctogadus glacialis*, was the principal species caught in the vicinity of 77°12'N lat., 168°12'W long.

The author suggests that, since these cod were only obtained in winter and only when the ice station was in the vicinity of the Chukchi Rise, that the fish were not following the ice in its movement, but rather that the ice passed over aggregations of fish. Dredge samples also yielded the greatest number of otoliths in the area of the Chukchi Rise. The author suggests that schools of polar cod undertake migrations across the shallow waters of the Chukchi Rise in mid-winter.

Single specimens of *Lycodes frigidus* and *Careproctus reinhardti* were also caught.

Wigutoff, N.B. and C.J. Carlson. 1950. A survey of the commercial fisheries possibilities of the Seward Peninsula area, Kotzebue Sound and certain inland rivers and lakes in Alaska. U.S. Fish Wildl. Serv. Fishery Leaflet 375. 24 p.

(not seen)

Wilimovsky, N.J. 1956. The utilization of fishery resources by the arctic Alaskan Eskimo. Nat. Hist. Mus. Stanford Univ., Occas. Pap. No. 2. 8 p.

This paper describes the utilization of arctic fish resources by North Slope communities from Point Hope, Alaska to Herschel Island, Canada. An attempt is made to compare the extent of utilization in the early 1950's with that in earlier periods in the history of these people. The data were gathered during the course of other studies, and include some 27 interviews with Eskimos and an examination of the literature pertaining to the fisheries.

The author first notes that, although arctic fish stocks are less numerous than those in more southern waters, local residents use a higher percent of the species present. In the 1950's, freshwater catches of grayling, whitefish, sheefish, trout and burbot were of economic value to the Eskimos. Marine species (salmon, smelt, cod and flounders) were exploited only slightly.

The author suggests that fish resources were under-utilized because:

> Fishing was, and is, not a highly regarded art, so many of its labors fell to women. There have never been rituals connected with it, as there were for practically all forms of hunting.... The reasons for this slight utilization of an otherwise valued economic resource may be traced in part to the social customs of these coastal people as well as to their economic needs. They are gregarious and inter/intra-family ties were and still are strong. It was not desirable for a part of the family to be away, more or less isolated from any settlement, as fishing

> at inland camps required. With an abundance of such marine mammals as seals, walrus and whale, there was no incentive to develop sea-fishing techniques to any degree.

There is an interesting note that salmon fishing in the Point Hope area "is carried out much more extensively today than in earlier times, if the limited finds of salmon spears in archeological sites can be taken as a true indication of fishing intensity...." Wilimovsky suggests that "perhaps this may be due to the general warming of the Arctic and the extension of salmon ranges to the north." [This appears to be a precursor to hypotheses like Nieman's (1963) "that annual fluctuations of water temperature, rather than availability of food, may be the determining factor responsible for the maximum northerly distribution of many benthophagic species" (cited in Feder and Jewett 1980)].

Wilimovsky summarizes:

> To the Arctic Alaskan Eskimo, fishing in general was never a highly important or significant occupation. Utilization of fish was secondary to exploitation of other animals.... Those Eskimos whose culture is built around a sea-mammal economy rely little on fish as food.... However, the few Eskimos living along the coast east of Barrow have come to use their fishery resource to a greater extent than in the past. It is quite clear that as long as the stock of sea mammals is abundant there is very little possibility that the Arctic Alaskan Eskimo (with the exception of the Anaktuvuk people) will come to exploit fishing to a greater extent.

Winslow, P. 1969. Investigation and cataloging of sport fish and sport fish waters in interior Alaska - char in northwestern Alaska. Annu. Rep. No. 15-A. Alaska Dep. Fish and Game 10:319-3321.

Portions of the author's abstract follow.

> This report presents the results of a study on anadromous Arctic char, *Salvelinus alpinus*, from the Wulik and Kivalina rivers.... Emphasis was placed on collecting life history, subsistence and sport history information.... An aerial count of char in the Wulik and Kivalina rivers revealed an estimated 46,000 char in the Kivalina and 180,500 to 225,600 char in the Wulik.... Native fishermen took an estimated 120,000 pounds of char (49,500 fish) from the Wulik River with seines during the autumn of 1968. An estimated 50-60 sport fishermen trips were made to the Wulik River in 1968.

Winslow, P.C. 1969. Comments on the proposed Wulik River commercial fishery with recommendations. Alaska Dep. Fish and Game, Sport Fish Div., Admin. Rep. 11 p.

(not seen)

Wolotira, R.J., T.M. Sample and M. Morin. 1979. Baseline studies of fish and shellfish resources of Norton Sound and the southern Chukchi Sea. Pages 258-572. *In*: Environ. Assess. Alaskan Cont. Shelf, OCS Environ. Assess. Prog. Final Rep. Prin. Invest. Vol. 6. BLM/NOAA, OCSEAP, Boulder, Colo.

This report presents a comprehensive examination of fish and shellfish resources of the marine environment from Norton Sound northward through the Bering Strait and into the southeastern Chukchi Sea. The authors also review the commercial and subsistence fisheries of the area from 1962 to 1976.

There are 15 families represented by 87 fish species found in Norton Sound and the southeastern Chukchi Sea. Of these, seven families composed of 78 species make up 85% of the total fish fauna. Benthic species make up 74% of the total fish fauna of the area. The fish fauna of the area are characterized by three groups: (1) cold water groups indigenous to arctic marine waters including arctic cod, longhead dab, arctic flounder, and a number of cottid and blennoid species; (2) a subarctic boreal group which includes saffron cod, yellowfin sole, Alaska plaice, starry flounder and Pacific herring, whose distribution is centered south of the study area in the Bering Sea of regions of the eastern and western Pacific; and (3) an anadromous freshwater group with several forms such as char, whitefish and smelt, whose marine distribution occurs only in estuarine and other nearshore environments.

Substantial morphometric, distributional and catch-per-unit effort data are presented in this report. There are no other reports of this scope or magnitude with the exception of the 'Project Chariot' studies near Cape Thompson (Alverson and Wilimovsky 1966; Smith *et al.* 1966).

The authors' summary of several major findings pertaining to fish follows:

(1) Results of the 1976 BLM/OCS demersal survey of Norton Sound, the southeastern Chukchi Sea, and adjacent waters indicate that highest relative abundance for nearly all fish and invertebrates occurred south of Bering Strait, especially in Norton Sound.

(2) Gadidae (cods) and Pleuronectidae (flounders) were the dominant fish families encountered during the survey and had a combined estimated biomass of over 33,000 [metric tons]. This amount accounted for 70% of the total fish biomass estimated for the survey area. Cottidae (sculpin), Osmeridae (smelts), and Clupeidae (herring) accounted for an additional 25% of the total fish biomass.

(3) The eight most abundant fish species in the survey region, by rank order of estimated biomass were: saffron cod, starry flounder, shorthorn sculpin, Pacific herring, toothed smelt, Alaska plaice, yellowfin sole, and arctic cod.

(4) Most of the dominant fish species were found in highest relative abundance in areas south of Bering Strait and where bottom waters were warmer than 4°C and shallower than 30 m...

(5) Arctic cod was an exception to relative abundance trends for the dominant fish species. Relatively high abundance of this species occurred at nearly all bottom temperatures and at depths greater than 20 m.

(6) Almost no fish species were encountered in either sufficient size or quantity to be considered as potential for commercial harvest. Pacific herring is the only non-salmonid species presently taken in a commercial fishery in the survey region. Recent harvests have been very small and attempts to greatly expand harvest levels do not appear likely.

(7) Survey information on age-length and length-weight relationships indicate age and growth differences north and south of the Bering Strait for several fish species. Pacific herring, toothed smelt, yellowfin sole, and Alaska plaice all displayed greater lengths-at-age and maximum sizes south of Bering Strait than to the north, while saffron cod data suggested the opposite - largest size and lengths-at-age in the north. Definite reasons for growth differences were identified and seem to suggest some stock segregation within the survey region.

(8) Little is known about spawning and nursery areas in the survey region. An examination of catch rates by stratum for the youngest two age groups of each dominant fish species provides some insight as to possible locations of spawning areas and nursery grounds. Highest relative abundance for young saffron cod, Pacific herring, starry flounder, Alaska plaice, and yellowfin sole was found in Norton Sound. For species with more arctic distributions, arctic cod and toothed smelt, either cold-deep waters or regions north of Bering Strait provided the areas of highest density of young fish.

(9) About 2/3 of the area surveyed during the 1959 AEC work in the southeastern Chukchi Sea coincided with portions of our 1976 survey region (primarily stratum 1N). A general comparison of species composition and relative species abundances between the 1959 and 1976 data for this overlapping region suggests that no major changes have occurred in the fish community of the southeastern Chukchi Sea since that earlier study.

Wohlschlag, D.E. 1956. Information from studies of marked fishes in the Alaskan Arctic. Copeia 4:237-242.

This report discusses technical aspects of mark-and-recapture studies of fishes in coastal waters near Barrow, Alaska. Some information on the distribution of least cisco and fourhorn sculpin in Elson Lagoon is also provided. Data indicate that least cisco use the area during the open-water season but move up to the Meade River by way of Admiralty Bay to spawn in the fall.

Yanagawa, C. 1971. Kotzebue chum salmon tagging project, 1966-1968. Alaska Dep. Fish and Game, Arctic-Yukon-Kuskokwim Region. Fish. Bull. No. 7.

(not seen)

POPULATION GENETIC STRUCTURE OF ARCTIC CHAR (*SALVELINUS ALPINUS*) FROM RIVERS OF THE NORTH SLOPE OF ALASKA

by

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Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 682

1987

ACKNOWLEDGMENTS

This study was funded by the Minerals Management Service, Department of the Interior, through an interagency agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program.

SUMMARY

Potential problems with oil and gas development in the Beaufort Sea area include the effects of offshore construction of causeways and other structures on anadromous species such as Arctic char (Salvelinus alpinus). By studying the amount and pattern of genetic variation in the populations while they are associated with their natal drainages, we can make inferences about the evolutionary history of northern Arctic char, and predict their ability to respond to changing environmental conditions.

Electrophoretic detection of protein variation makes it possible to discriminate among stocks using quantifiable characters having a genetic basis. This proven method requires a relatively small sample of fish from different populations for baseline data. Further, electrophoretically distinguishable characters have generally proven to be stable characteristics of fish stocks that have been studied. If the species of concern has a suitable stock structure, biochemical genetics methods can be used to estimate the percent composition of various stocks represented in samples from mixed aggregations.

The objectives of this project are to 1) characterize the amount and pattern of genetic variation in populations of anadromous Arctic char from major drainages of the North Slope of Alaska, 2) determine whether the population structure of North Slope char is such that genetic stock identification of mixed populations collected from offshore waters would be possible, and 3) describe how a sampling program would be designed to use genetic stock identification to determine which stocks would be affected by specific development projects.

Samples from fifteen populations of juvenile Arctic char were collected from ten tributaries to the Beaufort Sea. We used horizontal starch-gel electrophoresis to identify protein products of forty-one loci coding for twenty enzymes in three tissues. We measured the amount of variation, the pattern of variation (genotypic distribution) within population samples, the similarity between populations, their heterogeneity, and the degree of gene diversity among groups.

Northern Alaska Arctic char have more genetic variation than might be expected given the relatively narrow range of waters they inhabit and the harsh environmental conditions. With an average heterozygosity per locus of 5.1%, they are typical of fish species in general; at the upper end of the range observed in other salmonid fishes; and higher than most other Arctic char populations that have been studied.

The genetic identities (Nei 1972) among North Slope Arctic char populations are high (>.987), indicating fairly recent common ancestry. High similarity values do not imply lack of significant differences between populations. Heterogeneity tests indicate the distinctness of the populations and the complexity of the relationships between them. Almost all North Slope Arctic char populations are significantly genetically distinct from each other. Thus, fish from different drainages are not freely interbreeding, and are most likely true to their spawning streams. There is no simple correlation between genetic relationships and geographical proximity.

It is not possible to determine the underlying cause of the observed relationships among North Slope Arctic char populations from protein studies. Selection, migration, mutation, behavioral isolation, founder effects, random genetic drift (chance changes due to small populations size) and combinations of these and other forces may all contribute.

North Slope Arctic char do not have the magnitude of difference between groups exhibited by the non-migratory char of northern Europe. They do, however, compare with the population structure of anadromous Pacific salmon. This is relevant because genetic stock identification methods have been successfully applied to these salmonids, and can apparently be applied to North Slope Arctic char.

To do genetic stock identification there must be sufficient detectable genetic variation between populations of different major drainages, combined with a low within-group variability. Our data indicate that North Slope char have a relatively large amount of genetic variation; there are significant differences among populations; and the observed variation is partitioned such that there is as much difference between char from different drainages as there is among populations of sockeye and chum salmon where genetic stock identification has been used successfully. As such, we can anticipate successful application of this technique to the identification of char at specific offshore sites.

Management Implications

We have determined that North Slope char have a relatively large amount of genetic variation, and that populations are genetically distinct from each other. From this we know that different stocks are currently reproductively isolated from each other. Since they do mix to some unknown degree in feeding areas, the differences that have been established between stocks are maintained by homing behavior. Populations of each drainage are probably discrete, locally adapted units. It is not clear at this time how non-migratory forms are related to anadromous stocks.

It is unlikely that loss of any one stock would be mitigated by substitution of another. While the actual loci we have studied may be selectively neutral, underlying variation that is marked by these loci may be highly selected for in different environments, corresponding generally to different drainages. As such, Arctic char stocks of the North Slope should be managed as individual, unique gene pools.

Further work is needed to understand the relationships among populations. To get a complete picture of the resource, we should consider deliberately sampling resident populations. It is important that we identify and sample additional populations making major contributions to the Beaufort Sea admixture, as it is an important assumption of the GSI model that all major contributors to a mixed stock be represented in the baseline. It is also important to understand that genetic stock identification estimates the percent composition at only one point in space and time.

Distribution of offshore stocks of fish is related to environmental conditions which are highly variable from year to year. Also, Arctic char are highly mobile in offshore areas, so estimates should be made of stock composition at several times during the short summer feeding season. It must be realized that there will be considerable variation, regardless of study method used, between data from different years and different areas and at different times during the season. This means that stock identification must be done on a site-specific basis, with repeated sampling during the summer, and that data from more than one year will be required to establish the pattern of use by the fish.

TABLE OF CONTENTS

INTRODUCTION

Most current environmental concerns on the North Slope of Alaska are related to the impacts of oil exploration and development on fish and populations. Potential problems include the effects of offshore causeways and other structures on anadromous species such as Arctic char (Salvelinus alpinus) and Arctic cisco (Coregonus autumnalis). In offshore areas, these species are in mixed aggregations, which makes it difficult to determine specifically which stocks could be at risk.

Arctic char are of special interest because of their relatively low abundance, limited range in a narrow band of coastal waters, and their importance in subsistence fisheries. Studies (e.g. Furniss 1975; Craig and McCart 1975) characterizing the marine and freshwater phases of Arctic char life history emphasize the importance of the coastal area of the Beaufort Sea. Populations of Arctic char migrate from freshwater, springfed spawning and overwintering areas to nearshore marine feeding grounds. Migration studies using mark and recapture techniques indicate that movements are generally limited to an area adjacent to the river of origin (Furniss 1975). However, examples of extended migration and overwintering in drainages other than those used for spawning have been documented (Craig and McCart 1976; Glova and McCart 1974).

In order to determine which stocks could be affected by development, and possibly to predict how they would be affected, we need to understand the stock structure of both the inland and offshore stages of the Arctic char life history. By studying the amount and pattern of genetic variation in the populations while they are associated with their natal drainages, we can make inferences about the evolutionary history of northern Arctic char, and predict their ability to respond to changing environmental conditions. Also, with preliminary data we can determine the applicability of genetic stock identification methods to management problems involving the mixed stocks at specific offshore sites.

Most methods that have been used in the past to study the relationships among salmonid populations require intensive annual field sampling because the distinguishing characteristics are usually growth rings of scales and/or otoliths. The marks on these structures are determined by environmental differences reflected in patterns of fish growth, and are not static population characteristics. Acquisition of adequate sample sizes of salmon of known and unknown origin is essential to the success of stock identification using these characteristics. Large sample sizes are needed to develop the "standards" required for tests with specimens of unknown origin. In order to ensure that regional stocks are represented in the analysis, the sampling strategies must account for stock and species-specific characteristics relative to age and size of fish smolting and the intermingling of migrating stocks in coastal waters.

Electrophoretic detection of protein variation makes it possible to discriminate among stocks using quantifiable characters having a genetic basis. This proven method requires a relatively small sample of fish from different populations to establish baseline data. Further, electrophoretically distinguishable characters have generally proven to be stable characteristics of fish stocks that have been studied (see Utter et al. 1981), although there are exceptions (Wilmot, unpublished data).

If the species of concern has a suitable stock structure, biochemical genetics methods can be used to estimate the percent composition of various stocks represented in mixed aggregations sampled from offshore areas. The amount of effort required to study mixed stocks is relatively small using these techniques compared to methods requiring extensive extrinsically applied marks (Ihssen et al. 1981). This type of information provides site-specific information on stocks at risk from habitat alteration, and biological data at migratory stages of the life cycle of these natural populations.

Objectives

The objectives of this portion of the Arctic Fish Habitats and Sensitivities project are to: 1) characterize the amount and pattern of genetic variation in populations of anadromous Arctic char from major drainages of the North Slope of Alaska, 2) determine whether the population structure of North Slope char is such that genetic stock identification of mixed populations collected from offshore waters would be possible, and 3) describe how a sampling program would be designed to use genetic stock identification to determine which stocks would be affected by specific development projects.

METHODS

Samples from fifteen populations of Arctic char were collected from the North Slope of Alaska by U.S. Fish and Wildlife Service (USFWS) biologists of the Fairbanks Fisheries Assistance Office. Figure 1 shows the study area and Table 1 the sampling location, number of fish used for electrophoresis, and the date of collection. Minnow traps and electrofishing gear were used to catch juvenile char which were shipped to the Alaska Fish and Wildlife Research Center (AFWRC) laboratory in Anchorage either alive or frozen whole. Skeletal muscle, liver, and eye tissues were dissected from the samples in the laboratory and used for protein electrophoresis.

ELECTROPHORETIC METHODS

We used horizontal starch-gel electrophoresis to identify protein products of gene loci following the methods described by Utter et al. (1974). Buffers and staining procedures were after Allendorf et al. (1977), and isozyme nomenclature was that of Allendorf et al. (1983). Gel buffers included: AC (Clayton and Tretiak 1972) pH 6.3 - 6.8; AC+ (AC plus 30 mg NAD and one drop of mercaptoethanol); RW (Ridgway et al. 1970) pH 8.2; MF (Markert and Faulhaber 1965) pH 8.7.

Building on the work of Andersson et al. (1983), Hindar et

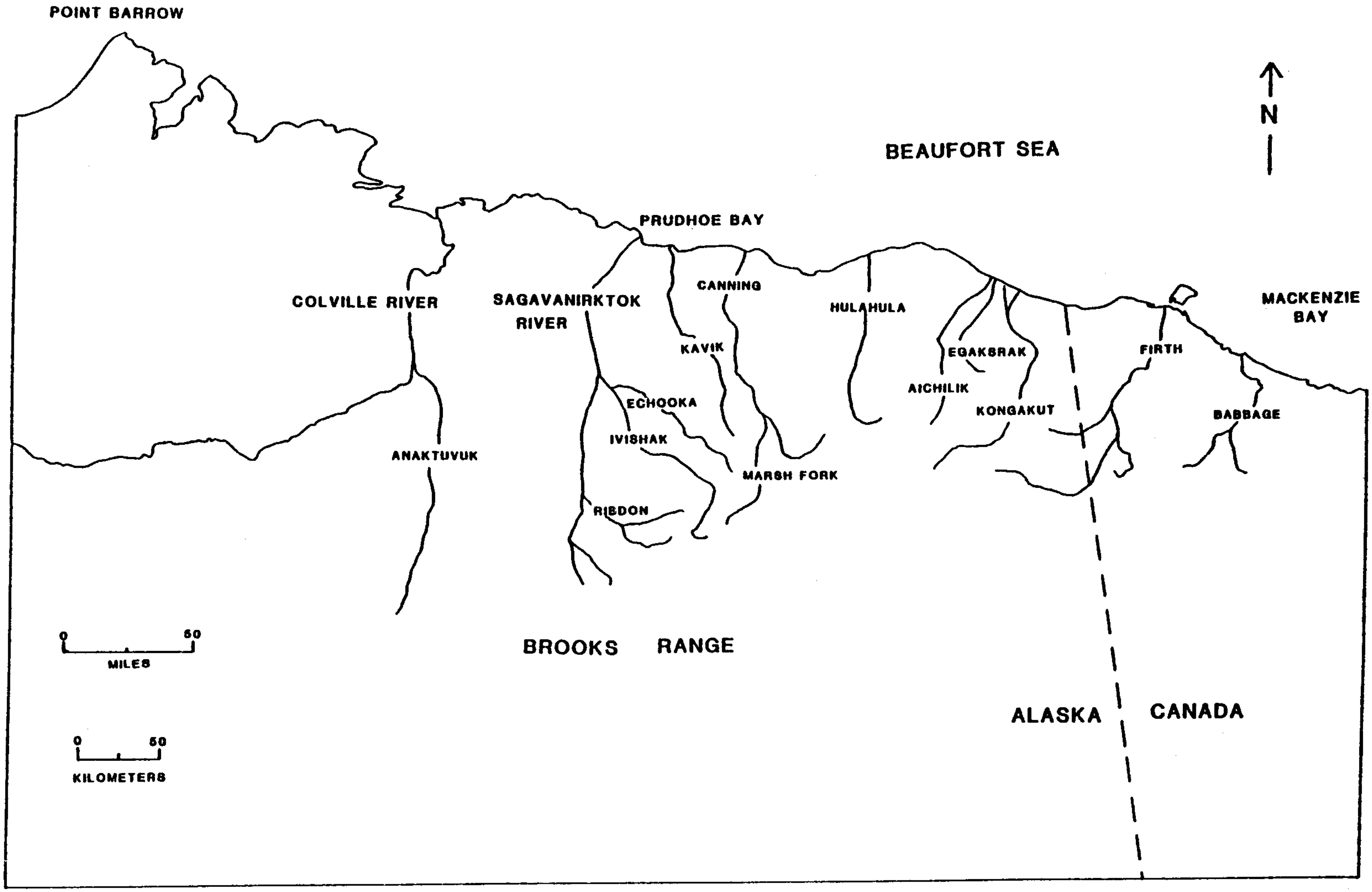

Figure 1. North Slope of Alaska study area for Arctic char genetic research.

Table 1. Population, location (latitude and longitude), number of char sampled, and date of collection.

Population	Location	Number	Date
Aichilik	69°22'N, 143°05'W	40	9/86
Anaktuvuk	68°42'N, 151°13'W	40	5/86
Babbage (Canoe River)	68°37'N, 138°42'W	35	9/86
Canning	69°54'N, 145°45'W	27	5/86
Canning Marsh Fork	69°05'N, 146°00'W	29	5/86
Echooka	69°15'N, 147°18'W	24	4/86
Egaksrak River	69°24'N, 142°35'W	41	5/86
Firth (Joe Creek)	68°57'N, 140°58'W	40	9/86
Hula Hula Site #1	69°45'N, 144°15'W	15	10/85
Hula Hula Site #2	69°28'N, 144°20'W	37	10/85
Hula Hula Site #3	69°18'N, 144°33'W	59	10/85
Ivishak	68°58'N, 148°08'W	50	5/86
Kavik	69°24'N, 146°34'W	40	4/86
Kongakut	69°31'N, 141°42'W	40	9/86
Ribdon	68°38'N, 148°12'W	40	5/86
Total Sampled		557	

al. (1986), Johnson (1984), Kartavtsev et al. (1983), Kornfield et al. (1981), and Robb Leary (University of Montana, personal communication), more than 25 enzymes were tested for activity and resolution on various buffers and tissues. Our statistical results are based on successful resolution of forty-one loci coding for twenty enzymes in three tissues (Table 2). Other tissues were tested but added little or no additional information. The loci we used are those with nearly complete data sets and consistent results, including good resolution and a repeatable pattern of expression.

Inferences were made regarding enzyme expression based on 1) assumptions of parallel expression with that of other salmonids with experimentally determined patterns of inheritance (especially Johnson 1984), 2) comparisons based on different tissue expression, and 3) on the known molecular subunit structure of the enzymes. Mobilities of enzymes were measured relative to the common electrophoretic phenotype observed in samples of Anaktuvuk River Arctic char.

In many cases, expression of different gene loci is specific to a particular tissue or tissues. Often the pattern of expression of genes among tissues is a species-specific trait. We studied tissues rather than blood because blood is difficult to collect; special handling is required to maintain the quality of blood samples; enzymes are less stable in blood; and because

Table 2. Enzymes, Enzyme Commission (E.C.) numbers, and loci examined in samples of Arctic char from northern Alaska. Buffers include: AC (Clayton and Tretiak 1972) pH 6.3-6.8; AC+ (AC plus 30 mg NAD and one drop of mercaptoethanol); RW (Ridgway et al. 1970) pH 8.2; MF (Markert and Faulhaber 1965) pH 8.7. Tissues include muscle (M), liver (L), and eye (E). The pairs of loci listed in parentheses are electrophoretically indistinguishable (isoloci). For this analysis they were considered as individual loci.

Enzyme	E.C. #	Loci	Buffer	Tissue
Acetylglucosaminidase	3.2.1.30	Hex1	RW	L
Adenylate kinase	2.7.4.3	Adk1,2	AC	M
Alcohol dehydrogenase	1.1.1.1	Adh1	RW	L
Aconitate hydratase	4.2.1.3	Aco3	AC	L
Aspartate aminotransferase	2.6.1.1	Aat1,2	RW, AC	L, E
		Aat(3,4)	RW, AC	M
Creatine kinase	2.7.3.2	Ck1,2	RW	M
		Ck3	RW	E
Glucose phosphate isomerase	5.3.1.9	Gpi(1,2),3	RW	M
Glyceraldehyde-3-phosphate dehydrog.	1.2.1.12	Gap(3,4)	AC+	E
Glycerol-3-phosphate dehydrogenase	1.1.1.8	G3p1	AC, RW	L, M
Glycyl-leucine peptidase	3.4.11	Gl1	MF	E
Isocitrate dehydrogenase	1.1.1.42	Idh1,2	AC	M
		Idh(3,4)	AC	L
Lactate dehydrogenase	1.1.1.27	Ldh1,2	RW	M
		Ldh4	RW	L
		Ldh3,4,5	RW	E
Leucyl-glycyl-glycine peptidase	3.4.13	Lgg1	MF	E
Malate dehydrogenase	1.1.1.37	Mdh(1,2)	AC	L
		Mdh(3,4)	AC	M
Malate dehydrogenase (NADP-dependent)	1.1.1.40	Me1,2,3	AC	M
		Me4	AC	L
Phosphoglucomutase	2.7.5.1	Pgm1,2	AC, RW	L, M
6-Phosphogluconate dehydrogenase	1.1.1.44	6Pg1	AC	M
Sorbitol (iditol) dehydrogenase	1.1.1.14	Sdh1	RW	L
Superoxide dismutase	1.15.1.1	Sod1	RW, AC	L
Xanthine oxidase*	1.2.3.2	Xo1	RW	L

* Observed phenotype probably represents diaphorase activity.

more information is available from tissues. Carmichael et al. (1986) found that of 64 loci they studied in largemouth bass, only 24 (37%) were adequately expressed in blood. Muscle tissue expressed 37 loci (57%) and liver, 39 (60%). A combination of liver and muscle expressed 80% of the loci tested. We have found that eye tissue adds at least four more loci to the combination of muscle- and liver-specific loci.

STATISTICAL METHODS

Sample size

Ideal sample size is evaluated based on the 95% probability of including variants in the sample, if those variants are present in some minimum frequency within the sample. For example, to be 95% sure of observing variants present in a sample in a frequency of at least 2%, N (the sample size) for a diploid organism would have to be approximately 40 ($.95^{2N} = .02$). We chose forty individuals as a reasonable sample size, though samples with less than forty were included in the analyses.

Amount of genetic variation

The amount of genetic variation is estimated by determining the percent of loci that are polymorphic (P), and the mean percent of heterozygous loci per individual (H). Expected average heterozygosity for each locus is calculated using allele frequencies of observed genotypes in each population and expected random mating (Hardy-Weinberg) proportions:

$$H = 1 - \left(\sum_{j=1}^{L} \sum_{i=1}^{A_j} P_{ij}^{2} \right) / L$$

where L is the number of loci, A_j is the number of alleles at the j^{th} locus, and P_{ij} is the frequency of the i^{th} allele at the j^{th} locus.

The standard criteria for polymorphism (P) is the percent of the loci examined in a population in which the frequency of the common allele is less than or equal to 0.99.

For this and subsequent analyses, isoloci (duplicated locus pairs with indistinguishable mobilities) were counted as two individual loci and all observed variation was attributed arbitrarily to only one locus of the pair.

Genotypic distribution

Observed genotypes in samples were tested for conformance to random mating (Hardy-Weinberg) proportions. A chi-square test was used to determine whether the frequency of genotypes for each locus equal those expected from calculations of probable combinations of alleles (with the frequencies we observed) joining at random. For each population sampled, a multiple simultaneous chi-square test was done by summing the chi-square values over all the variable loci, summing the degrees of freedom, and comparing these values to the expected distribution.

Genetic similarity

The genetic similarity between the 15 char samples was determined using computer programs by Donald Campton of University of Washington (UW). The program calculates Nei's index of genetic identity (1972; 1978) using the probability of identity of gene pairs between populations averaged over all loci. The normalized identity of genes between two populations, X and Y, is defined as:

$$I = J_{XY} / \mathrm{SQRT} (J_X J_Y)$$

where J_X, J_Y, and J_{XY} are the arithmetic means over all loci of the probabilities of identity between gene pairs among populations.

Identity values are scaled from 0.0 to 1.0; 0.0 corresponds to complete allele substitution at all loci, and 1.0 to populations that are electrophoretically indistinguishable at all loci studied. Genetic distance is calculated as the negative natural log of the identity value.

Genetic identity values were used in a clustering algorithm (UPGMA: Sneath and Sokal 1973) modified by Donald Campton (UW) to produce a dendrogram of relationships among populations. The average linkage method of clustering was used, and the analysis was weighted to reflect unequal sample sizes. The three Hula Drainage populations were combined because of the lack of heterogeneity among them.

We also used a multidimensional scaling procedure (Kruskal and Wish 1977) to show relationships among populations. This method uses Nei's indices of genetic similarity among populations and defines each population as a point in Euclidean space. The multidimensional construct is then reduced to a two-dimensional plot. As such, the relative distances among points on the diagram illustrate the relative genetic distance among populations.

Genetic heterogeneity

To test the heterogeneity between paired populations, we used multiple simultaneous G-tests (Sokal and Rohlf 1981). G-tests were performed for each locus, and G-values and degrees of freedom for each locus were summed over all loci in all pairs and tested against a chi-square distribution. Because of the robustness of the test, only cells with expected values less than 1.0 were combined.

The large number of non-independent pairwise comparisons (78) makes it possible that a percentage of the comparisons could appear significantly different by chance. Consequently, the probability value required to demonstrate a significant difference was modified for this analysis according to Cooper (1968) to eliminate spurious correlations.

Gene diversity analysis

Gene diversity analysis determines the source of observed variation, i.e., what proportion of the observed variation is between individuals within populations, as opposed to differences among populations or groups of populations. Our analysis was done with a computer program by Donald Campton (UW) based on the work of Nei (1973) and Chakraborty (1980). Modifications include use of simple unweighted arithmetic averages of population samples within sites rather than weighting gene frequencies within sites by the number of samples.

Sample data were analyzed in levels: as individual subpopulations (sites), as subpopulations of different drainages, and as a whole. The total amount of genetic variation of all populations studied was partitioned into within- and between-subpopulation diversity components. The total gene diversity (H_T) over all subpopulations equals the average heterozygosity within the subpopulations (H_S) plus the average gene diversity between subpopulations (D_{ST}). The diversity between subpopulations (D_{ST}) can be broken down to differences between sites within a drainage (D_{BS}) and differences between populations of different drainages (D_{BD}). The relative magnitude of gene differentiation among populations (G_{ST}) was estimated as D_{ST} / H_T or (D_{BS} + D_{BD}) / H_T, and can be expressed as a percentage.

Figure 2 shows how the North Slope char data were combined for this analysis, excepting that in the actual analysis the combination of Ivishak and Echooka was not considered.

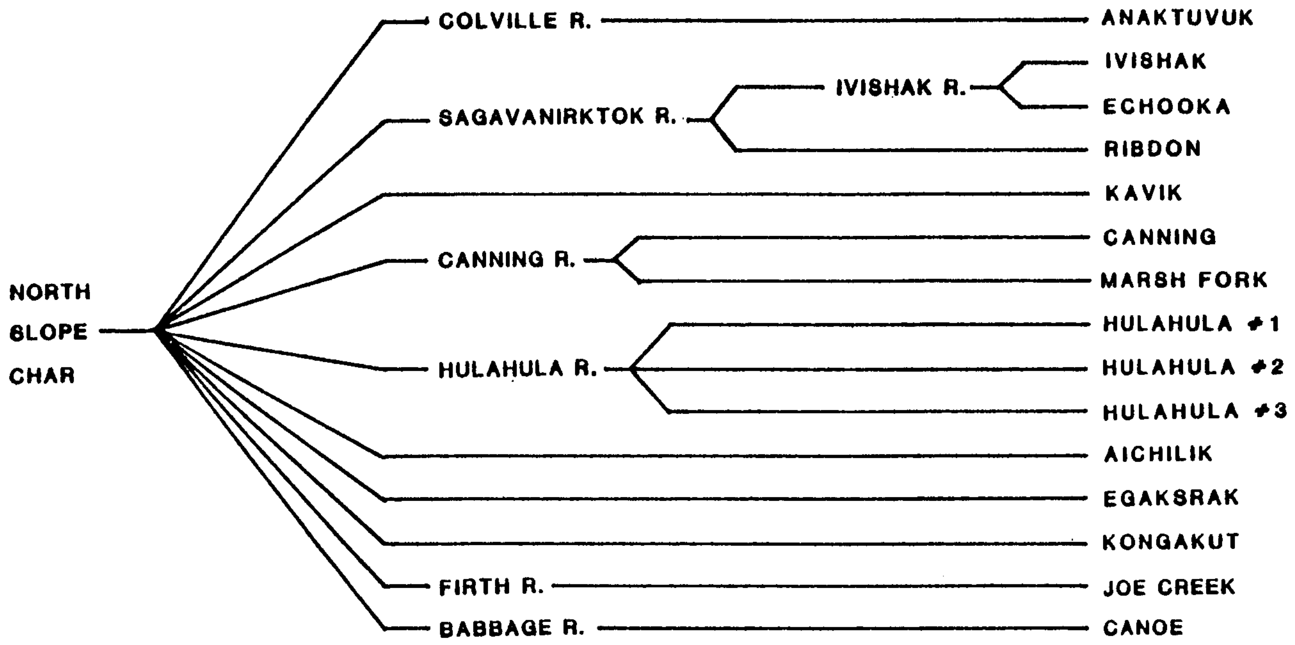

Figure 2. Hierarchical structuring used in the gene diversity analysis of 15 North Slope Arctic char populations.

RESULTS

The genetic variation of populations can be quantified, making it possible to determine not only the amount of variation within populations, but also the pattern of variation among them. We have measured the amount of variation, the pattern of variation (genotypic distribution) within population samples, the similarity between populations, their heterogeneity, and the degree of gene diversity among groups, studied hierarchically.

Amount of genetic variation

Allele frequencies and relative mobility of variable loci are listed in Appendix 1. Percent of loci polymorphic and average heterozygosity for the 15 populations of Arctic char sampled are reported in Table 3. Over 40% of the gene loci studied are variable in at least one of the populations. The values of P range from 13.2 to 29.3%. Average heterozygosity ranges from 3.1 to 7.0% for the samples, and the weighted average over all 15 populations is 5.1%.

Genotypic distributions

Significant deviation from expected values can indicate non-random mating, unequal fertility among parents, unequal viability

Table 3. Average percent of fish heterozygous per locus (H), and percent of loci examined that were polymorphic (P) in 15 populations of Arctic char from the North Slope of Alaska.

Population	% H	% P
Babbage (Canoe River)	4.72	15.0
Firth (Joe Creek)	5.17	29.3
Kongakut	5.92	22.0
Egaksrak	6.47	26.8
Aichilik	7.02	24.4
Hula Hula Site #1	4.12	13.2
Hula Hula Site #2	5.41	26.3
Hula Hula Site #3	4.47	23.7
Canning	6.21	25.0
Canning Marsh Fork	6.16	29.3
Kavik	3.14	15.0
Echooka	4.19	22.5
Ivishak	4.26	25.6
Ribdon	6.06	25.0
Anaktuvuk	5.37	23.1
Average	5.25	23.08

among offspring (selection), migration from other populations, or failure to collect a random sample from the population. In the 15 samples of Arctic char we studied, there is no evidence of departure from the expected genotypic distributions. The parental generations have apparently been mating at random (no more than one population was detected in any sample), and the collections appear to represent random samples of the populations.

Genetic similarity

No allele substitutions were observed at any locus. Genetic identities are high among North Slope char, all greater than or equal to 0.987 (corresponding to a genetic distance of 0.013). The values range up to complete identity, 1.000, and are reported in Table 4.

The dendrogram of Figure 3 illustrates the genetic relationships among Arctic char populations of tributaries of the Beaufort Sea. Three main groups are apparent at approximately the .9950 level. Figure 4 is another representation of the relationships among North Slope char populations, and illustrates relative Euclidean distances among subpopulations. Although loose clusters of points are evident, there is generally as much difference between points within a cluster as there is between points of different clusters.

Table 4. Matrix of Nei's (1978) gene identity values pairwise among 15 populations of Arctic char from the North Slope of Alaska.

1 Babbage	1.000														
2 Firth	.992	1.000													
3 Kongakut	.993	.998	1.000												
4 Egaksrak	.996	.992	.998	1.000											
5 Aichilik	.999	.990	.994	.998	1.000										
6 Hula #1	.991	.992	.997	.999	.993	1.000									
7 Hula #2	.992	.990	.996	.999	.994	1.000	1.000								
8 Hula #3	.991	.987	.994	.998	.991	1.000	1.000	1.000							
9 Canning	.991	.998	1.000	.997	.993	.997	.995	.993	1.000						
10 Marsh Fork	.997	.994	.996	.998	.999	.995	.992	.990	.997	1.000					
11 Kavik	.990	.997	.998	.996	.992	.998	.995	.993	.998	.996	1.000				
12 Echooka	.991	.998	.998	.994	.992	.997	.995	.992	.999	.996	1.000	1.000			
13 Ivishak	.991	.998	.998	.997	.993	.998	.995	.993	.999	.997	.999	.999	1.000		
14 Ribdon	.994	.998	1.000	.996	.993	.996	.995	.993	.998	.994	.997	.998	.998	1.000	
15 Anaktuvuk	.993	.999	.997	.995	.993	.993	.990	.987	.999	.998	.998	.998	.998	.996	1.000
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15

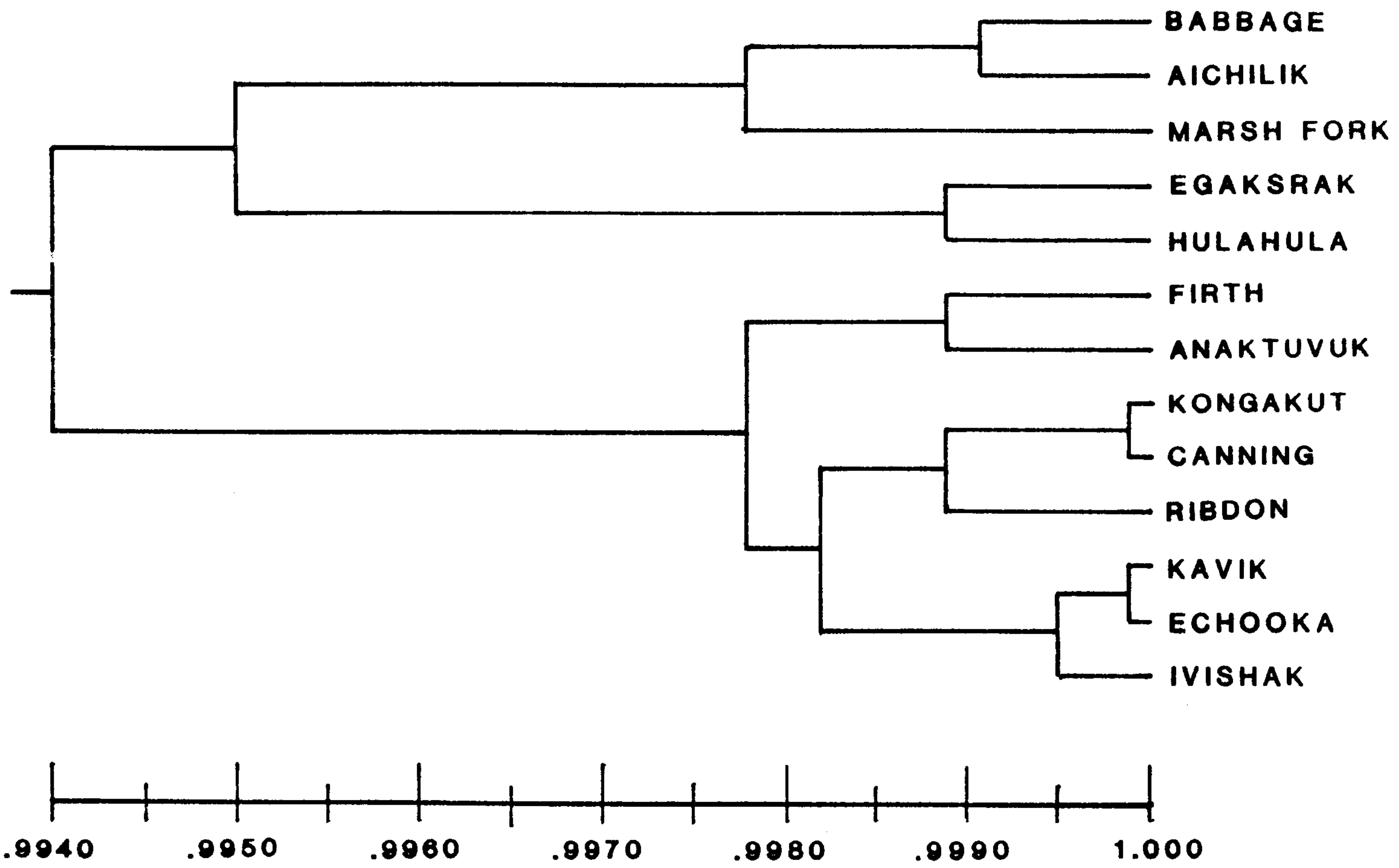

Figure 3. Dendrogram showing relationships of 15 populations of Arctic char from the North Slope of Alaska. The clustering program uses Nei's (1978) unbiased estimates of genetic identity.

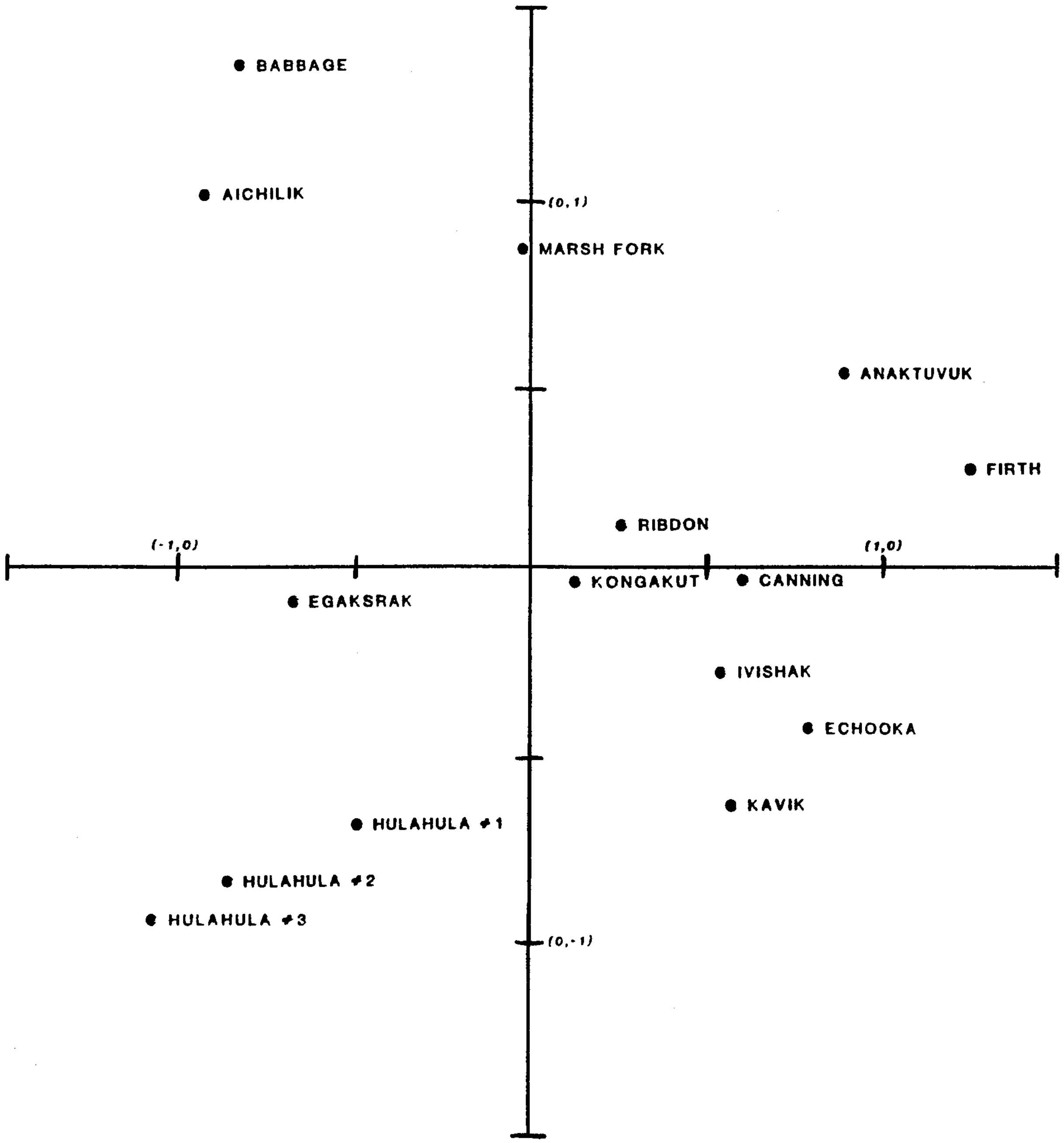

Figure 4. Plot of the relationships among North Slope Arctic char populations as determined using a multidimensional scaling procedure (Kruskal and Wish 1977). Scale of the diagram is standard Euclidean distance.

Genetic heterogeneity

Table 5 lists the results of the heterogeneity tests between North Slope Arctic char populations. The data for the three Hula Hula char samples were combined to simplify the table since they are not significantly different from each other. Sixty-nine out of 78 pairwise comparisons indicate significant genetic differences ($p < .05$) among North Slope char populations. A summary G-test, including all populations and all loci, shows that the Arctic char studied are highly different from each other ($G = 802.4$ with 127 degrees of freedom; $p \ll 0.001$).

Gene diversity analysis

Table 6 shows the absolute and relative magnitude of the diversity among subpopulations, analyzed hierarchically. Approximately 8% of the observed variation is due to differences among the populations of the ten drainages sampled. Less than 1% is due to differences among populations of different sampling sites within drainages. Variation among individuals within populations accounts for 91.5% of the total gene diversity.

Table 5. Matrix of genetic heterogeneity, tested pairwise among North Slope char populations. Data from the three Hula Hula populations were combined because they are not different from each other. The significance level was modified according to Cooper (1968) to reflect the number of pairwise tests (78).

1	Babbage	-												
2	Firth	*	-											
3	Kongakut	*	*	-										
4	Egaksrak	*	*	*	-									
5	Aichilik	*	*	*	NS	-								
6	Hula-all	*	*	*	*	*	-							
7	Canning	*	*	NS	*	*	*	-						
8	Marsh Fork	*	*	*	NS	NS	*	*	-					
9	Kavik	*	*	*	*	*	*	*	*	-				
10	Echooka	*	*	*	*	*	*	NS	*	NS	-			
11	Ivishak	*	*	*	*	*	*	NS	*	*	NS	-		
12	Ribdon	*	*	*	*	*	*	*	*	*	*	*	-	
13	Anaktuvuk	*	*	*	*	*	*	*	NS	*	*	*	*	-
		1	2	3	4	5	6	7	8	9	10	11	12	13

* = p <.05. NS = not significantly different.

Table 6. Gene diversity analysis among populations of Arctic char from the North Slope of Alaska. The average values represent data from all 15 sites from the ten drainages studied.

		Absolute gene diversity				Relative gene diversity (Percent)		
Drainage	# sites	Within sites	Between sites	Between drainages	Total	Within sites	Between sites	Between drainages
Hula Hula	3	.0456	.0008			98.29	1.71	
Canning	2	.0599	.0021			96.63	3.37	
Sagavanirktok	3	.0468	.0014			97.16	2.84	
Average	15	.0550	.0004	.0046	.0601	91.55	0.71	7.73

DISCUSSION

Genetic variation in populations is important because environmental alteration is inevitable, from both natural and man-caused conditions. Populations need to be responsive to change, and with less genetic variation there is a reduced potential to adapt to changing environments. While the immediate consequences of loss of variation are not known for Arctic char, in other species genetic variation is related to growth rate, developmental stability, survivorship, and the ability to compete (Frankel and Soule' 1981; Mitton and Grant 1984).

At the species level, genetic variation is present both within populations and distributed among populations. To determine how best to manage population to ensure their continued health, it is necessary to know both the amount and pattern of genetic variation. Studies using biochemical genetics methods have become increasingly important in fisheries management in the last two decades. Biologists have long recognized that salmonids form phenotypically (physically) recognizable subdivided populations. Homing behavior allows them to mix in feeding and rearing areas, while remaining reproductively isolated (Ricker 1972; Smith 1985).

Since the effect of environmental conditions is such a large component of the observed variation among stocks, it was very difficult before protein analysis to determine what proportion of the differences is genetic and thus to identify discrete stocks. With this knowledge it is possible to understand the natural system, make recommendations for ongoing management, and determine the direction for future study.

Amount of variation

North Slope Arctic char have more genetic variation than might be expected given the relatively narrow range of northern waters they inhabit and the harsh environmental conditions encountered. With a percent average heterozygosity per locus of 5.1%, they are typical of fish species in general (H = 5.1%: Nevo 1978); are at the upper end of the range observed in other salmonid fishes; and are higher than most other Arctic char populations that have been studied (Table 7).

Generally, Arctic char populations that have been studied are non-migratory, and have been profoundly influenced by repeated glaciations (Behnke 1972; Saunders and McKenzie 1971). Glacial action can cause loss of whole populations; result in small, isolated populations with low effective population size and the potential for inbreeding problems; and limit the number of fish founding new populations. All of these conditions lead to loss of variation and loss of variants. Northern Alaska Table

Table 7. Average heterozygosity (% H) in ten groups of salmonid fishes.

Species	Number of Populations	% H	Source of data
Brook char	8	8.1	Stoneking et al. 1981
Rainbow trout	55	6.0	Leary and Allendorf 1982
Arctic char (N. Slope)	15	5.1	This study
Arctic char (N. America)	5	2.9	Kornfield et al. 1981
Pacific salmon (5 species)	41	2.8	Allendorf and Utter 1979
Brown trout (Sweden)	38	2.5	Ryman 1983
Atlantic salmon (Sweden)	6	2.3	Stahl 1981
Arctic char (Norway)	15	1.7	Hindar et al. 1986
Arctic char (Sweden)	10	1.1	Andersson et al. 1983
Arctic char (Ireland)	9	1.1	Ferguson et al. 1981

Arctic char have probably benefitted both from the ice-free refuge during the last glaciations (McPhail and Lindsey 1970) and their anadromous life history strategy which permits migration among drainages. Both factors have likely contributed to maintenance of relatively high population sizes (preventing loss of variation) and the ability to successfully colonize this area.

Genetic similarity among populations

The genetic identity (Nei 1972; 1978) values among North Slope Arctic char populations are high, indicating fairly recent common ancestry. North Slope Arctic char populations exhibit a level of divergence typical of locally adapted populations as opposed to different species or even subspecies. Preliminary studies with the Arctic char-Dolly Varden char complex indicate that despite the number of different "morphotypes" and life history strategies, the overall genetic similarities are typically above 0.950, even between species (Robb Leary, University of Montana, personal communication).

High similarity values, though, do not imply lack of significant differences between Arctic char populations. The relationships between populations apparent from the clustering and multidimensional scaling figures indicate the distinctness of the populations and the complexity of the relationships between them. Comparison of these figures to the map of sample sites indicates that there is no simple correlation between genetic relationships and geographical proximity.

It is not possible to determine the underlying cause of the observed relationships among North Slope Arctic char populations from protein studies. Selection, migration, mutation, behavioral isolation, founder effects, random genetic drift (chance changes due to small populations size) and combinations of these and other forces may all contribute.

We cannot, for instance, determine at this time whether or not non-migratory (resident) populations of Arctic char were included among our samples. While we have no evidence of mixed populations within samples, we cannot tell if, for example, the population sampled from the Canning Marsh Fork or Ribdon River are actually non-anadromous.

Sampling for this project was designed to collect anadromous char from their spawning streams to determine whether or not populations from different drainages are genetically distinct. If they are reproductively isolated, we should be able to demonstrate significant genetic differences among populations from different drainages. Since adult Arctic char are known to "visit" or overwinter in non-natal drainages, juveniles were collected. Juveniles of resident and anadromous forms are essentially indistinguishable morphologically.

In other salmonid populations that have been studied, e.g., rainbow trout (Allendorf and Utter 1979) and brown trout (Ryman and Stahl 1981), only a small percentage of the divergence among populations is due to the ecological distinction between resident and migratory forms. Resident populations of North Slope Arctic char could either be composed of a separately evolved group with physiological or behavioral isolating mechanisms from migratory groups, or they could have arisen independently in various drainages where condition made it unfavorable or impossible to migrate. Thus, resident groups could either resemble each other across the North Slope, or could most closely resemble the migratory groups in their drainage, with local divergence due to selection or genetic drift (random changes) in presumably small populations.

The taxonomy of Arctic char has still not been fully resolved. Based on counts of gill rakers and pyloric caeca, McPhail (1961) identified three forms, two of them from the North American Arctic region. His Eastern form is lacustrine and the Western form is generally anadromous. McCart and Craig (1971), using the same morphological features, identified both forms in the Sagavanirktok River Drainage. Bain (1974) determined that resident and non-resident forms in the Babbage River Drainage are both derived from the Western form of Arctic char.

Apparently, genetic differences detected between resident and migratory forms can be due either to separate evolutionary lines or recent reproductive isolation. Recent divergence may be due to behavioral or physical isolation, which allows genetic differences do accumulate.

Though we are reasonably sure that we have sampled Arctic char from their natal streams, we cannot be sure, then, that we have studied only anadromous stocks. This might explain the unexpected relationships among samples within drainages as illustrated by the dendrogram (Figure 3). Though some clusters of populations on the dendrogram may be explained by this possibility, it is certainly possible that similarities among geographically isolated groups may be due to selection, founding events, or by chance convergence of electrophoretic phenotypes at structural loci.

For example, Anaktuvuk and Firth River Arctic char, which show up as a cluster on the dendrogram of genetic similarities, may or may not be closely related phylogenetically. They may not be genetically similar over the major portion of the genome. The enzyme loci we study may be selectively neutral, and similarities among populations may be due to random forces leading to their inclusion in the population. Major differences may exist at loci controlling characters subjected to dissimilar selective forces imposed by different environmental conditions. What the dendrogram does present is the divergence pattern observed for selectively neutral or nearly neutral loci among populations characterized by a very restricted amount of gene flow.

Also, because the computer program uses averages between populations to link them to each other, the dendrogram is not a direct reflection of pairwise tests of heterogeneity between population samples. It is not necessary to conclude that relationships among populations that cluster together on the dendrogram have biological meaning. Perhaps the multidimensional scaling plot is a better illustration of the true relationships among the populations studied; the populations actually are quite distinct from each other, as evidenced by the fact that they do not cluster tightly together.

Heterogeneity

Tests of genetic similarity between populations use all gene loci studied. Because over half the genes tested are electrophoretically indistinguishable in all the char populations, similarity calculations show the high degree of relatedness we have discussed. Heterogeneity tests, however, use only the gene loci that are variable to test for differences between populations, and consequently magnify the differences between them. Almost all North Slope Arctic char populations are significantly genetically distinct from each other. This information indicates that fish from different drainages are not freely interbreeding, and are most likely true to their spawning streams.

Genetic diversity

Knowing that Arctic char populations are genetically heterogeneous is not helpful unless we know at what level of the population structure they vary. Our results show that most of the diversity in North Slope Arctic char is between individuals within subpopulations, and that a seemingly small percent is due to differences between subpopulations. However, our data are more informative when related to the structures of other Arctic char populations and other salmonids.

Gene diversity analysis (Nei 1973) uses electrophoretic data to determine how much variation there is within each population of a species studied versus how much difference there is among populations or groups of populations. Salmonid populations are typically subdivided genetically (Allendorf and Utter 1979; Behnke 1972; Ryman and Stahl 1981) but there is considerable difference in how divergent subpopulations are from each other (Ryman 1983). Gyllensten (1986) has found correspondence between life history strategies in fish species, e.g., whether they are marine, anadromous, or freshwater forms, and the pattern of genetic diversity.

Much of the observed pattern among different ecological forms probably reflects population size and lack of barriers to migration. Freshwater fish obviously live in relatively small populations, and the combination of isolated bodies of water and tendency of salmonids to home results in reproductive isolation. While anadromous salmonids also exhibit strong homing behavior, they have more opportunities (less barriers) to stray. Further, migratory species may have been able to avoid some of the effects of repeated glaciations. The North Slope of Alaska was ice-free during the last Wisconsin glaciation (McPhail and Lindsey 1970). Hence, North Slope populations may have been able to maintain population size and consequently, genetic variation.

The total gene diversity (as average heterozygosity per locus) in several stocks of Arctic char and other salmonid fishes are summarized in Table 8. The table also shows the amount of the total diversity due to differences among individuals, and the percent of the variation due to differences among populations. Our data for North Slope char have been included for comparison. As evident from the table, Arctic char populations from Europe and eastern North America that have been studied have not only less variation, but also the pattern of variation derives from large differences between groups.

Table 8. Distributions of electrophoretically detectable gene diversity (Nei 1973) among Arctic char and other salmonid species. Total diversity is divided into that due to variation within each population versus that due to differences between populations (expressed as a percent).

Species	Data[a] source	No. popns	No. loci	Total diversity	Diversity within	% between
Arctic char (Sweden)	1	10	37	.011	.008	27.3
Arctic char (N. Am.)	2	5	26	.061	.029	52.4
Arctic char (Ireland)	3	9	27	.018	.011	38.9
Arctic char (N. Alaska)	4	15	41	.060	.055	8.3
Chinook salmon	5	80	17	.099[b]	.081	18.2
Chum salmon	6	13	12	.213[b]	.208	2.3
Sockeye salmon	7	13	26	.047	.043	8.5
At. salmon (Sweden)	8	6	45	.025	.023	8.0

[a] 1 - Andersson et al. 1983.
2 - Kornfield et al. 1981.
3 - Ferguson et al. 1981.
4 - This study.
5 - Wilmot unpublished summary.
6 - Wishard 1981.
7 - Grant et al. 1980.
8 - Stahl 1981.

[b] Amount of variation is overestimated when only variable loci are included in the analyses.

North Slope Arctic char do not have the magnitude of difference between groups exhibited by non-migratory char, but do compare with the population structure of anadromous Pacific salmon. This fact is particularly relevant because genetic stock identification methods have been successfully applied to these salmonids, and can give us an indication of whether this method can be applied to mixed stocks of North Slope Arctic char.

Genetic stock identification

The basis of genetic stock identification is electrophoretically detectable differences in genotype frequencies between stocks. To do genetic stock identification (GSI) there must be sufficient detectable genetic variation in the stocks to be studied. Variation between groups of populations, e.g., between those of major drainages, should be relatively high combined with a low within-group variability. Also, the baseline should represent the major populations contributing to the mixed stock to be analyzed.

Genotype frequency estimates are made for major stocks expected to contribute to the mixed stock (baseline data) and for samples taken from the mixed stocks. Maximum likelihood estimates of proportional contribution of different populations to the mixed stock are then made (Milner et al. 1981), based on the patterns observed in baseline samples.

Genetic stock identification is a useful tool in the study of fish populations. The GSI method has shown very good agreement with other methods of determining stock composition such as scale pattern analysis and coded wire tagging. It is currently used by the Washington Department of Fisheries, Olympia; Canadian Department of Fisheries and Oceans, British Columbia; and the National Marine Fisheries Service, Seattle.

This method may be useful for discrimination of populations of Arctic char in mixed populations using the offshore waters of the Beaufort Sea. Our data indicate that North Slope char have a relatively large amount of genetic variation; that there are significant differences among populations; and that the observed variation is partitioned such that there is as much difference between char from different drainages as there is among populations of sockeye and chum salmon where genetic stock identification has been used successfully. As such, we can anticipate successful application of this technique to the identification of char at specific offshore sites.

Recommendations

We have determined that North Slope char have a relatively large amount of genetic variation, and that populations we sampled are genetically distinct from each other. From this we know that different stocks are currently reproductively isolated from each other. Since they mix to some unknown degree in feeding areas, the differences that have been established between stocks are maintained by homing behavior. Populations of each drainage are probably discrete, locally adapted units. It is not clear at this time how non-migratory forms are related to anadromous stocks.

It is unlikely that loss of any one stock would be mitigated by substitution of another. While the actual loci we have studied may be selectively neutral, underlying variation that is marked by these loci may be highly selected for in different environments, corresponding generally to different drainages. As such, Arctic char stocks of the North Slope should be managed as individual, unique gene pools. Further study will make the relationships of anadromous and resident forms of this species more clear. With additional effort, using GSI methods, it would also be possible to understand more about the Arctic char in its migratory phase in the offshore areas.

Strategy

To expand our understanding of the genetic diversity and population structure of North Slope Arctic char, we should continue to use the techniques of biochemical genetics. Further work is needed to understand the relationships among populations, and to improve the data base for genetic stock identifications of migratory offshore stocks.

Many stocks of Arctic char living on the North Slope are not anadromous. Since we have no method of discriminating among resident and anadromous juveniles, we have assumed that those in the rivers are anadromous. To get a complete picture of the resource, we should consider deliberately sampling resident populations, e.g., those fish associated with springs or lakes.

It is important that we identify and sample additional populations making major contributions to the Beaufort Sea admixture, as it is an important assumption of the GSI model that all major contributors to a mixed stock be represented in the baseline. The baseline should particularly be expanded to include more samples from subpopulations from other tributaries in the drainages we have already begun studying.

An important consideration in doing genetic stock identification is that each analysis of a sample from the offshore stocks estimates, with predetermined expectations of precision and accuracy, the percent composition at only one point in space and time. Distribution of offshore stocks of fish is related to environmental conditions which are highly variable from year to year (Dick Marshall, USFWS, Anchorage, Alaska). Also, Arctic char are highly mobile in offshore areas, so estimates should be made of stock composition at several times during the short summer feeding season.

While we will surely know more about the use of offshore areas by anadromous char than we did before, it must be realized that there will be considerable variation, regardless of study method used, between data from different years and different areas and at different times during the season. This means that stock identification must be done on a site-specific basis, with repeated sampling during the summer, and that data from more than one year will be required to establish the pattern of use by the fish.

Even though the composition of stocks using the offshore area at any given area may change, baseline data can be used in more than one year. By doing offshore sampling and identifying the origin of the populations that are represented, we may find specifically which stocks are at risk at specific sites at several different times of the season.

Additional study would provide the opportunity to gain a more thorough understanding of the population structure of Arctic char in an area which, at this time, is relatively untouched by development. With an appropriate sampling strategy over space and time, genetic stock identification could yield data appropriate for site-specific approach to determining the use and timing of individual stocks in offshore waters. Knowledge of the natural system will afford us the information needed to address present concerns, and the basis for future conservation and management.

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Appendix 1. Gene frequencies of variable loci in 15 populations of Arctic char from the North Slope of Alaska and Canada. Variants of duplicated loci were arbitrarily assigned to one locus of the duplicate pair. Names of enzyme loci (abbreviated here) are in Table 2. ND = no data.

		Populations														
LOCI		AIC	ANA	BAB	CAN	ECH	EGA	FIR	HU1	HU2	HU3	IVI	KAV	KON	MAF	RIB
HEX1	100	.525	.859	.530	1.000	1.000	.806	1.000	1.000	.973	1.000	1.000	1.000	1.000	.638	1.000
	67	.475	.141	.470	--	--	.194	--	--	.027	--	--	--	--	.362	--
	N	40	39	33	20	23	31	40	13	37	59	49	40	40	29	40
ACO3	100	.550	.403	.700	.476	.478	.557	.392	.545	.435	.491	.561	.463	.550	.552	.587
	115	.175	.292	.028	.262	.109	.243	.243	.182	.242	.280	.204	.137	.163	.190	.113
	130	.275	.305	.272	.262	.413	.200	.365	.273	.323	.229	.235	.400	.287	.258	.300
	N	40	36	35	21	23	35	37	11	31	59	49	40	40	29	40
AAT1	100	1.000	.975	1.000	1.000	1.000	.986	.897	ND	ND	ND	ND	1.000	1.000	.983	ND
	33	--	.025	--	--	--	.014	.103	--	--	--	--	--	--	.017	--
	N	40	40	33	20	22	35	39	--	--	--	--	37	40	29	--
AAT3	100	.937	.925	1.000	.796	.935	.939	.950	ND	ND	ND	.980	1.000	.887	.931	.950
	75	.063	.075	--	.204	.065	.061	.037	--	--	--	.020	--	.113	.069	.050
	129	--	--	--	--	--	--	.013	--	--	--	--	--	--	--	--
	N	40	40	35	27	23	41	40	--	--	--	50	40	40	29	40
GPI1	100	1.000	.950	1.000	1.000	1.000	1.000	.950	1.000	1.000	1.000	.990	1.000	1.000	.983	.925
	55	--	.050	--	--	--	--	.050	--	--	--	.010	--	--	.017	.075
	N	40	40	35	27	24	41	40	15	36	59	50	40	40	29	40
GPI3	100	.775	.900	.628	.815	.896	.829	.763	.967	.843	.847	.920	.987	.700	.931	.667
	96	.225	.100	.372	.185	.104	.171	.237	.033	.157	.153	.080	.013	.300	.069	.333
	N	40	40	35	27	24	41	40	15	35	59	50	40	40	29	39
GAP3	100	.566	.934	ND	.780	.792	.500	.967	.455	.365	.283	.766	.750	.730	.750	.730
	null	.434	.066	--	.220	.208	.500	.033	.545	.635	.717	.234	.250	.270	.250	.270
	N	38	38	--	25	24	32	15	11	26	53	47	32	37	28	37
IDH2	100	1.000	1.000	1.000	.978	1.000	1.000	.963	1.000	.986	1.000	.980	.975	1.000	1.000	.950
	220	--	--	--	.022	--	--	.037	--	.014	--	.020	.025	--	--	.050
	N	40	37	35	23	24	35	40	15	36	59	50	40	40	29	40
IDH3	100	.888	1.000	1.000	.950	.978	.986	.949	1.000	.894	.983	1.000	.913	.937	.966	1.000
	80	.112	--	--	.050	.022	.014	.051	--	.106	.017	--	.087	.063	.034	--
	N	40	39	35	20	23	35	39	11	33	59	49	40	40	29	40

Appendix 1. Continued.

		Populations														
LOCI		AIC	ANA	BAB	CAN	ECH	EGA	FIR	HU1	HU2	HU3	IVI	KAV	KON	MAF	RIB
LDH5	100	.947	1.000	.986	.979	.978	.929	.963	1.000	.936	.966	.970	.987	.937	.983	.925
	97	.053	--	.014	.021	.022	.071	.037	--	.064	.034	.030	.013	.063	.017	.075
	N	38	35	35	24	23	35	40	15	39	59	50	40	40	29	40
MDH1	100	1.000	.956	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000
	128	--	.044	--	--	--	--	--	--	--	--	--	--	--	--	--
	N	37	34	35	20	23	35	40	13	37	59	49	40	40	29	40
MEE3	100	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.972	.975	1.000	1.000	1.000	1.000	1.000
	69	--	--	--	--	--	--	--	--	.028	.025	--	--	--	--	--
	N	40	40	35	23	24	35	40	15	36	59	50	40	40	29	40
PGM2	100	1.000	1.000	1.000	ND	ND	1.000	.987	1.000	.986	.983	1.000	1.000	1.000	1.000	1.000
	88	--	--	--	--	--	--	.013	--	.014	.017	--	--	--	--	--
	N	40	35	28	--	--	39	40	15	36	59	50	40	40	26	40
6Pgl	100	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	1.000	.990	1.000	1.000	1.000	.987
	95	--	--	--	--	--	--	--	--	--	--	.010	--	--	--	.013
	N	40	40	35	23	24	35	40	15	36	59	50	40	40	29	40
SDH1	100	.987	.886	1.000	.880	.913	.975	1.000	.929	1.000	.972	ND	1.000	.963	.897	1.000
	43	.013	.114	--	.120	.087	.025	--	.071	--	.028	--	--	.037	.103	--
	N	40	35	34	25	23	20	39	7	17	36	--	39	40	29	40
SOD1	100	.950	1.000	.956	.976	.978	.943	.987	.885	.903	.915	.969	1.000	.975	.983	.887
	115	.050	--	.015	.024	.022	.057	.013	.115	.097	.085	.031	--	.025	.017	.113
	87	--	--	.029	--	--	--	--	--	--	--	--	--	--	--	--
	N	40	35	34	21	23	35	40	13	36	59	49	40	40	29	40
XXO1	100	.750	.727	.780	.737	.932	.629	.778	ND	ND	ND	.804	ND	.676	.714	.809
	86	.250	.273	.220	.263	.068	.371	.222	--	--	--	.196	--	.324	.286	.191
	N	40	33	25	19	22	35	36	--	--	--	46	--	37	28	34

AIC = Aichilik; ANA = Anaktuvuk; BAB = Babbage; CAN = Canning; ECH = Echooka; EGA = Egakarak; FIR = Firth; HU1 = Hula Hula Site 1; HU2 = Hula Hula Site 2; HU3 = Hula Hula Site 3; IVI = Ivishak; KAV = Kavik; KON = Kongacut; MAF = Canning Marsh Fork; RIB = Ribdon

DISTRIBUTION AND SEASONAL ABUNDANCE OF JUVENILE SALMON AND OTHER FISHES IN THE YUKON DELTA

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Final Report

Outer Continental Shelf Environmental Assessment Program

Research Unit 660

July 1987

ACKNOWLEDGMENTS

The completion of this study could not have been accomplished without the aid of many individuals and organizations. We wish to thank all of the field team members including: Messrs. Richard Tyler, Dan Tyler, Clarke Beaudry, and Ms. Allison Reak. We also thank the ADF&G crew at Pilot Station for providing fish samples and Messrs. Larry Buklis and Jim Raymond (ADF&G) for providing supporting information concerning Yukon salmon. Special thanks to Mr. Calvin Van Zee, Envirosphere Company, for his assistance in obtaining and processing satellite images.

We are especially grateful to Mr. Jake Johnson and staff of the Emmonak Fisheries Cooperative for their generous assistance in repairs of field equipment. Logistical support was provided by the NOAA/OAD Helicopter Group, from Miami, Florida, and staff of the NOAA/Ocean Assessment Division, Anchorage. Special thanks to Messrs. Carl Anderson and Michael Meyer from NOAA for their concern and assistance in helping to make the job a little easier. We also thank Dr. David Carneggie and Mr. Michael Fleming, EROS Anchorage Field Office, U.S. Geological Survey, for providing the AVHRR digital tapes.

This study was funded in part by the Minerals Management Service, Department of the Interior, through an interagency agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program.

ABSTRACT

The purpose of this study was to identify the importance of aquatic habitats in the Yukon River Delta for juvenile salmon and other fishes, and to determine the vulnerability of these fish to the potential impacts of an oil spill. An investigation was conducted of the distributary channels, nearshore, and shallow offshore habitats to determine the outmigration timing, distribution, and seasonal abundance of juvenile salmon and other fishes in the Yukon River Delta. Fisheries and oceanographic data were collected from three surveys that began immediately following ice breakup (i.e., early June) and ended in mid-August 1986.

Results indicated that outmigration of juvenile chinook salmon and chum salmon began before ice breakup. Chinook salmon smolts peaked on several dates during June and July with the largest catches occurring during late June. The peak timing of the juvenile chum salmon outmigration occurs during the mid to latter part of June. Low numbers of both species continued to outmigrate during the rest of the summer. The lengths of all outmigrant chinook salmon exceeded 69 mm, which suggests that most smolts were age 1+. Outmigrant chum fry were comprised of three different size groups with average lengths ranging from 36 mm to 60 mm.

Chinook and chum juveniles utilized the outer delta front and delta platform habitats to a greater extent than the nearshore intertidal environment. Utilization of tidal slough and mudflat habitats were intermittent and restricted to regions near major distributary channels, whereas utilization of the offshore habitats was constant and relatively uniform along the delta front. There was no difference in the average size or size composition of juvenile salmon in lower river and other habitats which suggests that outmigrants were not residing in the shallow delta environment. The results indicate that the lower river, intertidal habitats, delta platform, and delta front are not utilized as a nursery area but rather as a migration corridor for juvenile salmon. Juvenile salmon that migrate through the delta front are most likely moving to deeper estuarine habitats in the prodelta.

The migratory routes through the delta and the utilization of delta habitats by juvenile salmon are thought to be influenced by the unique physiographic conditions. The network of sub-ice channels and the large river discharge carry juvenile salmon across the delta platform and distribute them along the delta front. Estuarine conditions that may be important rearing habitat exist only at the delta front and seaward as a result of the massive freshwater plume.

Peak outmigration of juvenile coregonid fishes occurred during July. Juvenile cisco were approximately three times more abundant than juvenile sheefish and juvenile whitefish. Intertidal mudflats and tidal sloughs are the most important habitats for these species.

Populations of juvenile salmon would be vulnerable to an oil spill in the offshore habitats and in the migration corridor. Outmigrants that may utilize the prodelta would be the most vulnerable to oil impacts because this habitat is located within the OCS lease area of Norton Sound. Sheefish, whitefish, and cisco populations would be highly vulnerable to an oil spill that reached the nearshore environment.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

1. INTRODUCTION

On March 15, 1983 the U.S. Department of the Interior accepted 59 bids for oil and gas exploration in Norton Sound (Sale No. 57). This lease sale area is located on the outer continental shelf just north of the Yukon River Delta (see map in Figure 2-1). Since this region supports a large subsistence and commercial fishery, baseline studies were needed to assess the potential impacts of oil and gas development. In response to this need for scientific information, the Outer Continental Shelf Environmental Assessment Program (OCSEAP), the National Oceanic and Atmospheric Administration (NOAA) contracted with LGL Ecological Research Associates, Inc. to conduct a literature review which resulted in an ecological characterization of the Yukon River Delta (Truett et al. 1984). This characterization identified the estuarine environment (including the nearshore delta platform and the delta distributaries influenced by marine water) as most vulnerable to adverse effects of oil in the delta. However, site specific information concerning physical processes, fish distribution, and habitat utilization in the Yukon River Delta was very limited. This information is necessary to assess potential environmental impacts and to enable management decisions necessary to protect fishery resources. Consequently, OCSEAP initiated a field investigation of the physical processes and fishery resources of the Yukon River Delta during 1984.

During winter 1984 and summer 1985 Envirosphere Company conducted an investigation of the distribution, seasonal abundance, and feeding dependencies of juvenile salmon and other fishes in the Yukon River Delta (Martin et al. 1986). Fish were collected from an area extending over 150 km of the delta coastline and from 40 km upriver to 30 km offshore. The results of this investigation indicated that delta habitats support diverse and productive fish communities. Juvenile salmon occurred in most delta habitats during the period from ice breakup to early August and the peak abundance occurred during the latter part of June. Growth of juvenile salmon during the outmigration period suggested temporary residency in the delta. The diet of juvenile salmon was limited to a narrow spectrum of drift, plankton and epibenthic taxa, which suggested a trophic dependency on the delta environment. Sheefish, whitefish, and cisco accounted for 65 percent of the total catch during 1985 and were the most widely distributed of all species in the Yukon River Delta. Juveniles of all three groups exhibited a peak downstream migration during July and were most abundant in the coastal mudflats and sloughs. Based on the distribution and abundance of juvenile salmon and other important fishes, the inner delta platform, mudflat, and tidal slough habitats were identified as sites where the greatest potential impact could occur from an oil spill. Active distributory channels also received high potential impact ratings, whereas, the delta front and mid-delta platform received the lowest ratings (Martin et al. 1986).

The 1984-85 investigation provided the most comprehensive survey of fisheries resources ever conducted in the Yukon River Delta. However, data concerning run timing, distribution, residency and diet were only general because the sampling effort was spread over a large geographic area and most sites were sampled only a few times. In particular, sampling was limited in the outer delta platform and delta front habitats. Information concerning the distribution and abundance of salmon and other fish in these habitats is needed in order to determine the potential vulnerability to impacts. More information is needed on fish abundance and habitat utilization during early June, immediately following ice break-up, since sampling was limited at this time during 1985. Also, results from 1985 suggest that the distribution of fish may be influenced by the dynamic physical processes (i.e., tidal flux, currents, and river flow) in the nearshore environment. Therefore more information concerning physical conditions and physical processes in the delta is needed in order to understand the distribution of fish in the Yukon delta. Envirosphere continued an investigation of the fisheries resources of the Yukon River Delta during 1986 in an effort to fill information needs and to address questions identified during the previous survey. Specific objectives addressed in this study include:

1. Identify the outmigration timing of juvenile salmon;

2. Determine the abundance, residence time and habitat utilization of juvenile salmon and other estuarine fishes; and,

3. Relate the distribution of juvenile salmon to the physical environmental conditions of the Yukon River delta.

Data obtained from this study and from the 1985 survey are used to address the three study objectives. Information concerning physical processes required for the third objective was limited because the primary focus of this study was biological. Data on the physical processes is currently being developed by a companion study (OCSEAP, RU 670) but the results were not available to incorporate into this report. Therefore, physical data collected during this study and information from Advanced Very High Resolution Radiometry (AVHRR) satellite imagery were used to provide a physical characterization of the Yukon Delta.

2. METHODS

2.1 DESCRIPTION OF STUDY AREA

The Yukon River Delta is located along the southwestern coast of Norton Sound, Alaska, which occupies the northeastern corner of the Bering Sea (Figure 2-1). The Yukon River is the 4th largest river in North America, has a maximum length of 3,185 km, drains an area of 855,000 km^2, and has an average annual discharge of 7,000 m^3/s (Czaya 1981). The modern delta is a relatively young geologic feature, beginning its development approximately 2,500 years ago when the river course shifted to where it currently enters Norton Sound (Dupre' 1978).

The geometry of the Yukon Delta is composed of a variety of depositional environments that are formed by a complex interaction of ice-, river-, and storm-dominated processes which affect sediment transport and deposition. A description of these environments is derived from Dupre' and Thompson (1979) and Dupre' (1980) as follows: The emergent portion of the delta (referred to as "delta plain," Figure 2-2) is characterized as a gentle sloping plain containing a complex assemblage of active and abandoned distributaries, levees, interdistributary marshes, and lakes. The active distributaries have a radically bifurcating pattern consisting of two large channels (1-1.5 km wide and 10-15 m deep) and numerous smaller channels (some as small as 20 m wide and 2-5 m deep) typically spaced every 1-2 km along the coast. Point bars and mid-channel bars are common, particularly along the larger distributaries. Intermediate to the active distributaries are numerous small tidal sloughs which extend into and drain marsh areas along the coast. The width and length of these channels vary with tidal level and they may become dry at low tide. Surrounding the emergent portion of the delta is the delta margin which includes the prograding tidal flats, distributary mouth bars, sub-ice platform, and associated sub-ice channels. Tidal flats are typically 100-1,000 m wide where they occur along the fringe of the delta plain. Unlike deltas in temperate areas, the Yukon Delta has a broad sub-ice platform

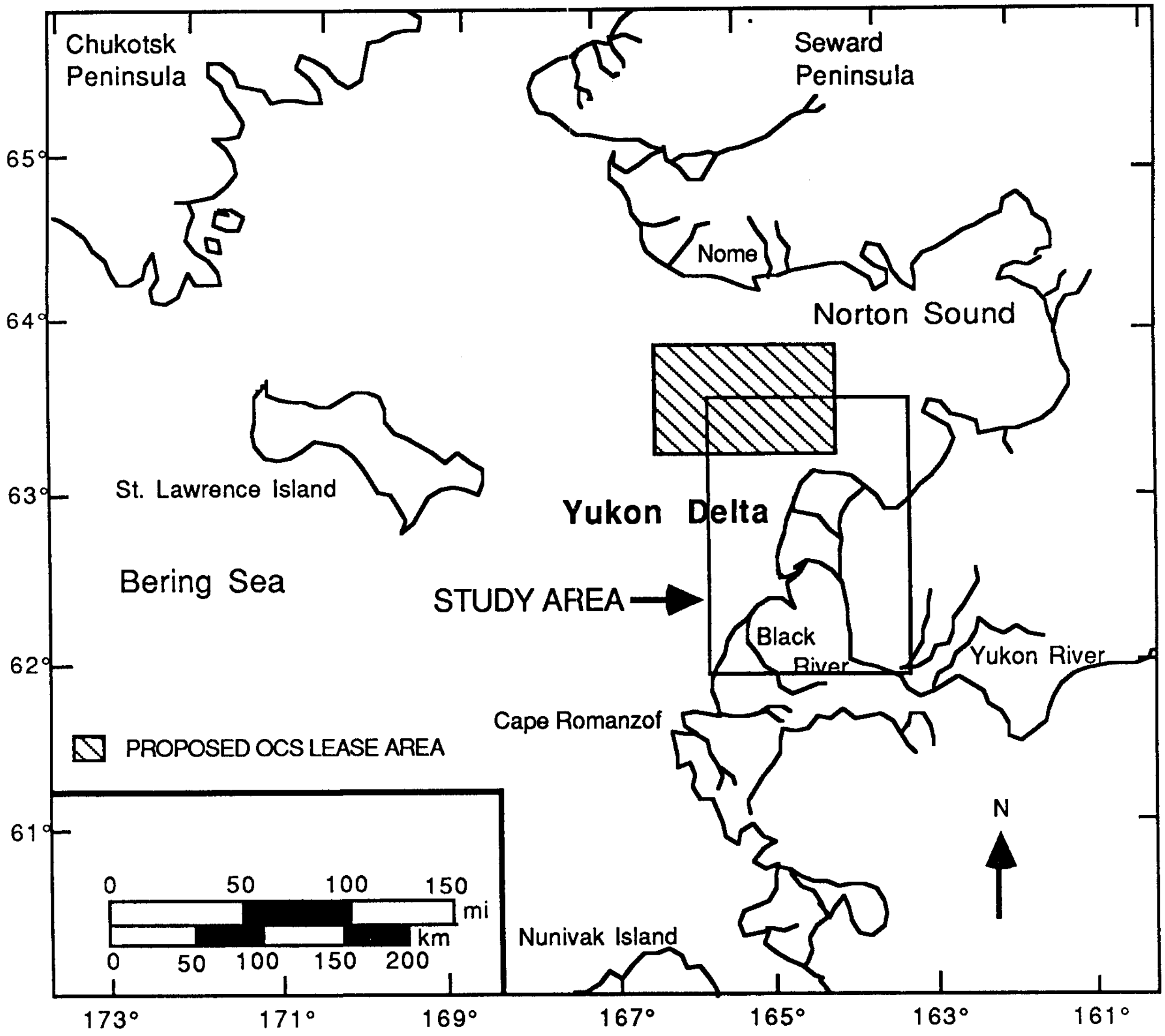

Fig. 2-1: Vicinity map of Norton Sound showing the location of the Yukon River Delta study area.

(here referred to as the delta platform) that extends 10-30 km offshore. The delta platform has an extremely gentle slope (1:1,000 or less) and typically shallow water (up to 3m). The sub-ice channels, which are unique among most deltas, are the offshore extensions of the major distributary channels. These subaqueous channels are most common on the western margin of the delta and are characteristically 0.5 to 1 km wide, 5-15 m deep, and extend up to 30 km across the delta platform. Adjacent to the delta platform is the steeper delta front (slope typically greater than 1:500) with water depth ranging 3 to 14 m. This zone is relatively narrow (approximately 10 km wide) except along the northwestern part of the delta where it includes a series of large (3-5 m high) shoals. The prodelta is the most distal edge of the deltaic sediments and extends up to 100 km offshore. The bottom in this zone has a gentle slope (typically 1:2,000) and water depths are relatively shallow (10-20 m).

2.2 SAMPLING PLAN

The primary emphasis of this study was to investigate the timing, distribution, and abundance of juvenile salmon in habitats that may be exposed to impacts from oil and gas development. Therefore, field survey timing and sampling locations were planned to provide these data and to extend the data base that was developed during 1985. During 1986 the sampling program was divided into three field surveys which occurred for 30 days, 7 days, and 8 days during June, July, and August, respectively. The June survey was scheduled to correspond with the timing of ice breakup in the Yukon Delta and the early phase of the juvenile salmon outmigration. The July and August surveys were scheduled to correspond with the postpeak and tail-end phases, respectively, of the outmigration period.

Samples were collected from 20 sites (Table 2-1) that were representative of the major and minor distributary, tidal slough, mudflat, delta platform and delta front habitats. The upper river stations (i.e., stations 14-16, Figure 2-3) were only sampled during early June prior to the time of ice breakup in the lower delta. Fish

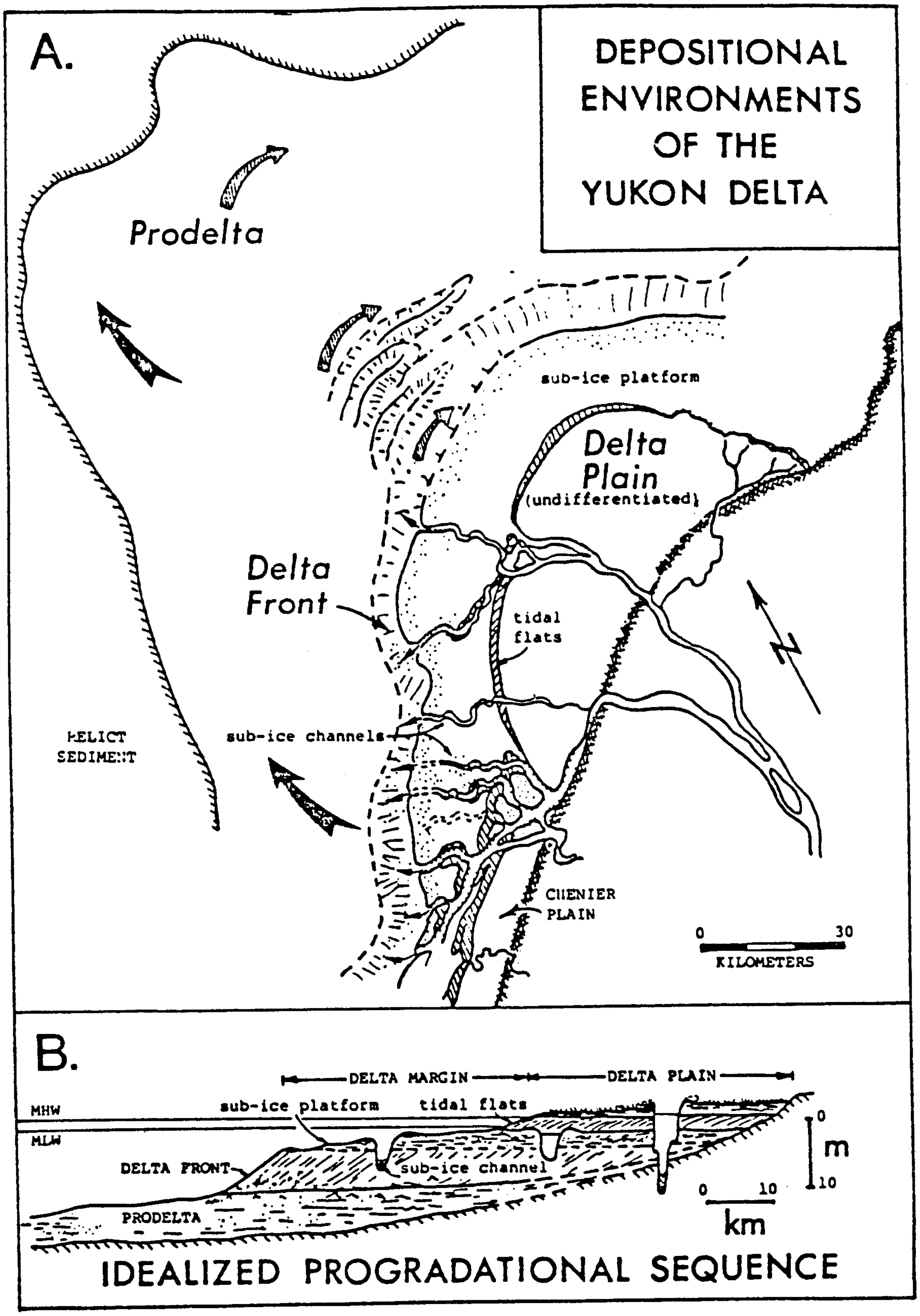

Fig. 2-2: Depositional environments of the modern lobe of the Yukon Delta (from Duprė and Thompson, 1979).

TABLE 2-1

Location and Description of Stations Sampled During the 1986 Field Season of the Yukon Delta Study

Station Number	Description	Latitude (N)	Longitude (W)
21	Delta front (sampled 6/6 only)	62° 40.61'	165° 37.53'
1	Delta front	62° 29.85'	165° 33.70'
2	Delta front	62° 40.62'	165° 28.62'
3	Delta front	62° 53.97'	165° 15.02'
41	Delta platform (sample 6/4 and 6/6 only)	62° 29.80'	165° 15.05'
51	Delta platform (sampled 6/6 only)	62° 38.85'	165° 23.69'
4	Delta platform	62° 30.06'	165° 27.58'
5	Delta platform	62° 40.69'	165° 23.05'
6	Delta platform	62° 54.00'	165° 05.64'
8	Coastal mudflat	62° 40.79'	164° 52.61'
9	Coastal mudflat	62° 56.42'	164° 49.08'
10	Tidal slough	62° 26.50'	165° 16.90'
11	Tidal slough	62° 40.74'	164° 51.72'
12	Tidal slough	62° 56.34'	164° 48.73'
13	Active distributary, major	62° 40.82'	164° 36.62'
17	Active distributary, minor	62° 45.79'	164° 30.58'
14	Upper Yukon River, St. Mary's	62° 00.95'	163° 13.87'
18	Upper Yukon River, Pilot Sta.	61° 56.75'	162° 52.77'
15	Andreafsky River	62° 03.10'	163° 08.67'
16	Andreafsky River, North Fk.	62° 05.13'	163° 03.75'

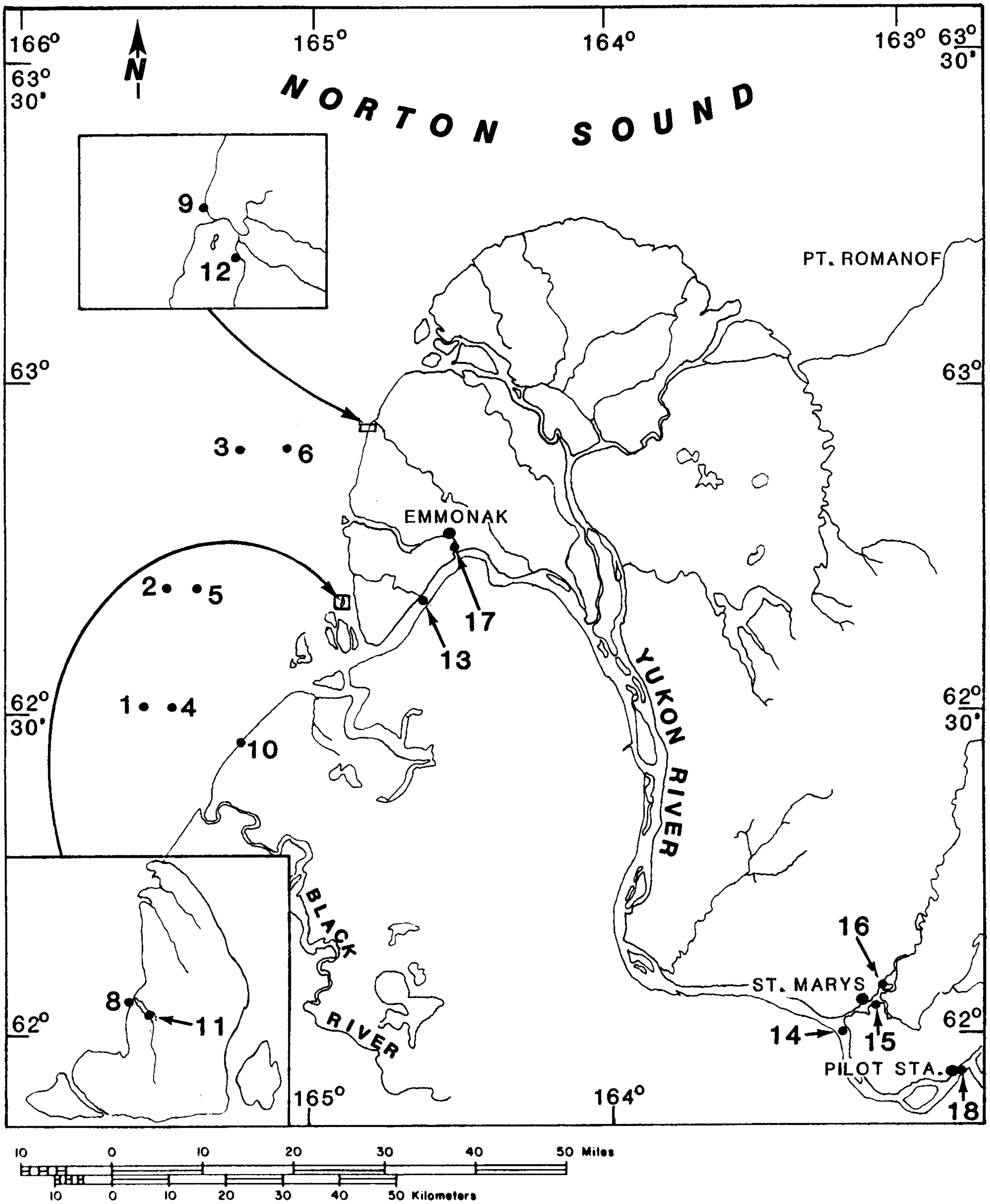

Fig. 2-3: Location of sample sites for the summer 1986 survey of the Yukon River Delta.

specimens collected from these stations were retained for the otolith study (see Section 2.5 for details). After ice breakup, all sampling was concentrated in the lower delta and offshore areas. Two stations were located in major and minor channels of the lower river in order to document the timing of the outmigration and the size composition of the outmigrant population. These stations were located a short distance (i.e., less than 25 km) upriver from the coast under the assumption that fish residency was not occurring at this point. Therefore, catch statistics from these sites would be indicative of the population just prior to entering the estuary. The distribution, abundance, and residency of fish was determined from samples collected at 11 sites which were located along the coast and offshore. These sample stations extended from the coastal tidal sloughs out to the delta front and were distributed along three transects (Figure 2-3). The two southern transects were located within the turbid water plume from Kwikuak Pass and the northern transect was located along the outer edge of this plume. Stations 1, 2, and 3 were positioned at approximately the mid-slope point along the delta front and stations 4, 5, and 6 were positioned within several kilometers of the outer edge of the delta platform (Figure 2-2). Several other stations that are located in the vicinity of these sites (i.e., stations 21, 41, and 51, Table 2-1) were also sampled during an initial reconnaissance survey. Stations 8 through 12 were located in tidal slough and intertidal mudflat areas.

2.3 SAMPLING TECHNIQUES

2.3.1 Water Quality and Physical Measurements

Discrete measurements of water temperature, conductivity, salinity, depth, and water transparency were measured at each fish sampling station. Surface and bottom measurements of temperature, conductivity, and salinity were measured *in situ* with a Beckman RS-5 conductivity/temperature instrument. A handheld thermometer and a YSI Model 31 conductivity meter were used as a backup and a 2 L Van Doren bottle was used to collect water samples. Water depths and water transparency were measured with an Echotec fathometer and a standard (200 mm diameter) secchi disc. Sea state was observed and recorded according to the World Meteorological Organization Sea State scale.

2.3.2 Fish Sampling

Fish were sampled with three types of active sampling gear. A 6.8 m wide surface tow net (Table 2-2) was used to sample the river channel, delta platform, and delta front habitats. A 45.7 m long beach seine and a 22.8 m long beach seine were used to sample the mudflat and tidal slough habitats, respectively (Table 2-2).

The tow net was selected as the primary sampling gear in place of the 136 m purse seine, which was used in 1985 (Martin et al. 1986), because the tow net was found to be more effective. Tests were performed during the first week of the survey to compare catches between the purse seine and tow net when both gears were deployed at the same site (Table 2-3). In three comparison tests the purse seine captured only juvenile chinook salmon in one test, whereas, the tow net caught both juvenile chum and chinook salmon from all three tests. The tow net also caught more juvenile salmon than the purse seine for an equal amount of effort as indicated from the results of the June 4th test. The purse seine was more effective, however, for catching larger fish and other fish species (e.g., cisco, whitefish, smelt, and sucker).

The tow net was deployed between two boats and towed against the direction of the current at an average speed of 0.8 m per second. The net was towed for a period of either 5 or 10 minutes and from 2 to 15 hauls were collected at a sample site. In most cases three 10-minutes hauls were collected from a site.

TABLE 2-2

Specifications for Fish Sampling Gear Used For the Summer 1986 Survey of the Yukon River Delta

Gear	Specification	
Tow Net	Overall size:	6.8 m wide x 1.8 deep at mouth and tapered to a 0.3 m x 0.3 m bag at the cod end. Total length 11.0 m.
	Front panel:	2.4 m long, 50.8 mm (stretch) knotless mesh.
	2nd panel:	2.4 m long, 38.1 mm (stretch) knotless mesh.
	3rd panel:	2.4 m long, 19.1 mm (stretch) knotless mesh.
	Bag:	3.7 m long, 7.9 mm (stretch) knotless mesh.
Long Beach Seine	Overall size:	45.7 m long x 1.2 m deep with bag located at one end.
	Bag:	4.6 m wide x 1.2 m deep x 3.0 m long, 7.9 mm (stretch) knotless mesh.
	Inner wings:	3.0 m long x 1.2 m deep and 4.6 m long x 1.2 m deep, 7.9 mm (stretch) knotless mesh.
	Outer wing:	33.5 m long x 1.2 m deep, 19.1 mm (stretch) knotless mesh.
Short Beach Seine	Overall size:	22.8 m long x 2.4 m deep at center and tapered to 1.8 m deep at end of wings, bag located in center.
	Bag:	7.7 m long x 2.4 m deep, 6.4 mm (stretch) knotless mesh.
	Wings:	two each, 7.7 m long x 2.4 m deep near center and tapered to 1.8 m deep at end, 12.7 mm (stretch) knotless mesh.

TABLE 2-3

Comparison of Species Composition and Catch Statistics for the Purse Seine and Tow Net

Station	Date	Gear	Number of hauls	Species	Catch	CPUE[a]	Mean Fork Length (mm)
14	6/1/86	Purse Seine	2	no fish	0	0	--
		Tow Net	7	chinook	3	0.43	105
				chum	12	1.71	38
				lamprey sp.	22	3.14	--
				burbot	8	1.14	--
13	6/4/86	Purse Seine	2	chinook	3	1.50	88
				whitefish sp.	1	0.50	112
				least cisco	8	4.00	222
				burbot	6	3.00	138
		Tow Net	3	chinook	7	2.33	90
				chum	16	5.33	39
				lamprey sp.	2	0.67	--
				burbot	1	0.33	--
13	6/5/86	Purse Seine	2	whitefish sp.	1	1.00	--
				least cisco	13	6.50	--
				boreal smelt	2	1.00	--
				longnose sucker	1	0.50	--
				burbot	1	0.50	--
		Tow Net	3	chinook	4	1.33	100
				chum	15	5.00	36
				lamprey	2	1.00	--
				burbot	1	0.33	--

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a/ Catch Per Unit Effort.

The 45.7 m beach seine was deployed by hand during the high tide period. Two round haul sets were collected from separate mudflat areas directly adjacent to the shore. The 22.8 m beach seine was set by hand and was pulled in the downstream direction in the tidal channels. Two 30 m long reaches were sampled during the high tide period.

2.3.3 Catch Processing

All fish were identified to species, when possible, and the total catch was enumerated. Juvenile whitefish (i.e., broad whitefish and humpback whitefish) and juvenile cisco (i.e., Bering cisco and least cisco) less than 75-100 mm cannot be readily distinguished in the field. Therefore, both species groups were labeled as whitefish and cisco, respectively. Lengths were measured from a representative sample (i.e., minimum of 40 individuals per species) of all salmon from each sample site. Also, a minimum of five juvenile salmon specimens from each site were retained in 70 percent ethanol for otolith and stomach analysis.

2.4 ANALYTIC PROCEDURES

2.4.1 Hydrographic Conditions

Temperature and Salinity Data

The surface and bottom temperature and salinity samples collected (from stations 1-6 and 8-10) during this sample program lend themselves to the development of a qualitative description of the hydrographic conditions on the delta platform and delta front for each day of the fisheries study. Data from four complete survey days have been selected to discuss the physical processes of the Yukon Delta. These survey days are June 12, June 15, June 19, and August 6 of 1986. Wind conditions for these four surveys are dominated by the mean north-northeast (NNE) flow that characterizes the spring conditions in Norton Sound.

In keeping with the desire to develop a qualitative description of the distribution of hydrographic properties in the study area, a somewhat stylized rectangular model of the study area was developed incorporating the nine sampling stations (Figure 2-4). In this model the sampling positions were spaced evenly across a grid that defines the ends and midpoints of the rectangle's sides and center. The nearshore stations are assumed to be on the delta platform, the intermediate station at the delta front, and the offshore station at the outer edge of the delta front. Fresh water input enters the modeled study area at two locations along the coastline representing the middle and southern mouths of the Yukon River (Figure 2-4). Because only surface and bottom water samples were collected at each station, distributions of the hydrographic properties are highly interpretive and should be considered as qualitative descriptions of the conditions in existence during the surveys.

The spatial distribution of three distinct water classifications are investigated in this analysis: fresher water (<5 ppt), intermediate salinity water (5 - 15 ppt), and marine water (> 15 ppt).

Meteorological and Hydrological Data

Meteorological conditions were not available from the Yukon Delta study region and therefore data from Nome, Bethel, and Nunivak Island were obtained (from AEIDC) to approximate the wind conditions for each survey day. These wind data were important to determine the direction and rate of transport of coastal water masses in the study area. These three meteorological stations showed good agreement in both wind speed and direction for the June study period with standard deviations of ±2.0 kts wind speed and ±4.0 degrees for direction.

River discharge was not measured during this study, therefore data were obtained from the U.S. Geological Survey, Anchorage. These data are based on measurements of river stage which were recorded on a water level recorder located at Pilot Station (Figure 2-3).

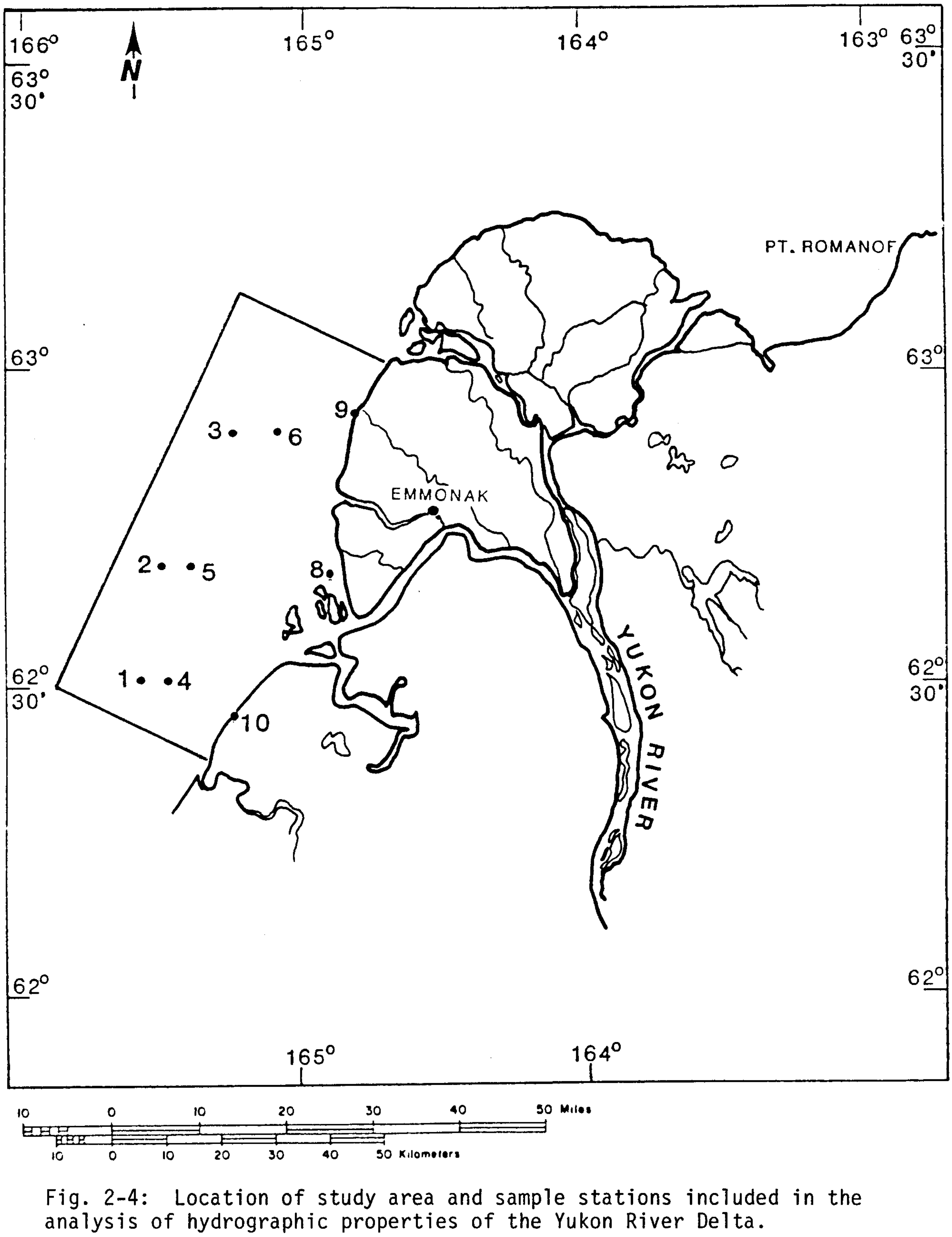

Fig. 2-4: Location of study area and sample stations included in the analysis of hydrographic properties of the Yukon River Delta.

Remote Sensing Data

NOAA AVHRR visible and thermal digital images were acquired for the 15 June 1986 fisheries survey date. These data were analyzed to determine the extent and behavior of the Yukon River sediment and thermal plumes. The digital images were acquired from the U.S. Geological Survey EROS field office (Anchorage) through the NOAA OCSEAP Anchorage office. Digital images were processed by Envirosphere's VAX-based image processing system using computer software originally developed by Scripps and the University of British Columbia. Processed images were displayed on a Raster Technologies Model One/25 Computer Color Graphics terminal. The general scheme of digital processing was as follows:

1) Read computer tape into Envirosphere VAX 11/71.

2) Reformat data as required depending on the satellite sensor system and the agency from which the computer tape was received.

3) Preprocess data including geometric and radiometric corrections to the digital data, apply the digital image mask to define the Yukon Delta study area, and navigate the image to essentially convert the image into a map.

4) Determine and apply a digital enhancement to the image to better define the physical characteristics of the study area.

5) Store the enhanced image on computer disk and video tape and take a color photograph of the enhanced image from the graphics terminal.

2.4.2 Data Recording and Archival

All field data were recorded on an electronic data logger known as a "Polycorder" from Omnidata International, Inc. An electronic data sheet was programmed specifically for this project and included error checking alarms which operated during the data entry process. Data stored in the Polycorder were downloaded daily and four data files were created with the aid of a portable microcomputer. One copy of the raw data file was recorded on a floppy disk and another copy was printed on paper. A third copy of the raw data file was edited for errors and stored on floppy disks. A backup copy of the edited data file was also created and archived.

After the field survey all the edited data files were combined to form one large data file. A hard copy of this file was created and visually checked for errors. Errors were also identified from a frequencies analysis. All the errors were corrected and a new edited version of the large data file was created.

2.4.3 Run Timing, Relative Abundance, and Density

Run timing and relative abundance was identified with histogram plots of catch per unit effort (CPUE) versus time for each sample station. The unit of effort was variable and depended upon gear. Catch in the tow net was standardized to a 10-minute haul; and, catch in the 45.7 m and 22.8 m beach seines was standardized to one round haul and one 30 m haul, respectively. Graphs for each species and station were compared in order to identify differences and similarities in the temporal utilization of habitat.

Density for juvenile salmon was expressed as the number of fish per square kilometer (no./km^2) of water surface area. Densities were calculated from a CPUE/density conversion factor which is based on the area sampled with one unit of effort for each gear type. Density equals:

$$\text{no./km}^2 = \text{CPUE} \times \text{conversion factor},$$

where the average area sampled and conversion factor for each gear are:

Gear	Area Sampled	Conversion Factor
Tow net	2,923 m^2	342
45.7 m Beach Seine	165 m^2	6,061
22.8 m Beach Seine	231 m^2	4,329

The average area sampled by the tow net was computed from measurements of the distance covered during typical 10-minute hauls (Table 2-4). Engine speed was held constant at 1,100 rpm for all tow net hauls. Thus, the water speed and distance covered by the tow net was constant regardless of differences in current velocity at each sample site. The area sampled by a round haul with the 45.7 m beach seine was assumed equal to the area of a circle with a circumference of 45.7 m. The area sampled by the 22.8 m beach seine was assumed equal to the product of a 30 m haul and the average width of a tidal slough (i.e., 7.7 m).

All estimates of fish density are considered to be conservative because no adjustments were made to compensate for gear efficiency. Gear efficiencies were not measured, but each type of gear is not 100 percent effective for catching all the fish within the area sampled. However, catch efficiencies were probably similar among the nets because each gear had small enough mesh to retain the target species and the turbid water conditions minimized the number of fish that could avoid and/or escape the nets.

2.4.4 Size Composition and Growth

Size composition was determined from length frequency analysis. Juvenile salmon were sorted by 3 mm size groups and length frequency distributions were computed for each habitat by sample period. Seven 4-5 day long sample periods were selected according to the clustering of sample dates which occurred during the survey.

Population growth rate during the survey period was computed by fitting a linear regression line to a plot of fish length with date. Population cohorts included in the regression were identified from the length frequency analysis.

TABLE 2-4

Estimates of Towing Speed, Area Sampled, and Volume of Water Sampled During Typical 10-Minute Hauls With a 1.8 M x 6.8 M Tow Net

Station	Date	Replicate	Flow Meter Revolutions[a/]	Distance (meters)	Speed (cm/sec)	Area Fished (m^2)	Volume Fished (m^3)
13	8/8	1	18,522	497.7	82.9	3,026	5,519
		4	15,651	420.6	70.1	2,557	4,664
		5	15,797	424.5	70.8	2,580	4,708
17	8/8	1	18,982	510.1	85.0	3,101	5,657
		2	16,629	446.9	74.5	2,717	4,956
		3	22,761	611.7	101.9	3,719	6,784
		4	16,917	454.6	75.8	2,764	5,041
Mean			17,894	480.9	80.1	2,923	5,333
S.D.			2,492	67.0	11.1	407.2	742.8

[a/] General Oceanics model 2030 digital flowmeter.

2.4.5 Associated Environmental Conditions

The relationship between fish abundance and important environmental parameters (i.e., surface and bottom temperature, surface and bottom salinity, and visibility) was investigated. Fish catch associations with the above parameters were determined for all delta platform and delta front stations (i.e., stations 1 through 6). Environmental associations were made during the period of peak abundance for chum and chinook salmon (i.e., June 12, 15, and 19). Each of the continuous environmental parameters were categorized and fish catches that were associated with each category were summed. Since fishing effort was not equal for each environmental category fish catch was adjusted by effort (i.e., catch multiplied by the effort in the category divided by the maximum effort in any category). The adjusted catch for each category was expressed as a percentage of the total adjusted catch for all categories combined.

2.5 CHUM SALMON OTOLITH STUDY

2.5.1 Sample Collection

Chum salmon specimens were retained for otolith analysis from each sample site during each survey period. These samples were used for the determination of residency and growth rate of juveniles during the outmigration period. In order to determine otolith increment periodicity several fish holding experiments were conducted. During each experiment, approximately 100 juveniles that were collected from either stations 13 or 17, were placed in a net pen (1.2 m x 1.2 m x 1.2 m with 7.9 mm mesh netting) and held for a period of 6 days. A random sample of 30-50 juveniles were sacrificed at the beginning and at the end of each experiment. The hypothesis was that the difference in the average number of increments between the beginning and end of the experimental period divided by six was equal to the incremental periodicity.

2.5.2 Laboratory Procedures

Fork length was measured for each fish used in the study. The left sagitta was dissected from each fish and placed medial side down on a glass plate in an array so that individuals processed together could be recognized. The array was covered with a rubber mold and cast in polyester resin. Using thin section grinding and polishing equipment, the otoliths were ground on the medial surface until the primordia were apparent with transmitted light microscopy. This surface of the preparation was then polished and fixed to a glass slide. The lateral surface of the otoliths were then sectioned and polished in the same fashion until a preparation approximately 90 microns thick was obtained.

Otoliths were analyzed using transmitted light at a magnification of 300x. Data were collected using an Optical Pattern Recognition System which employs a microscope, video camera and monitor, digitizing pad and microcomputer. Data collected included total otolith radius, the radius from the point of hatching to the edge of the otolith, the number of otolith increments in this latter segment and the width of those increments. Measurements were taken along a radius line which passed through the center of the primordial core and was located at a 70 degree angle to the long axis of the otolith. The hatching check was defined as the point of transition from very dark and irregularly spaced increments to much more weakly expressed and regularly spaced increments. Results from our laboratory experiments suggest that this transition corresponds to the time of hatching and that the dark, irregular increments represent the prehatching life history of the fish.

3. RESULTS

3.1 WATER QUALITY AND PHYSICAL MEASUREMENTS

3.1.1 Discrete Physical Measurements

Water quality and physical environmental conditions for each sampling date and station are shown in Appendix Table A. Salinity and conductivity data for the July 1986 survey period are missing due to equipment failure. Only one measurement (either surface or bottom) of salinity, conductivity, and temperature was collected from the mudflat and tidal slough habitats because the water was shallow (<2m) and assumed to be uniformly mixed.

Water quality and physical conditions were variable among the different habitats and changed within habitats during the summer. Water depths ranged from very shallow (i.e., 0.3 - 2.0 m) in the tidal slough and mudflat habitats to relatively deep (i.e., 5.0 - 13.0 m) in the river channel and delta front habitats. Warmer fresh water was predominant in the lower river during the summer. Water temperature varied from 5.5° C in early June to 17.1° C in mid-July. The tidal slough and mudflat habitats were slightly more brackish (salinity range 0.6 - 2.7 ppt) and several degrees warmer (temperature range 8.4 - 19.1° C) than the river. The peak water temperature in these habitats occurred in mid-June which was several weeks earlier than the peak temperature measured in the river. Differences in surface and bottom salinity in the delta platform and delta front indicated that water in these habitats was stratified. Stratification was most evident at the delta front stations during early June. Bottom temperature and salinity was near 0° C and 26 - 29 ppt, respectively, and surface temperature and salinity ranged 4 - 10° C and 7 - 14 ppt, respectively. By August the difference between surface and bottom conditions was less pronounced and the waters were more mixed.

Water clarity was low in most habitats throughout the summer and varied according to the distance from a distributary mouth. Secchi disc visibility was always less than or equal to 0.3 m in the river except on one occasion when 0.4 m was measured. Similarly, visibility in the mudflats was low, but visibility in the tidal channels was greater and ranged up to 0.9 m. Visibility generally increased with increasing distance from shore where measurements as great as 1.2 m were recorded at the delta front.

3.1.2 River Discharge

Discharge in the Yukon River during spring 1986 was substantially less than normal (Figure 3-1). The annual spring flood which normally precedes ice out in the lower river did not occur. Discharge peaked at approximately 580,000 cfs during the last week of May, but the river level did not exceed the banks. Discharge remained low throughout June and was substantially less than the more typical flows observed during 1985. Flows during the remainder of the summer were typical for this season.

3.1.3 Hydrographic Characterization

June 12, 1986

Winds ranged from 5 - 15 kts from the NNE on this survey day. In response to these winds, surface water would be expected to move generally toward the south along the western face of the Yukon Delta front. Superimposed on this mean southerly flow of water, an offshore velocity component would be induced in the upper water layer by a near-surface Ekman flow. The distribution of water masses seen in the on/offshore vertical sections of salinity indicate that this offshore surface flow tended to spread the fresher upper layer of water in an offshore direction (Figure 3-2a - c). A compensating onshore flow of deeper water can be expected to accompany this offshore upper layer flow as indicated by the deeper, more saline layer, which occurred at all three on/offshore transects (Figure 3-2a - c). The bulk of the

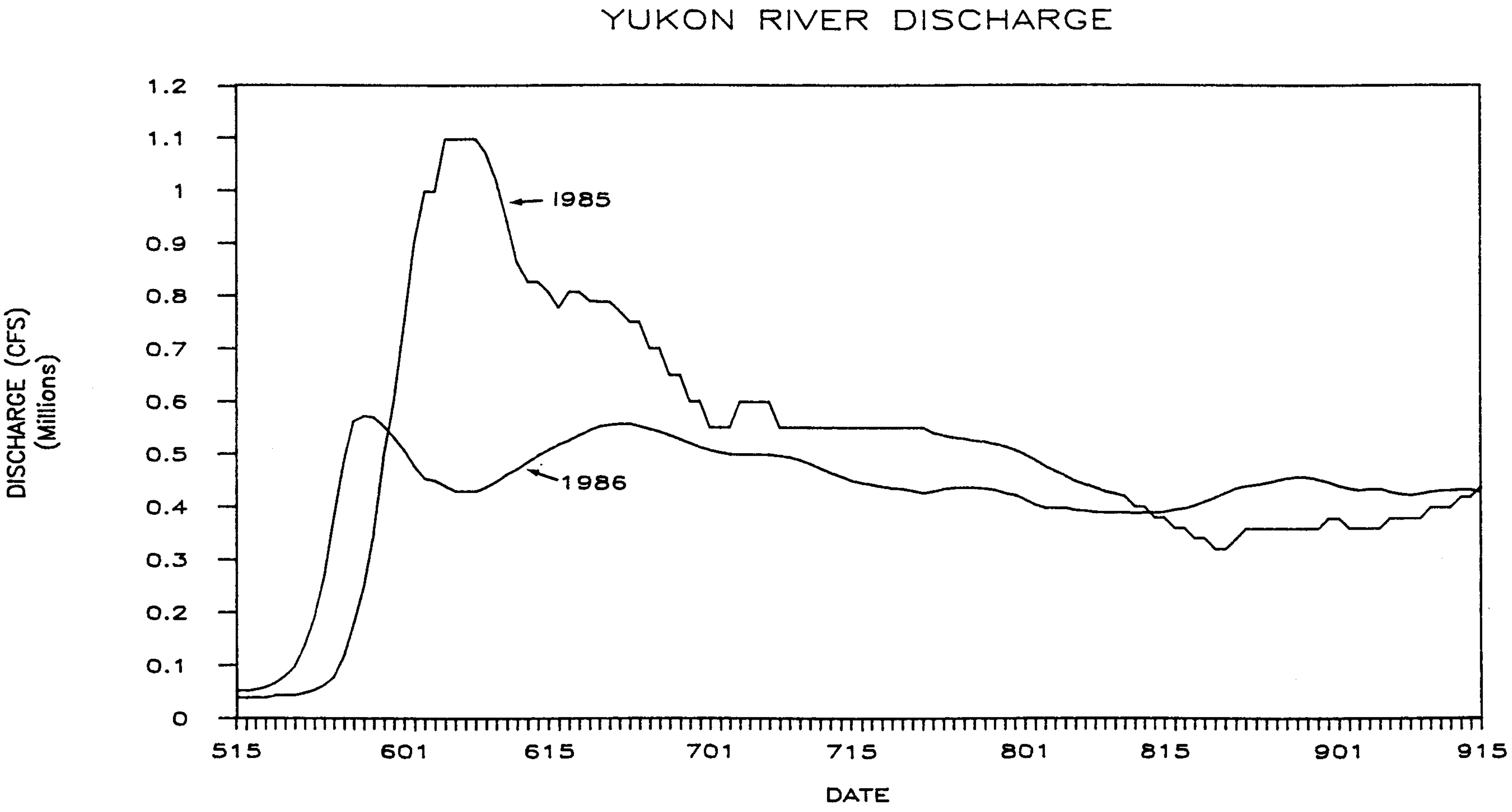

Fig. 3-1: Yukon River discharge at Pilot Station during summer 1985 and 1986. Based on provisional data from the U.S. Geological Survey, Anchorage, Alaska.

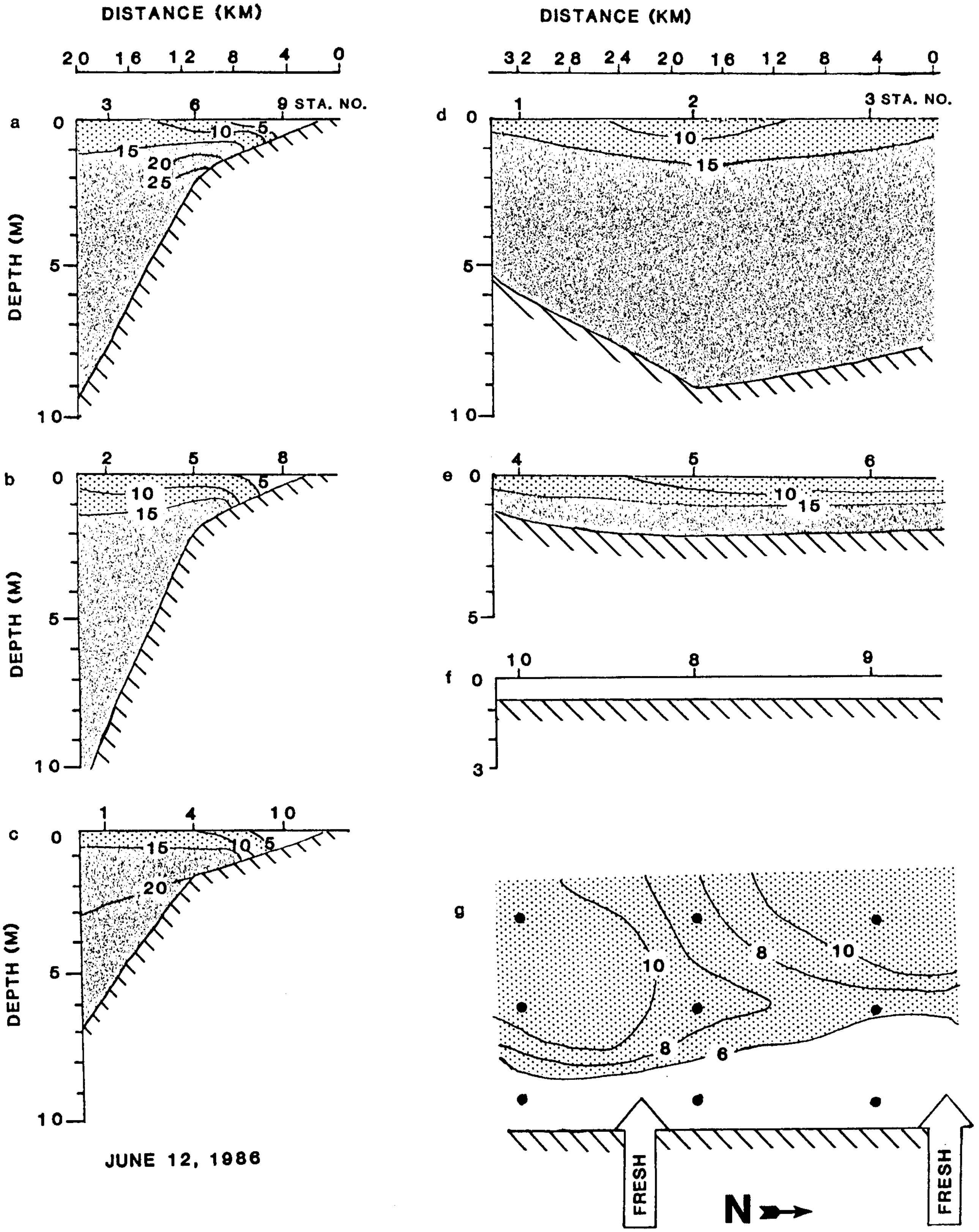

FIG. 3-2. Vertical sections of salinity for the on/offshore direction (a-c) and the along-shore direction (d-f). Graphical depiction of study area showing sample stations, horizontal contours of surface salinity, and sources of freshwater input to the area (g) for the June 12, 1986 survey of the Yukon River Delta.

fresher water (≤5 ppt) was generally contained in a narrow near-shore region inside of the 1 m isobath. Intermediate salinity water (5 - 15 ppt) was generally distributed in the upper 1.0 - 1.5 m of the water column in the region extending from the fresher nearshore water to beyond the furthest offshore station (Figure 3-2a - f). This layer of water appears to have coupled effectively with the NNE wind field while maintaining its identity from the deeper water. More marine water (>15 ppt) lay below this intermediate salinity water and generally filled the entire lower portion of the water column. Hydrographic distributions suggest a very dynamic system with net southerly wind driven water movement and superimposed estuarine circulation patterns complete with upwelling.

June 15, 1986

Winds on this survey day ranged from 5 -10 kts from the NNE. As described in the discussion of the previous survey, the wind field would be expected to move coastal water southward along the delta front. The two northernmost transects (Figure 3-3a - b) contained fresher (≤ 5 pt), nearshore water than did the southerly section (Figure 3-3), suggesting that the source of the fresher water may be from the north (middle mouth of the Yukon River Figure 2-4). This hypothesis is consistent with the southerly, wind driven movement of the nearshore water. Both the fresher and the intermediate salinity water are confined to the delta platform in the northern section (Figure 3-7a). The middle section shows that the intermediate salinity water extended throughout the offshore region in a 2 m thick upper layer. The fresher water in this section is confined to the nearshore in water depths less than 1 m. At the southern section, the offshore upperlayer flow had decreased the upper layer thickness to 1 m and allowed the marine water (> 15 ppt) to move more onshore under the upper layer to the 1.5 meter isobath. Wind mixing again was insufficient to mix the water column below 1 - 2 m.

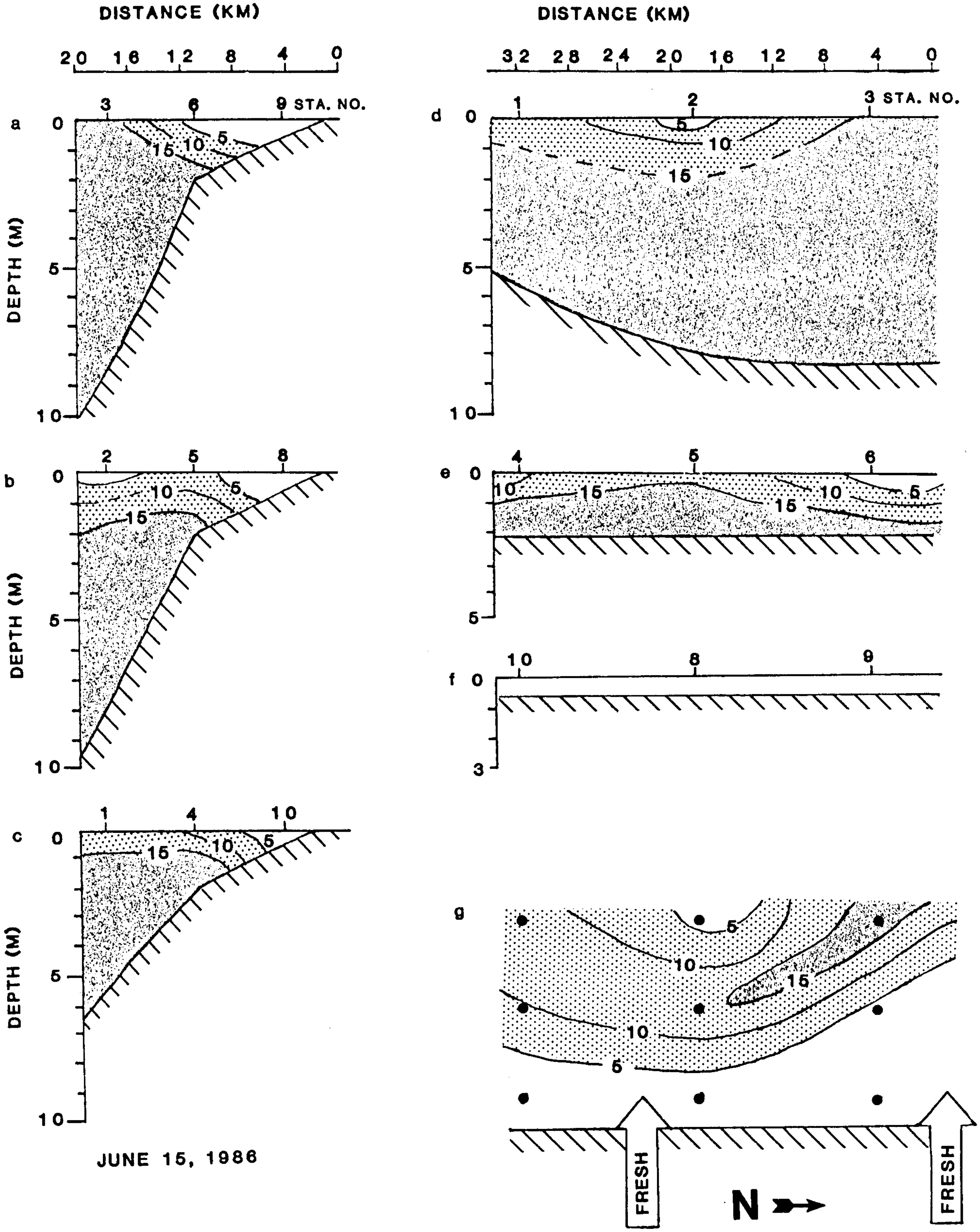

FIG. 3-3. Vertical section of salinity for the on/offshore direction (a-c) and the along-shore direction (d-f). Graphical depiction of study area showing sample stations, horizontal contours of surface salinity, and sources of freshwater input to the area (g) for the June 15, 1986 survey of the Yukon River Delta.

Satellite imagery from this day show similar distributions of surface temperature and water surface reflectivity (related to water clarity and total suspended solids (TSS), Groves and Stringer 1982) compared to the in-situ hydrographic samples. Figure 3-4 shows the Yukon Delta thermal and visible distributions on a regional scale. The thermal image (Figure 3-4a) indicates the warmer land, river, and nearshore water mass temperatures ranging from the warmest (red) to the somewhat cooler (yellow). As the river waters combine with more marine water on the delta platform they cool (green). Water temperatures in the river plume that extends beyond the delta front are cooler still (light blue). The Yukon River plume water can be seen as it moves off of the delta platform toward the west and then south in response to northeasterly winds. The solid light blue region corresponds to the 1 m thick layer of fresher (5-15 ppt), warm (5-10° C) water seen in the hydrographic data (Figure 3-3) on the delta platform. Just seaward of this region, thin plumes of the nearshore water can be seen moving offshore across the delta front, and overriding the brackish water (Figure 3-3). Cooler offshore water masses (darker blue) are distributed in a more or less random fashion beyond this area. Further offshore, near the edge of the picture, the northerly moving cooler Alaskan coastal water (purple) can be seen moving toward the Bering Strait.

Figure 3-4b also shows the corresponding visible image of the thermal configuration just discussed. In this image the colors, moving from red to yellow to green, indicate the reflectance (low to high) of an area. Groves and Stringer (1982) has shown that TSS can be related to the reflectance of the water surface if other conditions are the same. Research conducted by Envirosphere Company in Stefansson Sound, Alaska (Hachmeister, et al. 1986) also shows there is a relationship between Secchi depth and TSS. Although there is not a strong functional relationship established between the parameters, it is intuitively apparent that inverse Secchi depth is related to TSS. Therefore, the relationship between the AVHRR surface reflectance image and inverse Secchi depth might also be related. In this image (Figure 3-4b), the land that is not covered with a large percentage of water appears as

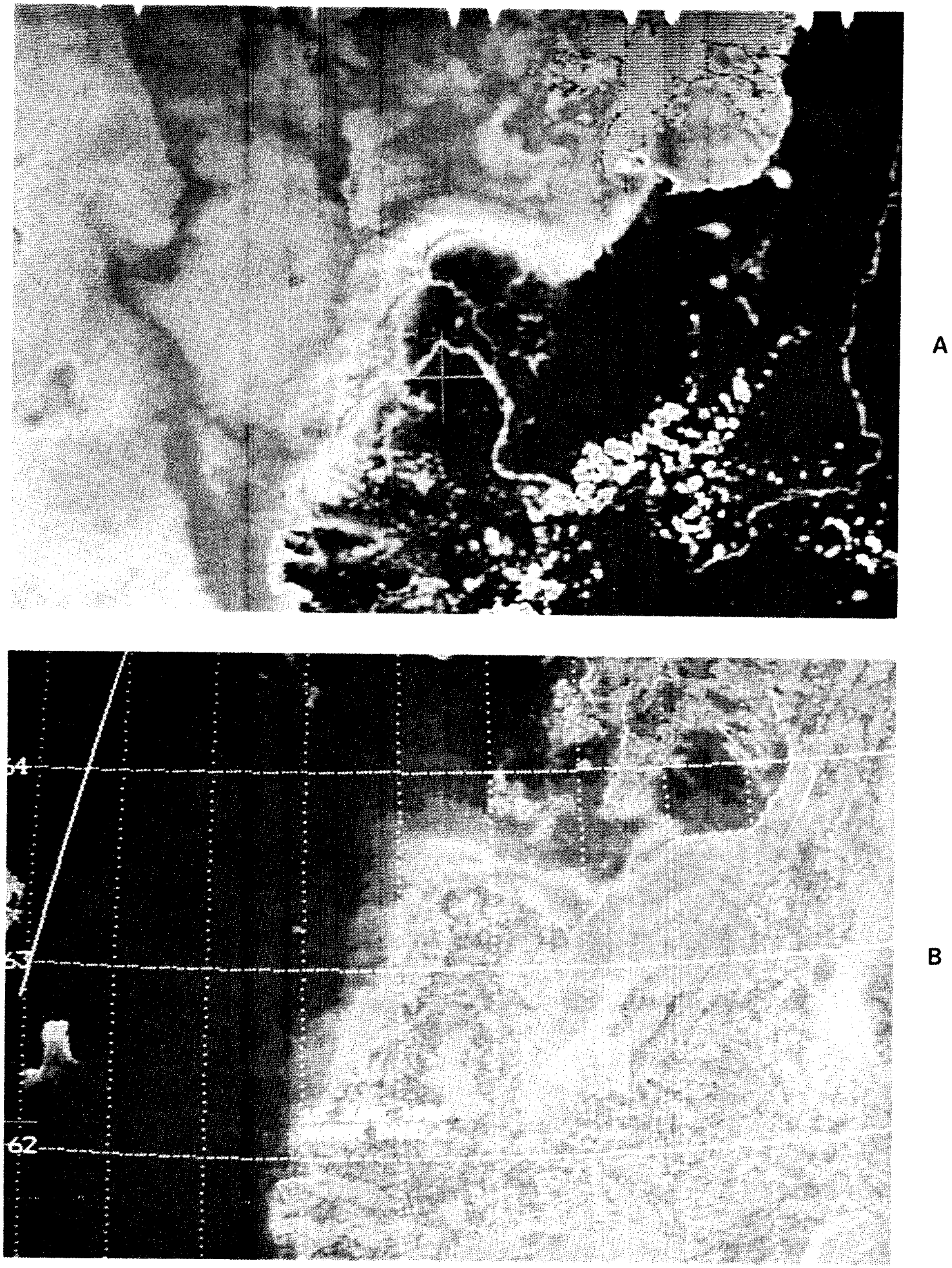

FIGURE 3-4

NOAA AVHRR Satellite Imagery of the Yukon River Delta, Approximate Scale 1:3 Million, June 15, 1986: A) Enhanced Thermal Infrared (Channel 4); B) Enhanced Visible (Reflected) (Channel 1).

blue. The purple region shows areas of very high reflectance that results from the presence of clouds. Assuming that reflectance (color) is an indication of sediment concentration, we see that the heaviest sediment concentrations are on the delta. These concentrations decrease somewhat moving off the delta platform and within 20 km from the coast onshore/offshore gradients become quite low. The lowest levels of suspended sediment occur in the colder coastal water mass (purple) previously identified in the thermal image. The long narrow band of green, immediately to the north of the delta, suggests very high concentrations of sediments. This is a very shallow region of the coastline and high particulate concentrations could result from resuspended bottom sediments near the mouth of the northern channel of the Yukon. These suspended sediments are then advected by wind driven (NNE winds) currents toward the west. Other small patches of green are observed in the shallow nearshore water just west of Emmonak and south of the southern mouth of the river.

Figure 3-5 shows an enlargement of the Yukon Delta region of the satellite image previously discussed. Details of the coastline and river channels have been added to this image to allow easy reference to visible thermal features along the coastline. The sampling stations where hydrographic measurements were collected are indicated with their corresponding station numbers. In Figure 3-5a, the warmer water (yellow) is seen in the shallow nearshore region where solar heating has increased the water temperature to that of the coastal land masses. This is most evident in the region around station 9 and along the northern edge of the delta, just north of Middle Mouth of the Yukon river. In the 1985 fisheries report (Martin et al. 1986) we had thought that these regions might be influenced by a marine water return flow. However,it is evident from the AVHRR images and our site surveys that this region is dominated by warm water which results from the broad intertidal mudflats. During low tide this area is characterized by exposed mudflats and large shallow (<20 cm) tidal pools.

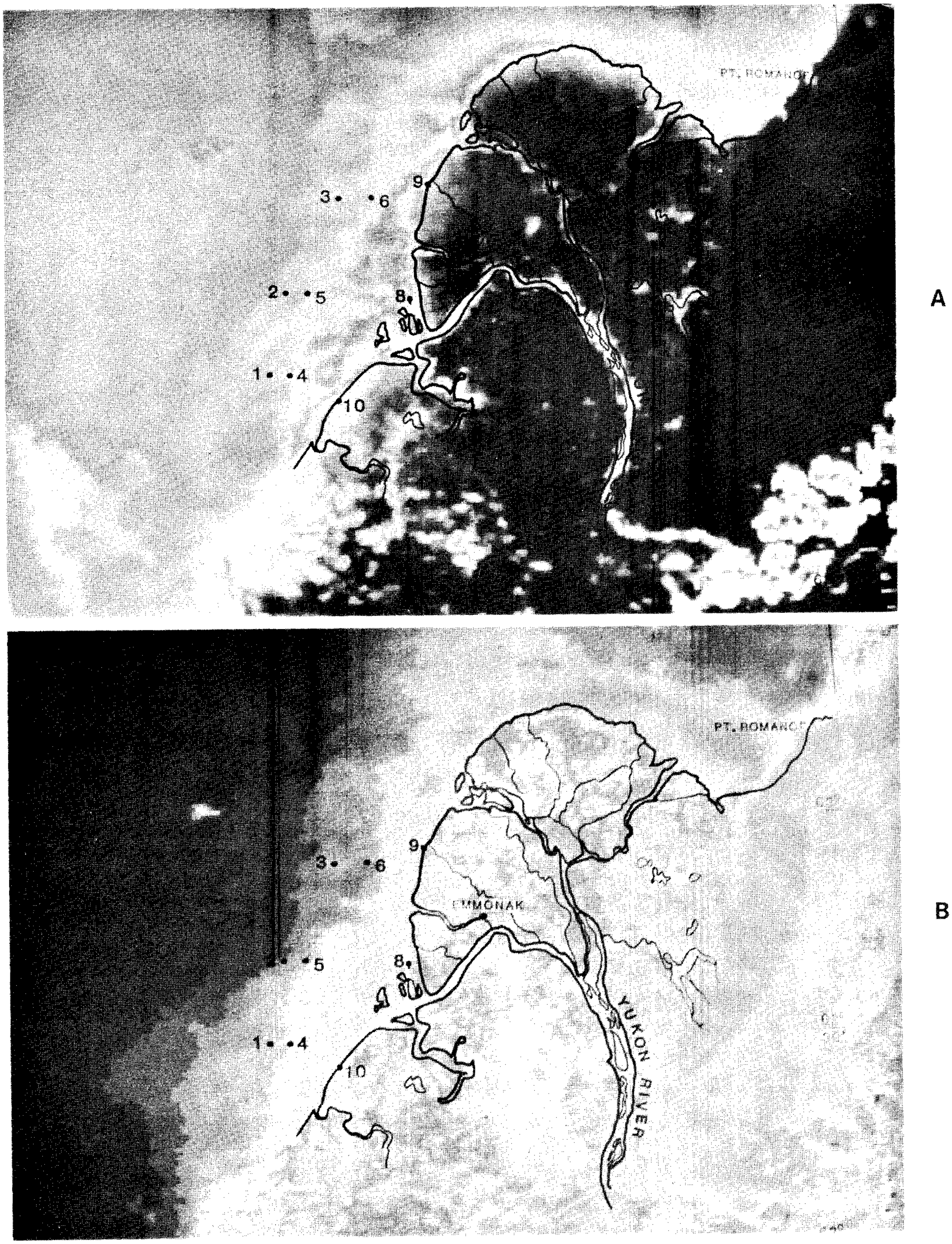

FIGURE 3-5

NOAA AVHRR Satellite Imagery of the Yukon River Delta, Approximate Scale 1:1.5 Million, June 15, 1986: A) Enhanced Thermal Infrared (Channel 4); B) Enhanced Visible (Reflected) (Channel 1).

Note that the river water is light blue and green in the channels and yellow where an image pixel (1 km by 1 km) overlaps the land mass (red) along the river bank. Detailed features of the plumes of light blue delta water moving off the delta platform can be seen as they override the cooler offshore water.

Surface temperature measurements collected on this day indicate that the offshore water (Stations 1, 2, and 3) ranged 10 - 15° C. The light blue water of the delta platform (Stations 4, 5, and 6) ranged 9 - 17°C and the shallow nearshore water was approximately 15 - 18° C. The light blue water just offshore of the north mouth of the river is very uniform in appearance which indicate temperatures were approximately 13 - 14°C. This region was identified as a region of possible intense mixing and sediment resuspension. The offshore region to the west of the delta platform appears very dynamic and extremely variable at small scales.

The corresponding visible image (Figure 3-5b) shows the details of the delta region with respect to the surface reflectance. The sediment plume (green) identified in Figure 3-4b can be seen in greater detail in this figure. In the region sampled by the measurement program, sediment concentrations are depicted by yellow through several shades of orange in two distant offshore zones defining the delta platform and the region just offshore of the delta front. In these zones the Secchi depth (which is inversely related to the TSS) ranged 0.2-1.2 m at stations 1-3 and 0.1-0.8 m at stations 4-6. Because no Secchi depths were recorded in offshore regions beyond the two zones described above, it cannot be determined how the further offshore distributions related to water clarity except that the reflectance is less and the clarity is assumed to be greater. Details of several higher turbidity regions can be seen south of the south mouth of the river near Station 10.

The high degree of spatial variability on the delta platform can be seen in Figure 3-6. Note that the subtle differences in temperature (Figure 3-6a) around the sampling stations would be advected

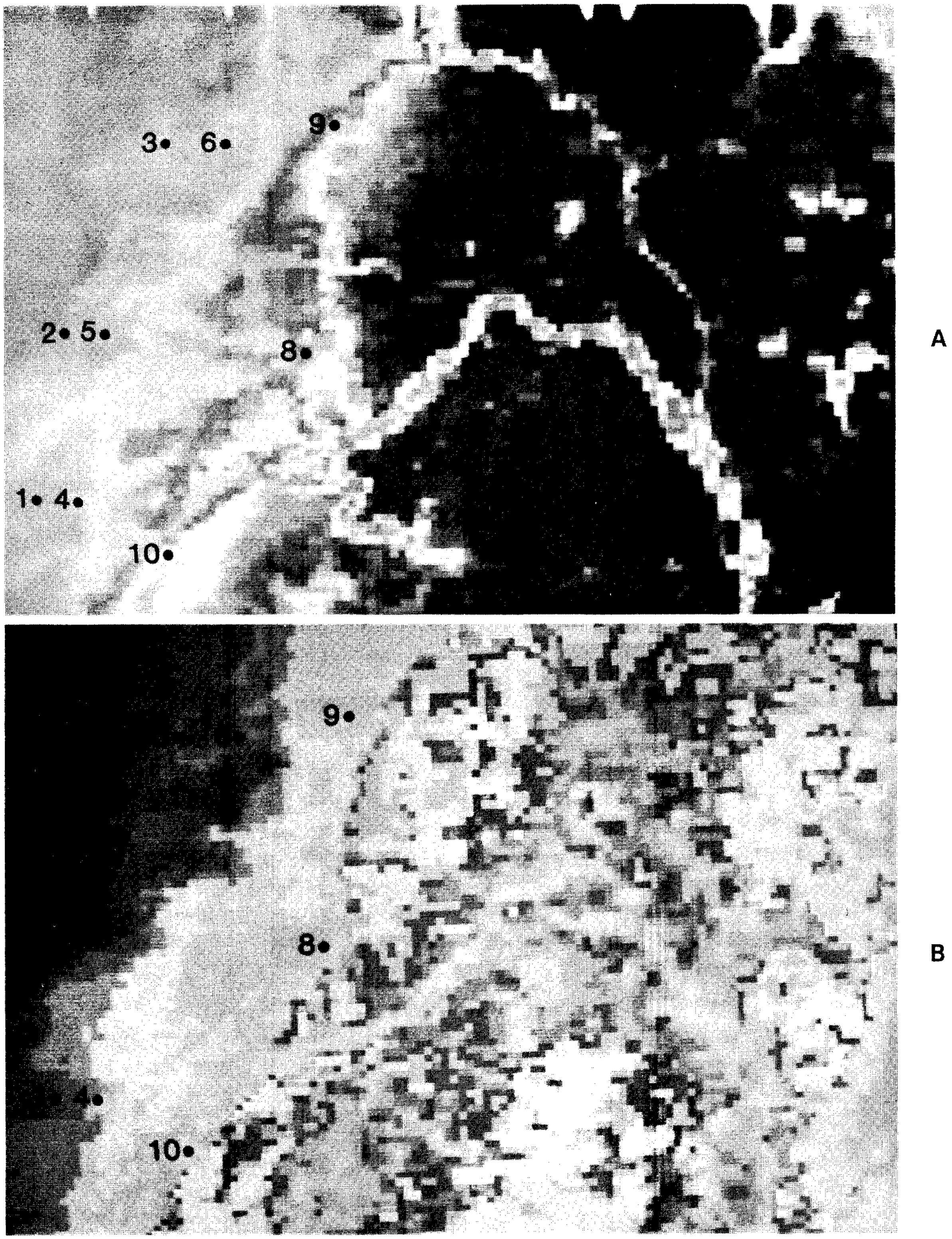

FIGURE 3-6

NOAA AVHRR Satellite Imagery of the Yukon River Delta, Approximate Scale 1:750,000, June 15, 1986: A) Enhanced Thermal Infrared (Channel 4); B) Enhanced Visible (Reflected) (Channel 1).

continuously across the delta by the wind driven current and that sampling of physical parameters on a given day is by no means synoptic relative to the advective changes occurring at a given station during the daily sampling period. Inland, the details of the river temperatures can also be seen more clearly. In the wider portions of the river, considerable difference in temperature can be seen between the river and the land. The visible image (Figure 3-6b) shows more distinction between the land mass (blue) and the water (orange) than did the thermal image. Note the offshore distance of Stations 9 and 10 in the visible image relative to the thermal image, where warm temperatures of the shallow water appear to extend the coastline offshore into the shallow water. The source of the highly turbid delta water can be seen in the central channel of the river where the color (TSS) of the river water is similar to that of the nearshore water.

June 19, 1986

During this survey, winds were 5 - 10 kts from the NNE. A considerable change had occurred in the hydrography of the study region in the three day period between the previous survey on 15 June and this survey. Fresher water ($\leq$5 ppt) extends beyond the outer station at all three of the sections (Figure 3-7). The sections show a considerable increase in the amount of fresher water in the region that occupied the upper 1 - 2 m of the water column at all stations. The intermediate salinity water (5 - 15 ppt) occupied most of the water column below the fresher water to a depth of 4 m. Examination of the wind field records indicate that no significant changes occurred from 15 - 19 June on the meteorology and it must be assumed that the observed hydrographic changes are a result of increased runoff and/or fresh water accumulation from the Yukon River (Figure 3-1). These conditions leave much of the delta platform with salinities less than 5 ppt. No indication of estuarine type water movement or upwelling are apparent on the delta platform in these data.

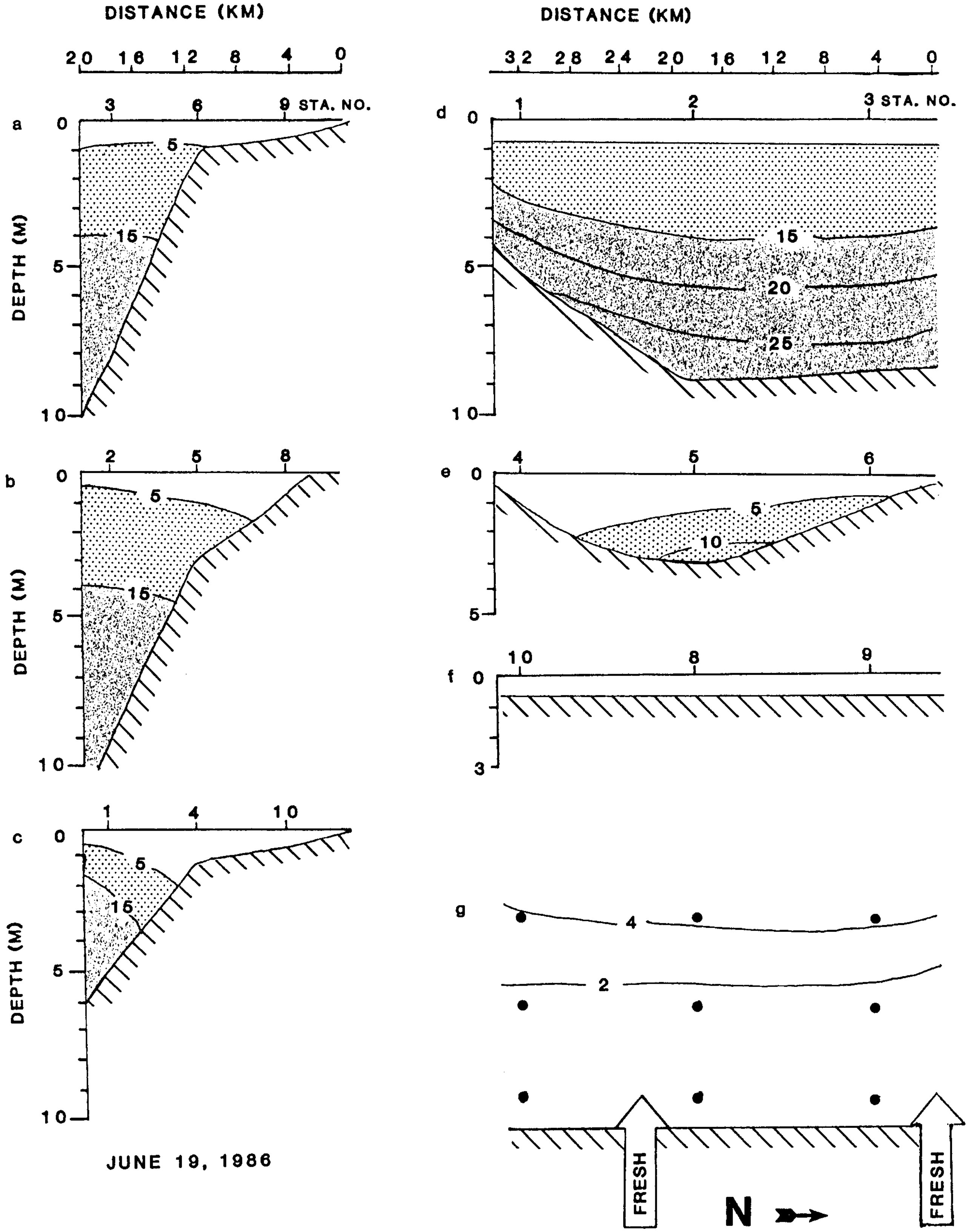

FIG. 3-7. Vertical sections of salinity for the on/offshore direction (a-c) and the along-shore direction (d-f). Graphical depiction of study area showing sample stations, horizontal contours of surface salinity, and sources of freshwater input to the area (g) for the June 19, 1986 survey of the Yukon River Delta.

August 6, 1986

Winds were 5 - 10 kts from the NNE during this survey. Observed hydrographic distributions (Figure 3-8) are indicative of a vertically well mixed system which might be brought on by sustained high winds and strong vertical mixing. However, no meteorological data are available for the days preceeding the survey for verification of this hypothesis. Fresher water was generally confined to within 4 - 10 km of the coastline. Little vertical stratification is indicated in the salinity sections and almost all salinity variability is in the on/offshore direction. Examination of the available temperature data also indicate no vertical stratification. Intermediate salinity water extended offshore from the fresher water out to 12 - 16 km in a vertically well mixed band approximately 6 km in width. As in the survey of 12 June, the observed distribution of salinity suggests that the source of fresher water in the study region is from the north. No effects of wind induced upwelling was observed along any of the transect lines.

3.2 CATCH SUMMARY

3.2.1 Effort

The sampling effort (i.e., in terms of sample frequency and date of sampling) was not evenly distributed among the delta habitats (Tables 3-1 and 3-2). The shallow mudflat and tidal slough stations were very difficult to reach during the June and early July period when helicopter usage was prohibited in these areas. Almost a full day of travel was required to sample one pair (i.e., mudflat and tidal slough) of sample sites. Therefore, most of the effort was concentrated on obtaining replicate samples from stations 8 and 11 (Table 3-1), which were representative of typical mudflat and tidal slough habitats, respectively. When the helicopter restrictions were not in effect (i.e., August), several additional coastal locations (i.e., stations 8 - 12) were sampled in order to examine spatial differences among these habitats. Poor weather and boat unavailability were the primary

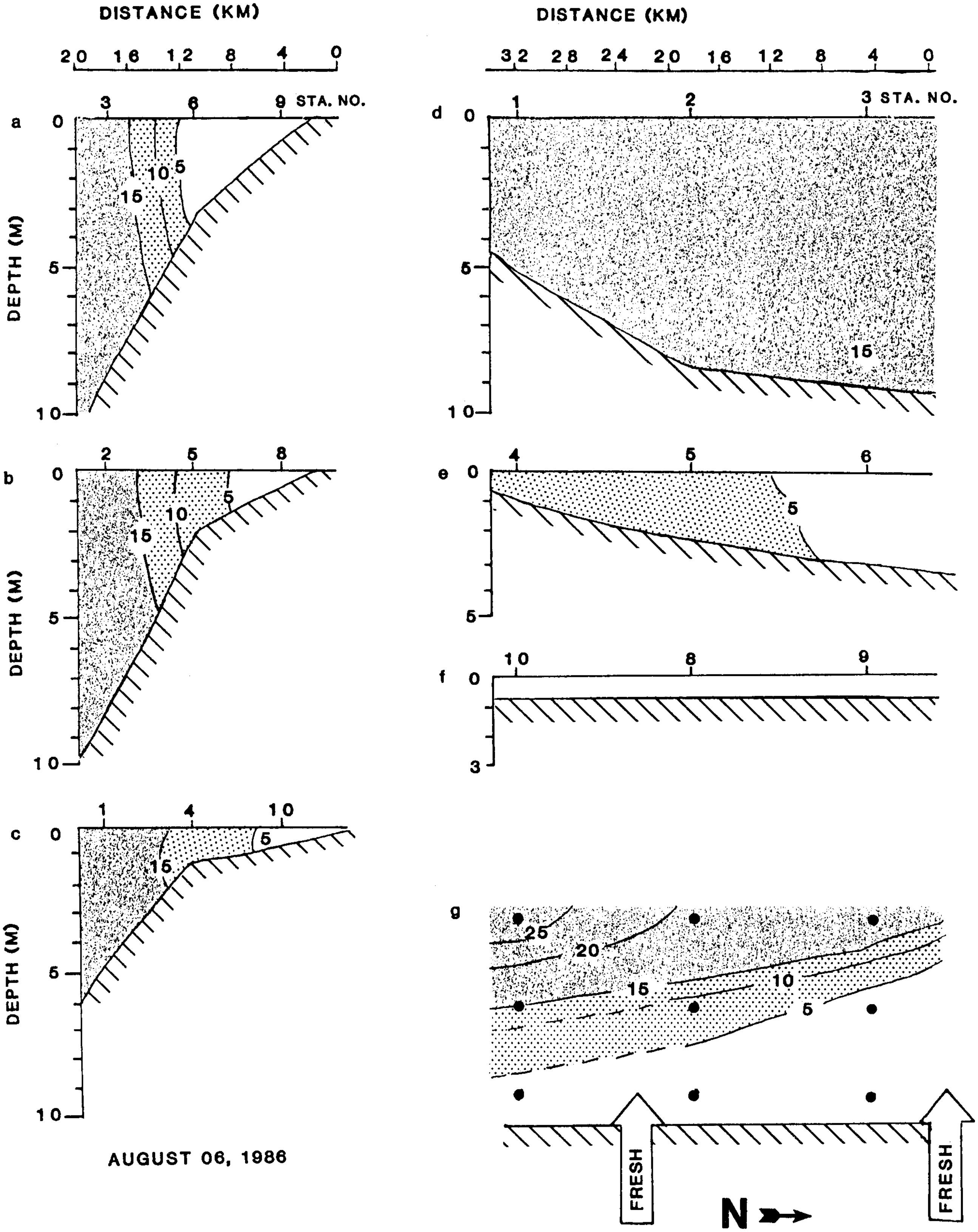

FIG. 3-8. Vertical sections of salinity for the on/offshore direction (a-c) and the along-shore direction (d-f). Graphical depiction of study area showing sample stations, horizontal contours of surface salinity, and sources of freshwater input to the area (g) for the August 6, 1986 survey of the Yukon River Delta.

TABLE 3-1
Summary of Sampling Effort (i.e., Number of Hauls) For Beach Seine and Purse Seine Gear During the Summer 1986 Survey of the Yukon River Delta

	Short Beach Seine[a]			
	Habitat/Station Tidal Slough			
Date	10	11	12	Total
6/10		2		2
6/14		2		2
6/17		2		2
6/22		2		2
6/24		2		2
6/25			2	2
7/12		2		2
7/13			2	2
8/04		2	2	4
8/05	2			2
TOTAL	2	14	6	22

	Long Beach Seine[b]		
	Habitat/Station Mudflats		
Date	8	9	Total
6/10	2		2
6/14	2		2
6/17	2		2
6/22	2		2
6/24	2		2
6/25		2	2
7/12	2		2
7/13		2	2
8/04	2	2	4
TOTAL	14	6	20

	Purse Seine		
	Habitat/Station River		
Date	13	14	Total
6/01		2	2
6/04	2		2
6/05	2		2
TOTAL	4	2	6

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[a] 30-meter haul.
[b] Round haul.

TABLE 3-2

Summary of Sampling Effort (i.e., Number of Hauls)[a] For the Tow Net During the Summer 1986 Survey of the Yukon River Delta

	Habitat/Station														
	Delta Front				Delta Platform					Lower River		Upper River			
Date	1	2	21	3	4	41	5	51	6	13	17	14	15	16	Total
5/31													1	1	2
6/01												7			7
6/02													3		3
6/04						2				3					5
6/05										3	15[b]				18
6/06	2		3			2		2							9
6/07											3				3
6/08											3				3
6/09										3	3				6
6/10											3				3
6/11											3				3
6/12	3	3		3	3		3		3						18
6/13										3	3				6
6/14										6[c]	3				9
6/15	3	3		3	3		3		3						18
6/17										3	3				6
6/18										3	3				6
6/19	3	3		3	3		3		3						18
6/20										5[c]	3				8
6/22										3	3				6
6/24										3	3				6
6/26										3	3				6
7/10											3				3
7/11	2			3	2				2						9
7/12										3	3				6
7/13											3				3
7/14	3	3		3	3		3		3						18
8/05										3	3				6
8/06	3	3		3			3		3						15
8/07										3	3				6
8/08										5	4				9
TOTAL	19	15	3	18	14	4	15	2	17	52	73	7	4	1	244

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a/ All hauls were 10 minutes except where indicated.
b/ One 10-minute tow and 14 5-minute tows.
c/ Five-minute tows.

factors restricting sampling of the delta front and delta platform. Ice blockage in the river mouth prohibited sampling prior to June 4th and stormy conditions during August prevented a second sample trip during this survey period (Table 3-2). The assignment of the primary sampling vessel (i.e., Munson boat) to another project after June 20th eliminated one offshore sampling trip during the latter part of June.

3.2.2 Species Composition and Distribution

The three sample surveys resulted in the capture of 26 species of fish (Table 3-3). Juvenile salmon ranked third in abundance and represented approximately 14 percent of the overall catch. Only stickleback and smelt were more abundant, each accounting for 40 and 29 percent of the catch, respectively. Most of the species caught were anadromous and pelagic type fishes, which was expected given the types of gear used and the environmental conditions sampled. However, a small number of marine and bottom type fishes were captured in the delta front and delta platform habitats.

The greatest variety and the largest number of fish species were caught in the delta platform and delta front habitats. Several marine bottom fish species (e.g., flounder, cod, and sculpin) were caught from these habitats despite the fact that only surface waters were sampled with the tow net. Ninespine stickleback, juvenile smelt, juvenile cisco, and juvenile chum salmon were the dominant species groups in these habitats. Mudflat and tidal slough habitats had a less diverse community which was mostly comprised of coregonid species. The lower river habitat was mostly composed of outmigrating juvenile salmon, juvenile cisco, and lamprey. A summary of all fish catches by species, station, and date is shown in Appendix Table B.

TABLE 3-3

Number of Fish Caught By Species and Habitat During Summer 1986 in the Yukon River Delta

Species	Scientific Name	Habitat						
		Delta Front	Delta Platform	Mudflat	Tidal Slough	Lower River	Upper River	All
Chinook Salmon	*Oncorhynchus tshawytscha*	33	41		1	444	177	696
Chum Salmon	*Oncorhynchus keta*	789	693	8	206	3079	60	4835
Pink Salmon	*Onrochynchus kisutch*					3	1	4
Arctic Char	*Salvelinus alpinus*		1			1	1	3
Sheefish	*Stenodus leucichthys*	1	17	52	5	257		332
Humpback Whitefish	*Coregonus pidschian*		3	73	27	4		107
Broad Whitefish	*Coregonus nasus*		2	14	6			22
Whitefish sp.		4	20	129	133	259		545
Bering Cisco	*Coregonus laurettae*		15	26	3			44
Least Cisco	*Coregonus sardinella*	9	130	39	23	44	6	251
Cisco sp.		629	897	23	35	1292		2876
Whitefish and Cisco					13	2		15
Boreal Smelt	*Osmerus eperlanus*	509	2564			5		3078
Smelt sp.		4214	4791	1				9006
Threespine Stickleback	*Gasterosteus aculeatus*				14			14
Ninespine Stickleback	*Pungitius pungitius*	9117	5500	44	1615			16276
Arctic Lamprey	*Lampetra japonica*	211	156			630		997
Lamprey sp.			1			5	22	28
Longnose Sucker	*Catostomus catostomus*			17		1		18
Northern Pike	*Esox lucius*				1			1
Burbot	*Lota lota*	4	170	15	48	34	8	279
Starry Flounder	*Platichthys stellatus*	3	7	43				53
Arctic Flounder	*Liopsetta glacialis*	7	47	25	176			255
Saffron Cod	*Eleginus gracilis*	173	23	1				197
Arctic Cod	*Boreogadus saida*	2	28					30
Fourhorn Sculpin	*Myoxocephalus quadricornis*	4	7		7			18
Sculpin sp.		1	1					2
Pacific Herring	*Clupea harengus pallasi*	498	119					617
Tubenose Poacher	*Pallasina barbata barbata*	1						1
Prickleback	*Lumpenus* sp.	3	2					5
Greenling	*Hexagrammos* sp.	3						3
Sandlance	*Ammodytes hexapterus*	3						3
TOTAL		16218	15235	510	2313	6060	275	40611
PERCENT		39.9%	37.5%	1.3%	5.7%	14.9%	0.7%	

3.3 CHINOOK SALMON

3.3.1 Migration Timing

Juvenile chinook salmon were caught on the first day of sampling in the Andreafsky River (stations 15 and 16 on May 31st) and the Yukon River (station 14 on June 1st) (Appendix Table B). Chinook juveniles were also present in the lower Yukon River on June 4th (Figure 3-9), which was the beginning of the sample program at stations 13 and 17. Juveniles were caught during all three survey periods, which indicate the outmigration was still in progress on August 8th, the last day of sampling. Catch per unit effort fluctuated greatly during the study period with the peak CPUE occurring during late June. Both sample stations showed similar trends in fish abundance over time, but the number of fish caught was consistently greater at station 17.

3.3.2 Distribution and Density

Juvenile chinook salmon were caught primarily in the delta front, delta platform, and lower river habitats (Table 3-4). No fish were caught at the mudflat sites but juveniles were caught in a tidal slough (i.e., Station 11) on one sample date. Fish were caught on the delta platform on the first day of sampling (i.e., June 4th) and occurred in this habitat prior to their occurrence in the delta front. Chinook salmon were caught in the delta front as late as July 13th, but were not detected in the delta platform at this time. Juvenile chinook salmon were not caught at any coastal or offshore station during the August survey despite their continued presence in the lower river.

The density of juvenile chinook salmon was highly variable over time and among habitats (Table 3-4). Temporal trends of density in the offshore habitats had unimodal patterns with peak densities occurring in mid-June. Densities in the river fluctuated greatly during the survey period with the largest peaks occurring during the latter half of June. The temporal trend in density in the offshore habitats did

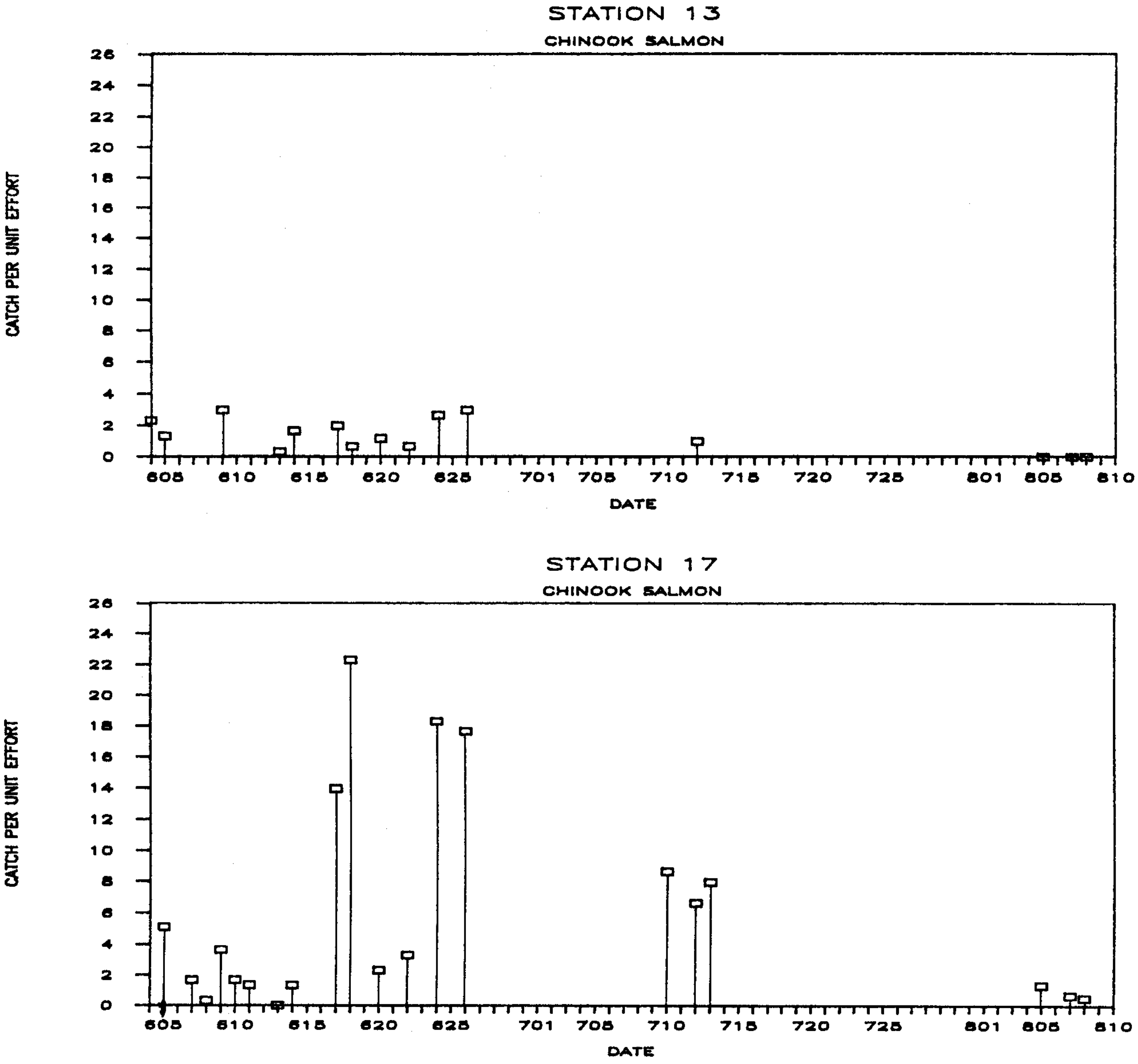

Fig. 3-9: Catch per unit effort of juvenile chinook salmon during summer 1986 from the lower river, stations 13 and 17, of the Yukon River Delta.

TABLE 3-4

Estimated Average Density (no/km^2) of Juvenile Chinook Salmon During Summer 1986 in the Offshore, Coastal, and Lower River Habitats of the Yukon River Delta

	Habitat/Station																	
	Delta Front				Delta Platform				Mudflats			Tidal Slough				Lower River		
Date	1	2	3	Mean	4	5	6	Mean	8	9	Mean	10	11	12	Mean	13	17	Mean
6/04	-	-	-	-	171[a]	-	-	171	-	-	-	-	-	-	-	798	-	798
6/05	-	-	-	-	-	-	-		-	-	-	-	-	-	-	456	1756	1539
6/06	0	0	-	0	0	171[a]	-	86	-	-	-	-	-	-	-	-	-	-
6/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	570	570
6/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	114	114
6/09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1026	1254	1140
6/10	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	-	570	570
6/11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	456	456
6/12	342	684	1140	722	342	342	0	228	-	-	-	-	-	-	-	-	-	-
6/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	114	0	57
6/14	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	570	456	532
6/15	114	228	1026	456	684	684	2052	1140	-	-	-	-	-	-	-	-	-	-
6/17	-	-	-	-	-	-	-	-	0	-	0	-	2165	-	2165	684	4788	2736
6/18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	228	7638	3933
6/19	0	114	0	38	0	114	114	76	-	-	-	-	-	-	-	-	-	-
6/20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	410	798	556
6/22	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	228	1140	684
6/24	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	912	6270	3591
6/25	-	-	-	-	-	-	-	-	-	0	0	-	-	0	0	-	-	-
6/26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1026	6042	3534
7/10	0	-	0	0	171	-	0	86	-	-	-	-	-	-	-	-	2964	2964
7/11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7/12	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	342	2280	1311
7/13	0	114	0	38	0	0	0	0	-	0	0	-	-	0	0	-	2736	2736
7/14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8/04	-	-	-	-	-	-	-	-	0	0	0	-	0	0	0	-	-	-
8/05	-	-	-	-	-	-	-	-	-	-	-	0	-	-	0	0	456	228
8/06	0	0	0	0	-	0	0	0	-	-	-	-	-	-		-	-	-
8/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	228	114
8/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	171	76

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[a] Estimated from catches at stations 41 or 51.

not appear to follow the density trends in the lower river. Comparisons among habitats, excluding the river, indicates the greatest density occurred in the tidal slough on June 12th. The absence of juveniles in this habitat at any other time indicates that the duration of habitat utilization was short term. Average densities of fish were generally greater in the delta platform than the delta front, but the difference between both habitats was relatively small.

Juvenile chinook salmon densities varied among stations within a habitat type. During the period of peak densities in the delta front (i.e., 6/12 and 6/15), there was a trend of increasing fish density from south to north (Table 3-4). This trend is not apparent in the delta platform, where fish densities were similar among two of the three stations during this time period. In the lower river, densities were consistently greater at station 17 than at station 13.

3.3.3 Size Composition

Juvenile chinook salmon ranged in size from 69 mm to 128 mm (Appendix Table B). Fish caught in the lower river during early June had a slightly greater mean length and a greater variation in size (i.e., larger standard deviation) than fish caught during late June (Figure 3-10). More than one length frequency mode is apparent during several sample periods which indicates more than one cohort size group was outmigrating from the Yukon River. The length frequency of a small number of fish (i.e., 8 fish) caught in August was not plotted. But the large variations in fish lengths from this sample (range 85 - 115 mm) indicates more than one size group of juveniles may occur at this time (Appendix Table B). Temporal trends in size compositions of chinook salmon caught in other habitats were not analyzed because catches were too small for a useful size frequency analysis.

A comparison of fish lengths among habitats during the period of peak abundance offshore (i.e., 6/12/86 - 6/15/86) indicates a close similarity in size composition among the delta front , delta platform, and lower river (Figure 3-11). Fish from all three habitats had a

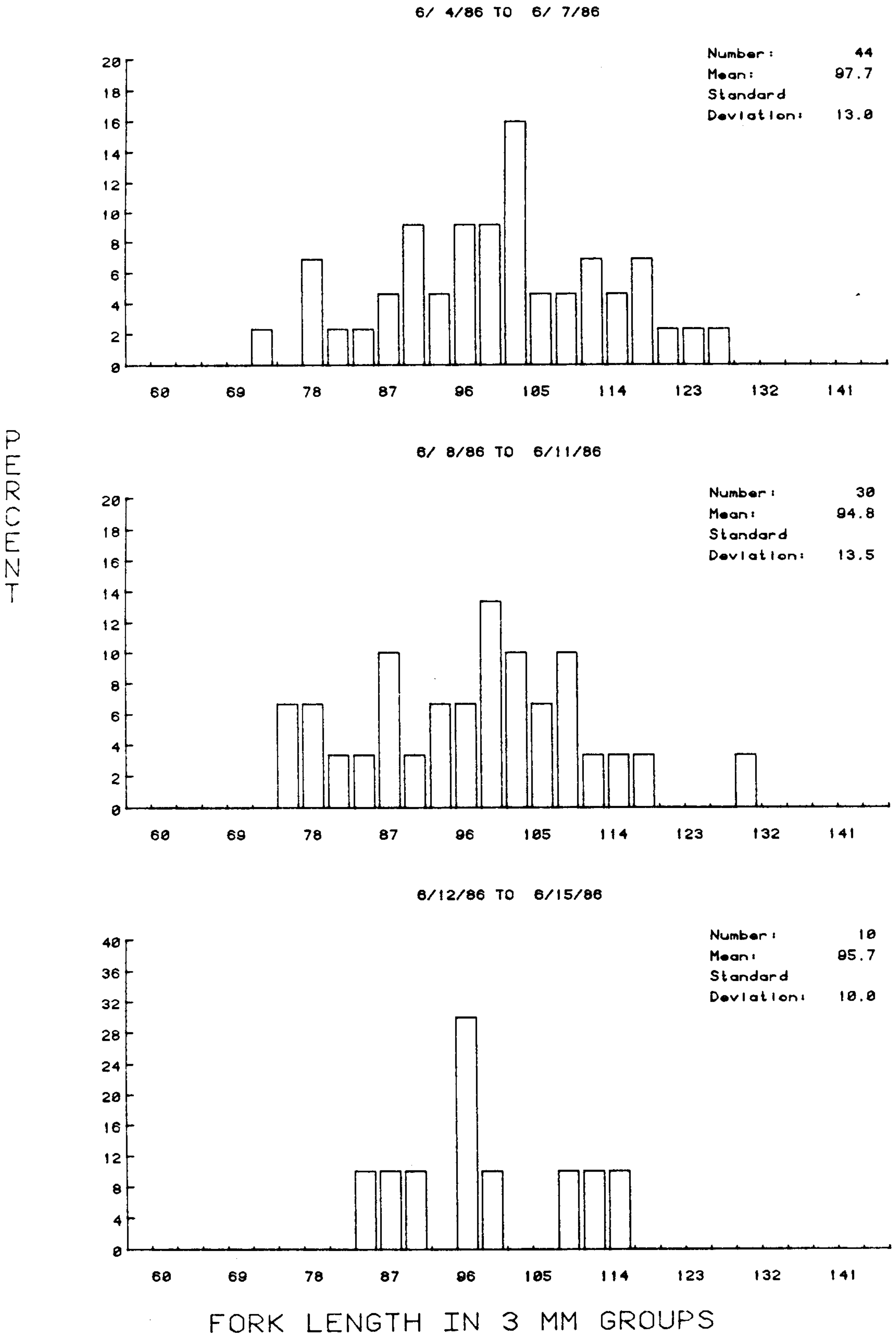

Fig. 3-10: Length frequency of juvenile chinook salmon by time period during summer 1986 from the lower river, stations 13 and 17, of the Yukon River Delta.

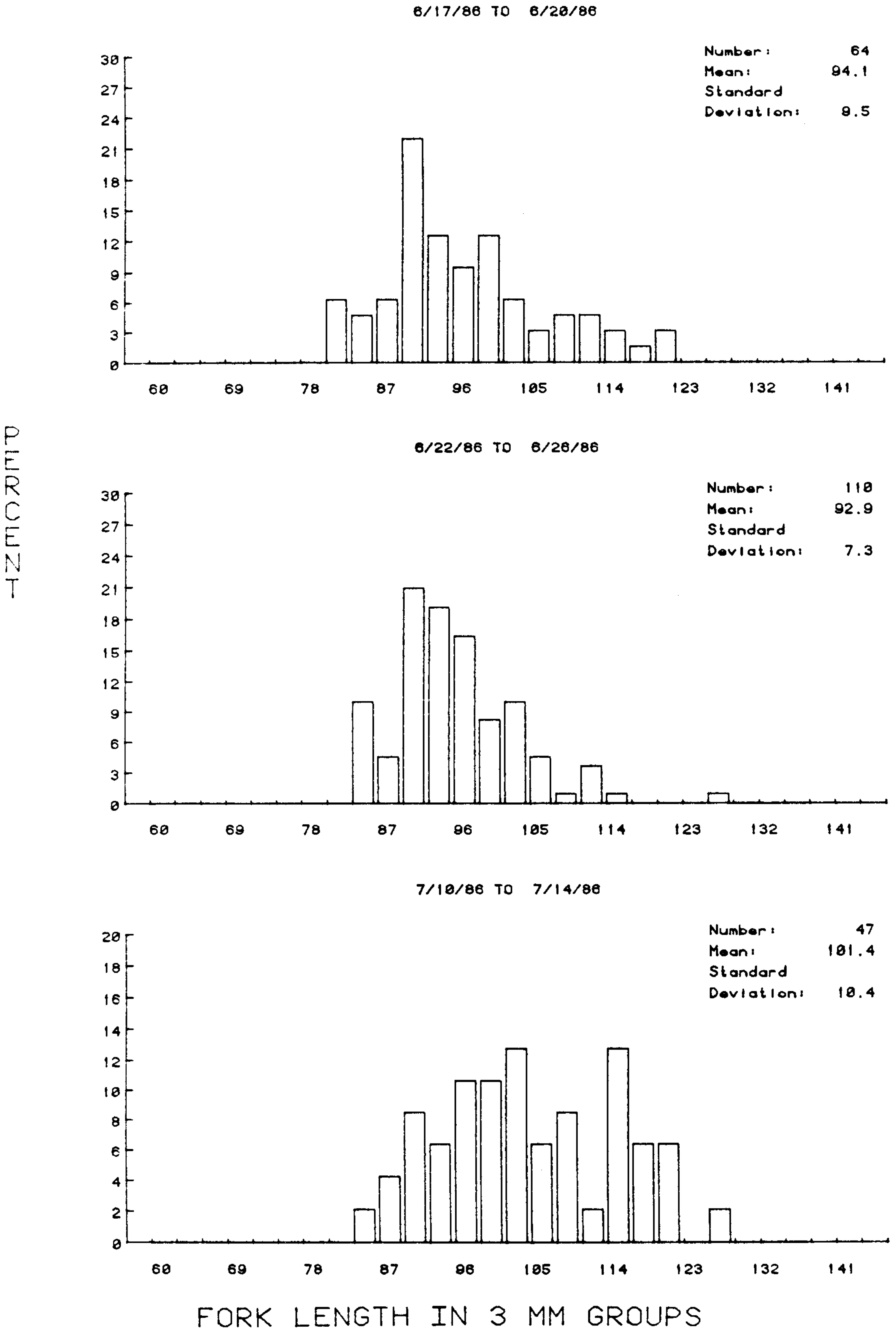

Fig. 3-10 (continued)

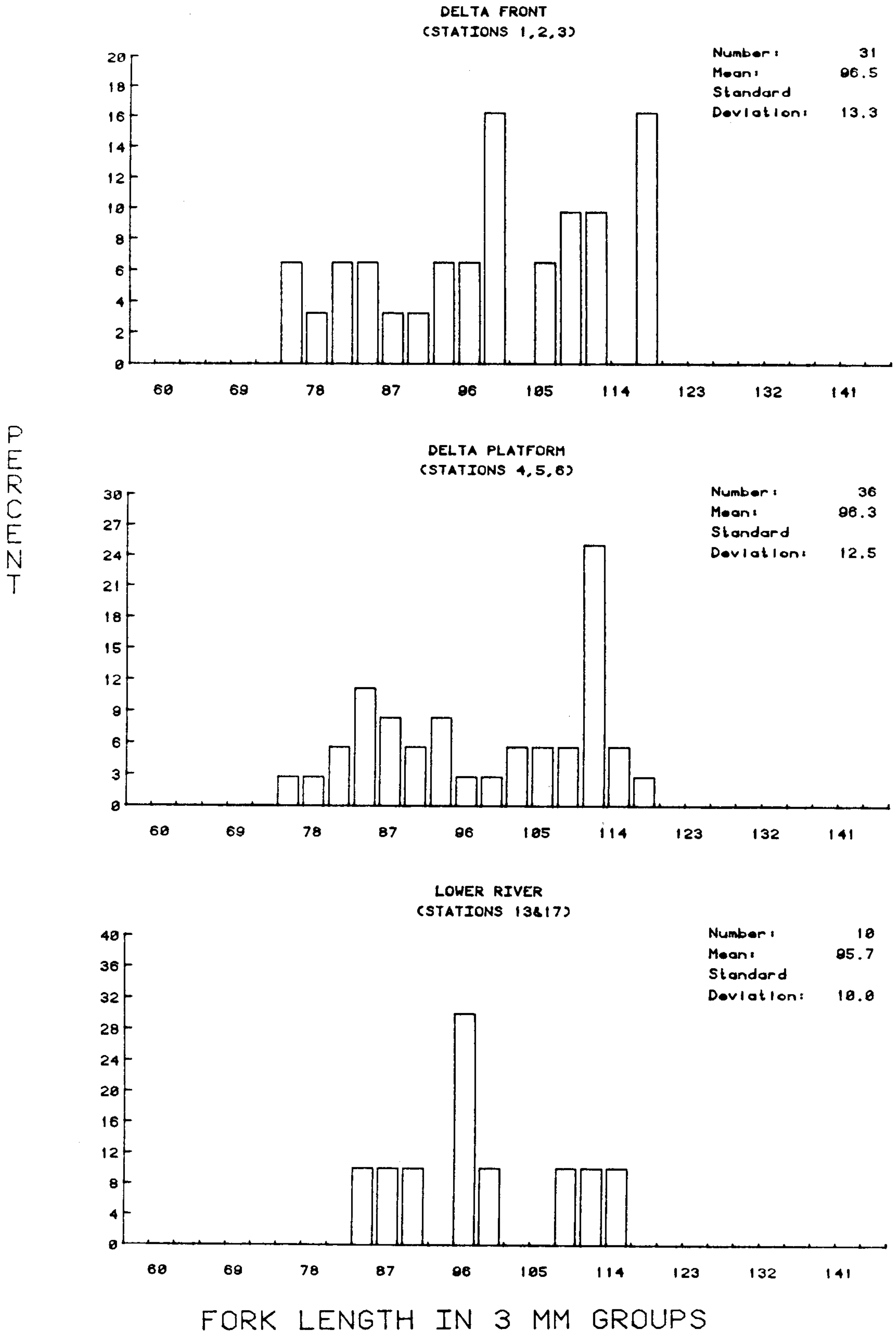

Fig. 3-11: Length frequency of juvenile chinook salmon during the period 6/12/86 to 6/15/86 from the lower river, delta platform, and delta front habitats of the Yukon River Delta.

bimodal size distribution with the nadir at approximately 102 mm and an average length of about 96 mm. Differences in size composition were evident, however, among the stations within the delta front and delta platform habitats (Figure 3-12 and 3-13). The percentage of small fish (i.e., <102 mm) and large fish (i.e., >102 mm) is not uniform among stations. A greater percentage of large fish occur at the northern stations (i.e., stations 3 and 6) than at the southern stations (i.e., stations 1 and 4).

3.3.4 Associated Environmental Conditions

The chinook salmon environmental associations for temperature, salinity, and visibility are shown in Tables 3-5 to 3-7, respectively. The diagonal from top left to bottom right on the temperature and salinity tables represents mixed water. Deviation from this diagonal represents stratified conditions. In most cases juvenile chinook salmon catches were associated with stratified conditions. Most fish were caught in relatively warm surface water (i.e., >6°C) with moderate to low salinity (i.e., <20 ppt) and cool bottom water (i.e., <6°C) with moderate to high salinity (i.e., >15 ppt). The largest catch of juvenile chinook salmon was associated with surface water temperatures that ranged 8-10°C, salinities that ranged 10-15 ppt, and water visibility that ranged greater than 0.5 m.

Highest catches were more associated with the deeper subtidal habitats (i.e., delta platform and delta front) than with the shallow intertidal habitats. Catches were not associated with any particular water depth in the offshore habitats.

3.4 CHUM SALMON

3.4.1 Migration Timing

Juvenile chum salmon were present in the catch during all three sample surveys (Figure 3-14). Low numbers of juvenile were caught in the Andreafsky River (stations 15 and 16) and Yukon River (station 14)

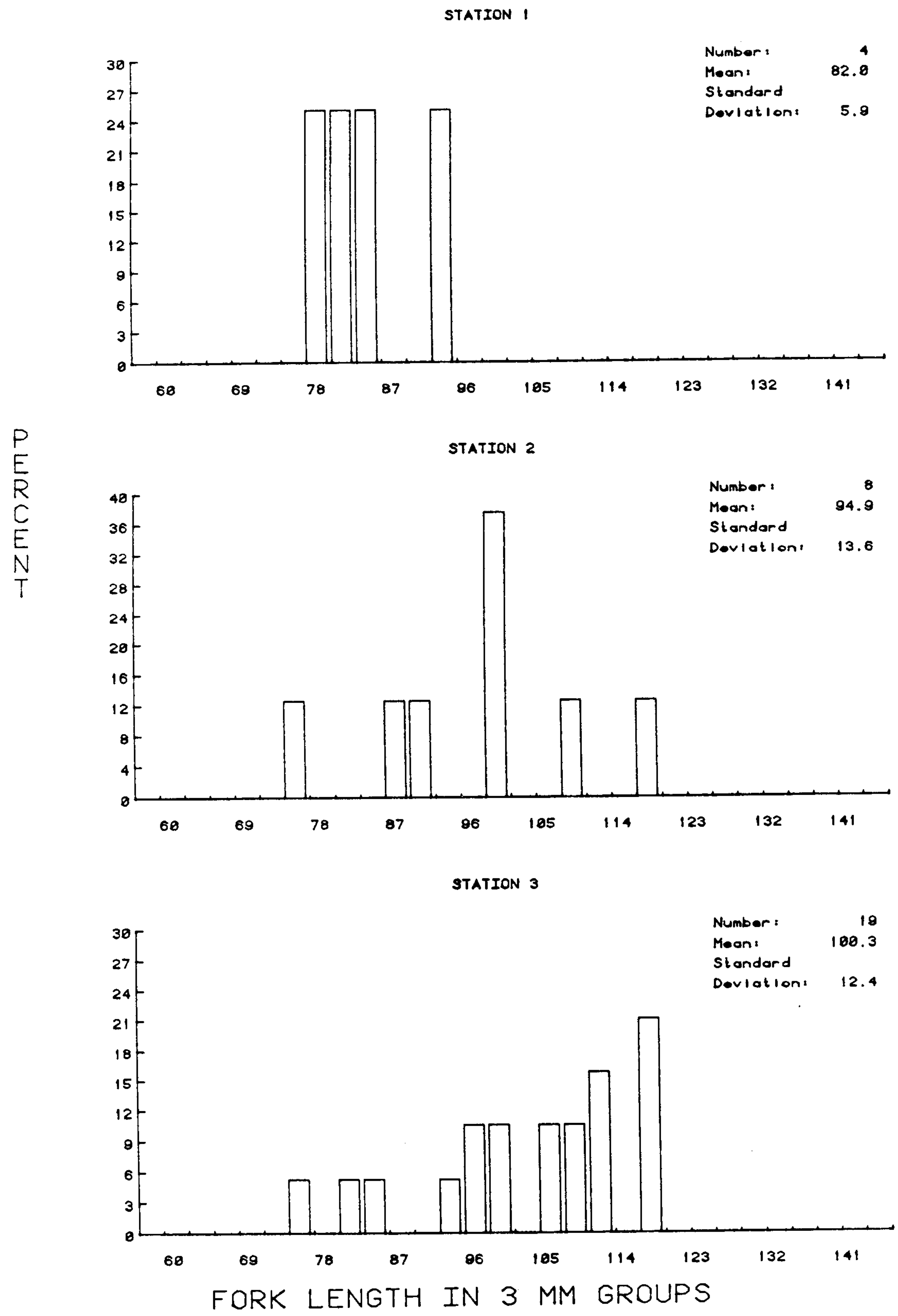

Fig. 3-12: Length frequency of juvenile chinook salmon during the period 6/12/86 to 6/15/86 from the delta front, stations 1, 2 and 3, of the Yukon River Delta.

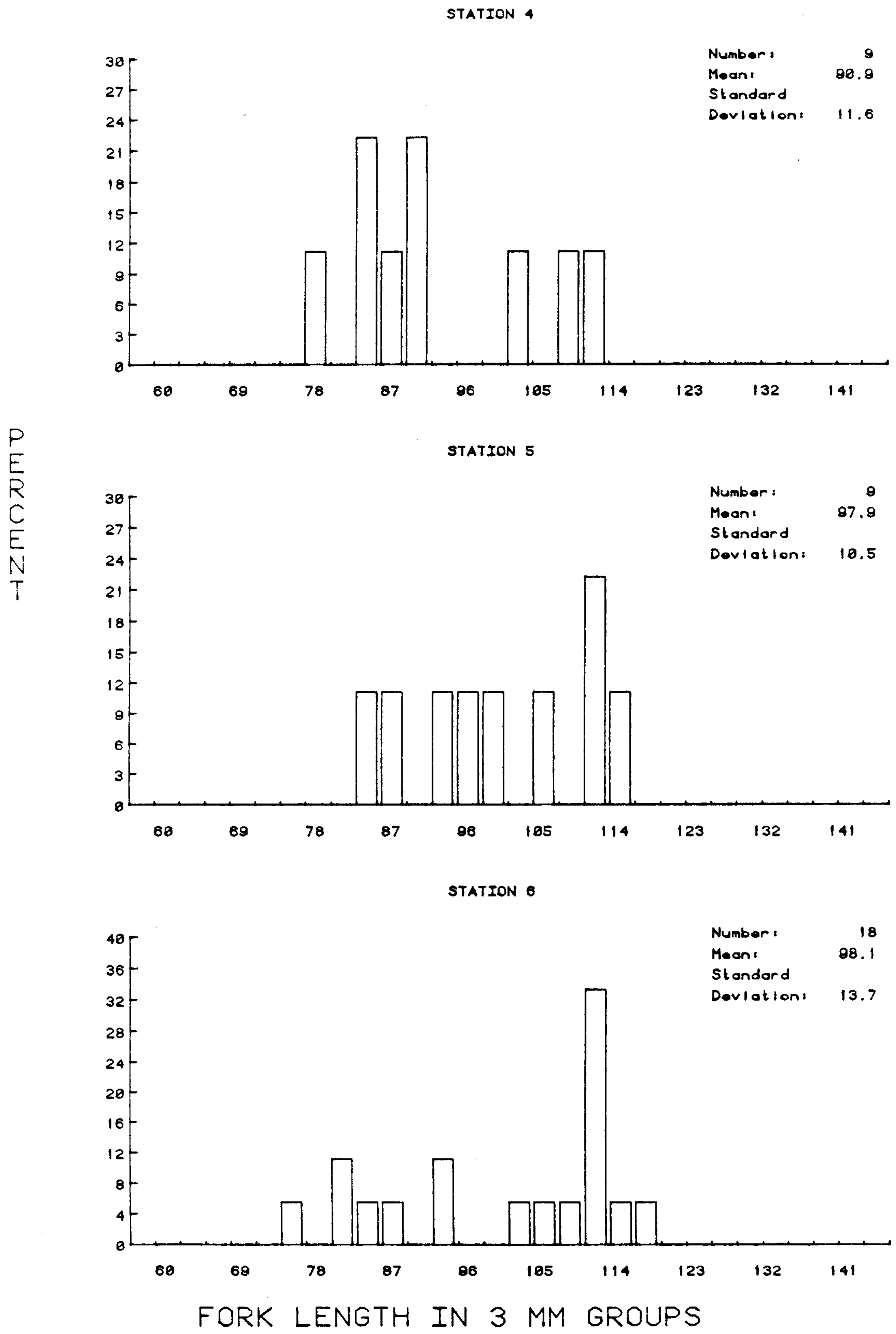

Fig. 3-13: Length frequency of juvenile chinook salmon during the period 6/12/86 to 6/15/86 from the delta platform, stations 4, 5 and 6, of the Yukon River Delta.

TABLE 3-5

Percentage Adjusted Catch of Chinook Salmon Associated With Surface and Bottom Temperature in the Delta Front and Delta Platform Habitats of the Yukon River Delta During June 12-19, 1986

Bottom Temperature (°C)	Surface Temperature (°C)										Total
	<0	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	≥16	
<0	-	-	-	-	-	-	-	-	-	-	-
0-2	-	-	-	-	8.2	27.2	12.9	2.7	5.4	-	56.5
2-4	-	-	-	-	-	16.3	0.0	-	-	-	16.3
4-6	-	-	-	-	-	8.2	-	-	-	-	8.2
6-8	-	-	-	-	-	-	0.0	16.3	-	-	16.3
8-10	-	-	-	-	-	-	-	-	-	-	0.0
10-12	-	-	-	-	-	-	2.7	-	-	-	2.7
12-14	-	-	-	-	-	-	-	0.0	-	-	0.0
14-16	-	-	-	-	-	-	-	-	-	-	-
≥15	-	-	-	-	-	-	-	-	-	-	-
TOTAL	-	-	-	-	-	8.2	51.7	15.6	2.7	21.8	-

TABLE 3-6

Percentage Adjusted Catch of Chinook Salmon Associated With Surface and Bottom Salinity in the Delta Front and Delta Platform Habitats of the Yukon River Delta During June 12-19, 1986

Bottom Salinity (ppt)	Surface Salinity (ppt) 0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	Total
0-5	0.0	-	-	-	-	-	-	-	0.0
5-10	2.6	-	-	-	-	-	-	-	2.6
10-15	-	-	-	-	-	-	-	-	-
15-20	-	15.4	7.7	-	-	-	-	-	23.1
20-25	2.6	7.7	15.4	-	-	-	-	-	25.6
25-30	0.0	9.0	16.7	23.1	-	-	-	-	48.7
30-35	-	-	-	-	-	-	-	-	-
35-40	-	-	-	-	-	-	-	-	-
TOTAL	5.1	32.1	39.7	23.1	-	-	-	-	

TABLE 3-7

Percentage Adjusted Catch of Chinook Salmon Associated With Water Visibility in the Delta Front and Delta Platform Habitats of the Yukon River Delta During June 12-19, 1986

Visibility (m)	Adjusted Catch (Percent)
0.-0.1	----
0.1-0.2	0.3
0.2-0.3	7.1
0.3-0.4	----
0.4-0.5	6.2
0.5-0.6	10.7
0.6-0.7	21.4
0.7-0.8	11.6
0.8-0.9	11.7
0.9-1.0	----
>1.0	32.1

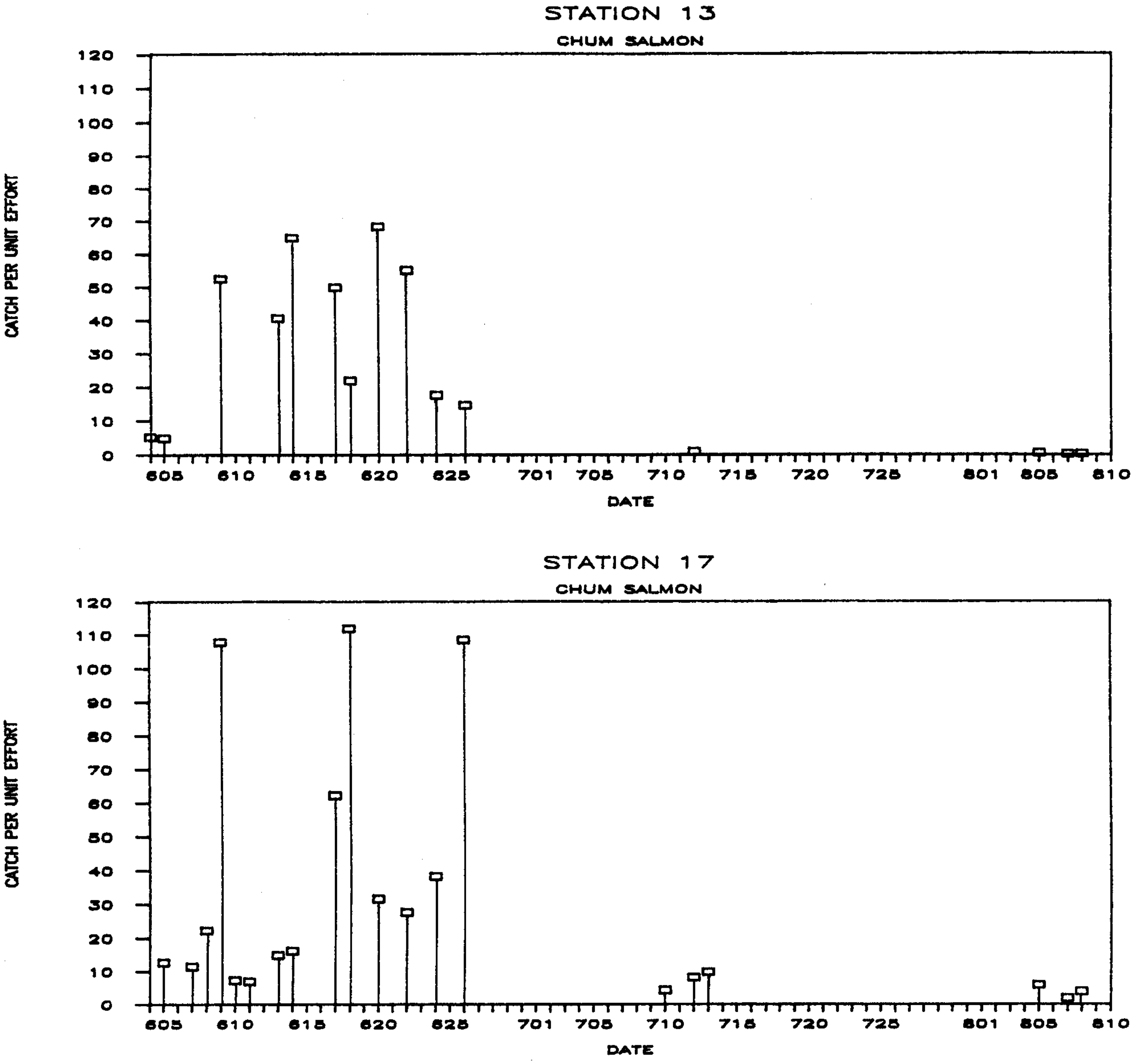

Fig. 3-14: Catch per unit effort of juvenile chum salmon during summer 1986, from the lower river, stations 13 and 17, of the Yukon River Delta.

during the first few days of sampling (i.e., May 31st and June 1st) (Appendix Table B). Catches were also low at the lower river stations during the first week of June. Catches increased greatly during the second week of June and CPUE fluctuated over a broad range during the remainder of the first survey period. Catches peaked three times at each station (i.e., stations 13 and 17), but the timing of the peak catches were not similar between both stations except for the first peak, which occurred on June 9th. During July and August, the CPUE at both sample stations was reduced to 10 or less fish and fluctuations were very small.

3.4.2 Distribution and Density

Juvenile chum salmon were caught in all five habitats during the summer, but the duration of fish occurrence was variable among habitats (Table 3-8). Fish were present in early June on the first date that each habitat was sampled. Juveniles were caught in the mudflat and tidal slough habitats for a short period during June and were caught in the delta front and delta platform habitats from early June to early August.

Densities of juvenile chum salmon were highly variable among habitats and over time (Table 3-8). Densities were an order of magnitude greater in the tidal slough (station 11) than at any other location. Densities peaked in the coastal habitats during mid-June and were highest in the offshore habitats during late June. During the period of peak density (i.e., 6/12 to 6/19), densities at the delta front showed a declining trend between stations 1 and 3. No trend was evident among delta platforms stations during the same time period.

3.4.3 Size Composition

Juvenile chum salmon ranged in length from 29 mm to 107 mm with the majority of fish being less than 70 mm (Appendix B). In the lower Yukon River at least three size groups were caught during the survey period (Figure 3-15). A group of large fish (i.e., group 1) with an

TABLE 3-8

Estimated Average Density (no/km^2) of Juvenile Chinook Salmon
During Summer 1986 in the Offshore, Coastal, and Lower River Habitats of the Yukon River Delta

	Habitat/Station																	
	Delta Front				Delta Platform				Mudflats			Tidal Slough				Lower River		
Date	1	2	3	Mean	4	5	6	Mean	8	9	Mean	10	11	12	Mean	13	17	Mean
6/04	-	-	-	-	171a/	-	-	171	-	-	-	-	-	-	-	1824	-	
6/05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1710	4400	3952
6/06	0	342a/	-	205	513a/	342a/	-	428	-	-	-	-	-	-	-	-	-	
6/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3990	3990
6/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7638	7638
6/09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	18012	36936	27474
6/10	-	-	-	-	-	-	-	-	9092	-	9092	-	19481	-	19481	-	2508	2508
6/11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	2394	2394
6/12	6498	7182	1824	5168	4788	4446	342	3192	-	-	-	-	-	-	-	-	-	-
6/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	13908	5130	9519
6/14	-	-	-	-	-	-	-	-	12122	-	12122	-	426407	-	426407	22230	5586	16682
6/15	20634	10488	1254	10792	2052	11970	15390	9804	-	-	-	-	-	-	-	-	-	-
6/17	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	17100	21318	19209
6/18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	7524	38304	22914
6/19	16872	11172	9918	12654	9918	21774	6840	12844	-	-	-	-	-	-	-	-	-	-
6/20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	23393	10830	18682
6/22	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	18810	9462	14136
6/24	-	-	-	-	-	-	-	-	3031	-	3031	-	0	-	0	6042	13110	9576
6/25	-	-	-	-	-	-	-	-	-	0	0	-	-	0	0	-	-	-
6/26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	5016	37164	21090
7/10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1482	1482
7/11	0		2850	1710	171	-	0	86	-	-	-	-	-	-	-	-	-	-
7/12	-	-	-	-	-	-	-	-	0	-	0	-	0	-	0	342	2850	1596
7/13	-	-	-	-	-	-	-	-	-	0	0	-	-	0	0	-	3420	3420
7/14	456	114	114	228	114	0	456	190	-	-	-	-	-	-	-	-	-	-
8/04	-	-	-	-	-	-	-	-	0	0	0	-	0	0	0	-	-	-
8/05	-	-	-	-	-	-	-	-	-	-	-	0	-	-	0	228	2052	1140
8/06	0	228	0	76	-	0	114	57	-	-	-	-	-	-	-	-	-	-
8/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	114	684	399
8/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	137	1368	684

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a/ Estimated from catches at stations, 21, 41, or 51.

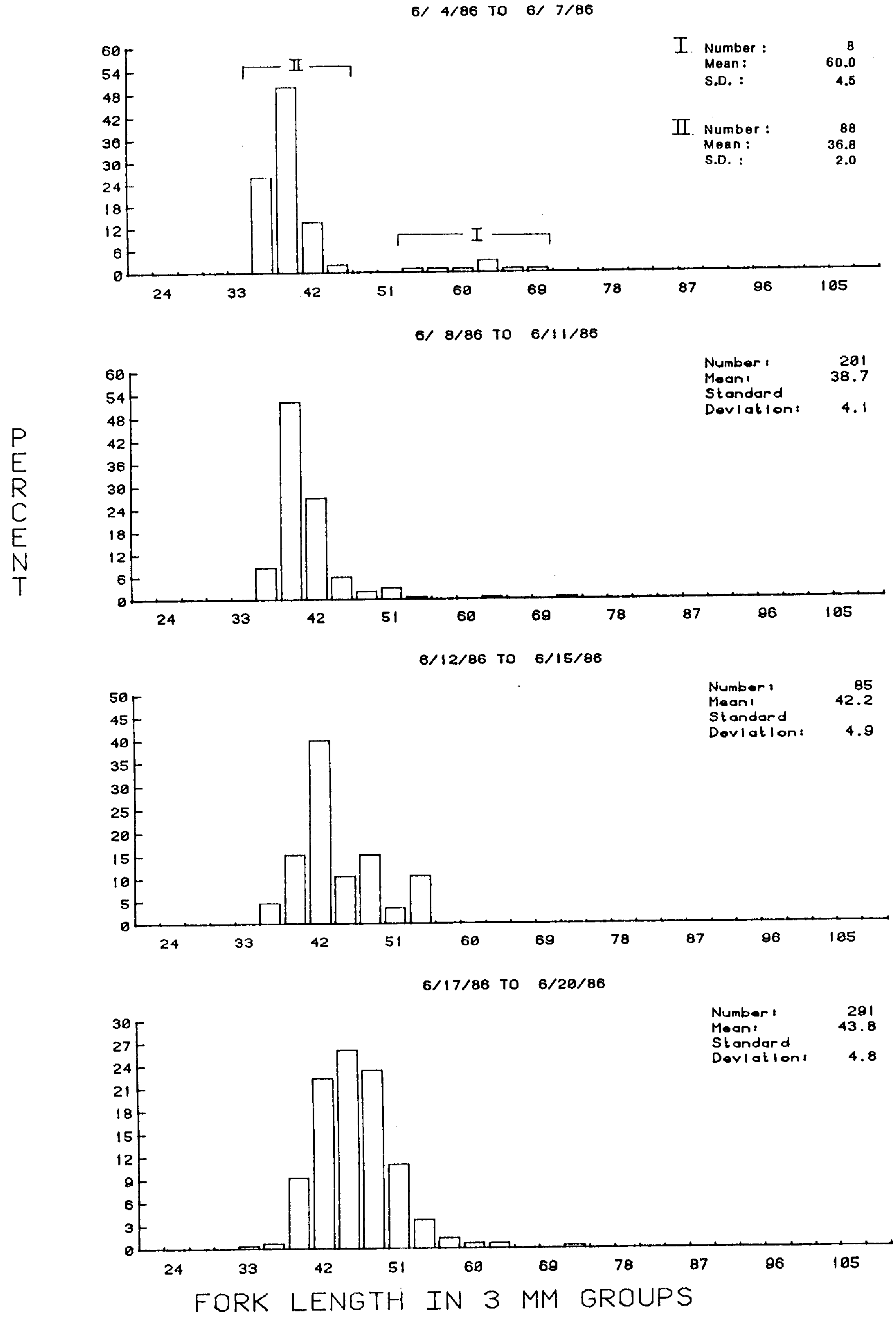

Fig. 3-15: Length frequency of juvenile chum salmon by time period during summer from the lower river, stations 13 and 17, of the Yukon River Delta.

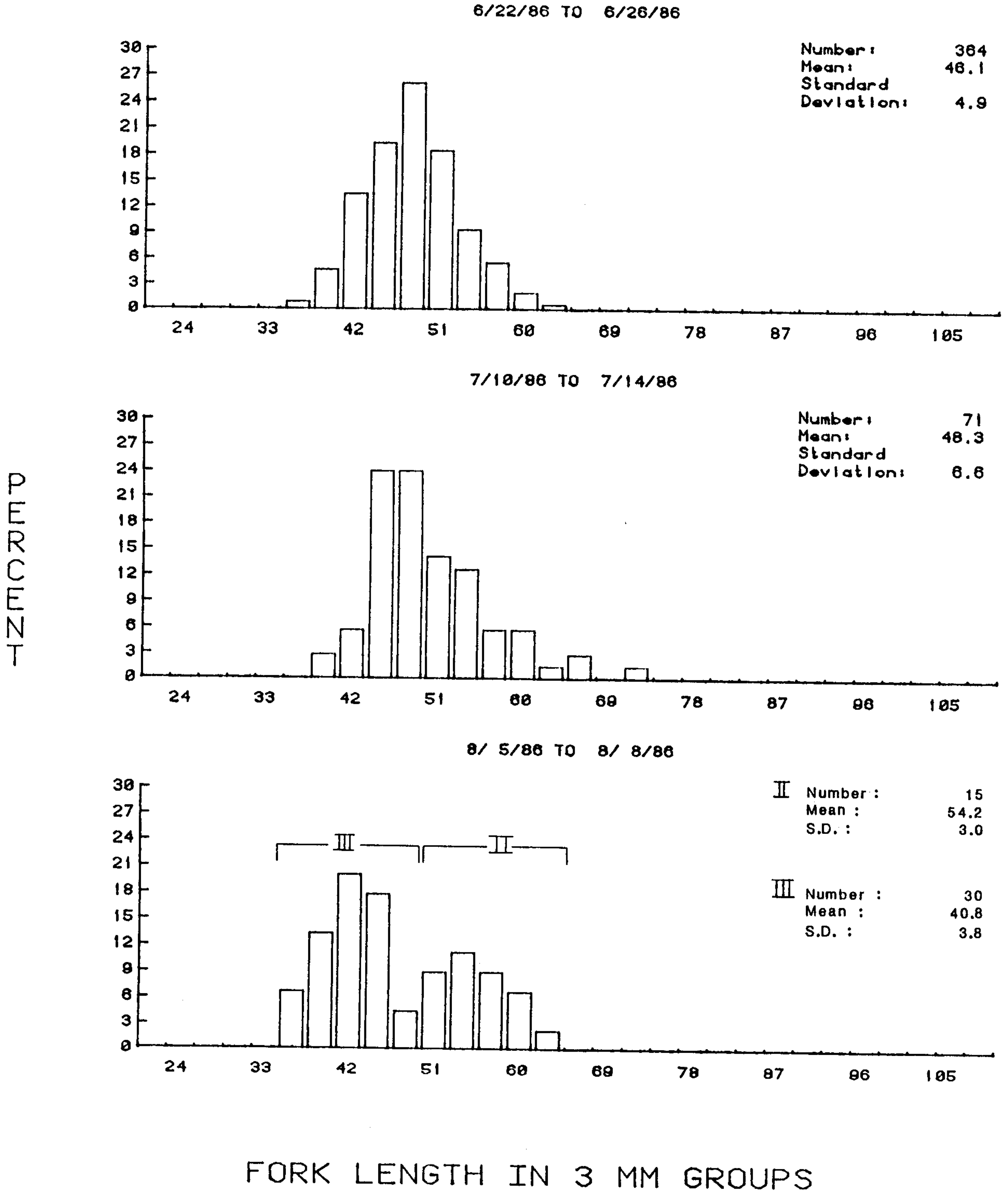

Fig. 3-15 (continued)

average length of 60 mm and a second group of smaller juveniles (i.e., group II) with an average length of 37 mm were caught during the first sample period. Size group I fish were not as abundant as fish from size group II and were not detectable in the catch after the June 20th sampling period. Size group II fish were present throughout the survey period and were identified as having an average length of 54 mm by the August sampling period. A third group of new smaller size fish with an average length of 41 mm were also caught during the August sampling period.

Size composition of juvenile chum salmon varied among different habitats during the same time period. The average size of fish in the lower river were slightly larger than fish from coastal or offshore habitats (Figures 3-16, 3-17, and 3-18). One size group of smaller fish were caught in the tidal slough and mudflat habitats (Figure 3-16, and Appendix B). Whereas, two size groups of fish were caught from the delta platform and delta front stations (Figure 3-16, and Appendix C). Also, several very large juveniles (i.e., 85, 93, and 107 mm fish, Appendix B) were caught from the offshore stations. but were not caught in the river.

3.4.4 Associated Environmental Conditions

Chum salmon environmental associations for temperature, salinity, and visibility are shown in Tables 3-9 to 3-11, respectively. Juvenile chum salmon catches were strongly associated with warm (i.e., 10-16°C) low salinity (i.e., <10 ppt) surface waters and stratified conditions. Catches were not associated with any particular water visibility level. Also, catches were highly variable among deep (i.e., delta front) and shallow habitats (i.e., delta platform and mudflat areas), which suggests that catches were not associated with any particular depth.

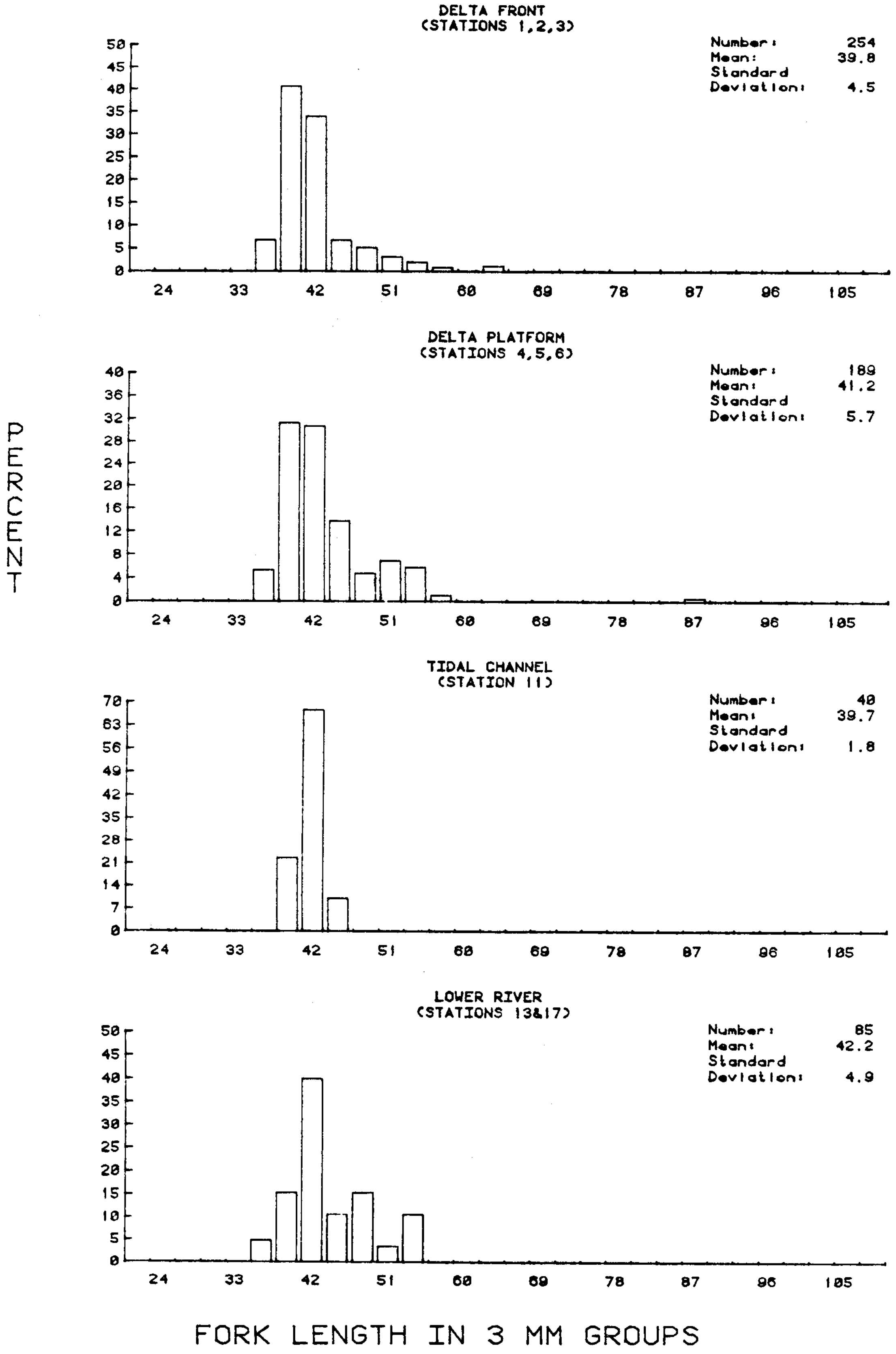

Fig. 3-16: Length frequency of juvenile chum salmon during the period 6/12/86 to 6/15/86 from offshore, tidal slough, and lower river habitats of the Yukon River Delta.

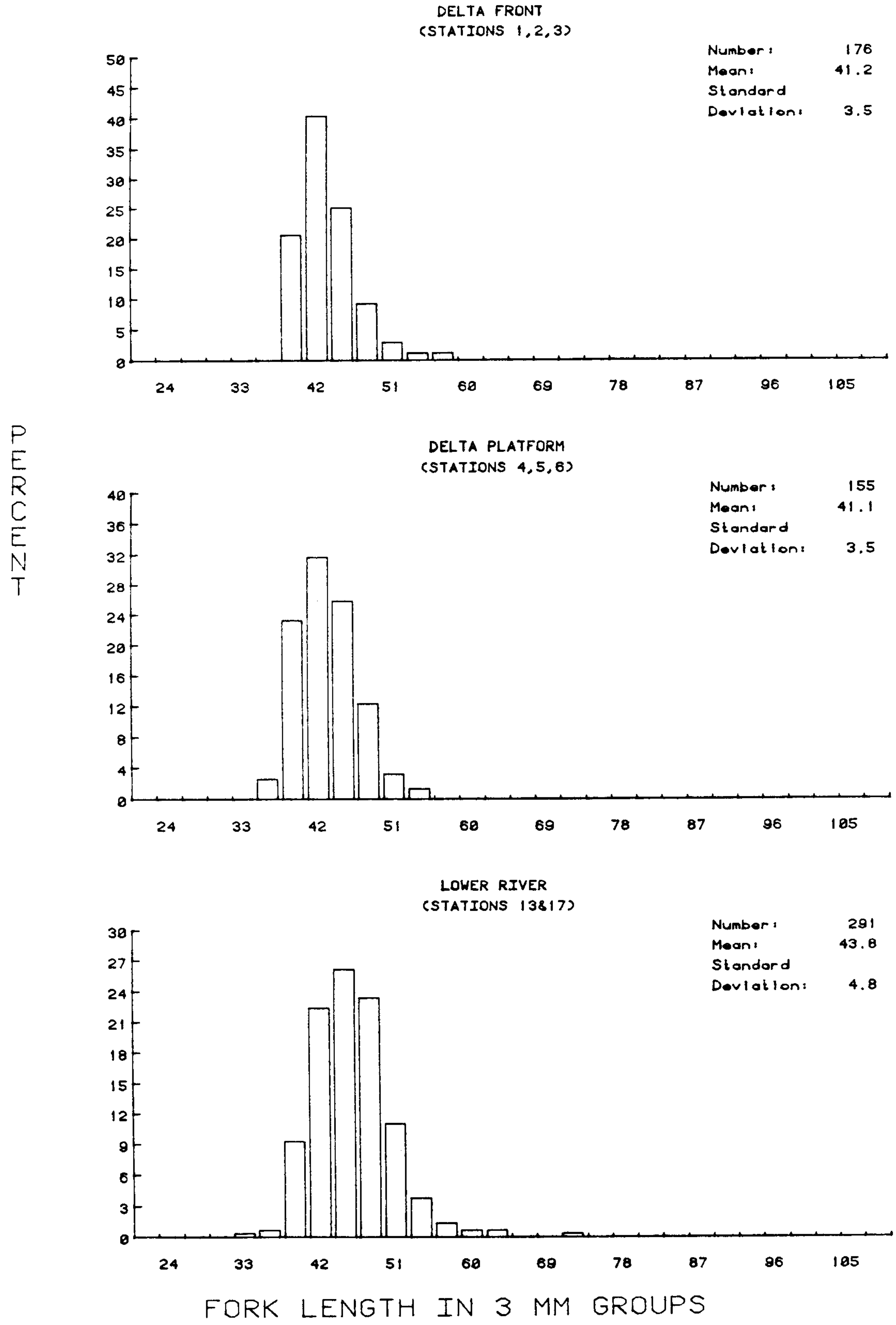

Fig. 3-17: Length frequency of juvenile chum salmon during the period 6/17/86 to 6/20/86 from offshore and lower river habitats of the Yukon River Delta.

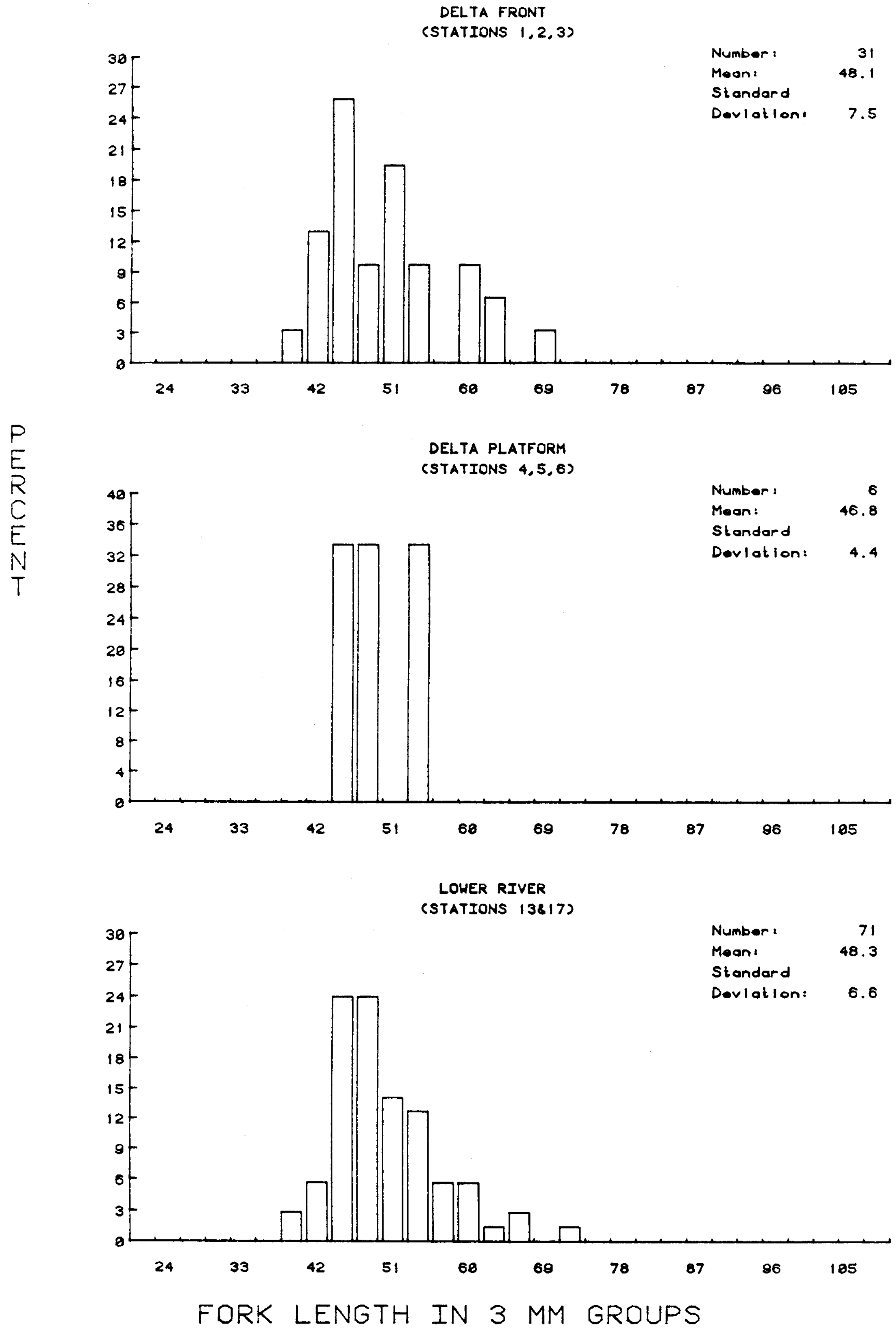

Fig. 3-18: Length frequency of juvenile chum salmon during the period 7/10/86 to 7/14/86 from offshore and lower river habitats of the Yukon River Delta.

TABLE 3-9

Percentage Adjusted Catch of Chum Salmon Associated With Surface and Bottom Temperature in the Delta Front and Delta Platform Habitats of the Yukon River Delta During June 12-19, 1986

Bottom Temperature (°)	Surface Temperature (°C)										Total
	<0	0-2	2-4	4-6	6-8	8-10	10-12	12-14	14-16	≥16	
<0	-	-	-	-	-	-	-	-	-	-	-
0-2	-	-	-	-	5.3	1.5	4.9	16.8	8.5	-	37.0
2-4	-	-	-	-	-	1.7	-	8.1	-		9.8
4-6	-	-	-	-	-	3.9	-	-	-	-	3.9
6-8	-	-	-	-	-	-	-	13.7	9.8		23.5
8-10	-	-	-	-	-	-	-	-	-	-	-
10-12	-	-	-	-	-	-	17.7	-	-	-	17.7
12-14	-	-	-	-	-	-	-	8.1	-	-	8.1
14-16	-	-	-	-	-	-	-	-	-	-	-
≥16	-	-	-	-	-	-	-	-	-	-	-
TOTAL	-	-	-	-	5.3	7.1	22.6	46.7	18.3	-	-

TABLE 3-10

Percentage Adjusted Catch of Chum Salmon Associated With Surface and Bottom Salinity in the Delta Front and Delta Platform Habitats of the Yukon River Delta During June 12-19, 1986

Bottom Salinity (ppt)	Surface Salinity (ppt)								Total
	0-5	5-10	10-15	15-20	20-25	25-30	30-35	35-40	
0-5	9.8	-	-	-	-	-	-	-	9.8
5-10	21.4	-	-	-	-	-	-	-	21.4
10-15	-	-	-	-	-	-	-	-	-
15-20	-	11.8	4.7	-	-	-	-	-	16.5
20-25	16.6	4.4	2.0	-	-	-	-	-	23.0
25-30	10.4	13.7	4.1	1.2	-	-	-	-	29.4
30-35	-	-	-	-	-	-	-	-	-
35-40	-	-	-	-	-	-	-	-	-
TOTAL	58.2	29.9	10.8	1.2	-	-	-	-	

TABLE 3-11

Percentage Adjusted Catch of Chum Salmon Associated With Water Visibility in the Delta Front and Delta Platform Habitats of the Yukon River Delta During June 12-19, 1986

Visibility (m)	Adjusted Catch (percent)
0-0.1	----
0.1-0.2	6.2
0.2-0.3	23.4
0.3-0.4	----
0.4-0.5	12.7
0.5-0.6	9.9
0.6-0.7	26.7
0.7-0.8	3.7
0.8-0.9	14.5
0.9-1.0	----
>1.0	2.8

3.4.5 Otolith Microstructure and Increment Periodicity

Sample Composition

Otoliths were extracted from 491 fish for examination of microstructure. The sampled fish ranged in length from 33.0 mm to 68.4 mm and were representative of specimens collected from 11 stations on 16 separate dates. Among all the specimens examined, 109 (22 percent) had otolith preparations from which no data could be collected, 19 (4 percent) had inherent problems in the physical structure of the otolith which also prevented data collections, and 24 (5 percent) were lost during dissection or preparation. Thus, 339 (69 percent) otoliths remained, upon which the results of this study were based.

Among the specimens examined, the number of post-hatching otolith increments ranged from 11-59 with a mean of 25.1 (Figure 3-19). There was a positive relationship between fish length and the number of post-hatch otolith increments (Figure 3-20).

Otolith Increment Periodicity

A key element in these otolith analyses was the ability to determine elapsed time by counting otolith increments produced with a known periodicity. To determine this periodicity, we analyzed otoliths from fish held in net pens to test the relationship between increments accrued and days elapsed during the experiment. The number of increments accrued was determined from the difference in the mean number of increments for fish collected at the start and at the end of a six-day holding period. Experimental results are shown in Table 3-12.

The results from each fish holding experiment were grouped according to the size of the test fish because differences in fish size affect increment number as shown in Figure 3-20. Changes in increment number can only be evaluated in three of the experimental groups where differences in fish size were not significant (Table 3-12).

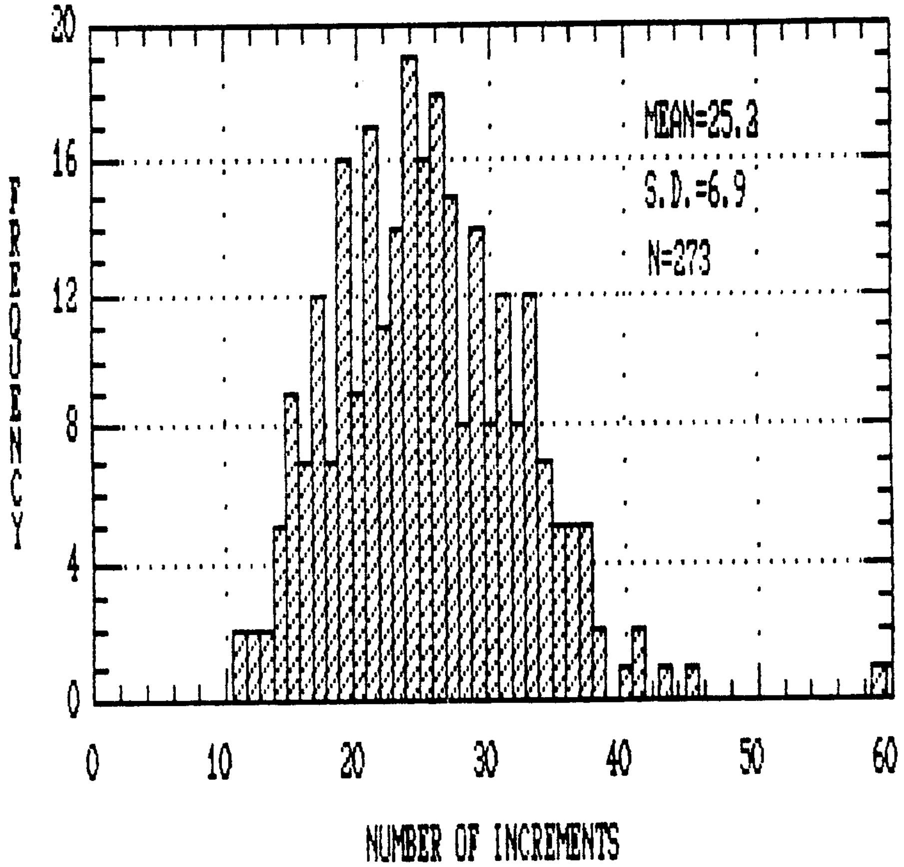

Fig. 3-19: Post-hatching otolith increment frequency for chum salmon collected during summer 1986 from the Yukon River Delta.

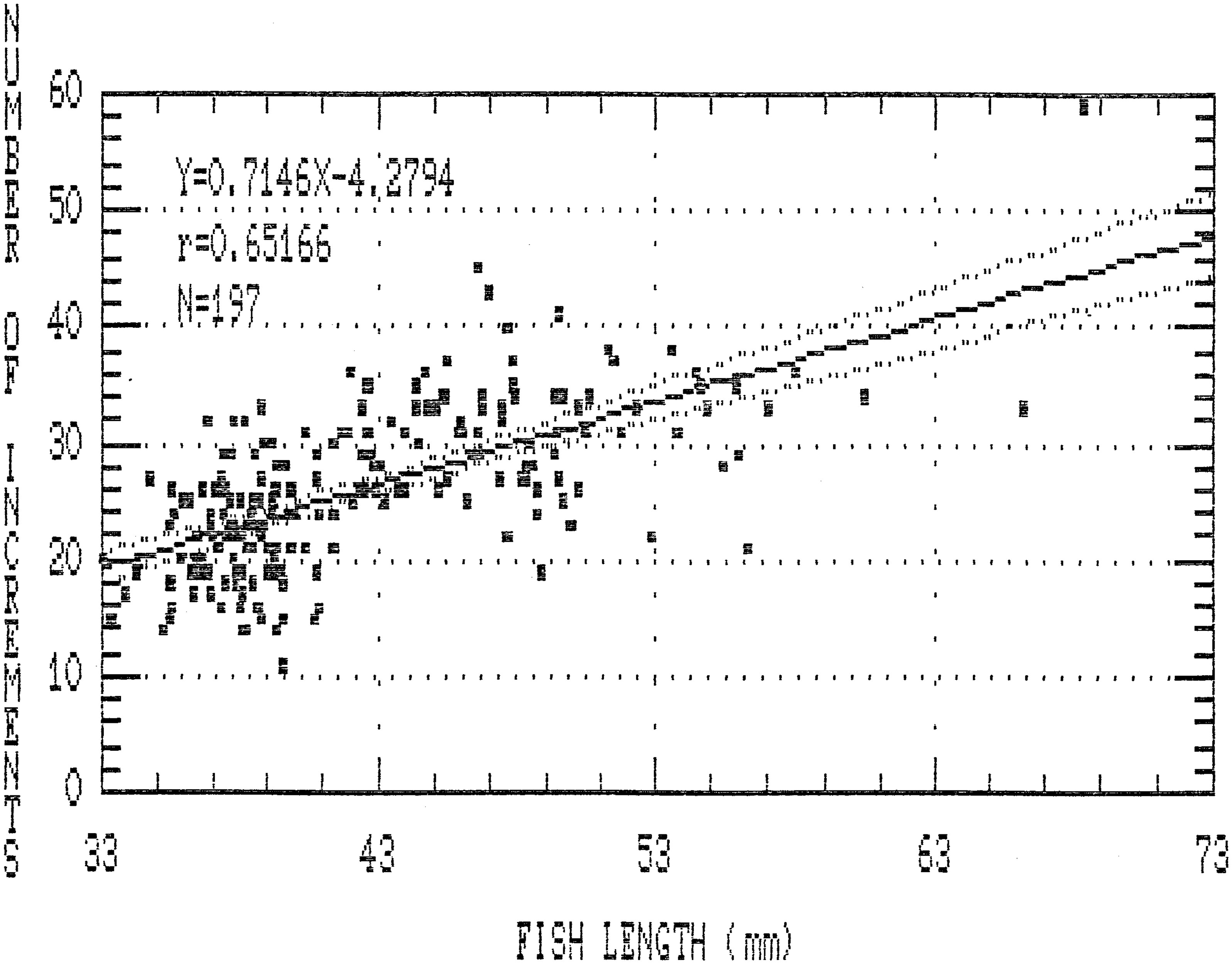

Fig. 3-20: Regression of post-hatch otolith increment number on length of chum salmon.

TABLE 3-12

Results of T-Tests on Fish Length and Otolith Increment Number, and Estimated Increment Periodicity For Chum Salmon From the Fish Holding Experiments

			Fish Length				Increment Count				
Experiment	Beginning or Ending Date	Sample Size	Range	Mean	S.D.	Signif. of t	Range	Mean	S.D.	Signif. of t	Periodicity (d/increment)
1a	6-14-86	24	34-52	40.1	4.6	0.469	14-33	22.6	5.5	0.019	1.6
	6-20-86	13	39-43	41.1	1.6		21-36	26.4	4.2		
1b	6-14-86	8	39-41	39.6	0.6	0.679	17-28	22.0	5.2	0.077	1.5
	6-20-86	7	39-41	39.8	0.9		23-36	25.9	4.6		
2a	6-20-86	23	38-55	44.3	4.5	0.014	14-33	24.0	5.4	0.004	0.8
	6-26-86	6	48-51	49.3	1.4		19-42	32.0	8.7		
2b	6-20-86	5	48-52	49.5	1.9	0.814	20-27	24.0	2.9	0.042	0.8
	6-26-86	6	48-51	49.3	1.4		19-42	32.0	8.7		

Results from the t-test on increment number (Table 3-12) indicate there was a significant increase ($\rho \leq 0.05$) in two of the test groups (i.e., 1a and 2b). Mean increment number increased by 3.8 or 8 increments, depending on experimental group, during the six day experimental period. This increase results in an increment periodicity that ranges from 0.8 to 1.6 d/increment. This large variation between the two experiments may be a function of the different size groups of fish that were tested.

In order to provide a better understanding of the potential effects of fish size or life stage on increment periodicity, an estimate of increment periodicity for alevins was examined. In this method incremental periodicity is assumed to be equal to the quotient of the number days between hatching and emergence; and the number of post-hatch otolith increments at the time of emergence. Studies conducted by Trasky (1974) and Francisco (1976, 1977) concerning the development of fall chum salmon in the Delta River (a tributary to the Yukon River) found that the time period from hatching to emergence ranged 25-48 days and averaged 39 days at temperatures ranging 1.1-1.5°C. Bakkala's (1970) comprehensive review of chum salmon studies indicated a period of 30 to 50 days, depending on water temperature, was needed for development. The temperature regime during the alevin stage for most Yukon chum is likely to be within the range observed in the Delta River. Therefore, a period of 40 days was assumed to be the most reasonable period for alevin development. The number of otolith increments at emergence was determined from the otolith data. Several studies on the early development of fall chum salmon from Yukon River tributaries found that most fry emerge at lengths of 31-36 mm (Raymond 1981, Francisco 1977, and Francisco and Dinneford 1977). Fifteen chum otoliths were examined from fish that were ≤ 36 mm. The number of post-hatch increments in these fish ranged 14-27 with an average of 19.8. Therefore, based on this data the increment periodicity during the alevin stage is estimated to be at least 2 days (i.e., $40/19.8 = 2.02$). A greater increment periodicity is possible because all of the fish that were examined were button-up-fry which had emerged at some earlier date. Thus the average number of post-hatch increments at emergence was most likely less than the number observed from button-up-fry. These data also show that daily increments at this life stage are highly unlikely, because development time from hatching to emergence requires more than 14-27 days.

3.4.6 Residency

The primary purpose of the otolith study was to measure the time elapsed after an individual fish reached the estuary in order to provide an estimate of residency. This would be accomplished by counting the number of otolith increments that are formed after the point of transition from freshwater growth to estuarine growth. The product of this count and the increment periodicity would be equivalent to the duration of estuarine utilization. The criterion for determining the beginning of estuarine residency was identified by Volk et al. (MS) and Neilson et al. (1985) as the region in which there was a step-wise increase in increment width near the edge of the otolith compared to the width of previous increments. This change in increment width was associated with an increase in growth rate, which corresponded with entry into an estuary.

Otoliths from juvenile chum salmon that were caught on the delta platform and delta front were examined for the presence of changes in increment width. This examination was focused on the outermost 16 post-hatch increments because this region of the otolith would have been formed during the last 13 to 26 days (assuming increment periodicity of 0.8 or 1.6, Table 3-12) before fish capture (Figure 3-21). A one-way analysis of variance test of increment width by increment number indicated no significant difference ($p \leq 0.05$) in increment width. Therefore, no transition in increment width could be identified and estimates of estuarine residency, if any, could not be determined from the otolith data.

The relative age of the juvenile outmigrant chum that utilize each habitat can be determined from the number of post-hatch increments if we assume that all fish had a similar history of changes in increment periodicity. A comparison of mean increment number for fish among different habitats during the peak outmigration period indicates that

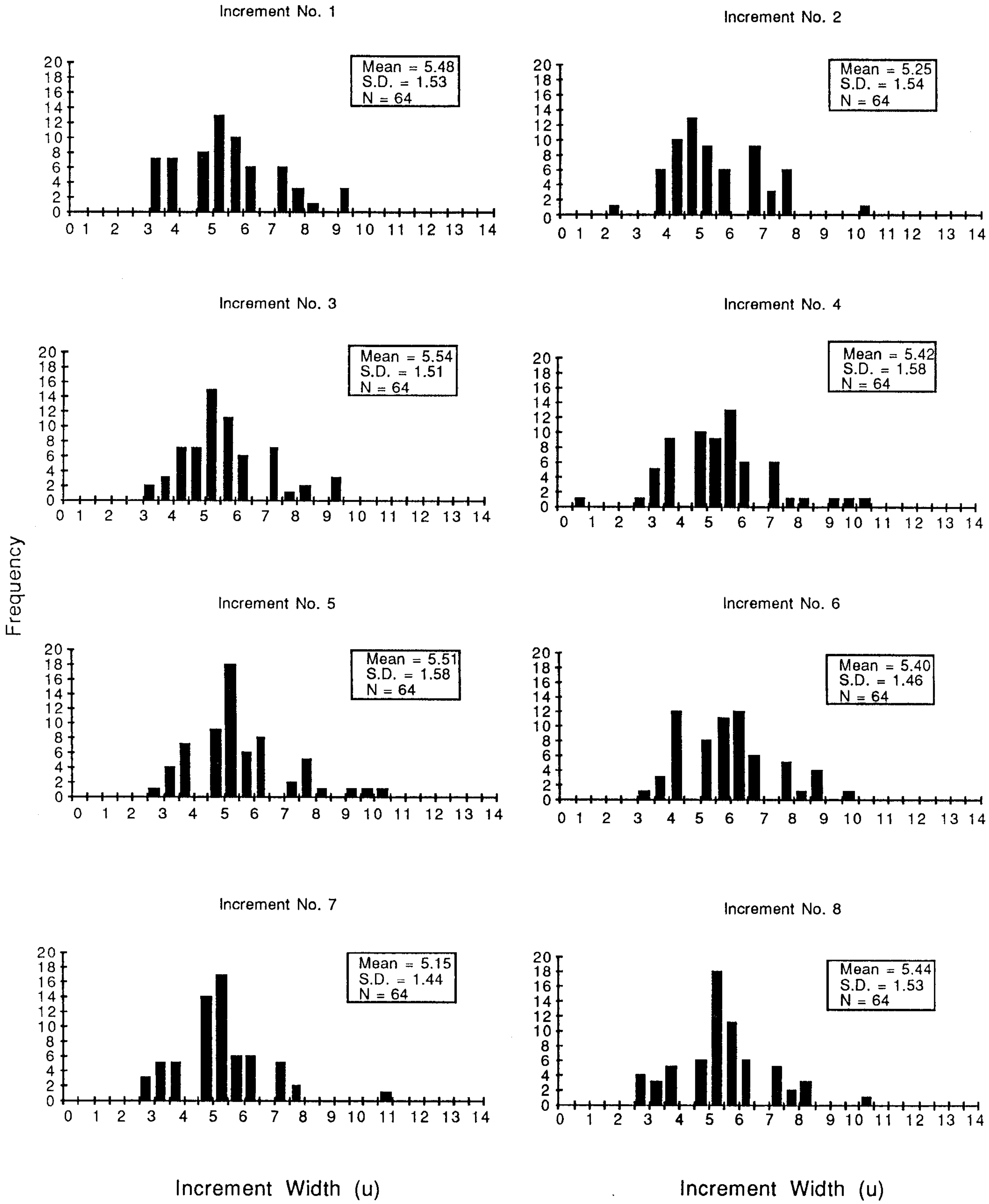

Fig. 3-21: Frequency histograms and statistics of otolith increment widths for 16 outer increments from chum salmon caught in the delta platform and delta front of the Yukon River Delta.

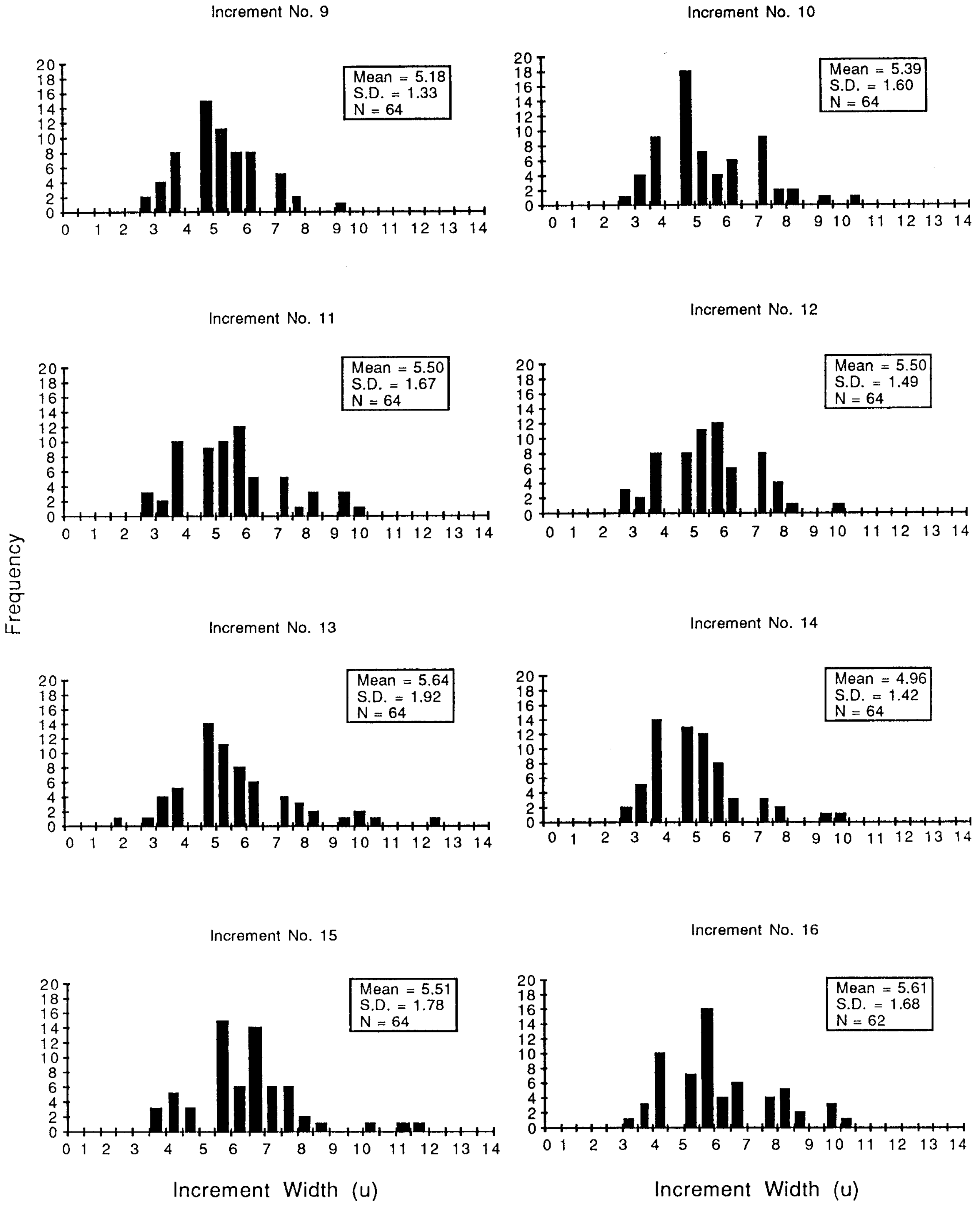

Fig. 3-21, continued.

fish in the lower river have significantly more ($p \leq 0.05$) increments than fish in the nearshore and offshore habitats (Table 3-13). This suggests that juvenile chum in the lower river are approximately 6 to 11 days older (assuming increment periodicity is either 0.8 or 1.6 from Table 3-12) than juveniles in other habitats.

3.4.7 Growth

Three size groups of juvenile chum salmon were identified in the lower river during the outmigration period (see Section 3.4.1). Fish in size groups I and III (Figure 3-15) were caught only during early June or early August, respectively. Therefore, fish length data were insufficient to make any estimates of growth rate for these two groups. Fish in size group II, however, were present throughout the three sample surveys (Figure 3-15). Outmigrants averaged 36.8 mm in early June and 54.2 mm in early August. A regression of fish length by time after the first sample date indicates the population growth rate was 0.31 mm/day during the outmigration period (Figure 3-22). This growth rate is most likely biased on the low side of true growth rate because of immigration and emigration, to and from the study area, respectively. Also, the validity of this growth rate is based on the assumption that group II fish all hatched at approximately the same time.

3.5 OTHER FISHES

Catch results for sheefish, whitefish, cisco, smelt, and herring are presented in this section because these species are considered important for either commercial or subsistence fisheries. Catch results for other lesser important species are only presented in Appendix Table B.

TABLE 3-13

Mean and 95 Percent C.I. of Otolith Increment Number For Juvenile Chum Salmon By Habitat and Results of a Multiple Range Test on Increment Number Among Habitats. Data From the Period of Peak Outmigration, June 10-24, 1986

Location	Stations	N	Mean	95 Percent C.I.	Similarity[a]	
Tidal Channel	11	16	19.9	17.7-22.1	x	
					x	
Delta Front	4,5	30	20.1	18.1-22.1	x	
					x	
Delta Platform	1,3	23	21.2	19.7-22.7	x	
					x	
Lower River	13, 17	39	27.0	24.8-29.3		x

---

[a] Non-overlapping x's indicate groups that are significantly different at the 0.05 level. Data was tested by the Student Newman Keuls Procedure.

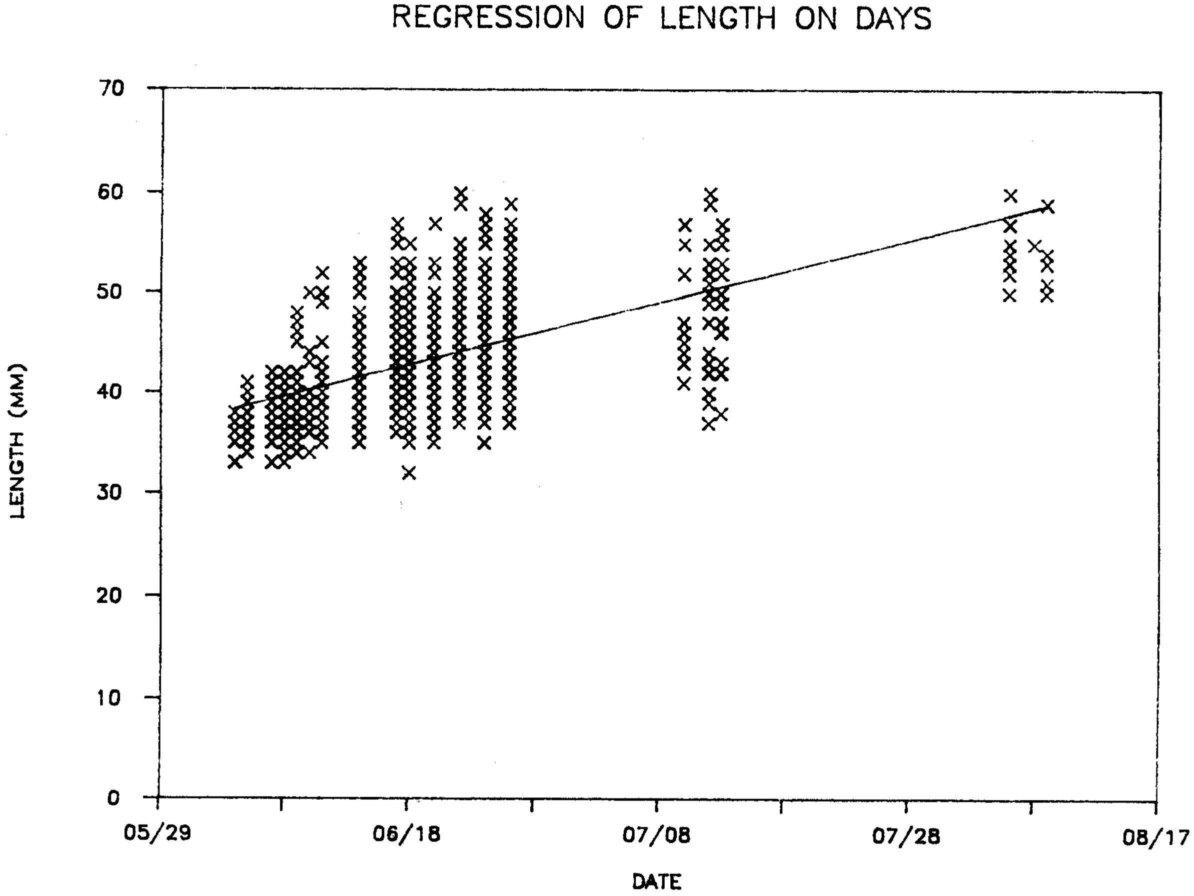

Fig. 3-22: Plot of length with time for juvenile chum salmon caught in the lower Yukon River (i.e., stations 13 and 17, Group II) during summer 1986. Line fitted by regression where y = 37.16 + 0.31x, N = 1107, r = 0.58.

3.5.1 Migration Timing

Juvenile sheefish, juvenile whitefish, and juvenile cisco were the only important anadromous species that were caught in significant numbers in the lower river (Table 3-3). Smelt are also anadromous, but no juveniles were caught in the lower river during the three sample surveys. The timing of the juvenile outmigration of coregonids was similar among all three species (Figure 3-23). Low numbers of fish were caught during June and August and peak catches occurred during the July survey. Juvenile cisco were approximately three times more abundant than juvenile sheefish and juvenile whitefish.

3.5.2 Distribution and Density

Cisco's were the most broadly distributed of all the coregonid fishes that were caught during 1986 (Tables 3-14, 3-15, and 3-16). High densities of cisco were found in both coastal and offshore habitats. Whereas, sheefish and whitefish were more concentrated in the coastal habitats. Sheefish had the most restrictive distribution with most fish occurring at the mudflat stations. Their temporal distribution and abundance were not directly related to the July outmigration period since many older individuals of each species were caught during the June survey. Whitefish were generally the most abundant of the coregonid fishes with mean habitat density ranging up to 43,000/km.

Boreal smelt, juvenile smelt, and Pacific herring were caught predominantly at the delta front and delta platform stations (Table 3-3). Boreal smelt were caught only during the June survey, whereas, juvenile smelt were most abundant during the July and August surveys (Table 3-17). Juvenile smelt densities ranged up to $300{,}000/km^2$, which is the highest density of any species caught from the offshore habitats. Pacific herring were caught during all surveys and were most abundant at the delta front during July.

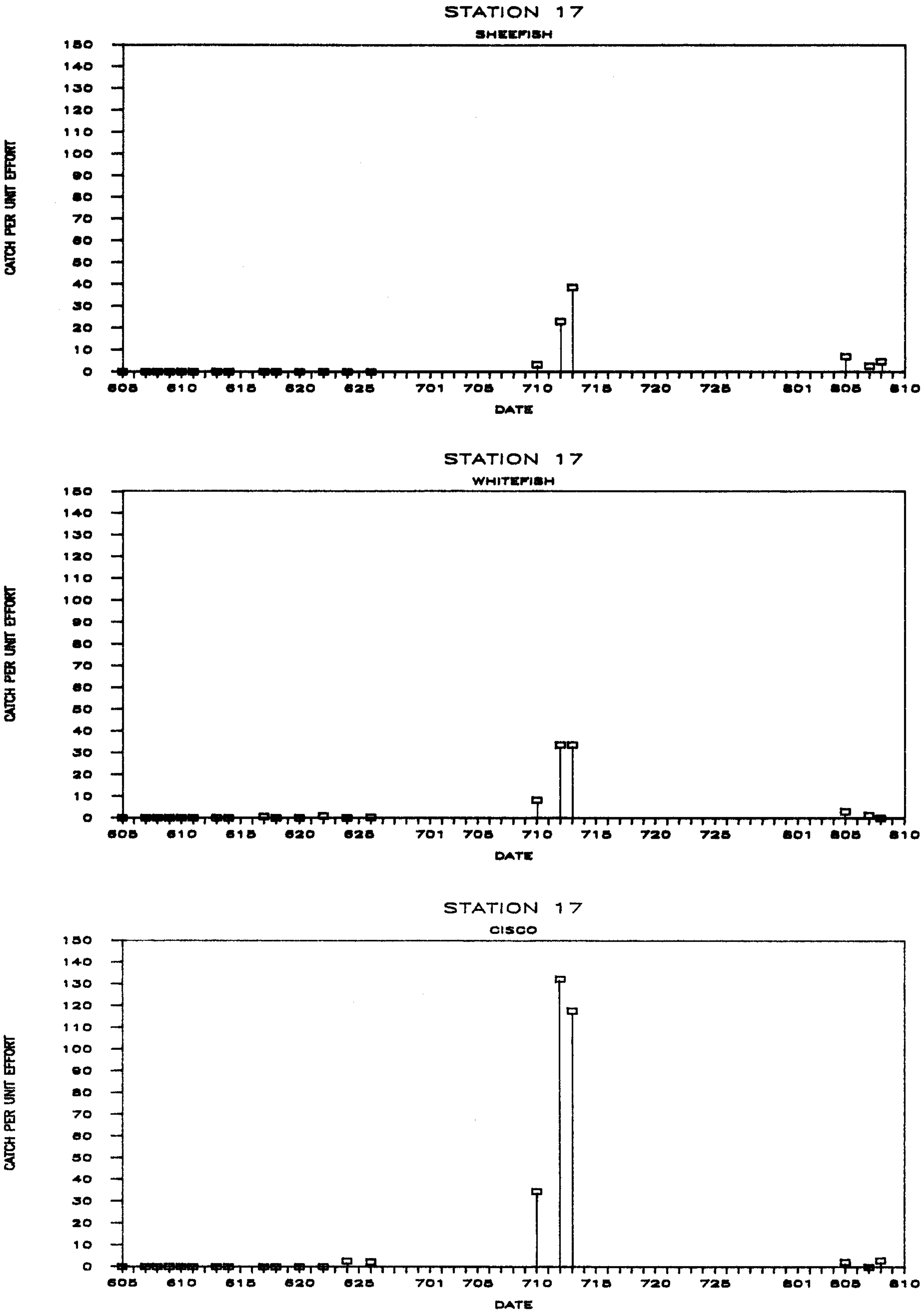

Fig. 3-23: Catch per unit effort of juvenile sheefish, juvenile whitefish, and juvenile cisco during summer 1986, from the lower river, station 17, of the Yukon River Delta.

TABLE 3-14

Estimated Average Density (no/km^2) of Sheefish During Summer 1986 in the Offshore, Coastal, and Lower River Habitats of the Yukon River Delta

	Habitat/Station																	
	Delta Front				Delta Platform				Mudflats			Tidal Slough				Lower River		
DATE	1	2	3	Mean	4	5	6	Mean	8	9	Mean	10	11	12	Mean	13	17	Mean
6/04	-	-	-	-	171	-	-	171	-	-	-	-	-	-	-	0	-	0
6/05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/06	0	0	-	0	0	0	-	0	-	-	-	-	-	-	-	-	-	-
6/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/10	-	-	-	-	-	-	-	-	3031	-	3031	-	0	-	0	-	0	0
6/11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/12	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-
6/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/14	-	-	-	-	-	-	-	-	15153	-	15153	-	0	-	0	0	0	0
6/15	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-
6/17	-	-	-	-	-	-	-	-	6061	-	6061	-	2165	-	2165	0	0	0
6/18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/19	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-
6/20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/22	-	-	-	-	-	-	-	-	18183	-	18183	-	0	-	0	0	0	0
6/24	-	-	-	-	-	-	-	-	3031	-	3031	-	0	-	0	0	0	0
6/25	-	-	-	-	-	-	-	-	-	3031	3031	-	-	0	0	-	-	-
6/26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
7/10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	1140	1140
7/11	0	-	0	0	171		171	171	-	-	-	-	-	-	-	-	-	-
7/12	-	-	-	-	-	-	-	-	9092	-	9092	-	0	-	0	342	7866	4104
7/13	-	-	-	-	-	-	-	-	-	12122	12122	-	-	0	0	-	13224	13224
7/14	0	0	114	38	114	342	1140	532	-	-	-	-	-	-	-	-	-	-
8/04	-	-	-	-	-	-	-	-	0	87885	43942	-	8658	0	4329	-	-	-
8/05	-	-	-	-	-	-	-	-	-	-	-	0	-	-	0	228	2394	1311
8/06	0	0	0	0		0	0	0	-	-	-	-	-	-	-	-	-	-
8/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	570	912	741
8/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	274	1625	874

TABLE 3-15

Estimated Average Density (no/km^2) of Whitefish (i.e., Humpback Whitefish and Broad Whitefish) During Summer 1986 in the Offshore, Coastal, and Lower River Habitats of the Yukon River Delta

	Habitat/Station																	
	Delta Front				Delta Platform				Mudflats			Tidal Slough				Lower River		
Date	1	2	3	Mean	4	5	6	Mean	8	9	Mean	10	11	12	Mean	13	17	Mean
6/04	-	-	-	-	285	-	-	285	-	-	-	-	-	-	-	0	-	0
6/05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	61	-
6/06	0	0	-	0	1083	0	-	542	-	-	-	-	-	-	-	-	-	-
6/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/10	-	-	-	-	-	-	-	-	18183	-	18183	-	4329	-	4329	-	0	0
6/11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/12	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-
6/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/14	-	-	-	-	-	-	-	-	11112	-	11112	-	0	-	0	0	0	0
6/15	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-
6/17	-	-	-	-	-	-	-	-	4041	-	4041	-	7215	-	7215	0	76	38
6/18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	76	0	38
6/19	0	0	0	0	0	0	0	0	-	-	-	-	-	-	-	-	-	-
6/20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/22	-	-	-	-	-	-	-	-	11112	-	11112	-	2165	-	2165	0	114	57
6/24	-	-	-	-	-	-	-	-	17173	-	17173	-	2886	-	2886	0	0	0
6/25	-	-	-	-	-	-	-	-	-	43437	43437	-	-	47619	47619	-	-	-
6/26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	38	19
7/10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	950	950
7/11	0	-	152	91	0	-	0	0	-	-	-	-	-	-	-	-	-	-
7/12	-	-	-	-	-	-	-	-	24244	-	24244	-	2886	-	2886	304	3838	2071
7/13	-	-	-	-	-	-	-	-	-	4041	4041	-	-	5772	5772	-	3838	3838
7/14	0	0	0	0	38	0	0	13	-	-	-	-	-	-	-	-	-	-
8/04	-	-	-	-	-	-	-	-	16163	68691	42427	-	16595	2165	9380	-	-	-
8/05	-	-	-	-	-	-	-	-	-	-	-	28139	-	-	28139	0	342	171
8/06	0	0	0	0	-	0	0	0	-	-	-	-	-	-	-	-	-	-
8/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	152	76
8/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	23	0	13

TABLE 3-16

Estimated Average Density (no/km^2) of Cisco (i.e., Least Cisco and Bering Cisco) During Summer 1986 in the Offshore, Coastal, and Lower River Habitats of the Yukon River Delta

	Habitat/Station																	
	Delta Front				Delta Platform				Mudflats			Tidal Slough				Lower River		
Date	1	2	3	Mean	4	5	6	Mean	8	9	Mean	10	11	12	Mean	13	17	Mean
6/04	-	-	-	-	2280	-	-	2280	-	-	-	-	-	-	-	0	-	0
6/05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	15	-
6/06	0	0	-	0	3078	0	-	1539	-	-	-	-	-	-	-	-	-	-
6/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	38	190	114
6/10	-	-	-	-	-	-	-	-	12122	-	12122	-	722	-	722	-	0	0
6/11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0
6/12	0	0	0	0	0	76	418	165	-	-	-	-	-	-	-	-	-	-
6/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	38	0	19
6/14	-	-	-	-	-	-	-	-	6061	-	6061	-	8658	-	8658	38	0	25
6/15	0	0	0	0	0	38	874	304	-	-	-	-	-	-	-	-	-	-
6/17	-	-	-	-	-	-	-	-	2020	-	2020	-	5051	-	5051	0	0	0
6/18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/19	0	0	76	25	0	0	38	13	-	-	-	-	-	-	-	-	-	-
6/20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	0	0	0
6/22	-	-	-	-	-	-	-	-	6061	-	6061	-	5772	-	5772	0	0	0
6/24	-	-	-	-	-	-	-	-	7071	-	7071	-	0	-	0	0	380	190
6/25	-	-	-	-	-	-	-	-	-	24244	24244	-	-	0	0	-	-	-
6/26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	190	266	228
7/10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	3952	3952
7/11	1938	-	17062	11012	3135	-	34257	18696	-	-	-	-	-	-	-	-	-	-
7/12	-	-	-	-	-	-	-	-	1010	-	1010	-	2886	-	2886	14934	15086	15010
7/13	-	-	-	-	-	-	-	-	-	9092	9092	-	-	17316	17316	-	13414	13414
7/14	1444	3268	988	1900	3458	3382	2318	3053	-	-	-	-	-	-	-	-	-	-
8/04	-	-	-	-	-	-	-	-	0	21214	10607	-	1443	1443	1443	-	-	-
8/05	-	-	-	-	-	-	-	-	-	-	-	722	-	-	722	76	266	171
8/06	38	38	38	38	-	418	76	247	-	-	-	-	-	-	-	-	-	-
8/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	190	266	228
8/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	91	342	203

TABLE 3-17

Estimated Average Density (no/km^2) of Boreal Smelt, Smelt sp., and Pacific Herring
During Summer 1986 in the Delta Front and Delta Platform Habitats of the Yukon River Delta

	Boreal Smelt								Smelt sp.								Pacific Herring							
	Delta Front				Delta Platform				Delta Front				Delta Platform				Delta Front				Delta Platform			
Date	1	2	3	Mean	4	5	6	Mean	1	2	3	Mean	4	5	6	Mean	1	2	3	Mean	4	5	6	Mean
6/04	-	-	-	-	22059	-	-	22059	-	-	-	-	0	-	-	0	-	-	-	-	0	-	-	0
6/05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/06	0	0	-	0	48906	1539	-	25223	2565	0	-	1026	0	0	-	0	0	1824	-	1094	0	171	-	86
6/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/09	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/11	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/12	114	0	0	38	0	228	27360	9196	0	0	0	0	0	0	0	0	0	0	114	38	114	684	2508	1102
6/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/14	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/15	114	228	0	114	0	456	0	152	0	0	0	0	0	0	20976	6992	0	798	0	266	0	2736	6042	2926
6/17	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/18	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/19	38190	16644	2736	19190	46512	72162	97242	71972	0	0	0	0	0	0	0	0	1254	6384	1026	2888	0	228	0	76
6/20	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/22	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/24	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/25	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
6/26	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7/10	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7/11	0	-	0	0	0	-	0	0	312075	-	26562	140767	215460	-	135603	175532	7866	-	7980	7934	1197	-	0	599
7/12	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7/13	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
7/14	0	0	0	0	0	0	0	0	17214	80940	64410	54188	177270	54150	36594	89338	15960	10374	1596	9310	228	0	0	76
8/04	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8/05	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8/06	0	0	0	0	-	0	0	0	26790	18810	35910	27170	-	20520	2622	11571	114	1254	2850	1406	-	114	0	57
8/07	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
8/08	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-

4. DISCUSSION

4.1 CHINOOK SALMON

4.1.1 Outmigration

The outmigration period for juvenile chinook salmon most likely begins before ice breakup and probably extends to early autumn. Catches of chinook smolts on the first day of sampling indicates that outmigration was in progress before the 1st of June. Similarly, catches of smolts during the August survey suggests the migration extended past this time. Chinook salmon smolts began migrating out of the upper Yukon River tributaries as early as mid April (Table 4-1) and could have reached the delta by early May. For example, smolts leaving the Delta River on April 12th could reach the Yukon Delta by May 1st if the fish moved passively with the current. Assuming a minimum current velocity of 1 m/s a fish could move at a rate of 86.4 km/day and would require approximately 20 days to travel from the Delta River to the mouth of the Yukon River. If juveniles leaving the upper river tributaries during August continue to outmigrate (Table 4-1) the end of the outmigration period could extend to early September.

The catch of chinook salmon smolts peaked on several dates during June and July with the largest catches occurring during late June. These results suggest that the peak of the outmigration occurred during the latter part of June. Since sampling was not conducted during early July it was not possible to know if another peak occurred. However, the migration timing for smolts from upper river tributaries (Table 4-1) indicates that most of these smolts would have reached the delta during mid to late June if fish travelled at a minimum rate of 86 km/day. Some stocks (e.g., Delta River) however, exhibit a very early outmigration from the upper river and result in a peak movement through the Delta that probably occurs during May. The declining trend in catches during early June (Figure 3-5) may indicate the tail end of an early outmigrating stock.

TABLE 4-1

Outmigration Timing and Size at Outmigration of Chinook Salmon Smolts from the Yukon River Drainage (Adapted from Table 3 in Raymond, 1981)

River	Distance[a/] (km)	Outmigration Dates			Mean Length (mm)	n	Reference
		From	To	Peak			
Yukon	2,462	5-21*	6-23	5-29	76.3	130	Walker 1976
		5-26	6- 1	5-28	88.0	31	"
Hodzana	1,443	6- 2	8-17	6- 5	78.8	57	Gissberg and Benning 1965
				7-10			"
Delta	1,659	4-12	5-16	4-28	93.0	22	Francisco 1977
				5-14			"
Salcha	1,553	5-16*	6- 8*	5-26	73.0	488	Trasky 1974
				6- 4			"
Chena	1,496	5-14*	6-20	6- 1	76.7	51	Ross 1973-1975
		5- 3	5-30	5- 9	79.6	187	"
		5- 7	5-23	5-14	86.2	22	"
		5- 4	5-16	5-11	75.0		Williamson 1981
Clear Creek	1,380	4-30*	5-22	5- 8	71.3	38	Raymond 1981
Yukon	101	6- 8	7- 7*	6-13	96.0	14	Barton 1979
Yukon	25	6- 4*	8- 8*	6-18	96.8	313	This report

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a/ Distance from the mouth of the Yukon River.

* Indicates that the outmigration was in progress when the sampling started or ended.

Information on the outmigration timing for chinook salmon smolts from other western Alaska Rivers is not well documented. No information, for example, could be found for the Kuskokwim River. However, several years of outmigration data are available from the Susitna River, which is located along the south central coast of Alaska and has freezeup and breakup timing similar to that of the mid-river tributaries of the Yukon River. In the Susitna River, chinook salmon presmolts were found to have moved out of river slough habitats by early May (Stratton 1986) and large numbers of smolts were caught in the lower river immediately following ice breakup in late May (Roth et al., 1986). This suggests that the smolt outmigration in the Susitna River probably begins in late winter-early spring, which is similar to the timing indicated by data from the Yukon River. The smolt outmigration in the Susitna River also peaks during late June and smolts continue to dribble out through to September (Roth et al., 1986, Roth and Stratton 1985).

The age composition of outmigrant juvenile chinook salmon was not determined but the size composition of the juveniles suggests that ages 0, 1, and older individuals probably occurred in the catch. Juveniles caught during June were most likely age 1 and older because the length of all fish exceeded 69 mm. Chinook salmon fry (i.e., age 0) would likely be much smaller than 69 mm during this period. For comparison, juvenile chinook salmon fry in the Delta River, Chena River, and Clear Creek during June ranged 31-45 mm, 32-62 mm, and 34-40 mm, respectively (Francisco 1977, Walker 1983, and Raymond 1981). Whereas, age 1 smolts from the Delta River at the same time ranged 71-110 mm (Francisco 1977). During the period of July through August it is possible that age 0 fry could be mixed together with age 1 and older chinook salmon smolts. Juveniles caught during the July and August surveys ranged 82-123 mm. The smaller individuals would fit within the size range of outmigrant age 0 chinook salmon caught in the Susitna River, which ranged 40-88 mm in July and 46-94 mm in August (Roth and Stratton 1985). Only a small percentage of the juveniles caught during this period were small enough to be considered age 0 smolts. Therefore, if age 0 smolts actually existed they probably represent only a minor portion of the total smolt outmigration Scales collected from adult chinook salmon, which were caught in the lower Yukon River indicate that fish with less than one year of freshwater growth represent a very small percentage of the total adult population (John Wilcox, ADF&G personal communication).

4.1.2 Distribution and Habitat Utilization

There was a large variation in the density of juvenile chinook salmon among the coastal and offshore habitats. The results suggest that the outer delta platform and the delta front habitats are utilized to a greater extent than the mudflat or tidal slough habitats. The one time capture of chinook smolts in the tidal slough at Station 11, and their absence from this site and the adjacent mudflats, indicates that utilization of nearshore habitats was limited. This apparent absence of smolts is probably real and not due to low sampling effort, since these stations were sampled five times during June and the northern most stations (i.e., Station 9 and 12) were also sampled once during this period.

The distribution of juvenile chinook salmon in the Yukon Delta may be affected by river outflow in the sub-ice channels. The high discharge during the outmigration period results in a very strong flow of freshwater that moves out the sub-ice channels to the delta front. Juveniles migrating downstream in the major distributaries could be carried 20 to 30 km offshore and would completely bypass the nearshore and most of the delta platform habitats. In the Columbia River, chinook salmon yearlings were mostly found migrating in mid-river and most fry were found nearshore (Dawley et al. 1985). Since outmigrants in the Yukon River were composed largely of yearlings and older smolts it is likely that most of these chinook smolts did not encounter the nearshore habitats and were flushed out to the delta front. A small portion of the outmigrants, however, were entrained in the small distributary channels and were not carried across the delta platform. These fish encounter the nearshore areas and utilize the mudflat and tidal slough habitats. The juveniles that were caught in a tidal slough at Station 11 could have migrated out from any number of small distributaries that were located within 5 km of this site.

The relationship between fish size and habitat preference may also be an important factor affecting the distribution of juvenile chinook salmon in the Yukon River Delta. Generally, the smallest juveniles were found in the nearshore areas of the inner estuary and the larger juveniles occur in the offshore areas of the outer estuary. In some cases there appears to be a threshold size governing the movement into deeper or higher salinity waters (Healey 1982). In the Nanaimo River Estuary when fry migrants reached 70 mm they began to leave that habitat. Also, yearly smolts mostly occurred in the outer estuary during April-June, after which they migrate away from the coastal waters (Healey 1980). In the Yaquina Bay Estuary of Oregon small juvenile chinook (average 88 mm) were found in the nearshore areas of the upper estuary and larger juveniles (average 106 mm) were found in the offshore areas (Meyers 1980). Reimers (1973) also found a similar size related distribution for juvenile chinook in the Sixes River Estuary. In the Yukon Delta the juvenile outmigrants were all larger than 69 mm. These larger juveniles may have reached the threshold size required for movement into deeper and higher salinity water. This would explain why chinook smolts occurred most often in the vicinity of the delta front where intermediate salinity conditions prevailed.

The catch results suggest that environmental conditions in the surface water may affect the distribution and abundance of juvenile chinook salmon in the Yukon Delta. Surface water quality is considered to be most important because the vertical distribution of juveniles in other estuaries indicates that juvenile salmon are concentrated near the top 2-3 meters (Stober et al. 1973, Dawley et al. 1985). Also, the catch data from this survey are only representative of the surface water environment because the tow net sampled to 1.8 m deep. In the Yukon Delta most juveniles were caught in the delta front and outer delta platform areas where visibility was greater than 0.5 m and surface waters were relatively cool (i.e., 8°-10°C) with intermediate salinities (i.e., 5-15 ppt). Determination of which factor or combination of factors is affecting this distribution is not possible because the environmental conditions are physically related. Each environmental factor along could have an effect on habitat utilization. For example, juveniles may be seeking areas with higher visibility because turbid water may inhibit feeding. Studies with juvenile rainbow trout and juvenile coho have found that feeding is significantly reduced or ceased when turbidity levels exceed a specific threshold (Noggle 1978, Olsen et al. 1973, Brett and Groot 1963). If this relationship applies to juvenile chinook salmon, then this would explain why there was a greater utilization of the offshore areas. Based on the distribution of turbid waters from the AVHRR images, (Figure 3-4 to 3-6) smolts must move 10-20 km offshore in order to find waters with a Secchi disk depth greater than 0.5m.

Outmigrants also could have been seeking a more optimal temperature level. Brett (1952) has determined that temperatures of 9-14°C are the preferred range for chinook salmon. Temperatures in the river and in the offshore areas were within this range during the peak outmigration period. However, temperatures in the nearshore areas ranged up to 19.1°C and were greater than the preferred range most of the time. These warmer conditions may explain why utilization of the nearshore habitats was limited.

Salinity levels could also affect the distribution of juvenile chinook salmon. During June the discharge from the Yukon River is so large that estuarine conditions do not exist within 10-20 km of the coastline. Juvenile chinook would not find brackish water until they migrated out to the outer delta platform and delta front. The intermediate salinity levels that occur in these areas may be needed as a transition zone for juveniles while they adapt to saltwater conditions. As the river discharge declines during the summer, this zone of intermediate salinity water progressively moves closer to the coastline. By August the delta front was dominated by marine water and the transition zone had moved far into the delta platform but not into the nearshore areas. No juvenile chinook were caught at either the nearshore or offshore stations at this time. The absence of fish in the catch could be due to their low density at this time and/or their utilization of the transition areas on the delta platform which were not sampled.

Evidence from other investigations suggests that the distribution and abundance of juvenile salmon in estuaries is influenced by the abundance of food. Healey (1978) found that the abundance of juvenile chinook salmon was positively correlated with the amount of food in their stomachs in different regions of the Georgia Strait. He concluded that these results suggest that the young salmon congregate in the best feeding areas. Healey (1982) also indicated that the growth and abundance of chinook salmon was greater in the Nanaimo Estuary compared to the Nitinat Estuary because food resources were greater in the latter. Food habits studies of juvenile chinook salmon have found larval fish were the primary component in the diet for smolts in the outer estuaries of Yaquina Bay and Georgia Strait (Myers 1980, Healey 1978) and ranked third in importance in the Nanaimo Estuary (Healey 1982). In the Yukon Delta high densities of juvenile smelt were found in the delta front. These fish and zooplankton in this estuarine zone may influence the abundance of juvenile chinook salmon in the Yukon Delta as well.

4.1.3 Residency

There was no difference in the average size or size composition of the juvenile outmigrants among the lower river, delta platform, and delta front habitats during the peak outmigration period. This would suggest that juveniles were not residing in the offshore habitats long enough for changes in average size to be detectable. The duration of residence, if any, is probably very short because the smolts were large enough to move into the marine environment. The majority of the smolts leaving the Yukon River reared for one or two years in freshwater. In other rivers, these older smolts generally do not utilize the nearshore waters, but instead migrate directly to the outer estuary and coastal marine environment (Healey 1982). Healey (1983) observed that these "stream type" chinook salmon occur predominantly in Alaska rivers and larger rivers (e.g., Fraser and Columbia Rivers) south of Alaska. He found that these larger smolts utilized the coastal waters of Georgia Strait for about two months and then moved further seaward in Juan de Fuca Strait during late summer. Samples were not collected from the outer portion of the delta front and the prodelta. Therefore, it is unknown whether juvenile chinook salmon utilize these deeper water habitats. It is possible that the areas sampled in this survey represent a transition zone that is located just on the inner edge of what may be the primary estuarine rearing area for Yukon smolts.

4.2 CHUM SALMON

4.2.1 Outmigration

The outmigration period for juvenile chum salmon from the Yukon River appears to begin prior to ice breakups and probably extends to early autumn. Since juveniles were caught on the first and last days of sampling it is reasonable to assume that fish were migrating prior to June and continued after the August survey. Chum fry migrating from upper river tributaries in early April (Table 4-2) could reach the delta by early May, which is several weeks prior to ice breakup. Similarly, fry leaving upper river tributaries during late August (e.g., Hodzana River, Table 4-2) would not reach the delta until early September. In 1985 the field survey continued to September 18th and juvenile chum were caught as late as September 13th (Martin et al. 1986).

The highest catch of chum salmon fry occurred on June 18th but other high catches also occurred throughout the month of June. During 1985 the peak catches occurred during June 20-25 (Martin et al., 1986) and during 1977 Barton (1983) had the largest catches on June 13-15. These results would suggest that the peak timing of the juvenile chum outmigration occurs during mid to late June. A similar timing for the peak outmigration of chum salmon was observed in the Noatak River in Kotzebue Sound (Merritt and Raymond 1983) and in the Susitna River in

TABLE 4-2

Outmigration Timing and Size at Outmigration of Chum Salmon Smolts from the Yukon River Drainage (Adapted from Table 3 in Raymond, 1986)

River	Distance[a/] (km)	Outmigration Dates			Mean Length (mm)	n	Reference
		From	To	Peak			
Delta	1,659	4-17	5-27	4-24	34.2	92	Francisco 1976
		4- 2	5-25*	4-28	34.6	1,426	"
				5-18			"
		4- 9	4-20	4- 9	32.0	72	Dinneford and Francisco 1977
				4-18			"
Salcha	1,553	5-16*	6- 8*		39.5	106	Trasky 1974
		5-10	5-30	5-20	34.6	27	Francisco 1976
Chena	1,496	5-22	7- 3*	6-12	41.3	142	"
		5- 8	6-27	5- 8	36.2	139	"
		5- 6	6- 7	5-21	35.9	228	"
		5- 2	5-18	5-11	35.0		Williamson 1981
Hodzana	1,443	6-2	8-24*	6- 5	39.2	474	Gissberg and Benning, 1965
Tanana	1,378	5- 9*	6-22*	6- 2	35.8	274	Raymond and Saugstad, 1986
		5-14*	6- 5	5-22	36.5	201	Raymond and Saugstad, 1986
Rodo	719		5-13*		33.6	7	Fred DeCicco, unpub. 1981 data
Bear Creek	636	5-22	6-20*		38.2	69	"
Anvik	530	5-22	7-26*		36.0		Buklis, 1983
Innoko	512		5-25*		33.6	7	Fred DeCicco, unpub. 1981 data
Yukon	101	6- 7*	7- 2	6-13	41.0	265	Barton 1979
Yukon	25	6- 4*	8- 8*	6-18	43.7	1,078	This Report

[a/] Distance from the mouth of the Yukon River.

* Indicates that the outmigration was in progress when the sampling started or ended.

Cook Inlet (Roth and Stratton 1985, Roth et al., 1986). This timing of the peak outmigration is later than chum fry outmigrations from rivers further south. In the Fraser River the peak of chum salmon outmigration occurs during late April and early May (Levy and Northcote 1982), and in Puget Sound streams the migration peaks typically from late March to early May (Simenstad et al., 1982).

The presence of more than one size group and the large average size (i.e., 60 mm) of one group of chum salmon outmigrants suggests migration timing and juvenile size may be related to different stocks. The larger fish (i.e., group I, Figure 3-15) that outmigrated during early June were most likely fall chum salmon. Most juvenile chum begin to emigrate from Yukon River tributaries at approximately 35 mm in length (Figure 4-2). In order to grow to an average size of 60 mm these fish would have had to emerge from 30 to 80 days earlier, assuming a growth rate of 0.3 - 0.8 mm per day (from table 4-4). Fall chum salmon which spawn in tributaries with upwelling groundwater (Buklis and Barton, 1984) are known to emerge during April in many upper Yukon River tributaries (Francisco 1976, Dinneford and Francisco 1977). For example, in the Delta River water temperature in a fall chum salmon redd was 6.6°C during November 1975 and fry were emerging as early as April 2 the following spring (Francisco 1977). These fish would have sufficient time to grow to 60 mm by early June. These large size chum may also be hatchery fish that were liberated from the Clear Creek Hatchery by the Alaska Department of Fish and Game (ADF&G). Approximately 1 million chum fry averaging 49.5 mm were released on May 5-6, 1986, into Clear Creek (tributary of Nanana River) (Jim Raymond, ADF&G, personal communication).

The smaller size chum caught during June were most likely summer chum salmon. This stock of fish generally spawns in lower river runoff streams (Buklis and Barton, 1984) where development is slow, hence emergence from these tributaries does not begin until mid to late May (see Bear Creek, Anvik R., and Innoko R. Table 4-2). Since less time is required to reach the delta from these tributaries, the small size of summer chum fry indicates very little growth occurred since emergence. A second group of similarly small chum fry occurred during

August (Group III, Figure 3-15) and may be summer chum salmon, as well. The reason for this unusually late outmigration, and the life history of these later summer outmigrants, needs further investigation.

4.2.2 Distribution and Habitat Utilization

Juvenile chum salmon were more widely distributed and occurred more frequently in the offshore habitats than in the coastal habitats. These results suggest that the outer delta platform and the delta front habitats were utilized to a greater extent than the mudflat or tidal slough habitats. Although the highest density of juvenile chum was detected in a tidal slough (i.e., Station 12, Table 3-8), their inconsistent utilization of this habitat suggests this was not an important environment. Similarly, the low frequency of occurrence in mudflat habitats suggests this environment may not be important as well.

The spatial distribution of juvenile salmon in the Yukon River Delta is unlike the distribution of chum observed in other estuaries. In small estuaries of British Columbia (i.e., Nanaimo, Cowichan, and Courtenay), Healey (1982) observed the following general pattern. Upon entry to the estuary juvenile chum would utilize the shallow intertidal marsh and fringe areas during high tide. During low tide fish would concentrate in flowing tidal creeks and adjacent delta channels. Habitat utilization was size related and as fish grow they progressively moved from the inner to the outer estuary. A similar pattern of habitat utilization for chum fry in Puget Sound estuaries was described by Simenstad et al. (1982). In the Fraser River Delta significant numbers of chum fry utilize the side channels and sloughs for rearing until the fish reach an average size of 46 mm (Levy and Northcote, 1982). Chum fry that bypass the sloughs and leave the river are dispersed by the plume and occur in nearshore nursery areas away from the delta (Healey 1980). After rearing in these shallow water environments, juvenile chum from the Fraser move into deeper water habitats in the Strait of Georgia where they reach an average size of 90-100 mm during the period of peak abundance (i.e., June - early July).

The difference in the distribution of juvenile chum in the Yukon Delta compared to other estuaries may be related to the different hydrographic conditions. The nearshore environment of the Yukon Delta is very different than those typical of small estuaries in British Columbia or Puget Sound. For example, true estuarine conditions do not occur in the nearshore habitats of the Yukon Delta during the outmigration period. The intertidal mudflat areas are typically freshwater dominated, very shallow (<0.5 mm), highly turbid, and relatively warm (see AVHRR images Figure 3-4 to 3-6). During the ebb tide, generally 1-2 km of mudflats are dewatered and only small shallow ponds (<20 cm deep) or shallow streams from tidal sloughs remain. Chum salmon that may utilize this habitat would have to move out quickly to the subtidal areas to find refuge. These subtidal areas would likely be poor habitat as they are very shallow, with no vegetation, and have sand-silt substrates. Therefore, much of the coastal habitats are not very suitable or accessible for juvenile rearing. Only the coastal areas adjacent to the large distributaries where the tidal flats are less extensive would be more accessible for juvenile rearing. Also, only the juveniles that migrate along the rivers edge are likely to find these nearshore habitats. As described for juvenile chinook salmon, outmigrant chum salmon in the major distributaries will most likely be distributed to the delta front by the strong river outflow.

Habitat utilization by juvenile chum salmon within the Yukon Delta distributaries and tidal channels is probably very similar to the Fraser River Delta. Data from the 1985 Yukon survey (Martin et al., 1986) indicate a broad distribution of juvenile chum in active distributaries, adjacent tidal channels, and lake outlet streams. Movement into tidal channels and outlet streams, however, was related to tidal backwater effects as juveniles were seldom found in these habitats at low tide, even though many of these channels were accessible at this time. The amount of river discharge during June probably affects fish distribution and habitat access as well. During 1985 most of the delta was covered by water, whereas during 1986 many of the smaller channels and distributaries were not connected to the river.

Utilization of the outer delta platform and delta front by juvenile chum was greater than utilization of the coastal habitats. The small average size of juveniles found in these habitats suggests that little or no rearing is occurring in this environment and that juveniles must be rearing in some other habitat before migration to open ocean. The average size of chum juveniles in the offshore habitats was slightly smaller than outmigrants from the river during the same time period (see Figure 3-16 to 3-18). The relative age of these fish was also less than fish from the river (see Table 3-13). This would indicate that all but the largest and oldest outmigrants from the river were probably moving directly to the delta front. Most of the fish utilizing the delta platform and delta front habitats were in the 40-50 mm size category and all the fish were less than 70 mm. In other estuaries the size of chum salmon juveniles at migration from inshore to deeper estuarine habitats ranged 40-75 mm and the size at migration from deeper estuarine habitats to the open ocean ranged 70-130 mm (Table 4-3). Therefore, compared to other estuaries the small size of juvenile chum utilizing the delta front indicates that this habitat may function as the inner estuary or staging area for juveniles before movement to deeper water habitats. The deeper water in the prodelta (Figure 2-2) may serve as the outer estuary for juvenile outmigrants and may be an important habitat prior to ocean migration. On the other hand, juvenile chum could move out from the Yukon plume and northward with prevailing current (Truett 1985) and rear in the deeper offshore habitats of Norton Sound. Healey (1980) examined the distribution of chum juveniles in Georgia Strait during summer and found that juveniles were less abundant in the Fraser plume than in other regions. Further investigations of the delta front, prodelta and Norton Sound, are necessary in order to identify the spatial and temporal utilization of this preocean rearing habitat.

4.2.3 Determining Residency With Otoliths

The results of the otolith analysis suggest that increment periodicity may not be constant for the early life stages of juvenile chum salmon. Periodicity appears to range from approximately 2 d/increment for pre-

TABLE 4-3

Sizes of Chum Salmon Juveniles in Estuarine Habitats
(Adapted from Iwamoto and Salo, 1977)

Location	Size (mm) at Migration	Reference
Migration From Inner to Outer Estuary		
Big Qualicum, B.C.	75	Allen (1974)
Puget Sound, Washington	50-60	Feller (1974)
Hood Canal, Washington	40-50	Schreiner (1977)
Bellingham Bay, Washington	65	Tyler (1964)
Migration From Outer Estuary to Open Ocean		
Big Qualicum, B.C.	120	Allen (1974)
Little Port Walter, Alaska	130	Lagler and Wright (1962)
Hokkaido, Japan	70-100	Sano and Kobayashi (1952)

emergent alevins to 0.8 d/increment for 50 mm outmigrant fry. The question is, is this wide variation in increment periodicity real? Research has shown that increment formation rates can vary from both less than and greater than one per day (Campanca and Neilson 1985). Environmental variables such as photoperiod, temperature, and feeding regime are known to have an influence on the rate of otolith deposition (Neilson and Geen 1982, 1985; Jones 1984). Juvenile chum salmon in the Yukon River would experience large variations in physical environmental conditions during the alevin and fry outmigrant stages. For example, photo period (at 64°N) varies from 13 hr/d during the alevin-early fry stage (i.e., early April) to 23 hr/d during the peak of the outmigration (i.e., mid-June). Water temperature during this period will range from 5°C to 15°C. Food supply would vary greatly in quantity and quality as fish change from indogenous to exogenous feeding and as they migrate from a clear tributary to a turbid river and through the delta/estuarine environment. Therefore, a variation in increment formation rate is not unlikely for Yukon chum salmon.

This apparent variation in increment periodicity for Yukon chum salmon prohibits us from estimating fish age or elapsed time from increment counts. Instead, the number of increments can only be viewed as a relative measure of age. More information is needed on factors that may cause a transition in increment periodicity and when these transitions occur during juvenile development.

The results of the 1986 otolith analysis do not concur with the results from 1985 concerning residency. The 1985 results suggested that juvenile chum may have been residing in some delta habitats. This interpretation was based on: 1) the identification of an outer edge zone where increment width showed a stepwise increase over the preceding increments; and, 2) the assumption that this zone corresponded with the transition from a riverine to an estuarine or delta environment. It is now evident, however, from the analysis of a large number of otoliths in 1986 that the outer edge zone identified in

1985 was the post-hatching zone. Therefore, the wider increments in this zone were not an indicator of estuarine residency but rather an approximate measure of age and a record of growth since hatching.

4.2.4 Residency

Residency of juvenile chum salmon in the offshore habitats examined in this study was either not occurring or was too short (i.e., less than 1 to 2 weeks) to be detected. The slight difference in size composition of outmigrants from the lower river compared to juveniles from the delta front or delta platform during the same time periods (Figures 3-16 to 3-18) indicates that juveniles could not have been residing for very long. The young relative age of the juveniles in the offshore habitats compared to the age of juveniles in the river supports this hypothesis. Juvenile chum are most likely moving through the lower river, bypassing the coastal habitats, and moving directly to the delta front. Fish in the delta front apparently do not reside long and continue their outmigration either to a deeper estuarine habitat or to the open ocean.

The short residence of juvenile chum salmon in the Yukon Delta is not uncommon compared to residency in other estuaries. Healey (1979) found that residence times in the Nanaimo Estuary varied between 0 and 18 days over two years of observations. In the Fraser River Delta, chum residency in tidal marsh channels ranged up to 11 days (Levy and Northcote 1982) and in the Skagit River Delta chum residency ranged 0 to 12 days (Foley, personal communication cited in Shepard 1981). Healey (1979) showed that juveniles arriving early during spring remained longer than fry arriving later. Iwamoto and Salo (1977) cite several studies indicating that fish size influenced distribution and residency. In the Yukon Delta neither migration timing nor fish size seem to affect estuarine residency since no residency was detected.

4.2.5 Growth

In the Yukon Delta growth rates of chum salmon were not affected by the transition from a riverine environment to the shallow delta platform and delta front. Growth rate was uniform during the last 13 to 26 days prior to fish capture, as demonstrated by the consistency in otolith increment widths (Figure 3-21). These results suggest that juvenile chum in the Yukon River do not require the shallow nearshore habitats for growth as do, for example, chum in estuaries of British Columbia and Puget Sound (Healy 1982, Simenstad et al 1982). These results also suggest that food availability in the Yukon River may not be a limiting factor during the outmigration period. Food habits studies that were conducted in 1985 (Martin et al. 1986) showed that only 16 percent of the chum stomachs examined were empty. Therefore, outmigrant chum must be obtaining sufficient food in order to maintain a fairly uniform growth rate.

Growth rate of juvenile chum salmon was not measured during this study but was estimated from fish length data. This growth rate estimate (i.e., 0.31 mm/d) is probably biased on the low side because of the effects of immigration and emigration on the size of fish in the sample population. This estimate indicates that the growth rate of chum salmon in the Yukon River is similar to the growth rates reported for chum in other freshwater environments (Table 4-4).

4.3 VULNERABILITY TO OIL AND GAS DEVELOPMENT

The vulnerability of a habitat to impacts from a potential oil spill is largely dependent upon the location and elevation of the habitat. In the Yukon Delta, habitats can be ranked in order of their relative vulnerability as follows:

TABLE 4-4

Growth Rate of Juvenile Chum Salmon in Freshwater

Location	Habitat	Growth Rate (mm/d)	Temperature (°C)	Reference
Susitna, R, AK	Freshwater	.25-.45[a]	3.6-11.8	Roth and Stratton (1985), Roth et al. (1986)
Laboratory, B.C.	Freshwater	.66-.82[b]	14.0°-16.0°	Le Brasseur (1969)
Clear Creek, Yukon R, AK	Freshwater	.22[a]	1.8°-10.0°	Raymond (1981)
Yukon R, AK	Freshwater	.31[a]	6.8°-17.1°	This Report

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[a] Represents a population growth rate (after Ricker 1975) computed from mean length data.

[b] Fish fed on excess ration grew at 5.4 percent body weight per day. Converted to mm/d for 40 mm and 50 mm fish using length-weight regression from Roth et al. (1986).

1) delta front and delta platform
2) intertidal mudflats and tidal sloughs
3) active distributaries
4) inactive distributaries and connected lakes

Therefore, juvenile salmon that utilize the delta front or delta platform would be the most vulnerable to impacts from oil because these habitats are in close proximity to the oil and gas lease area (Figure 2-1). Whereas, fish that may occur in inactive distributaries or connected lakes would be the least likely to be impacted because oil would only reach these habitats by a large storm surge event.

Results from this investigation and the 1985 fish investigations (Martin et al., 1986) indicated that the major distributaries, nearshore habitats near the distributary mouths, the outer delta platform, and the delta front are primarily utilized as a migration corridor for juvenile salmon. An oil spill during the outmigration period that may reach any of these habitats could have a significant impact on Yukon river salmon stocks. Based on the 1985 data, Martin et al. (1986) indicate that the nearshore habitats (i.e., inner delta platform and tidal sloughs) were the most important for juvenile salmon and that an impact in these habitats would have the greatest effect on those populations. However, based on the 1986 data, it is evident that the nearshore habitats are not as important as previously thought. Additional fish sampling in the offshore areas indicates that the outer delta platform and the delta front are more important for the juvenile outmigrant populations. The 1986 data also suggests that the prodelta may be a very important rearing area for juvenile chum salmon prior to their ocean migration. If the latter is true, fish that utilize the prodelta would be the most vulnerable to oil impacts because this habitat is partially located within the proposed OCS lease area. More information is needed concerning the distribution and duration of habitat utilization in the prodelta and Norton Sound region in order to assess potential impacts from oil and gas development.

The distribution of sheefish and whitefish observed in this survey and in the 1985 survey (Martin et al. 1986) indicates that the intertidal mudflats and tidal sloughs are the most important habitats utilized by these species. These species and their populations would be highly vulnerable to an oil spill that reached the nearshore environment. Similarly, juvenile cisco were very abundant in the nearshore habitats and in the delta platform. Unlike juvenile salmon, the juvenile whitefish, sheefish, and cisco do not migrate far beyond the nearshore environments. Instead, they utilize these shallow coastal habitats for rearing throughout the summer and early fall. In winter, however, these habitats are frozen and the coregonids are assumed to move into the deeper active distributaries within the delta. This continuous, year-round utilization of the delta habitats makes the coregonid species potentially vulnerable to oil and gas development during all seasons.

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APPENDIX A
WATER QUALITY DATA AND PHYSICAL CONDITIONS DURING SUMMER 1986 IN THE YUKON RIVER DELTA

Station	Date	Depth (m)	Bottom Conductivity (mmhos/cm)	Bottom Salinity (ppt)	Bottom Temperature (°C)	Surface Conductivity (mmhos/cm)	Surface Salinity (ppt)	Surface Temperature (°C)	Secchi Depth (m)	Sea State[a/]
1	6/06	7.5	22.3	26.1	0.0	15.0	14.3	3.9	0.7	2
1	6/12	6.0	23.7	27.4	0.4	16.0	14.1	7.2	0.9	3
1	6/15	5.5	24.4	27.3	1.1	10.7	8.0	13.2	0.5	4
1	6/19	5.0	25.7	23.6	6.3	5.7	3.8	12.0	0.2	3
1	7/11	5.5	-	-	8.6	-	-	16.0	0.3	3
1	7/14	6.0	-	-	11.7	-	-	13.0	0.4	2
1	8/06	5.0	30.0	26.6	9.4	30.0	27.0	9.8	0.5	2
2	6/12	9.0	24.0	28.3	0.0	9.2	7.1	10.8	-	3
2	6/15	8.0	24.2	28.0	0.1	6.3	4.3	15.2	0.3	2
2	6/19	9.0	25.5	29.2	0.0	6.0	4.1	11.9	0.2	3
2	7/14	9.0	-	-	10.3	-	-	14.9	0.2	2
2	8/06	8.5	27.1	23.8	9.7	22.1	18.8	10.2	0.3	2
3	6/12	8.0	23.9	29.2	0.0	14.9	12.9	8.2	0.8	4
3	6/15	8.5	24.3	29.2	0.0	19.5	16.4	10.0	1.1	3
3	6/19	8.5	25.3	27.2	3.2	6.3	4.6	12.1	0.2	1
3	7/11	8.5	-	-	5.5	-	-	14.5	1.2	4
3	7/14	9.0	-	-	9.5	-	-	15.5	0.2	3
3	8/06	9.0	30.8	27.1	10.1	23.4	19.8	10.7	0.5	2
4	6/12	1.5	19.9	19.9	4.1	14.1	12.1	8.0	0.8	3
4	6/15	2.0	23.3	23.9	3.5	16.8	13.9	9.6	0.5	2
4	6/19	1.0	2.1	1.4	12.6	2.4	1.3	12.1	0.2	3
4	7/11	1.5	-	-	15.3	-	-	16.0	0.3	3
4	7/14	1.5	-	-	13.9	-	-	14.1	0.2	2
5	6/12	2.0	21.5	23.6	1.5	11.3	9.0	10.2	0.6	3
5	6/15	2.0	19.9	18.3	6.5	8.5	6.0	14.7	0.7	2
5	6/19	3.0	7.8	5.7	10.9	2.4	1.5	11.6	0.2	3
5	7/14	1.7	-	-	13.9	-	-	14.9	0.2	3
5	8/06	3.5	11.6	9.1	10.8	10.3	7.9	11.0	0.3	2
6	6/12	2.0	23.6	27.9	0.3	8.3	6.6	10.9	0.5	3
6	6/15	2.0	20.0	18.7	6.2	5.7	3.5	17.2	0.4	3
6	6/19	3.5	3.6	5.2	11.8	2.6	1.5	12.3	0.2	1
6	7/11	2.0	-	-	16.0	-	-	16.2	0.1	3
6	7/14	2.5	-	-	15.0	-	-	15.0	0.2	3
6	8/06	3.0	2.9	3.0	11.1	2.4	1.7	11.2	0.2	2

APPENDIX A (Continued)
WATER QUALITY DATA AND PHYSICAL CONDITIONS DURING SUMMER 1986 IN THE YUKON RIVER DELTA

Station	Date	Depth (m)	Bottom Conductivity (mmhos/cm)	Bottom Salinity (ppt)	Bottom Temperature (°C)	Surface Conductivity (mmhos/cm)	Surface Salinity (ppt)	Surface Temperature (°C)	Secchi Depth (m)	Sea State[a]/
8	6/10	0.5	1.2	0.8	9.4	-	-	-	-	2
8	6/14	0.3	1.3	1.0	15.2	-	-	-	0.2	2
8	6/17	0.5	-	-	-	-	-	15.4	0.3	2
8	6/22	0.5	2.1	1.3	17.0	-	-	-	0.4	1
8	6/24	0.5	1.0	0.7	10.0	-	-	-	0.2	2
8	7/12	0.7	-	-	-	-	-	14.5	0.2	2
8	8/04	0.3	-	-	-	-	-	11.7	0.1	1
9	6/25	1.0	1.8	1.4	9.1	1.8	1.3	9.2	0.1	2
9	7/13	0.5	-	-	-	-	-	13.5	0.3	2
9	8/04	0.5	-	-	-	-	-	12.5	0.2	2
10	8/05	0.6	-	-	-	-	-	10.1	0.6	1
11	6/10	1.5	1.3	1.0	8.5	1.3	0.9	8.7	0.5	1
11	6/14	1.5	1.5	0.9	19.1	1.4	0.8	17.8	0.8	2
11	6/17	2.0	-	-	-	-	-	16.1	0.5	1
11	6/22	1.0	3.8	2.6	12.7	3.8	2.7	13.5	0.9	0
11	6/24	0.5	1.0	0.6	10.2	1.0	0.6	10.2	0.6	1
11	7/12	2.0	-	-	-	-	-	13.5	0.2	1
11	8/04	1.5	-	-	-	-	-	10.8	0.1	1
12	6/25	1.5	2.2	1.7	8.4	2.2	1.8	8.8	0.3	1
12	7/13	2.0	-	-	-	-	-	13.5	0.4	0
12	8/04	2.0	-	-	-	-	-	11.5	0.5	1
13	6/04	10.0	1.4	0.9	6.5	1.2	0.9	6.8	0.2	2
13	6/05	9.0	1.1	0.8	7.6	1.1	0.8	7.6	0.2	0
13	6/09	9.0	1.3	0.8	9.9	1.3	0.8	10.2	0.4	2
13	6/13	10.0	1.3	0.8	12.7	1.4	0.9	12.9	0.3	2
13	6/14	6.0	1.3	0.8	13.3	1.3	0.8	13.3	0.2	2
13	6/17	9.0	2.7	1.8	14.6	2.9	1.9	14.6	0.3	2
13	6/18	9.0	2.0	1.2	13.7	2.1	1.1	13.8	0.2	3
13	6/20	9.5	2.1	1.3	13.8	2.6	1.4	13.8	0.2	1
13	6/22	10.0	2.5	1.8	14.6	2.7	1.8	14.5	0.2	0
13	6/24	10.0	1.0	0.6	14.4	1.0	0.6	14.3	0.2	3
13	6/26	10.0	1.9	1.3	13.6	1.5	0.9	13.7	0.2	3
13	7/12	10.0	-	-	17.0	-	-	17.1	0.2	3
13	8/05	10.5	-	-	12.7	-	-	13.0	0.1	3
13	8/07	10.5	0.7	0.3	12.6	0.7	0.4	12.8	0.2	2
13	8/08	9.5	0.7	0.3	12.8	0.7	0.3	12.7	0.1	1

APPENDIX A (Continued)
WATER QUALITY DATA AND PHYSICAL CONDITIONS DURING SUMMER 1986 IN THE YUKON RIVER DELTA

Station	Date	Depth (m)	Bottom Conductivity (mmhos/cm)	Bottom Salinity (ppt)	Bottom Temperature (°C)	Surface Conductivity (mmhos/cm)	Surface Salinity (ppt)	Surface Temperature (°C)	Secchi Depth (m)	Sea State[a/]
14	6/01	10.0	-	-	-	-	-	4.9	0.1	1
15	5/31	-	-	-	-	-	-	9.1	0.9	0
15	6/02	6.0	1.1	1.1	8.0	1.1	0.8	8.2	0.9	1
16	5/31	-	-	-	-	-	-	-	-	0
17	6/05	10.0	-	-	-	-	-	9.0	-	0
17	6/07	9.5	1.2	0.8	9.4	1.2	0.8	9.3	0.2	1
17	6/08	10.0	1.2	0.8	10.1	1.3	1.0	10.0	0.2	1
17	6/09	8.0	1.2	0.8	10.2	1.2	1.0	10.2	0.3	1
17	6/10	9.0	1.2	0.8	11.5	1.1	0.8	11.4	0.4	2
17	6/11	8.0	1.2	0.9	11.8	1.2	0.8	11.8	0.3	0
17	6/13	8.5	1.1	0.6	13.1	1.2	0.9	13.2	0.3	2
17	6/14	10.0	1.4	0.9	13.9	1.4	0.9	13.8	0.2	2
17	6/17	10.0	2.1	0.8	14.7	2.4	1.4	14.9	0.2	2
17	6/18	11.0	2.4	1.6	13.6	2.3	1.0	13.8	0.2	2
17	6/20	10.0	2.1	1.3	13.6	2.7	1.7	13.9	0.2	1
17	6/22	7.0	2.5	1.6	14.5	2.8	1.8	14.6	0.2	0
17	6/24	9.0	1.0	0.6	14.4	1.0	0.6	14.5	0.2	2
17	6/26	9.0	1.5	1.0	13.6	1.6	1.0	13.7	0.2	2
17	7/10	11.0	5.6	2.7	17.9	5.7	2.5	-	0.2	1
17	7/12	10.0	-	-	16.4	-	-	16.7	0.2	1
17	7/13	10.0	-	-	17.0	-	-	17.1	0.2	1
17	8/05	8.0	-	-	12.8	-	-	12.8	0.1	1
17	8/07	9.5	0.7	0.4	12.5	0.7	0.4	12.5	0.1	1
17	8/08	9.5	0.7	0.4	12.7	0.7	0.5	12.7	0.1	1
17	8/08	9.5	0.7	0.4	12.7	0.7	0.5	12.7	0.1	1
21	6/06	13.0	23.4	28.5	0.0	8.7	8.3	4.1	1.0	2
41	6/04	2.0	1.1	1.1	3.5	1.2	0.8	3.4	0.2	2
41	6/06	1.0	1.3	1.1	3.9	1.3	1.1	3.9	0.2	2
51	6/06	2.5	22.0	25.4	0.0	6.6	5.5	5.4	0.3	2

[a/] World Meteorological Organization sea state scale

APPENDIX B
FISH CATCH AND FISH LENGTH STATISTICS GROUPED BY SPECIES, STATION, AND DATE FOR THE 1986 SUMMER SURVEY OF THE YUKON RIVER DELTA

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
CHINOOK SALMON											
1	6/12	Tow Net	3	3	1.00	1.73	3	83.33	77	90	6.51
	6/15	Tow Net	1	3	0.33	0.58	1	78.00	78	78	
2	6/12	Tow Net	6	3	2.00	1.00	6	94.17	72	116	14.73
	6/15	Tow Net	2	3	0.67	1.15	2	97.00	87	107	14.14
	6/19	Tow Net	1	3	0.33	0.58	1	88.00	88	88	
	7/14	Tow Net	1	3	0.33	0.58	1	101.00	101	101	
3	6/12	Tow Net	10	3	3.33	0.58	10	103.90	82	115	9.69
	6/15	Tow Net	9	3	3.00	5.20	9	96.33	74	115	14.46
4	6/12	Tow Net	3	3	1.00	1.73	3	92.00	82	105	11.79
	6/15	Tow Net	6	3	2.00	1.73	6	90.33	76	110	12.53
	7/11	Tow Net	1	2	0.50	0.71	1	95.00	95	95	
5	6/12	Tow Net	3	3	1.00	1.00	3	100.33	92	112	10.41
	6/15	Tow Net	6	3	2.00	1.00	6	96.67	83	109	11.36
	6/19	Tow Net	1	3	0.33	0.58	1	98.00	98	98	
6	6/15	Tow Net	18	3	6.00	5.57	18	98.11	72	116	13.65
	6/19	Tow Net	1	3	0.33	0.58	1	102.00	102	102	
11	6/17	Beach Seine-75	1	2	0.50	0.71	1	115.00	115	115	
13	6/04	Tow Net	7	3	2.33	1.53	7	92.71	69	125	17.90
	6/04	Purse Seine	3	2	1.50	0.71	3	95.00	77	109	16.37
	6/05	Tow Net	4	3	1.33	1.53	4	99.75	75	122	22.38
	6/09	Tow Net	9	3	3.00	2.65	9	101.33	72	128	17.20
	6/13	Tow Net	1	3	0.33	0.58	1	93.00	93	93	
	6/14	Tow Net	5	6	1.67	3.20	5	98.60	87	111	9.53
	6/17	Tow Net	6	3	2.00	1.00	6	85.50	79	89	4.04
	6/18	Tow Net	2	3	0.67	1.15	2	92.50	89	96	4.95
	6/20	Tow Net	3	5	1.20	1.10	3	91.67	83	98	7.77
	6/22	Tow Net	2	3	0.67	0.58	2	90.50	83	98	10.61
	6/24	Tow Net	8	3	2.67	3.79	8	89.38	82	95	4.69
	6/26	Tow Net	9	3	3.00	2.65	4	93.50	85	110	11.39

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
	7/12	Tow Net	3	3	1.00	1.73	3	106.67	96	116	10.07
14	6/01	Tow Net	3	7	0.43	0.53	3	105.67	79	128	24.79
15	5/31	Tow Net	78	1			78	94.65	73	117	11.63
	6/02	Tow Net	69	3	23.00	16.37	19	94.00	71	126	19.39
16	5/31	Tow Net	27	1	27.00		27	97.78	85	116	8.57
17	6/05	Tow Net	40	15	5.13	4.97	25	100.08	83	118	9.51
	6/07	Tow Net	5	3	1.67	0.58	5	93.00	78	112	12.77
	6/08	Tow Net	1	3	0.33	0.58	1	96.00	96	96	
	6/09	Tow Net	11	3	3.67	1.15	11	89.00	72	106	10.88
	6/10	Tow Net	5	3	1.67	1.15	5	91.40	75	110	12.93
	6/11	Tow Net	4	3	1.33	1.15	4	100.25	94	107	5.85
	6/14	Tow Net	4	3	1.33	1.53	4	92.75	83	110	12.28
	6/17	Tow Net	42	3	14.00	1.00	15	94.80	85	119	9.99
	6/18	Tow Net	67	3	22.33	2.52	31	95.48	78	114	8.91
	6/20	Tow Net	7	3	2.33	2.52	7	95.71	80	117	13.36
	6/22	Tow Net	10	3	3.33	1.15	10	92.80	83	108	7.32
	6/24	Tow Net	55	3	18.33	5.69	34	93.50	84	123	7.83
	6/26	Tow Net	53	3	17.67	1.53	52	93.21	81	109	6.93
	7/10	Tow Net	26	3	8.67	14.15	1	113.00	113	113	
	7/12	Tow Net	20	3	6.67	5.13	19	101.89	87	123	12.46
	7/13	Tow Net	24	3	8.00	2.65	24	99.83	82	117	8.60
	8/05	Tow Net	4	3	1.33	0.58	4	101.00	85	115	12.33
	8/07	Tow Net	2	3	0.67	0.58	2	112.50	110	115	3.54
	8/08	Tow Net	2	4	0.50	0.58	2	112.00	111	113	1.41
41	6/04	Tow Net	1	2	0.50	0.71	1	112.00	112	112	
51	6/06	Tow Net	1	2	0.50	0.71	1	103.00	103	103	
					CHUM SALMON						
1	6/12	Tow Net	57	3	19.00	8.89	56	38.70	35	46	2.43
	6/15	Tow Net	181	3	60.33	35.13	68	40.00	33	52	4.33
	6/19	Tow Net	148	3	49.33	34.44	45	41.64	36	55	4.23
	7/14	Tow Net	4	3	1.33	1.53	4	49.50	40	62	10.02

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
2	6/12	Tow Net	63	3	21.00	19.29	62	39.74	35	61	5.60
	6/15	Tow Net	92	3	30.67	5.03	41	40.83	36	53	4.36
	6/19	Tow Net	98	3	32.67	3.79	68	41.66	36	56	3.46
	7/14	Tow Net	1	3	0.33	0.58	1	57.00	57	57	
	8/06	Tow Net	2	3	0.67	0.58	2	83.00	59	107	33.94
3	6/12	Tow Net	16	3	5.33	2.08	16	37.44	35	40	1.93
	6/15	Tow Net	11	3	3.67	3.79	11	43.64	36	61	7.13
	6/19	Tow Net	87	3	29.00	29.44	63	40.38	36	48	2.96
	7/11	Tow Net	25	3	8.33	8.02	25	47.72	36	68	7.21
	7/14	Tow Net	1	3	0.33	0.58	1	43.00	43	43	
4	6/12	Tow Net	42	3	14.00	9.85	41	39.15	34	51	3.42
	6/15	Tow Net	18	3	6.00	2.65	18	44.00	37	85	11.27
	6/19	Tow Net	87	3	29.00	5.57	41	40.20	34	47	3.04
	7/11	Tow Net	1	2	0.50	0.71	1	46.00	46	46	
	7/14	Tow Net	1	3	0.33	0.58	1	51.00	51	51	
5	6/12	Tow Net	39	3	13.00	6.24	39	40.03	35	54	4.68
	6/15	Tow Net	105	3	35.00	16.09	50	42.88	35	55	5.63
	6/19	Tow Net	191	3	63.67	7.09	54	40.93	35	48	3.37
6	6/12	Tow Net	3	3	1.00	1.00	3	38.67	38	40	1.15
	6/15	Tow Net	135	3	45.00	6.08	38	41.45	35	50	4.12
	6/19	Tow Net	60	3	20.00	4.36	60	41.82	35	52	3.68
	7/14	Tow Net	4	3	1.33	0.58	4	46.00	42	53	4.97
	8/06	Tow Net	1	3	0.33	0.58	1	33.00	33	33	
8	6/10	Beach Seine-150	3	2	1.50	0.71	3	36.67	34	38	2.31
	6/14	Beach Seine-150	4	2	2.00	2.83	4	38.50	38	39	0.58
	6/24	Beach Seine-150	1	2	0.50	0.71	1	42.00	42	42	
11	6/10	Beach Seine-75	9	2	4.50	0.71	9	37.00	32	39	2.18
	6/14	Beach Seine-75	197	2	98.50	55.86	40	39.70	36	43	1.79
13	6/04	Tow Net	16	3	5.33	2.89	16	39.38	33	62	8.88
	6/05	Tow Net	15	3	5.00	1.00	15	36.40	35	38	0.74
	6/09	Tow Net	158	3	52.67	10.02	46	39.93	34	69	6.10
	6/13	Tow Net	122	3	40.67	13.65					
	6/14	Tow Net	195	6	65.00	6.29	36	41.89	35	53	4.21

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
	6/17	Tow Net	150	3	50.00	17.35	47	45.51	38	70	5.96
	6/18	Tow Net	66	3	22.00	4.36	49	44.76	36	52	3.57
	6/20	Tow Net	171	5	68.40	30.31	32	43.25	36	57	5.21
	6/22	Tow Net	165	3	55.00	7.00	55	45.64	38	60	4.66
	6/24	Tow Net	53	3	17.67	12.22	53	45.43	35	56	4.51
	6/26	Tow Net	44	3	14.67	2.31	44	48.91	39	57	4.33
	7/12	Tow Net	3	3	1.00	1.00	3	51.00	42	59	8.54
	8/05	Tow Net	2	3	0.67	0.58	2	46.50	36	57	14.85
	8/07	Tow Net	1	3	0.33	0.58	1	49.00	49	49	
	8/08	Tow Net	2	5	0.40	0.55	2	41.50	38	45	4.95
14	6/01	Tow Net	12	7	1.71	1.70	12	37.50	29	61	9.49
15	6/02	Tow Net	43	3	14.33	13.58	43	37.14	35	40	1.19
16	5/31	Tow Net	5	1	5.00		5	36.00	34	37	1.22
17	6/05	Tow Net	103	15	12.87	7.62	30	40.90	34	66	9.84
	6/07	Tow Net	35	3	11.67	7.51	35	37.46	33	42	2.28
	6/08	Tow Net	67	3	22.33	5.13	67	37.58	33	42	1.86
	6/09	Tow Net	324	3	108.00	12.53	45	37.36	34	48	2.39
	6/10	Tow Net	22	3	7.33	3.06	22	38.77	34	50	3.41
	6/11	Tow Net	21	3	7.00	3.61	21	42.33	35	52	5.08
	6/13	Tow Net	45	3	15.00	8.54					
	6/14	Tow Net	49	3	16.33	5.13	49	42.41	35	53	5.31
	6/17	Tow Net	187	3	62.33	20.60	55	44.16	36	55	4.76
	6/18	Tow Net	336	3	112.00	26.00	61	42.54	32	55	4.27
	6/20	Tow Net	95	3	31.67	7.77	47	42.98	35	62	4.58
	6/22	Tow Net	83	3	27.67	10.60	56	46.07	37	59	4.94
	6/24	Tow Net	115	3	38.33	12.10	63	45.54	35	58	5.55
	6/26	Tow Net	326	3	108.67	4.73	93	45.84	37	59	4.84
	7/10	Tow Net	13	3	4.33	2.52	13	47.92	41	57	5.48
	7/12	Tow Net	25	3	8.33	4.04	25	47.80	37	71	7.52
	7/13	Tow Net	30	3	10.00	3.46	30	48.57	38	65	6.28
	8/05	Tow Net	18	3	6.00	1.00	18	47.28	35	60	7.09
	8/07	Tow Net	6	3	2.00	1.73	6	43.50	37	55	6.09
	8/08	Tow Net	16	4	4.00	2.45	16	43.75	35	59	7.65

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
21	6/06	Tow Net	3	3	1.00	0.00	3	34.33	34	35	0.58
41	6/04	Tow Net	1	2	0.50	0.71	1	37.00	37	37	
	6/06	Tow Net	3	2	1.50	2.12	3	56.00	36	93	32.08
51	6/06	Tow Net	2	2	1.00	0.00	2	35.50	34	37	2.12
PINK SALMON											
15	6/02	Tow Net	1	3	0.33	0.58	1	34.00	34	34	
17	6/05	Tow Net	1	15	0.13	0.52	1	37.00	37	37	
	7/12	Tow Net	2	3	0.67	0.58	2	420.00	410	430	14.14
ARCTIC CHAR											
15	6/02	Tow Net	1	3	0.33	0.58	1	142.00	142	142	
17	6/05	Tow Net	1	15	0.13	0.52	1	175.00	175	175	
41	6/04	Tow Net	1	2	0.50	0.71					
SHEEFISH											
3	7/14	Tow Net	1	3	0.33	0.58					
4	7/11	Tow Net	1	2	0.50	0.71					
	7/14	Tow Net	1	3	0.33	0.58					
5	7/14	Tow Net	3	3	1.00	1.00					
6	7/11	Tow Net	1	2	0.50	0.71					
	7/14	Tow Net	10	3	3.33	3.21					
8	6/10	Beach Seine-150	1	2	0.50	0.71					
	6/14	Beach Seine-150	5	2	2.50	0.71					
	6/17	Beach Seine-150	2	2	1.00	0.00					
	6/22	Beach Seine-150	6	2	3.00	1.41					
	6/24	Beach Seine-150	1	2	0.50	0.71					
	7/12	Beach Seine-150	3	2	1.50	2.12					
9	6/25	Beach Seine-150	1	2	0.50	0.71					
	7/13	Beach Seine-150	4	2	2.00	2.83					
	8/04	Beach Seine-150	29	2	14.50	3.54					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
11	6/17	Beach Seine-75	1	2	0.50	0.71					
	8/04	Beach Seine-75	4	2	2.00	1.41					
13	7/12	Tow Net	3	3	1.00	1.00					
	8/05	Tow Net	2	3	0.67	0.58					
	8/07	Tow Net	5	3	1.67	0.58					
	8/08	Tow Net	4	5	0.80	0.84					
17	7/10	Tow Net	10	3	3.33	1.15					
	7/12	Tow Net	69	3	23.00	9.85					
	7/13	Tow Net	116	3	38.67	8.96					
	8/05	Tow Net	21	3	7.00	1.73					
	8/07	Tow Net	8	3	2.67	2.89					
	8/08	Tow Net	19	4	4.75	2.75					
41	6/04	Tow Net	1	2	0.50	0.71					

HUMPBACK WHITEFISH

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
8	6/10	Beach Seine-150	4	2	2.00	1.41					
	6/14	Beach Seine-150	7	2	3.50	2.12					
	6/22	Beach Seine-150	4	2	2.00	0.00					
9	6/25	Beach Seine-150	39	2	19.50	21.92					
	7/13	Beach Seine-150	2	2	1.00	1.41					
	8/04	Beach Seine-150	17	2	8.50	10.61					
11	6/17	Beach Seine-75	4	2	2.00	1.41					
	6/22	Beach Seine-75	2	2	1.00	0.00					
	8/04		10	2	5.00	2.83					
12	6/25		5	2	2.50	0.71					
	7/13		5	2	2.50	0.71					
	8/04		1	2	0.50	0.71					
17	6/05	Tow Net	4	15	0.53	1.60					
41	6/04		3	2	1.50	2.12					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
BROAD WHITEFISH											
8	6/10	Beach Seine-150	14	2	7.00	9.90					
11	6/10	Beach Seine-75	6	2	3.00	4.24					
41	6/04	Tow Net	2	2	1.00	1.41					
WHITEFISH SP.											
3	7/11	Tow Net	4	3	1.33	2.31					
4	7/14	Tow Net	1	3	0.33	0.58					
8	6/14	Beach Seine-150	4	2	2.00	0.00					
	6/17	Beach Seine-150	4	2	2.00	1.41					
	6/22	Beach Seine-150	7	2	3.50	4.95					
	6/24	Beach Seine-150	17	2	8.50	7.78					
	7/12	Beach Seine-150	24	2	12.00	1.41					
	8/04	Beach Seine-150	16	2	8.00	5.66					
9	6/25	Beach Seine-150	4	2	2.00	0.00					
	7/13	Beach Seine-150	2	2	1.00	1.41					
	8/04	Beach Seine-150	51	2	25.50	23.33					
10	8/05	Beach Seine-75	39	2	19.50	4.95					
11	6/17	Beach Seine-75	6	2	3.00	1.41					
	6/22	Beach Seine-75	1	2	0.50	0.71					
	6/24	Beach Seine-75	4	2	2.00	1.41					
	7/12	Beach Seine-75	4	2	2.00	0.00					
	8/04	Beach Seine-75	13	2	6.50	0.71					
12	6/25	Beach Seine-75	61	2	30.50	43.13					
	7/13	Beach Seine-75	3	2	1.50	0.71					
	8/04	Beach Seine-75	2	2	1.00	1.41					
13	6/04	Purse Seine	1	2	0.50	0.71	1	112.00	112	112	
	6/05	Purse Seine	1	2	0.50	0.71					
	6/18	Tow Net	2	3	0.67	0.58					
	7/12	Tow Net	8	3	2.67	1.53					
	8/08	Tow Net	1	5	0.20	0.45					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
17	6/17	Tow Net	2	3	0.67	1.15					
	6/22	Tow Net	3	3	1.00	0.00					
	6/26	Tow Net	1	3	0.33	0.58					
	7/10	Tow Net	25	3	8.33	1.15					
	7/12	Tow Net	101	3	33.67	24.66					
	7/13	Tow Net	101	3	33.67	19.43					
	8/05	Tow Net	9	3	3.00	0.00					
	8/07	Tow Net	4	3	1.33	0.58					
41	6/06	Tow Net	19	2	9.50	3.54					
					BERING CISCO						
9	6/25	Beach Seine-150	22	2	11.00	15.56					
	7/13	Beach Seine-150	2	2	1.00	1.41					
	8/04	Beach Seine-150	2	2	1.00	1.41					
10	8/05	Beach Seine-75	1	2	0.50	0.71					
11	6/22	Beach Seine-75	1	2	0.50	0.71					
12	8/04	Beach Seine-75	1	2	0.50	0.71					
41	6/06	Tow Net	15	2	7.50	10.61					
					LEAST CISCO						
1	8/06	Tow Net	1	3	0.33	0.58					
2	7/14	Tow Net	4	3	1.33	1.15					
	8/06	Tow Net	1	3	0.33	0.58					
3	6/19	Tow Net	2	3	0.67	0.58					
	8/06	Tow Net	1	3	0.33	0.58					
5	6/12	Tow Net	2	3	0.67	1.15					
	6/15	Tow Net	1	3	0.33	0.58					
	8/06	Tow Net	11	3	3.67	0.58					
6	6/12	Tow Net	11	3	3.67	3.21					
	6/15	Tow Net	23	3	7.67	10.02					
	6/19	Tow Net	1	3	0.33	0.58					
	8/06	Tow Net	2	3	0.67	0.58					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
8	6/10	Beach Seine-150	12	2	6.00	4.24					
	6/14	Beach Seine-150	6	2	3.00	1.41					
	6/17	Beach Seine-150	2	2	1.00	1.41					
	6/22	Beach Seine-150	6	2	3.00	0.00					
	6/24	Beach Seine-150	7	2	3.50	0.71					
9	6/25	Beach Seine-150	2	2	1.00	0.00					
	7/13	Beach Seine-150	4	2	2.00	0.00					
11	6/10	Beach Seine-75	1	2	0.50	0.71					
	6/17	Beach Seine-75	6	2	3.00	0.00					
	6/22	Beach Seine-75	5	2	2.50	3.54					
12	7/13	Beach Seine-75	11	2	5.50	7.78					
13	6/04	Purse Seine	8	2	4.00	5.66	8	221.50	73	297	68.37
	6/05	Purse Seine	13	2	6.50	6.36					
	6/09	Tow Net	1	3	0.33	0.58					
	6/13	Tow Net	1	3	0.33	0.58					
	6/14	Tow Net	1	6	0.33	0.82					
	8/07	Tow Net	5	3	1.67	2.89					
15	6/02	Tow Net	4	3	1.33	2.31					
16	5/31	Tow Net	2	1	2.00		2	92.50	74	111	26.16
17	6/05	Tow Net	1	15	0.13	0.52					
	6/09	Tow Net	5	3	1.67	2.08					
	6/24	Tow Net	2	3	0.67	0.58					
	8/07	Tow Net	7	3	2.33	1.53					
41	6/04	Tow Net	40	2	20.00	0.00					
	6/06	Tow Net	39	2	19.50	9.19					
					CISCO SP.						
1	7/11	Tow Net	34	2	17.00	8.49					
	7/14	Tow Net	38	3	12.67	2.08					
2	7/14	Tow Net	82	3	27.33	12.50					
3	7/11	Tow Net	449	3	149.67	49.66					
	7/14	Tow Net	26	3	8.67	3.21					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
4	7/11	Tow Net	55	2	27.50	9.19					
	7/14	Tow Net	91	3	30.33	9.29					
5	7/14	Tow Net	89	3	29.67	12.10					
6	7/11	Tow Net	601	2	300.50	113.84					
	7/14	Tow Net	61	3	20.33	3.51					
8	7/12	Beach Seine-150	1	2	0.50	0.71					
9	7/13	Beach Seine-150	3	2	1.50	2.12					
	8/04	Beach Seine-150	19	2	9.50	2.12					
11	6/14	Beach Seine-75	12	2	6.00	7.07					
	6/17	Beach Seine-75	1	2	0.50	0.71					
	6/22	Beach Seine-75	2	2	1.00	1.41					
	7/12	Beach Seine-75	4	2	2.00	0.00					
	8/04	Beach Seine-75	2	2	1.00	1.41					
12	7/13	Beach Seine-75	13	2	6.50	4.95					
	8/04	Beach Seine-75	1	2	0.50	0.71					
13	6/26	Tow Net	5	3	1.67	2.89					
	7/12	Tow Net	393	3	131.00	35.38					
	8/05	Tow Net	2	3	0.67	1.15					
	8/08	Tow Net	4	5	0.80	0.84					
17	6/24	Tow Net	8	3	2.67	1.53					
	6/26	Tow Net	7	3	2.33	4.04					
	7/10	Tow Net	104	3	34.67	9.87					
	7/12	Tow Net	397	3	132.33	48.64					
	7/13	Tow Net	353	3	117.67	24.95					
	8/05	Tow Net	7	3	2.33	1.15					
	8/08	Tow Net	12	4	3.00	0.82					

WHITEFISH AND CISCO

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
11	6/24	Beach Seine-75	13	2	6.50	3.54					
17	6/24	Tow Net	2	3	0.67	1.15					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
					BOREAL SMELT						
1	6/12	Tow Net	1	3	0.33	0.58					
	6/15	Tow Net	1	3	0.33	0.58					
	6/19	Tow Net	335	3	111.67	52.32					
2	6/15	Tow Net	2	3	0.67	0.58					
	6/19	Tow Net	146	3	48.67	45.83					
3	6/19	Tow Net	24	3	8.00	8.54					
4	6/19	Tow Net	408	3	136.00	28.16					
5	6/12	Tow Net	2	3	0.67	1.15					
	6/15	Tow Net	4	3	1.33	0.58					
	6/19	Tow Net	633	3	211.00	43.14					
6	6/12	Tow Net	240	3	80.00	61.58					
	6/19	Tow Net	853	3	284.33	140.20					
13	6/05	Purse Seine	2	2	1.00	0.00					
	6/09	Tow Net	2	3	0.67	0.58					
	6/13	Tow Net	1	3	0.33	0.58					
41	6/04	Tow Net	129	2	64.50	34.65					
	6/06	Tow Net	286	2	143.00	4.24					
51	6/06	Tow Net	9	2	4.50	2.12					
					SMELT SP.						
1	6/06	Tow Net	15	2	7.50	0.71					
	7/11	Tow Net	1	2	912.50	95.46					
	7/14	Tow Net	151	3	50.33	26.41					
	8/06	Tow Net	235	3	78.33	46.46					
2	7/14	Tow Net	710	3	236.67	45.96					
	8/06	Tow Net	165	3	55.00	21.79					
3	7/11	Tow Net	233	3	77.67	69.76					
	7/14	Tow Net	565	3	188.33	37.53					
	8/06	Tow Net	315	3	105.00	21.79					
4	7/11	Tow Net	1	2	630.00	346.48					
	7/14	Tow Net	1	3	518.33	140.12					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
5	7/14	Tow Net	475	3	158.33	59.23					
	8/06	Tow Net	180	3	60.00	26.46					
6	6/15	Tow Net	184	3	61.33	51.78					
	7/11	Tow Net	793	2	396.50	178.90					
	7/14	Tow Net	320	3	107.00	2.88					
	8/06	Tow Net	23	3	7.67	2.31					
8	6/14	Beach Seine-150	1	2	0.50	0.71					

THREESPINE STICKLEBACK

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
12	7/13	Beach Seine-75	12	2	6.00	7.07					
	8/04	Beach Seine-75	2	2	1.00	1.41					

NINESPINE STICKLEBACK

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
1	6/06	Tow Net	106	2	53.00	38.18					
	6/12	Tow Net	1	3	346.67	92.22					
	6/15	Tow Net	457	3	152.33	32.59					
	6/19	Tow Net	1	3	356.67	141.45					
	7/11	Tow Net	23	2	11.50	0.71					
	7/14	Tow Net	274	3	91.33	23.07					
	8/06	Tow Net	165	3	55.00	22.91					
2	6/12	Tow Net	974	3	324.67	239.06					
	6/15	Tow Net	805	3	268.33	110.95					
	6/19	Tow Net	1	3	548.00	266.57					
	7/14	Tow Net	256	3	85.33	91.53					
	8/06	Tow Net	115	3	38.33	10.41					
3	6/12	Tow Net	409	3	136.33	158.34					
	6/15	Tow Net	12	3	4.00	1.00					
	6/19	Tow Net	1	3	423.33	248.71					
	7/11	Tow Net	292	3	97.33	57.13					
	7/14	Tow Net	57	3	19.00	4.58					
	8/06	Tow Net	140	3	46.67	16.07					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
4	6/12	Tow Net	746	3	248.67	69.01					
	6/15	Tow Net	115	3	38.33	11.72					
	6/19	Tow Net	237	3	79.00	61.51					
	7/11	Tow Net	2	2	1.00	0.00					
	7/14	Tow Net	3	3	1.00	1.00					
5	6/12	Tow Net	1	3	470.67	412.85					
	6/15	Tow Net	489	3	163.00	41.90					
	6/19	Tow Net	1	3	343.33	335.31					
	7/14	Tow Net	207	3	69.00	104.85					
	8/06	Tow Net	90	3	30.00	30.41					
6	6/12	Tow Net	21	3	7.00	3.46					
	6/15	Tow Net	85	3	28.33	18.90					
	6/19	Tow Net	373	3	124.33	5.51					
	7/11	Tow Net	163	2	81.50	45.96					
	8/06	Tow Net	20	3	6.67	0.58					
8	6/10	Beach Seine-150	18	2	9.00	5.66					
	6/14	Beach Seine-150	7	2	3.50	3.54					
	6/17	Beach Seine-150	3	2	1.50	0.71					
	6/22	Beach Seine-150	4	2	2.00	2.83					
	6/24	Beach Seine-150	2	2	1.00	0.00					
	8/04	Beach Seine-150	1	2	0.50	0.71					
9	6/25	Beach Seine-150	1	2	0.50	0.71					
	8/04	Beach Seine-150	8	2	4.00	5.66					
10	8/05	Beach Seine-75	840	2	420.00	113.14					
10	8/05	Beach Seine-75	840	2	420.00	113.14					
11	6/10		9	2	4.50	2.12					
	6/14		15	2	7.50	0.71					
	6/17		6	2	3.00	1.41					
	6/24		3	2	1.50	2.12					
	8/04		1	2	0.50	0.71					
12	6/25		1	2	0.50	0.71					
	7/13		4	2	2.00	2.83					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
	8/04		736	2	368.00	45.25					
21	6/06	Tow Net	8	3	2.67	0.58					
41	6/04		42	2	21.00	9.90					
	6/06		452	2	226.00	96.17					
51	6/06		13	2	6.50	0.71					
					ARCTIC LAMPREY						
1	6/12		12	3	4.00	3.61					
	6/15		17	3	5.67	3.06					
	6/19		49	3	16.33	10.02					
	7/14		3	3	1.00	1.00					
2	6/12		11	3	3.67	3.21					
	6/15		41	3	13.67	2.89					
	6/19		53	3	17.67	1.53					
	7/14		2	3	0.67	1.15					
3	6/19		9	3	3.00	0.00					
	7/11		14	3	4.67	2.08					
4	6/12		14	3	4.67	4.04					
	6/15		16	3	5.33	3.06					
	6/19		25	3	8.33	1.53					
	7/11		1	2	0.50	0.71					
5	6/12		14	3	4.67	1.53					
	6/15		32	3	10.67	4.04					
	6/19		38	3	12.67	2.31					
	7/14		1	3	0.33	0.58					
6	6/12		3	3	1.00	1.00					
	6/19		11	3	3.67	1.15					
13	6/09		9	3	3.00	3.00					
	6/13		13	3	4.33	5.86					
	6/14		35	6	11.67	6.86					
	6/17		234	3	78.00	14.00					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
	6/18		121	3	40.33	18.34					
	6/20		41	5	16.40	3.58					
	6/22		42	3	14.00	5.20					
	6/24		48	3	16.00	4.36					
	6/26		29	3	9.67	11.24					
17	6/08		3	3	1.00	0.00					
	6/13		1	3	0.33	0.58					
	6/14		5	3	1.67	1.53					
	6/17		9	3	3.00	2.65					
	6/18		16	3	5.33	5.03					
	6/20		14	3	4.67	3.06					
	6/22		5	3	1.67	1.53					
	6/24		1	3	0.33	0.58					
	6/26		4	3	1.33	1.53					
41	6/06		1	2	0.50	0.71					

LAMPREY Sp.

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
4	7/14		1	3	0.33	0.58					
13	6/04		2	3	0.67	0.58					
	6/05		2	3	0.67	1.15					
14	6/01		22	7	3.14	2.67					
17	6/05		1	15	0.07	0.26					

LONGNOSE SUCKER

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
8	6/17	Beach Seine-150	11	2	5.50	4.95					
	6/22		6	2	3.00	2.83					
13	6/05	Purse Seine	1	2	0.50	0.71					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
NORTHERN PIKE											
11	6/17	Beach Seine-75	1	2	0.50	0.71					
BURBOT											
1	7/14	Tow Net	1	3	0.33	0.58					
2	6/12		1	3	0.33	0.58					
8	6/10	Beach Seine-150	2	2	1.00	1.41					
	6/14		1	2	0.50	0.71					
	6/17		4	2	2.00	1.41					
	7/12		3	2	1.50	0.71					
	8/04		1	2	0.50	0.71					
9	6/25		4	2	2.00	0.00					
11	6/10	Beach Seine-75	5	2	2.50	0.71					
	6/14		16	2	8.00	1.41					
	6/17		1	2	0.50	0.71					
	6/22		2	2	1.00	1.41					
	6/24		2	2	1.00	1.41					
	7/12		3	2	1.50	0.71					
	8/04		7	2	3.50	0.71					
12	6/25		3	2	1.50	0.71					
	7/13		5	2	2.50	2.12					
	8/04		4	2	2.00	1.41					
13	6/04	Tow Net	1	3	0.33	0.58					
	6/04	Purse Seine	6	2	3.00	1.41	6	137.67	70	245	71.59
	6/05	Tow Net	1	3	0.33	0.58					
	6/05	Purse Seine	1	2	0.50	0.71					
	7/12	Tow Net	5	3	1.67	2.08					
14	6/01		8	7	1.14	1.46					
17	6/05		9	15	1.20	1.82					
	7/10		4	3	1.33	1.15					
	7/13		5	3	1.67	1.53					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
	8/05		1	3	0.33	0.58					
	8/07		1	3	0.33	0.58					
21	6/06		2	3	0.67	0.58					
41	6/04		54	2	27.00	11.31					
	6/06		116	2	58.00	7.07					
					STARRY FLOUNDER						
1	6/19		1	3	0.33	0.58					
2	7/14		1	3	0.33	0.58					
	8/06		1	3	0.33	0.58					
4	6/15		1	3	0.33	0.58					
6	7/14		1	3	0.33	0.58					
9	6/25	Beach Seine-150	1	2	0.50	0.71					
	8/04		42	2	21.00	1.41					
41	6/06	Tow Net	5	2	2.50	0.71					
					ARCTIC FLOUNDER						
1	7/11		1	2	0.50	0.71					
	8/06		1	3	0.33	0.58					
2	8/06		1	3	0.33	0.58					
3	6/19		4	3	1.33	1.53					
4	6/15		4	3	1.33	0.58					
	6/19		15	3	5.00	0.00					
	7/11		7	2	3.50	0.71					
5	7/14		2	3	0.67	0.58					
6	6/19		1	3	0.33	0.58					
	7/11		18	2	9.00	9.90					
9	6/25	Beach Seine-150	7	2	3.50	0.71					
	8/04		18	2	9.00	0.00					
10	8/05	Beach Seine-75	176	2	88.00	66.47					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
					SAFFRON COD						
1	6/19	Tow Net	50	3	16.67	3.51					
	7/14		3	3	1.00	1.73					
	8/06		25	3	8.33	7.02					
2	6/19		57	3	19.00	3.00					
	7/14		1	3	0.33	0.58					
	8/06		6	3	2.00	2.65					
3	6/12		2	3	0.67	1.15					
	6/19		18	3	6.00	1.73					
	7/11		11	3	3.67	4.04					
4	6/19		4	3	1.33	0.58					
	7/14		2	3	0.67	0.58					
5	6/12		1	3	0.33	0.58					
	6/19		4	3	1.33	1.15					
	8/06		1	3	0.33	0.58					
6	6/12		3	3	1.00	1.00					
	6/19		6	3	2.00	1.73					
	7/11		2	2	1.00	0.00					
9	6/25	Beach Seine-150	1	2	0.50	0.71					
					ARCTIC COD						
1	6/15	Tow Net	1	3	0.33	0.58					
2	6/15		1	3	0.33	0.58					
4	6/15		1	3	0.33	0.58					
5	6/15		7	3	2.33	2.08					
41	6/06		19	2	9.50	13.44					
51	6/06		1	2	0.50	0.71					

APPENDIX B (Continued)

Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
					FOURHORN SCULPIN						
1	8/06		1	3	0.33	0.58					
2	7/14		1	3	0.33	0.58					
3	7/11		2	3	0.67	1.15					
4	6/19		4	3	1.33	0.58					
5	6/19		1	3	0.33	0.58					
	7/14		1	3	0.33	0.58					
6	7/14		1	3	0.33	0.58					
10	8/05	Beach Seine-75	7	2	3.50	0.71					
					SCULPIN Sp.						
2	7/14	Tow Net	1	3	0.33	0.58					
4	6/12		1	3	0.33	0.58					
					PACIFIC HERRING						
1	6/19		11	3	3.67	3.51					
	7/11		46	2	23.00	5.66					
	7/14		140	3	46.67	20.11					
	8/06		1	3	0.33	0.58					
2	6/15		7	3	2.33	1.53					
	6/19		56	3	18.67	2.08					
	7/14		91	3	30.33	19.86					
	8/06		11	3	3.67	2.52					
3	6/12		1	3	0.33	0.58					
	6/19		9	3	3.00	2.65					
	7/11		70	3	23.33	26.41					
	7/14		14	3	4.67	4.16					
	8/06		25	3	8.33	7.57					
4	6/12		1	3	0.33	0.58					

APPENDIX B (Continued)

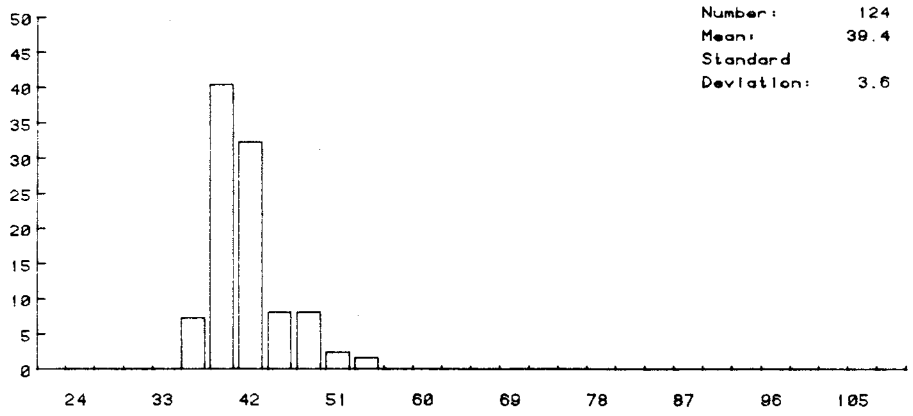
Station	Date	Gear	Catch	Reps	CPUE	SD Catch	N	Mean Length	Minimum Length	Maximum Length	SD Length
	7/11		7	2	3.50	0.71					
	7/14		2	3	0.67	0.58					
5	6/12		6	3	2.00	1.73					
	6/15		24	3	8.00	3.61					
	6/19		2	3	0.67	0.58					
	8/06		1	3	0.33	0.58					
6	6/12		22	3	7.33	6.66					
	6/15		53	3	17.67	18.90					
21	6/06		16	3	5.33	4.04					
51	6/06		1	2	0.50	0.71					
POACHER Sp.											
3	8/06		1	1	1.00						
PRICKLEBACK Sp.											
2	6/15		1	3	0.33	0.58					
3	6/19		1	3	0.33	0.58					
	7/11		1	3	0.33	0.58					
5	8/06		1	3	0.33	0.58					
6	8/06		1	3	0.33	0.58					
GREENLING											
1	8/06		1	3	0.33	0.58					
2	8/06		1	3	0.33	0.58					
3	8/06		1	3	0.33	0.58					
SANDLANCE											
2	6/19		1	3	0.33	0.58					
3	8/06		2	3	0.67	0.58					

APPENDIX C

LENGTH FREQUENCY OF JUVENILE CHUM SALMON BY STATION AND TIME PERIOD DURING SUMMER 1986

STATION 1
CHUM SALMON

6/12/86 TO 6/15/86



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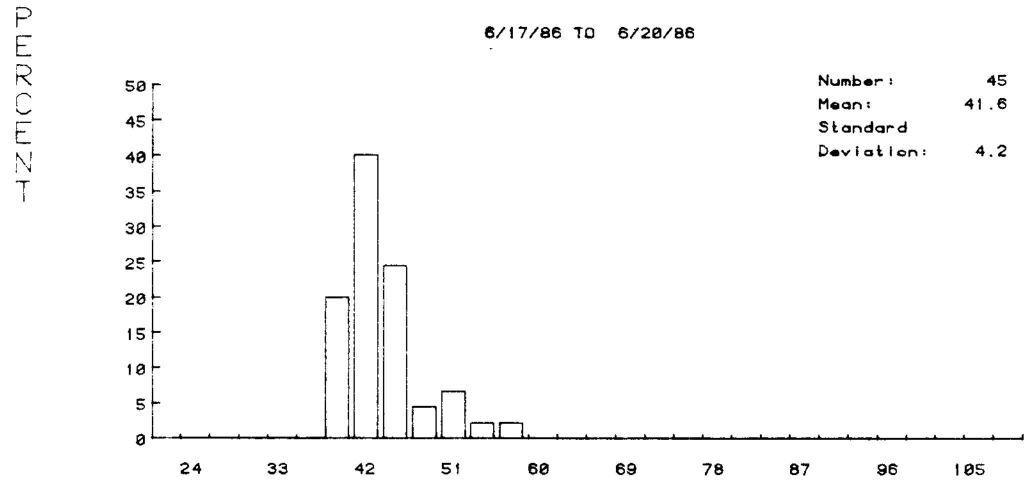
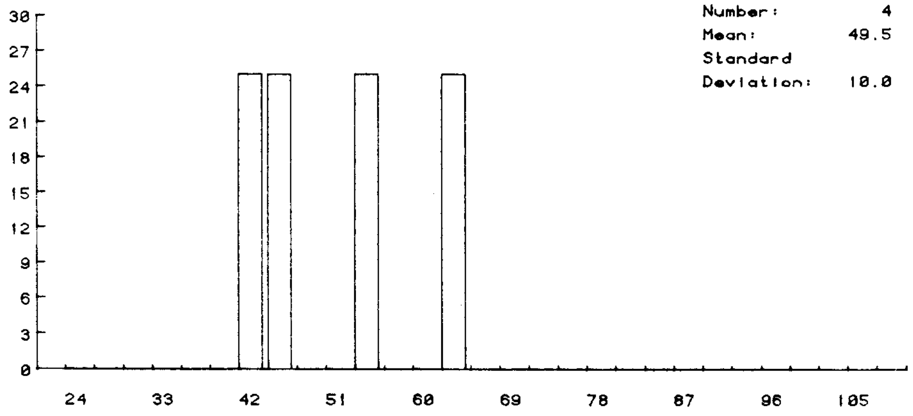
Mean: 39.4
Standard Deviation: 3.6

6/17/86 TO 6/20/86



Number: 45
Mean: 41.6
Standard Deviation: 4.2

7/10/86 TO 7/14/86

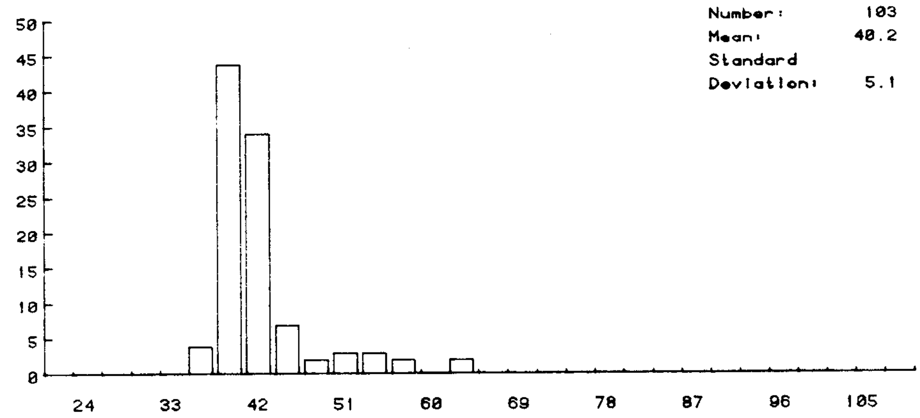


Number: 4
Mean: 49.5
Standard Deviation: 10.0

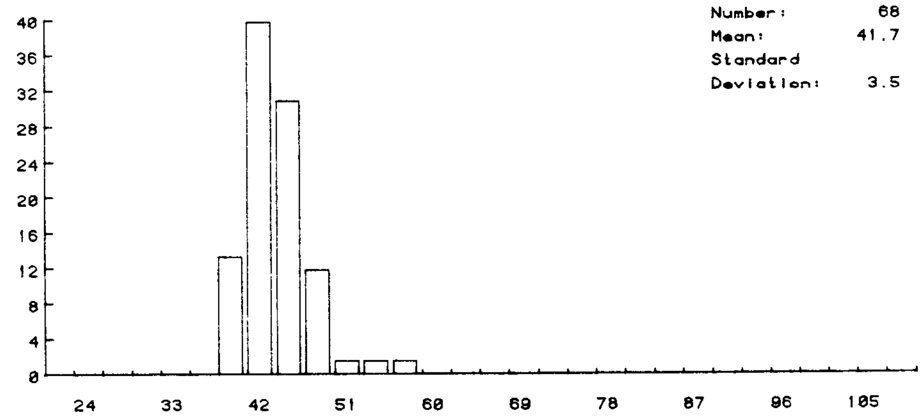
FORK LENGTH IN 3 MM GROUPS

STATION 2
CHUM SALMON

6/12/86 TO 6/15/86

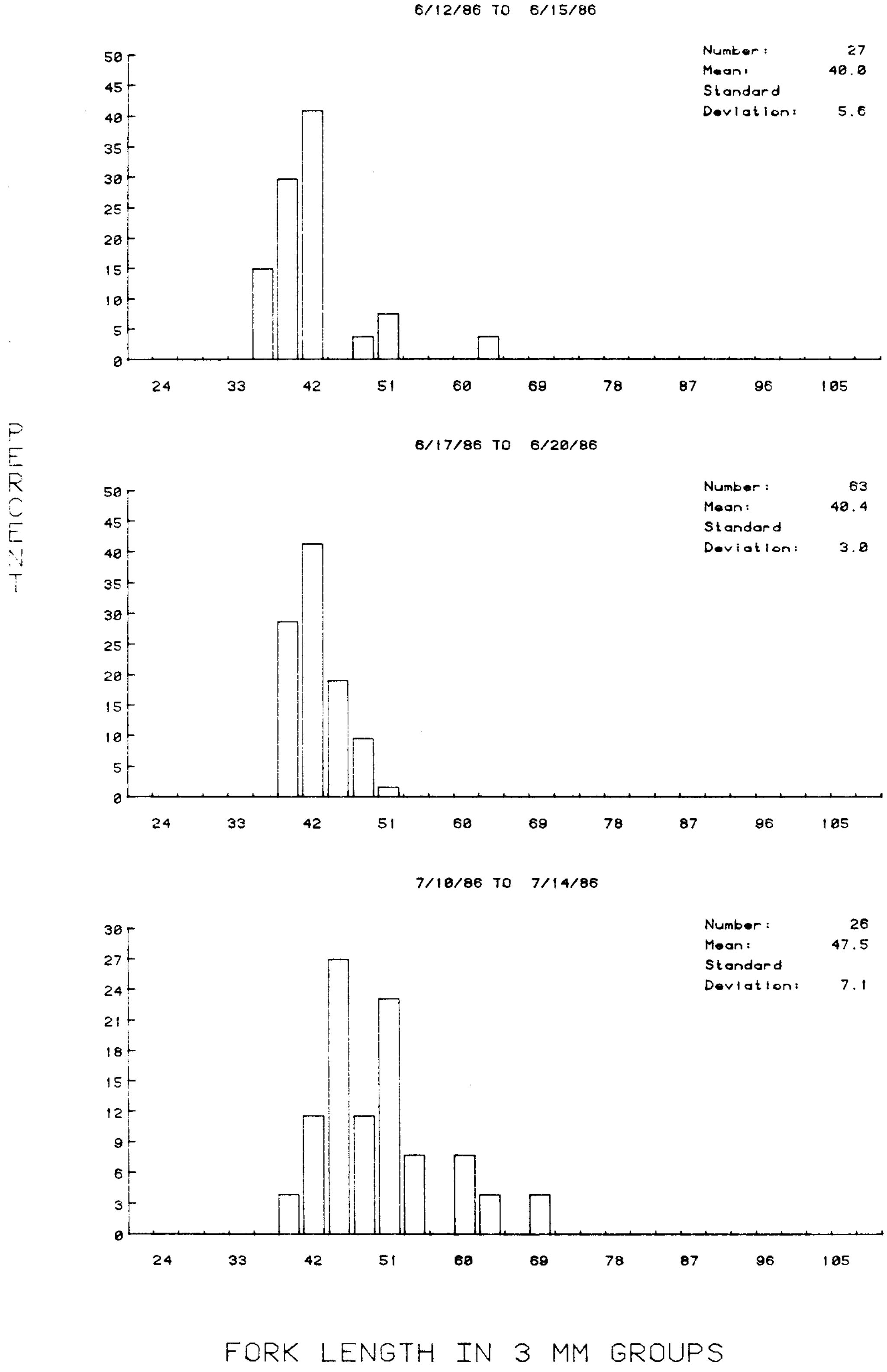


6/17/86 TO 6/20/86



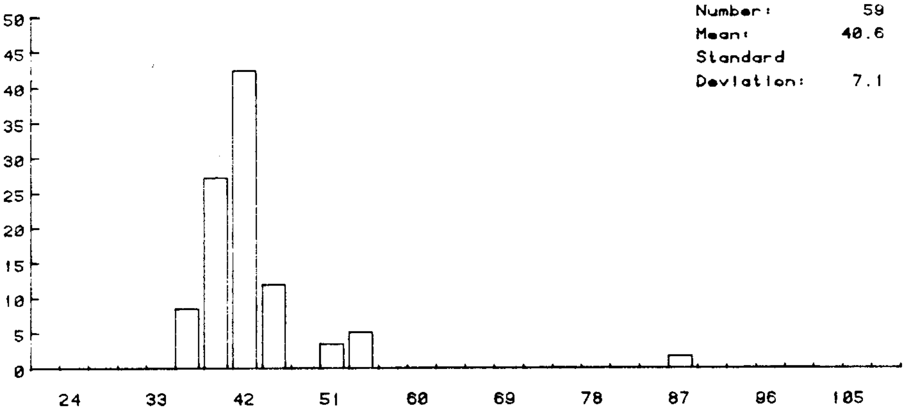
FORK LENGTH IN 3 MM GROUPS

STATION 3
CHUM SALMON



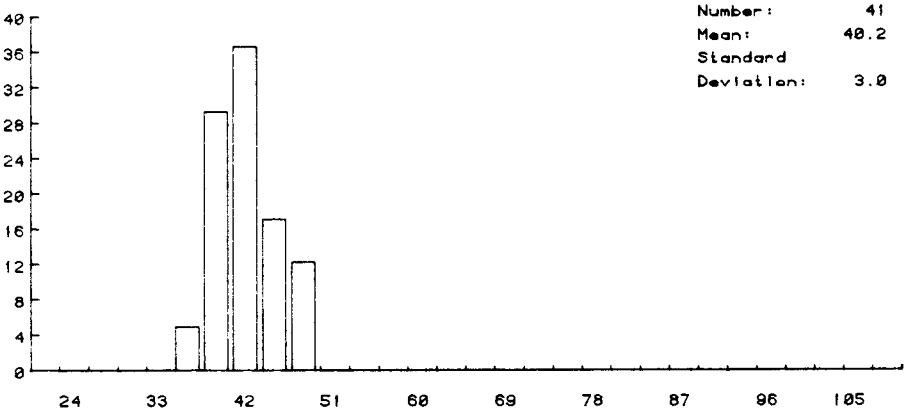
STATION 4
CHUM SALMON

6/12/86 TO 6/15/86

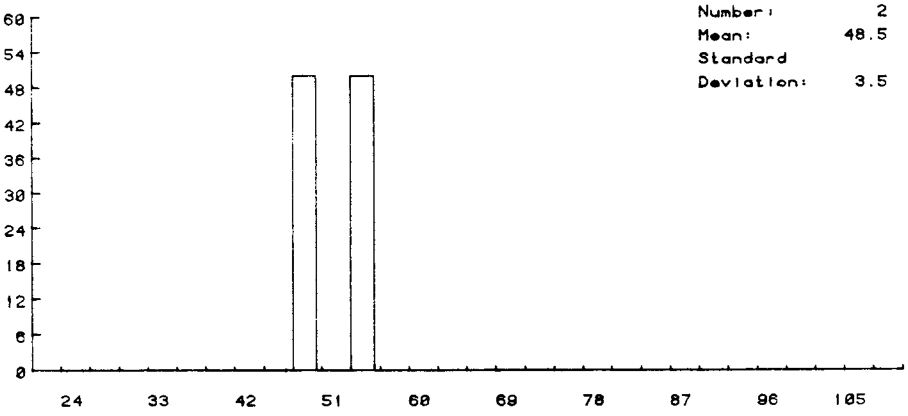


PERCENT

6/17/86 TO 6/20/86

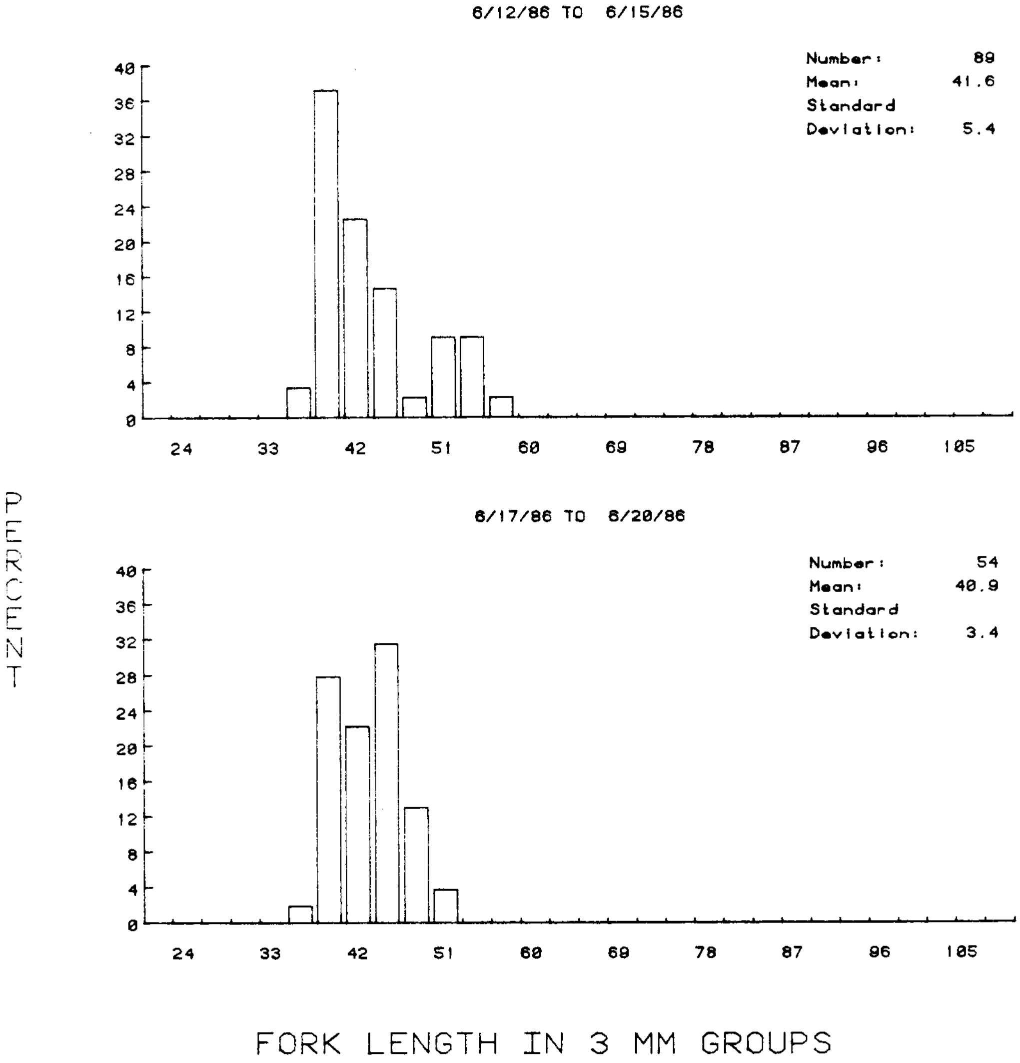


7/10/86 TO 7/14/86



FORK LENGTH IN 3 MM GROUPS

STATION 5
CHUM SALMON



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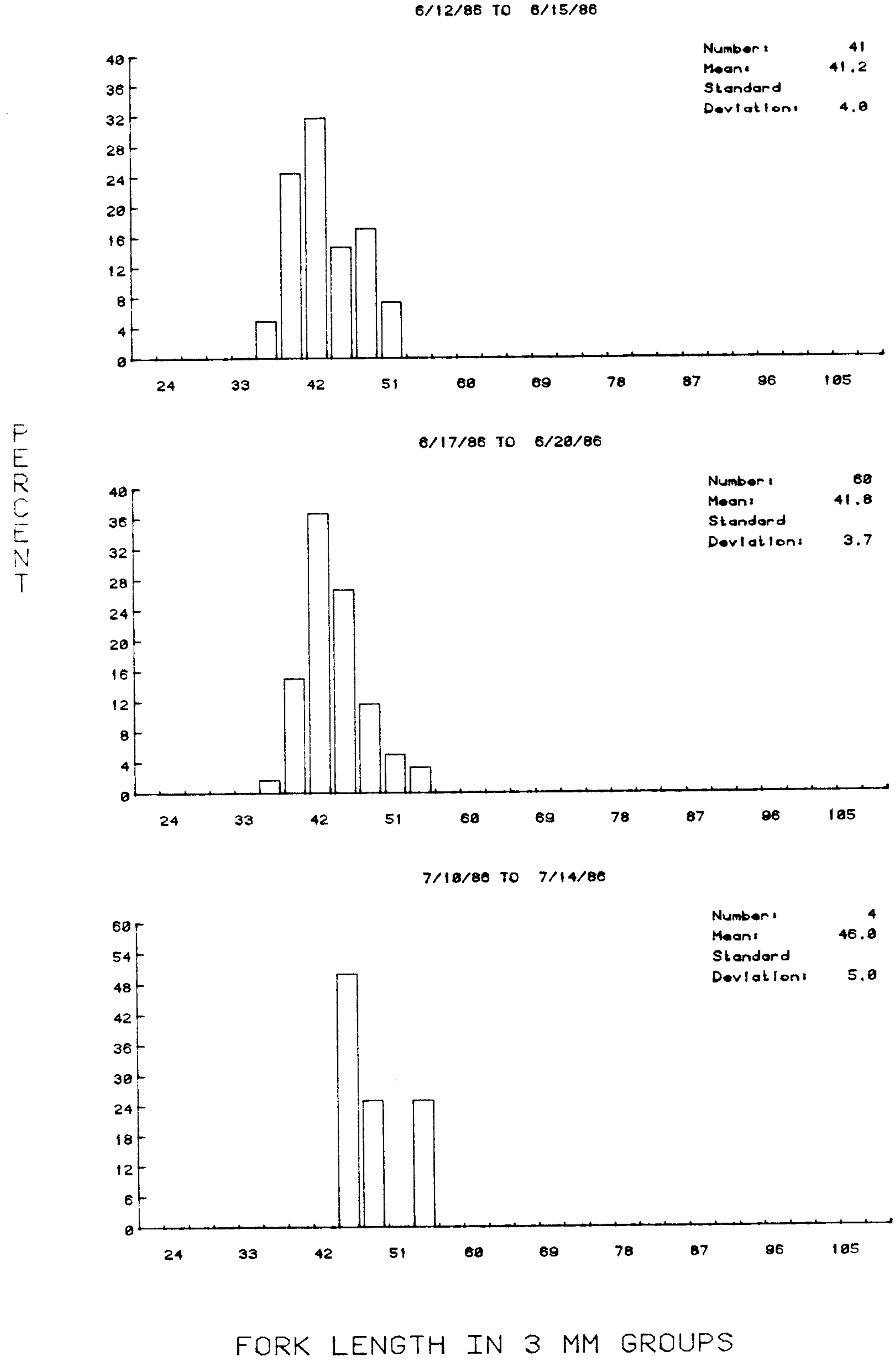

EARLY LIFE HISTORY OF PACIFIC HERRING IN AUKE BAY, ALASKA: RELATIONSHIPS OF GROWTH AND SURVIVAL TO ENVIRONMENTAL CONDITIONS

by

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Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 695

May 1989

ACKNOWLEDGMENTS

This study was wholly funded by the Minerals Management Service of the Department of the Interior, through an interagency agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program.

I thank the COTR of this project, L. Jarvela, (NOAA) and the Project Director, G. Stewart, (Envirocon Pacific Limited), for their advice and support. D. Ingledue of the Alaska Department of Fish and Game office in Douglas, Alaska, provided information on herring spawn timing and locations in the Auke Bay - Lynn Canal area. Dr. M. Stekoll of the University of Alaska Southeast, and J. McConnaghey surveyed the subtidal zone off the spawning beaches with SCUBA. I thank the members of the APPRISE team: A. J. Paul and K. O. Coyle of the Institute of Marine Science, University of Alaska, Fairbanks, and D. A. Ziemann and L. D. Conquest of the Oceanic Institute of Hawaii, for permission to use their data on the physical and biological environment of Auke Bay. I also thank B. Wing, J. Landingham, A. Celewycz and A. Wertheimer of the Auke Bay Laboratory (NMFS, NOAA) for their advice and assistance. Dr. C. Low enumerated and identified the zooplankton samples, and R. Sandbrook identified the gut contents of herring larvae and juveniles. G. Stockdale provided indispensable boathandling skills throughout the field season and K. Bartness sorted most of the plankton samples. P. Hagen loaded the software for the Optical Pattern Recognition System and E. Wilson mounted the herring otoliths. T. Quinn of the University of Alaska Southeast provided a copy of the program NORMPC. K. George and G. Ricard typed the manuscript.

ABSTRACT

The primary objective of this study was to measure growth, fitness and survival of Pacific herring, *Clupea harengus pallasi*, larvae, and the concentrations of their prey and predators in Auke Bay, Alaska. The secondary objective was to assess the importance of food and predator concentrations to growth, fitness and survival of larvae so as to identify the factors which may contribute to year-class success or failure.

Five cohorts of herring were spawned in Auke Bay at an average rate of one every 19 d from April 18 to June 30. The eggs of the second and third cohort were found in the upper intertidal zone at the head of the Bay. Both spawnings were less than 250 m in length and had an average width of 5 m. They produced approximately 9.8×10^8 and 4.8×10^8 viable larvae, respectively.

Herring larvae feed primarily on the synchronously developing juvenile and adult stages of the dominant pelagic copepods, and secondarily on other small pelagic invertebrates including mollusc veligers, polychaete larvae and small fish eggs. Concentrations of prey of larval herring were calculated for 12 length classes of herring from zooplankton samples collected with a 165 μm mesh net and from densities of copepod nauplii taken with a 24 μm mesh net by members of the APPRISE project. Prey concentrations ranged from 20 to 171 mg dry weight$\cdot$m^{-3} over the May to July sampling season.

Three classes of invertebrate predators of herring larvae were identified: 10 species of jellyfish, hyperiid amphipods of the genus *Parathemisto*, and the chaetognath *Sagitta elegans*. Mean predator concentrations at date ranged from 0.9 to 34,027.7 mg$\cdot$m^{-3}, with a geometric mean of 150.2 mg$\cdot$m^{-3}. Jellyfish made up over 95% of the average concentration of predators at date.

Population growth rates in length of larval and juvenile herring were calculated from length-frequency analysis; they were essentially linear over

the larval stage and the early juvenile stage: 0.311, 0.299, 0.312, and 0.386 $mm \cdot d^{-1}$ for cohorts 1, 2, 3 and 4, respectively. None of the rates were significantly different from each other, and all fell within the range reported for other populations of Pacific and Atlantic herring larvae.

Specific growth rates, G_W, of herring larvae ranging from 3.4 to 19.6 $\% \cdot d^{-1}$ were estimated from the width of the outermost ring of the sagittal otoliths. Nine percent of the variation in G_W was explained by a dome-shaped relationship between G_W and age of the larvae, and 4% of the variation was explained by a direct relationship between G_W and ln-transformed mean prey concentration. There was no relationship between G_W and water temperature. Fitness of herring larvae was measured with a morphometric condition factor, CF2. A direct relationship between CF2 and age explained 24% of the variation in CF2 and a dome-shaped relationship between CF2 and ln-transformed prey concentration explained an additional 5% of the variation in CF2. The relatively weak correlation between G_W and CF2 and environmental factors was due to a lack of contrast in the environmental data; average temperatures of the upper 20 m of the water column fell within a narrow range of 7.2 to 8.2°C, and the range of prey concentration is one in which the growth response of herring larvae approaches saturation.

G_W was 2.3 $\% \cdot d^{-1}$ higher, on average, than that predicted from an equation developed by Kiorboe and Munk (1986) from the growth of laboratory-reared Atlantic herring, Clupea harengus harengus, larvae. This suggests that Auke Bay herring larvae fed on high-density patches of prey that were not detected by plankton-net tows that integrated the upper 30 m of the water column. It also indicates that Kiorboe and Munk's (1986) equation may be applicable to natural ecosystems for the purpose of predicting minimum specific growth rates of herring larvae from prey concentrations.

The G_W and fitness data indicated that growth of herring larvae in Auke Bay was only weakly related to food concentrations, which suggests that if growth and survival are directly related to each other, then survival must also have been weakly correlated with prey concentration, and, perhaps, more highly correlated with non-trophic agents of mortality such as predator concentration. This hypothesis was tested by comparing the rates of total mortality of cohorts 1, 2 and 3 with environmental factors.

Before estimating total mortality it was necessary to determine the rates of emigration of larvae out of the sampling area in Auke Bay. No significant advection or diffusion of herring larvae out of Auke Bay was measured and population models incorporating advection and diffusion explained less variation in density of herring larvae than simpler models that assumed a single loss rate. These results suggest that the larvae may have been retained within the Bay, but sampling outside of the Bay would have been required to confirm this hypothesis.

Total mortality, Z_t, of larvae was best described as decreasing with age, t (d), according to a Pareto-type function, $Zt=\beta t^{-1}$, where β is a coefficient having values of 3.068, 0.785 and 2.660 for cohorts 1, 2 and 3, respectively. These rates were supplemented by calculating mortality rates for the period between hatching and the earliest date at which larvae were captured. Cohort 2 had an egg-larval mortality of 0.93 d^{-1} for ages 0 to 1 d, whereas cohort 3 had a rate of 0.12 d^{-1} for ages 0 to 20 d. Total mortality was most highly correlated with age of larvae, followed by body weight and spatial patchiness of the larvae. It was not significantly correlated with physical condition of the larvae or with the concentration of predators.

This study shows that growth and fitness of Auke Bay herring larvae in 1988 was not strongly dependent on prey concentration, a conclusion which does not support the critical period hypothesis of year-class formation. This study provides much less conclusive results concerning the causes of mortality. A direct link between survival and prey concentration is suggested by the coincidence of high mortality and lower specific growth rates and morphological fitness in cohort 2, and by the absence of a correlation between mortality rate and predator concentration. However, mortality rates of cohorts 1, 2 and 3 are also correlated with factors related to the ability of larvae to evade predation: age, body size and spatial patchiness.

In order to better answer these questions, I recommend that future studies of the early life history of Pacific herring in Alaska focus on making more accurate measurements of growth, fitness and mortality, and on measuring the parameters of larger populations of herring larvae in order to test for the effects of density-dependence. This requires population modelling combined with hydrodynamic modelling in order to measure accurate rates of dispersal and mortality of the larvae, and the use of biochemical means for measuring recent growth rates of herring larvae.

TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

Page

LIST OF APPENDICES

The following appendices are available upon request from NOAA/OMA/OAD Alaska Office, Federal Bldg., U.S. Court House Room A13, 222 W. 8th Ave., #56, Anchorage, AK 99513-7543.

A	Summary of plankton net tows made in Auke Bay.
B	Summary of catches of juvenile herring in Auke Bay.
C	Lengths of Pacific herring larvae and juveniles.
D	Numbers and densities of herring larvae captured in Auke Bay.
E	Morphometry, dry weight and condition factors of herring larvae and juveniles.
F	Number and width of herring otolith rings, radii of otoliths and recent growth rates calculated from ring width.
G	Gut contents of herring larvae and juveniles collected in Auke Bay, 1988.
H	Mean densities of copepod nauplii at 3 stations in Auke Bay, 1988, collected by APPRISE project personnel.
I	Densities of zooplankton collected in Auke Bay by Envirocon Pacific Ltd. with 165 μm mesh nets.
J	Prey field of Auke Bay herring.
K	Concentrations of prey for herring larvae in Auke Bay in 1988.
L	Diameter and dry weight of gelatinous predators.
M	Concentrations of invertebrate predators of herring larvae in Auke Bay in 1988.
N	APPRISE temperature/salinity/density data from Auke Bay Monitor (ABM) station.
O	Water temperatures of Auke Bay measured by Envirocon Pacific Ltd.
P	Surface water temperatures and salinities of Auke Bay measured by Auke Bay Laboratory personnel.

LIST OF FIGURES

LIST OF FIGURES (Continued)

LIST OF TABLES

1. INTRODUCTION

This is the final report of a study of the early life history of Pacific herring, Clupea harengus pallasi, in Auke Bay, Alaska. Stocks of Pacific herring in Alaska have fluctuated considerably in size due to exploitation and to variation in recruitment (Rounsefell 1930, Reid 1971, Fried and Wespestad 1985). The proximate causes of the variation in recruitment are changes in the rate of egg production and in the survival rates of the egg, larval and juvenile stages; the ultimate causes are presumed to be the environmental factors that are responsible for these changes in population parameters. This study was designed to identify the environmental factors that are responsible for variation in survival of herring larvae in Auke Bay, Alaska. The primary objective was to measure the relationships between growth and survival of herring larvae and the concentrations of their prey and their predators and water temperature.

The question of how closely related are recruitment of Alaska herring and environmental factors is important because the development of the oil and gas reserves of Alaska's continental shelf has the potential to reduce the quality of inshore habitat and thereby reduce herring recruitment, or at least increase its variability. Pacific herring are expected to be vulnerable to changes in inshore habitat because they spawn in the intertidal zone and their larvae and juveniles feed and grow in estuaries and embayments.

The study was carried out in Auke Bay, Alaska, a semi-enclosed bay in southeast Alaska. Auke Bay was chosen because it is a spawning site for herring, and because it is the site for APPRISE (Association of Primary Production and Recruitment in a Subarctic Ecosystem), a multidisciplinary and multi-year study of the relationship between the phytoplankton spring bloom and the subsequent recruitment of commercially important species of fish and invertebrates in Auke Bay. APPRISE includes detailed measurements of the physical environment, and the phytoplankton, zooplankton and larval fish communities of the pelagic zone. Some of these data were used in this study.

2. STUDY SITE

Auke Bay (58°22'N; 134°40'W) is a small bay of 11.5 km^2 area located approximately 20 km north of Juneau (Figs. 1 and 2). The sides of the Bay are generally steep, falling to an average depth of 40 m over most of the Bay. Three major streams flow into the Bay: Auke Creek, Auke Nu Creek and Waydelich Creek and several minor streams including Bay Creek. Surface tides in Auke Bay are semidiurnal with diurnal inequality.

Shirley and Coyle (1986) summarized the research that has been conducted on the hydrography, current patterns and plant and animal communities of Auke Bay. Recent information on these components of the Auke Bay ecosystem has been collected as part of the on-going APPRISE research program (APPRISE Staff 1986, 1987, 1988, 1989). Carlson (1977, 1980) reports that Auke Bay is part of the home range of the Lynn Canal - Auke Bay herring stock, one of 5 separate herring stocks in southeast Alaska. Iverson (1972), Kirk (1973), Tetra Tec (1983) and Nebert (1989) have described current flow in Auke Bay as varying with season and tide pattern. During the summer the upper water layer of the stratified water column moves in a counter-clockwise gyre with current speeds up to 10 $cm \cdot s^{-1}$. Surface currents flow into the Bay along the north shore and along the southwest shore between Spuhn Island and the Mendenhall Peninsula and water flows out of the Bay between Coghlan and Spuhn Islands. With the decay of stratification of the water column in October, the counter-clockwise gyre is replaced by a complicated, tidally-forced, two- or three-cell circulation pattern.

Annual salinity and temperature cycles in Auke Bay from 1960 top 1968 were summarized by Bruce et al. (1977). The Auke Bay water column is unstratified from November to March with surface temperatures and salinities ranging from 3 to 5°C and 30 to 31 ppt, respectively. Stratification begins in April with rising air temperatures and fresh water input from snow melt and is complete by July at which time surface temperatures and salinities are approximately 14°C and 10 to 15 ppt, respectively. The pycnocline is at 20 m, below which temperatures and salinities are 5 to 8°C and 28 to 30 ppt, respectively. Storms and decreasing air temperatures destratify the water column in September and October.

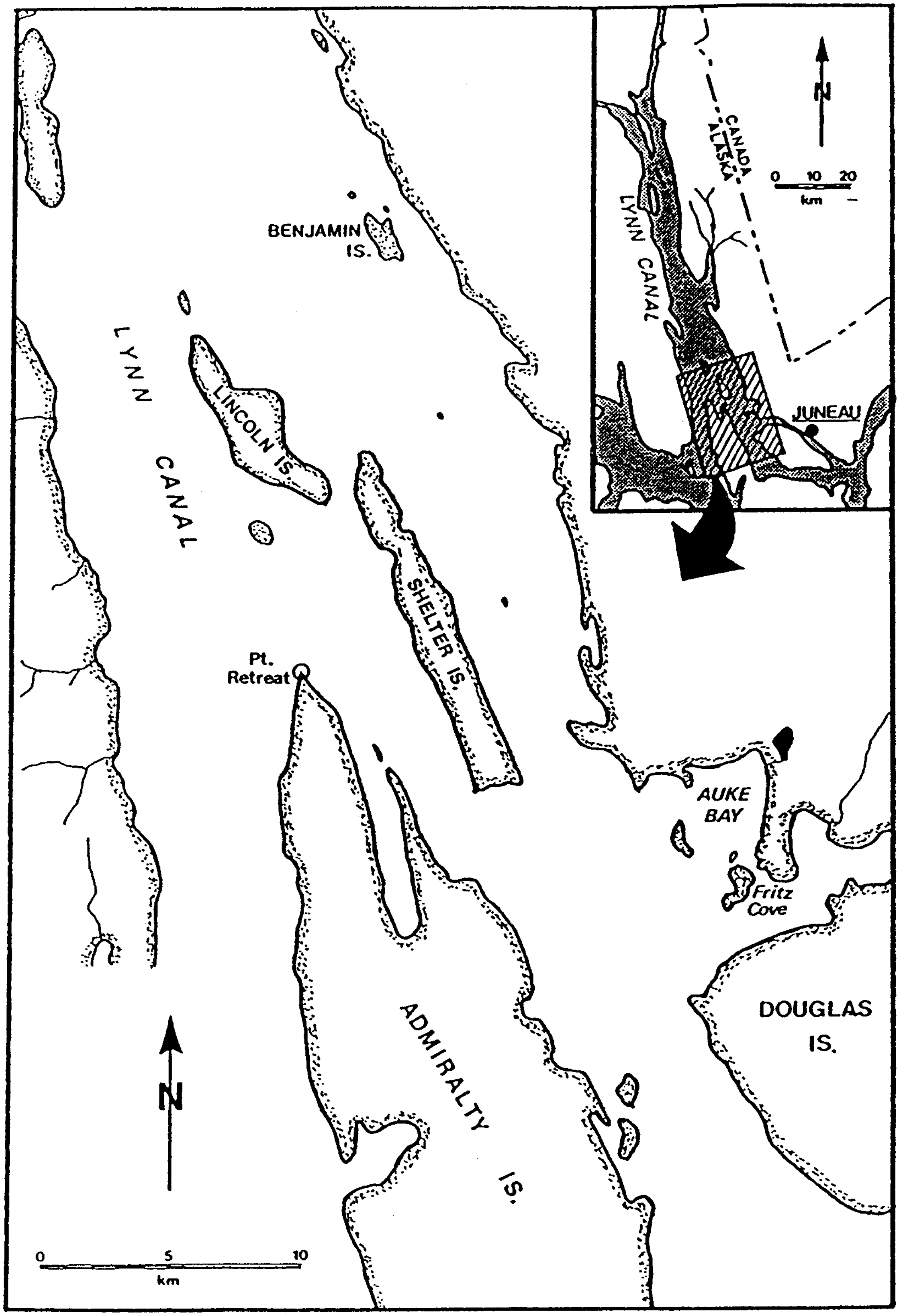


Figure 1 : MAP OF THE AUKE BAY–LYNN CANAL AREA

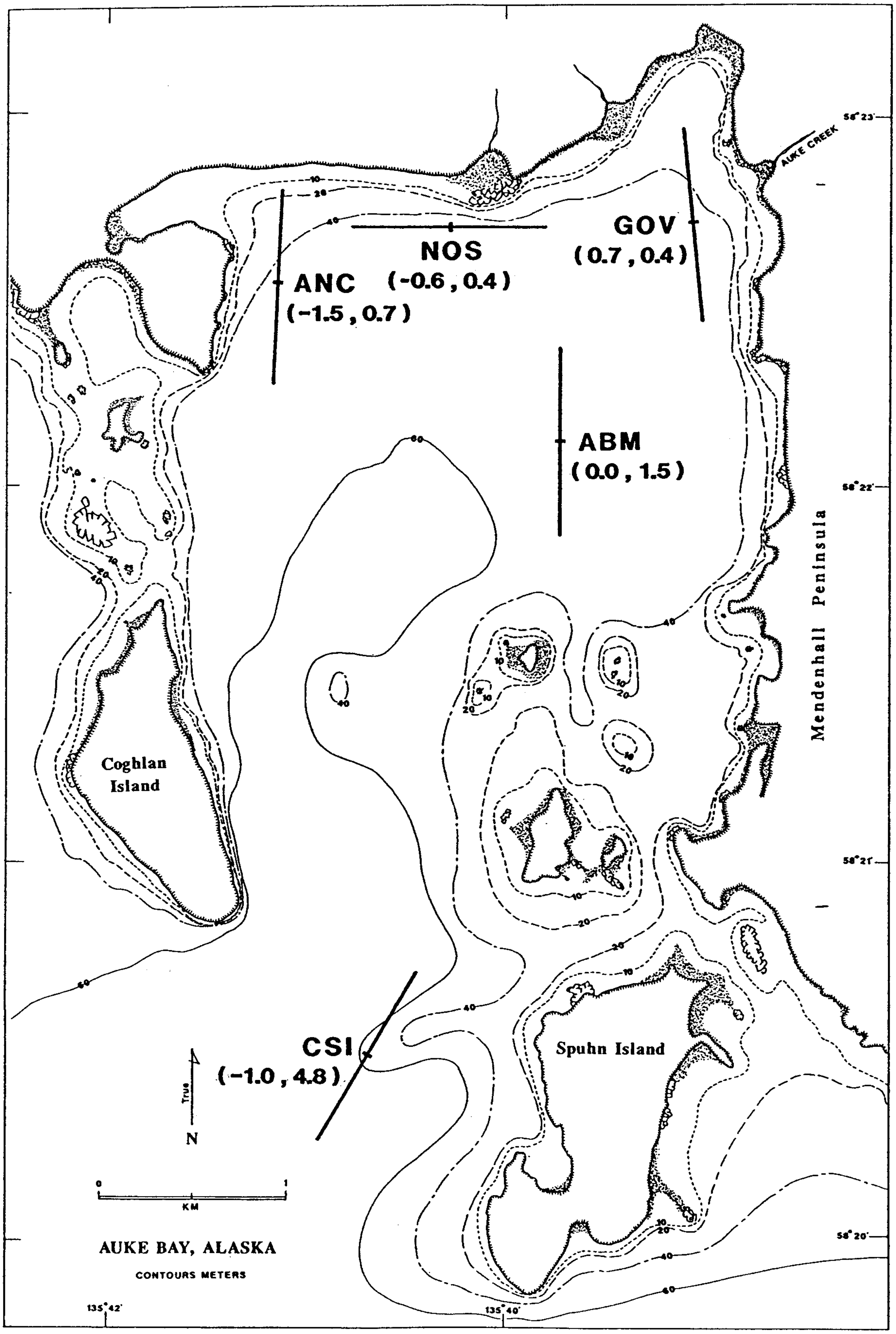


Figure 2 : MAP OF AUKE BAY SHOWING THE PLANKTON SAMPLING STATIONS AND THEIR X-Y COORDINATES

3. MATERIALS AND METHODS

3.1 **Temperature and Salinity**

Temperature and salinity profiles were measured by both the APPRISE team and Envirocon Pacific Ltd. (EPL), but the former data set was by far the most complete and was the primary data set used in this study. It was based on a CTD-meter with built-in memory that was lowered to a depth of 40 m, equilibrated for 1 min, and then retrieved at a speed of approximately 5 $m \cdot min^{-1}$. Surface temperatures and salinities were also measured by personnel of the Auke Bay Laboratory (NOAA).

3.2 **Plankton Sampling**

3.2.1 Field Techniques

Five stations were sampled in Auke Bay: off the breakwater of the Government dock (GOV), North Station (NOS), Auke Nu Cove (ANC), Auke Bay Monitor (ABM), and mid-way between Coghlan and Spuhn Islands (CSI) (Fig. 2). Plankton samples were taken from May to July, 1988, with 3 m long bongo nets each having a mouth diameter of 0.6 m and a hard plastic cod end. A General Oceanics mechanical flowmeter was placed off center in one of the 2 nets in order to measure the volume of water filtered in a tow. Nets with mesh sizes of 333 and 505 µm were used for capturing herring larvae, and nets with a mesh size of 165 µm were used for capturing their macrozooplankton prey.

The nets were towed at approximately 2 $m \cdot s^{-1}$ in a double oblique pattern from the surface to a maximum depth of 30 m and back to the surface. Contents of the codends were immediately preserved in either 5% formaldehyde and seawater for condition factor analysis or 37% isopropyl alcohol for otolith analysis. The latter samples were drained on a 165 µm mesh screen and rinsed in freshwater before alcohol was added. Almost all of the plankton samples were taken during daylight between 900 and 2000 hours, but at least one tow was taken at night between 2330 and 0130 hours every second sampling date, in order to correct the densities of herring larvae for evasion of the nets in daylight.

Densities of the main microzooplankton component of the diet of herring larvae, copepod nauplii, were taken from measurements made by members of the APPRISE project. This data was obtained from water bottle samples collected at 5 m depths from the surface to 30 m at 3 stations in Auke Bay once every 7 d from April 5 to June 21, 1988. The water from each bottle cast was filtered through a 24 µm mesh, and the material retained on the mesh was preserved in 5% formaldehyde and seawater. The copepod nauplii in each sample were counted under a dissecting microscope, into 3 length classes: <150 µm, 150-350 µm, and >350 µm.

3.2.2 Laboratory Analysis

3.2.2.1 Herring Larvae

All fish larvae in the 333 and 505 µm formalin and alcohol samples were sorted from the plankton samples under a dissecting microscope, but only the herring larvae underwent further processing. Only those larvae which were unmistakably herring were processed, and all borderline fish were classified as non-herring. Herring larvae that are fixed and preserved in alcohol decompose during storage and one of the first body parts to be lost is the double row of melanophores on the ventral surface that is the primary means for separating this species from eulachon, Thaleichthys pacificus, and sandlance, Ammodytes hexapterus, larvae. Decomposition was slowed by replacing the alcohol within 24 h of capture, by sorting fish larvae from the plankton as soon as possible, and by storing the larvae in large volumes of alcohol.

All herring were counted and measured for standard length (L or notochord length) to the nearest 0.1 mm with the vernier scale of a compound microscope. Up to 5 formalin-preserved larvae from each cohort in each sample were randomly chosen for morphometric measurements. The cohorts were defined by their length ranges which were generally non-overlapping. Four morphometric characters were measured to the nearest 0.01 mm with an ocular micrometer: anal body depth (ABD), the dorsal-ventral depth at the anus, excluding the gut; pectoral body depth (PBD), measured at the pectoral girdle, including the gut; head width (HW), measured across the dorsal surface of the head, including the eyeballs; and eye diameter (ED), always measured along the antero-posterior axis of the eye. The larvae were then rinsed in fresh water, dried at 60°C for 24 h, stored in a desiccator for 24 h and weighed to the nearest 1 µg on an electrobalance to obtain dry weight (W). The dimensions of the larvae were corrected for shrinkage or expansion caused by capture in towed nets using Gompertz models calibrated for Pacific herring larvae by McGurk (1985b).

Preservation in alcohol without prior fixation in formalin renders fish larvae extremely fragile so it was not possible to measure their morphometry or their dry weight. Length was corrected for shrinkage due to net capture. Otoliths were removed from 6 fish from each sample for aging; the fish were chosen using length frequency plots so that at least one fish was taken from each of the 3 major cohorts present in the samples.

3.2.2.2 Zooplankton

Each 165 µm zooplankton sample was split several times and one subsample was completely identified and enumerated to the species level under a dissecting microscope. Length and width was measured for several specimens of each taxon in order to calculate dry weight from length-weight relationships taken from the scientific literature.

3.3 Prey Field of Herring

A definition of the diet of larval and juvenile herring in Auke Bay was first attempted from an analysis of their gut contents. About 25 larvae and 25 juveniles were picked at random out of the total set of formalin-preserved samples. The fish were chosen so that there was 1 for every 1 mm length bin over the 10 to 40 mm length range. The standard length of each fish was measured, the gut was opened under a dissecting microscope and all organisms found within were counted and identified. The lengths and widths of 30 organisms from each gut were then measured with an ocular micrometer. This information is listed in Appendix G and it was reviewed in Appendix J. It was supplemented by a review of the scientific literature on diet of Pacific herring larvae. This review is also in Appendix J.

In order to establish rules for the rigorous definition of the prey field, it was necessary to know the expected maximum and minimum lengths and widths of prey for each length interval of herring larvae. The maximum, mean and minimum lengths of prey from the southern British Columbia data shown in Table J1 of Appendix J were regressed on the mid-point of the herring length interval. Maximum and mean length of prey were highly correlated with herring length, but minimum length was not significantly correlated (Table J2 and Fig. J1). These results were supplemented by regressions of maximum, mean and minimum prey width on fish length reported by Checkley (1982) for feeding experiments with laboratory-reared Atlantic herring larvae exposed to natural zooplankton (Table J2).

Based on this analysis, I defined the prey field of herring larvae in Auke Bay as all taxa listed in Appendix I which have been found at least once before in a previous study of the diet of Pacific and Atlantic herring larvae, and which are smaller in length and width than the maximum lengths and widths predicted by the regression equations of Table J2. Comparisons were made first between the average prey length and expected maximum prey length because the relationships between prey length and predator length were established from data on Pacific herring. Organisms larger than the expected maximum length were rejected; the widths of the smaller, accepted organisms were then compared to the expected maximum width predicted from Checkley's

(1982) work on Atlantic herring larvae. Those that were below the maximum were finally accepted for the prey field. This procedure was done for each herring length interval using the expected maximum lengths and widths.

The final prey field includes all species of calanoid copepods of the appropriate size, all species of harpacticoid copepods, cladocerans, mollusc veligers, polychaete larvae and small fish eggs (Table J3). It excludes monstrilloid (parasitic) copepods, all species of Cnidaria, barnacle nauplii and cypris, isopods, nemertean worms, the arrow worm Sagitta elegans, bryozoan cyphonautes, and echinopluteus and asteroid larvae because they have never been found in even trace amounts in the guts of herring larvae, and it excludes fish larvae and large fish eggs, several species of large calanoid copepods, the hyperiid amphipod Parathemisto, the tunicate Oikopleura doica, crab and shrimp zoea and juveniles, and small adult polychaete worms because they are too long or too wide for herring larvae. Ostracods were not included because they were found in only one sample from Auke Bay.

This prey field does not include copepod eggs because neither this study nor APPRISE used techniques that could accurately measure copepod egg density. Copepod eggs are too small (10 µm in diameter) and too easily broken to be sampled even with the water bottle system used by APPRISE. They are best sampled using techniques usually employed for phytoplankton enumeration (Dr. C. Low, Victoria, B.C., personal communication).

3.4 Prey Concentration

Prey density was derived by combining the densities of zooplankton defined as prey of herring larvae that were collected by EPL's 165 µm mesh plankton nets with the densities of copepod nauplii collected as part of APPRISE.

Prey concentration (mg dry weight$\cdot$m^{-3}) was calculated from prey density (numbers$\cdot$m^{-3}) using dry weight-length and dry weight-width relationships reported in the literature. Concentrations of all stages of copepods and cladocerans were calculated by first converting body width to wet weight using Pearre's (1980) equation for marine copepods

(1) $Y = 1.5598\ X^{2.9776}$

where Y = wet weight (mg) in formalin, and X = width (mm). Wet weight in formalin was then converted to live wet weight by assuming a 10% loss in weight during storage (Pearre 1980), and live wet weights were converted to live dry weights by assuming an 80% water content. Concentration of mollusc veligers was calculated from data on mean live dry weight and mean length for larvae of the oyster, Ostrea edulis, reared in culture from release to an age of 12 d by Holland and Spencer (1973). A regression of live dry weight on length was

(2) $Y = 0.5900\ X^{3.6966}$
$n = 4;\ r^2 = 0.99;\ P<0.01$

where Y = mean live dry weight (mg), and X = mean length (mm). Concentrations of polychaete trochophores and small fish eggs were calculated by assuming a spherical volume [= $4/3\ \pi\ r^3$, where r = radius (mm)], a specific gravity of 1 $g \cdot cm^{-3}$, and a water content of 80%, i.e.

(3) $Y = 0.2 \times 1\ mg \cdot mm^{-3} \times 4/3\ \pi\ r^3 = 0.1047\ X^3$

where Y = live dry weight (mg), and X = length (mm).

3.5 Predator Concentration

Three classes of invertebrate predators were identified from the zooplankton collected in the 165 μm mesh tows and listed in Appendix I: gelatinous predators, which in this study consisted of at least 10 species of jellyfish (Cnidaria), the pelagic hyperiid amphipods Parathemisto spp., and the chaetognath Sagitta elegans. These organisms were chosen because they are large enough to prey on young herring larvae and because examination of the gut contents of field-caught jellyfish (Stevenson 1962, Moller 1980b, Robinson 1988), and Parathemisto spp. (Sheader and Evans 1975, Yamashita et al. 1985), and laboratory predation experiments with jellyfish (Arai and Hay 1982, Bailey and Batty 1983, Bailey 1984, Purcell et al. 1987), with Parathemisto spp. (Yamashita et al. 1984), and with other species of hyperiid amphipod (Westerhagen and Rosenthal 1976), and with chaetognaths (Kuhlmann 1977) show that these organisms are predators of fish larvae.

Two species of carnivorous copepods which have been previously identified as potential predators on fish larvae: Tortanus discaudatus (Robinson 1988), and Centropages abdominalus (Turner et al. 1985), were not identified as such in this study because the specimens captured in Auke bay were too small to be significant predators on herring larvae. Theilacker and Lasker (1974) showed that euphausiid shrimps can feed on small fish larvae, and a large population of the euphausiid Thysanoessa raschii inhabits the near-bottom habitat of Auke Bay (Krieger 1987, Carls 1987). However, euphausiids were not considered in this study because they were never found in the 165 μm mesh zooplankton samples.

Of the 57 jellyfish captured in the 165 μm mesh tows, 23 (40%) were too damaged to be assigned a species or a bell diameter. Three rules were used to assign them to size classes: (1) if other jellyfish had been caught at the same dates and stations, then they were assigned to those size classes; (2) if no other jellyfish had been caught at that station on the same date, then they were assigned to the size classes of jellyfish captured at other stations on the same date; and (3) if no other jellyfish had been caught on that date, then they were assigned to size classes on the basis of the frequency distribution of size classes for the entire study period.

Densities of jellyfish were converted to concentrations by, first, correcting the measured bell diameter to live diameter by assuming a 7% shrinkage due to preservation and storage in 5% seawater formalin. This number was taken from Larson's (1985) data on shrinkage of 8 species of jellyfish stored for 2 to 32 mo. The derivation of this number is described in section 1.0 of Appendix L. Second, live bell diameter was converted to dry weight using the equation

(4) $Y = 0.01\ X^{2.65}$

$r^2 = 0.91, n = 215, P<0,001, SE_b = 0.06$

where Y = dry weight (mg) and X = live bell diameter (mm) derived from data on 7 species of jellyfish captured in Saanich Inlet, British Columbia, and reported by Larson (1985). The derivation of equation (4) is reviewed in section 2.0 of Appendix L.

Densities of Parathemisto were converted to concentrations by using the weight-length regression for Parathemisto guadichaudi that was reported by Williams and Robins (1979)

(5) $Y = 0.0064\ X^{2.4614}$

where Y = live dry weight (mg), and X = length (mm). A weight-length regression for P. japonica that was reported by Yamashita et al. (1985) is very similar to equation (5). Densities of S. elegans were converted to concentrations using a dry weight-length equation reported by Sameoto (1971)

(6) $Y = 9.7 \times 10^{-4}\ X^{2.365}$

where Y = dry weight (mg) and X = live length (mm).

Herring larvae become less vulnerable to capture by jellyfish, Parathemisto and S. elegans as they grow in size and develop proportionately higher swimming speeds. Bailey (1984) and Purcell et al. (1987) both reported decreases in capture success of herring larvae with increased length of herring larvae, but only Bailey (1984) reported sample sizes that were large enough to calculate a significant regression between capture success and length

(7) $$Y = 0.2397\exp(-0.1721X)$$

$$r^2 = 0.83,\ n = 14,\ P<0.01,\ SE_b = 0.0225$$

where Y = number of fish larvae eaten$\cdot$h^{-1} $\cdot$ (cross-sectional area of medusa)$^{-1}$, X = mean length (mm) of fish larvae, and SE_b = standard error of the exponent. This equation was derived from data on 5 species of fish including Atlantic herring.

Equation (7) cannot be used directly to adjust predator concentrations for decreasing vulnerability of herring larvae to capture because predicted capture success is higher than would be expected in a natural ecosystem since Bailey's (1984) experiments were conducted in containers of only 0.005 m^3 volume. de Lafontaine and Leggett (1987) recently reported a highly significant inverse relationship between predation mortality of fish larvae and the volume of the experimental enclosure. Predation mortality rates of the same magnitude as those measured in natural ecosystems can only be replicated in enclosure volumes of at least 3.2 m^3. However, equation (7) can be used indirectly to adjust predator concentration by assuming that the effect of enclosure volume is to change the rate at which predators encounter prey, and not to affect the relationship between capture success and escape swimming speed. Then total predator concentration can be adjusted by the ratio of equation (7) at length L to equation (7) at length of hatch, i.e.

(8) $$Y_t = X_t V_t = X_t \exp[-0.1721(L_t - 8.8)]$$

where Y_t = adjusted total predator concentration (mg$\cdot$m^{-3}) at age t, V_t = index of vulnerability (range: 0 to 1), X_t = total predator concentration (mg$\cdot$m^{-3}) of at age t, and L = mean length (mm) of herring larvae at age t.

3.6 Spawn Surveys

Aerial surveys of the Auke Bay - Lynn Canal area were conducted by biologists of the Douglas office of the Alaska Department of Fish and Game (ADFG), every day or every second day from April 22 to May 15, 1988. They covered the shores of the mainland and the islands in Lynn Canal from Berners Bay to the southern end of Douglas Island. The surveyors searched for eggs on intertidal kelp, milt in the water, herring schools close to spawning beaches and bird and sea mammal activity. I conducted foot surveys of beaches in Auke Bay at least once a week from April 30 to June 19, 1988. At this time the shoreline of the Bay was searched with binoculars for flocks of seabirds feeding on spawn, and local residents of the Bay were interviewed at the three docks at the head of the Bay.

Herring spawn in Auke Bay was mapped with methods modified from the ADFG herring spawn survey protocol (e.g. Blankenbeckler 1987). Total length of spawn was measured by placing a rope marked in meter intervals along the upper limit of the spawn. Width of spawn was measured along transects established perpendicular to this rope at 1 to 10 m intervals. The distance between transects was reduced from the ADFG standard of 400 or 800 m to 1 to 10 m because the total lengths of the 2 spawnings that were mapped were less than 400 m long and because the spawn was distributed in patches with dimensions of only 1 to 30 m. A SCUBA survey was conducted to determine what proportion of the spawn was subtidal.

At each sampling date, samples of spawn were taken at 5 sites in order to estimate egg density and total egg number. The sites were chosen to represent the average spawn density estimated by eye over the nearby area. All of the vegetation and attached spawn were collected from within a 0.1 m^2 sample frame and immediately preserved in Gilson's fluid in water tight plastic bags.

In the laboratory the Gilson's fluid was decanted and the sample was placed in a fine mesh bag in a funnel until drops of fluid fell from the funnel at a rate of less than 1 min^{-1}. The wet sample was weighed on a balance and the type of vegetation was recorded. The mixture was then soaked in 5% formaldehyde and 28 ppt seawater for 24 h in order to assure a constant volumetric displacement. Each sample was drained, blotted dry on absorbent paper and its total volume measured as the amount of water it displaced in a large measuring vessel. The water was drained, the sample was blotted dry again and mixed thoroughly by hand and two subsamples of 5 ml volume each were removed and preserved in 5% formaldehyde and 28 ppt seawater. The number of eggs in each of the two subsamples was counted under a dissecting microscope. The number of $eggs \cdot m^{-2}$ was the mean number of $eggs \cdot ml^{-1}$ multiplied by the total volume of the sample and then multiplied by 10.

Hatching dates of cohorts 2 and 3 were forward-calculated from the known dates of spawning obtained from the spawn surveys using the average daily surface water temperatures of Auke Bay and Alderdice and Velsen's (1971) equation

$$(9) \qquad Y = 0.7648 + 0.4367X + 0.0235X^2$$

where Y = development rate ($\% \cdot d^{-1}$) and X = temperature (°C).

Spawning dates of cohorts 1, 4 and 5 were back-calculated from the known dates of hatching obtained from the growth models using surface water temperatures of Auke Bay and equation (9).

The percent of eggs that hatched into viable larvae was calculated from Alderdice and Velsen's (1971) equation

$$(10) \quad Y = 22.7560 + 1.5441X_1 + 13.8280X_2 - 0.0787X_1^2 - 0.9684X_2^2 + 0.1356X_1X_2$$

where Y = percent viable hatch, X_1 = mean surface water temperature (°C) and X_2 = mean surface salinity (ppt).

3.7 Juvenile Surveys

Juvenile herring were captured with dipnets as they schooled off the Auke Bay Government dock from August 14 to 25. One sample of juvenile herring was captured with a beach seine off the western beaches of Spuhn Island on August 15 by personnel of the Auke Bay Laboratory. Half of each sample was preserved in 5% formalin and half in 37% isopropyl alcohol.

Standard length of all fish in both formalin- and alcohol-preserved samples was measured to the nearest mm. No morphometric characters were measured because McGurk's (1985a) multivariate condition factor is applicable only to larvae less than 20 mm long. A subsample of 5 formalin-preserved fish were dried at 60°C for 24 h and weighed to the nearest 1 µg on a balance.

3.8 Otolith Analysis

The two sagittal otoliths of an alcohol-preserved larva were removed with fine probes under a dissecting microscope and prepared for examination with techniques described by Neilson and Geen (1980) and McGurk (1984a). The otoliths were placed convex side down on a glass slide and embedded in clear plastic nail polish. The small otoliths of young larvae were examined without further treatment, but those of large larvae were ground to the midplane using "Imperial" brand lapping film (3M Canada Inc.) in order to remove overburden that obscured the ring pattern. Particle sizes of 30 and 0.3 µm were used in the initial grinding and final polishing steps, respectively. Grinding was done with a grinding jig described by Neilson and Geen (1980).

An Optical Pattern Recognition System (OPRS: Biosonics Inc., Seattle, Wash., U.S.A.) was used to count the number of rings, measure the radius of each otolith, and measure the width of the outer 4 rings. This system consists of a video camera attached to a compound microscope, a colour monitor and a desk-top computer with a hard-disc drive. OPRS used a frame grabber that digitized the video signal and re-displayed it on the monitor. A data acquisition program enhanced the ring pattern in the image by sharpening edges. Otolith radius was always measured along the longest axis of the otolith because herring otoliths become increasingly ovoid as they grow larger. Ring widths were measured at a minimum of 2 places on the otolith and the mean widths were used in all calculations.

3.9 Herring Length Frequency Analysis

Length frequency plots were the primary means for the classification of larvae and juveniles into cohorts. Plots were constructed for every sample that had at least 1 herring and for every sampling date that had at least 1 herring. In many samples the separate cohorts were clear and unmistakable and no further information was required to distinguish them. In other samples the length distributions were not clear because the mean lengths of the cohorts were close together or because the sample size was too low to allow reliable separation of cohorts by simple observation. In the former cases a computer program, NORMPC, was used to partition the data into cohorts. This program is a PC-version of a FORTRAN program documented by Tomlinson (1971) that partitions a length frequency into a number of normal sub-populations using a least-squares algorithm. Best results were obtained when external information was available to provide preliminary estimates of the number of cohorts, their hatching dates and their expected mean lengths and standard deviations. I followed an iterative approach to the problem: first, I calculated preliminary mean lengths and standard deviations for the samples that could be readily separated into cohorts by observation. Then, using hatching dates calculated from spawning dates using daily mean surface water temperatures in Auke Bay and expected average growth rates of Pacific herring larvae from the literature (Stevenson 1962, McGurk 1987a), I assigned preliminary estimates of mean length to each cohort at each date and sampling site. These preliminary estimates were used as starting parameters for NORMPC, which then calculated more accurate mean lengths, standard deviations and numbers for each cohort at each date and sampling site. These standard deviations were used to assign ranges of length appropriate for each cohort at each date, and the ranges were used to classify larvae in those samples that contained too few larvae to employ NORMPC. This procedure was repeated several times until I was confident that each larvae and juvenile had been accurately classified into its cohort. As a final check, lengths were plotted on date for each cohort and outliers, if present, were identified and reassigned.

3.10 Growth Models

Four models of growth were fit to the length-at-date data:

Linear:

(11) $L = 8.8 + b(t - t_0)$

where L = length (mm) at Julian date t, t_0 = Julian date at hatch, and b = growth rate ($\mathrm{mm \cdot d^{-1}}$);

Gompertz:

(12) $L = 8.8\exp\left[\frac{A_0}{a}\exp\{1 - \exp[-a(t - t_0)]\}\right]$

where A_0 = rate of growth (d^{-1}) at t_0, and a = rate (d^{-1}) at which A_0 decreases with Julian date;

von Bertalanffy:

$$(13) \qquad L = Linf\{1 - \exp[-K(t - t_0)]\}$$

where Linf = length (mm) at infinite time, and K = growth coefficient (d^{-1}); and

Logistic:

$$(14) \qquad L = b1 + \frac{b2}{1 + \exp(-b3((t-t_0)-b4))}$$

where b1 (mm), b2 (mm), b3 (d^{-1}), and b4 (d) are parameters.

These modified models were necessary because fitting a growth curve to length-at-date date is the reverse of the conventional procedure where absolute age is usually known but initial size is not. In this case, the absolute age of the larvae was not known with as much certainty as the average length of yolk sac larvae. By fixing initial size at the average length of yolk sac larvae in Auke Bay (8.8 mm, Appendix C) a growth model could then estimate the Julian date at which L=8.8 mm and so estimate the date 2.5 d after the hatching date of each cohort.

Specific rates of recent growth in dry weight were calculated from the widths of the 4 outermost rings of the sagittal otoliths as

$$(15) \qquad G_W = \frac{1}{t} \ln \left[\frac{W_1}{W_n}\right] \times 100$$

where G_W = specific rate of growth (% dry weight·d^{-1}), W_1 = dry weight (µg) at capture, W_n = dry weight (µg) before deposition of the n^{th} otolith ring, and t = time (d) required to deposit 1 ring. Both W_1 and W_n were calculated from length at capture and length before deposition of the nth ring, respectively, with a weight-length equation, and both lengths were calculated from otolith radius using a regression of length on ln(otolith radius). The calculated otolith radius before the nth ring was deposited was radius at capture minus the summed widths of n outer rings. The time period for which G_W as calculated was the reciprocal of the slope of the regression of ring number on date of capture for all cohorts combined.

3.11 Weight-Length Relations

Three allometric models were fit to the ln-transformed weight-length data of each cohort and to the combined data of all cohorts: the standard linear or double-logarithmic model, a Gompertz-type model derived by Theilacker (1980) by eliminating time from 2 Gompertz equations describing growth in weight and length, and a logistic model.

Double-logarithmic:

(16) $\ln W = \ln(a) + b \ln L$

where a ($\mu g \cdot mm^{-1}$) and b are parameters;

Gompertz-type:

(17) $\ln W = b1 - b2(b3 - \ln L)^{b4}$

where b1 = the natural logarithm of the asymptotic dry weight (μg), b3 = the natural logarithm of the asymptotic length (mm), b4 = the ratio of the decay parameters in the Gompertz curves describing weight and length, and b2 has no obvious biological interpretation; and

Logistic:

(18) $\ln W = b1 + \left(\frac{b2}{1 + \exp(-b3(\ln L - b4))} \right)$

where b1 (μg), b2, b3 and b4 (mm) are parameters.

3.12 Condition Factors

The 4 morphometric characters were used with length and dry weight to calculate 2 condition factors: relative condition factor (Ricker 1975)

$$(19)\qquad CF1 = \frac{W}{\hat{W}}$$

where $\hat{W}$ = weight (μg) predicted from length using the weight-length equation for the combined data of all cohorts; and McGurk's (1985a) multivariate condition factor for Pacific herring larvae

$$(20)\qquad CF2 = 14.191 - 4.389\ln L + 2.184\ln ABD + 2.197\ln PBD$$
$$-12.331\ln HW + 3.770\ln ED + 0.419\ln W.$$

CF2 classifies a Pacific herring larvae as feeding or starving primarily on the width of the head and, secondarily, on the depth of the body. Both variables shrink with starvation and expand with feeding. CF2 can only be calculated for non-yolk-sac larvae, and it classifies as starving fish that are both reversibly and irreversibly starving. $CF2<0$ identifies feeding larvae and $CF2>0$ identifies reversibly and irreversibly starving larvae. CF2 [called CV1 in McGurk (1985a, 1986a) and CF in McGurk (1989)] was shown by Robinson (1988) to be highly correlated ($r^2=0.87$, $P<0.01$) with the ratio of RNA to DNA in the tissue of Pacific herring larvae, which confirms that CF2 is an accurate index of physical condition.

3.13 Advection, Diffusion and Patchiness

Advection of herring larvae was examined by first calculating the centroid or center of mass of each cohort in x-y coordinates for each age at which data from 3 stations was available, and then plotting the distance of each successive centroid from the original one. The slope of the relationship between distance and time is an estimate of the advection rate. The x-y coordinate system for Auke Bay is shown in Fig. 2. The origin was set at the spawning beach of cohorts 2 and 3: the high tide level midway between Bay and Waydelich Creeks. The y-axis extended directly offshore on a direct north-south axis paralleling the western shore of the Mendenhall Peninsula. The x-axis roughly paralleled the north shore of the Bay. The coordinates of each sampling station were assumed to be the midpoints of the average linear distance travelled during a 10 min plankton tow.

The x-coordinate of a centroid for age t is

$$(21) \qquad \overline{X}(t) = \frac{\sum_{i=1} N_{ti}\, x_i}{\sum_{i=1} N_{ti}}$$

where N_{ti} = density (number·m^{-3}) of herring larvae at age t and position i and x_i = x-coordinate of position i. The y-coordinate of the centroid, $\overline{Y}_t$, was calculated similarly.

Diffusion of larvae from their hatch sites was calculated as the slope of the relationship between the spatial variance of the larvae

$$(22) \qquad s_{xy}^2 = 2[s_x^2 \cdot s_y^2]^{\frac{1}{2}}$$

and age. Spatial variance in the x-axis at age t was calculated as

$$(23) \qquad s_{xt}^2 = \frac{\sum_{i=1} N_{ti}\,(X_i - X_t)^2}{\sum_{i=1} N_{ti}}$$

s_{yt}^2 was calculated similarly. s_{xy}^2 was calculated only for dates at which 2 or more positive densities were measured.

Spatial patchiness at age of herring larvae was measured with Lloyd's (1967) index

$$p = 1 + \left[\frac{\frac{s^2}{N_t} - 1}{N_t}\right] \tag{24}$$

where N_t = mean larval density ($\text{number} \cdot m^{-3}$) at age t, for a series of tows, and s^2 = variance of the density (not to be confused with spatial variance of density, s_{xy}^2). Lloyd's (1967) index is a measure of how many more times more crowded an average individual is relative to an individual in a population with the same mean density but randomly distributed. A completely random distribution means that $N_t = s^2$ and $p = 1.0$.

Patchiness was calculated for sets of samples taken on the same day using mean densities of pairs of samples taken at the same station. Both zero and non-zero counts were used in the calculation of the mean densities at station and in the calculation of patchiness because it was assumed that non-zero counts represented true zeros resulting from the patchy distribution of the larvae. Auke Bay is a sufficiently small sampling area that it is very unlikely that zero counts represented samples taken outside the retention zone of the population.

3.14 Population Models

3.14.1 Total Larval Mortality

Total larval mortality was estimated by fitting 3 types of population model to the densities of herring larvae in Auke bay: linear, Pareto-type and advection-diffusion. The linear model is the simplest population model used in larval fish ecology because it describes all dynamics with a single age-independent loss rate

(25) $N_t = N_0 \exp(-Zt)$

where N_t = density (number·m^{-3}) at age t (d), N_0 = density at hatch (t = 0) and Z = loss rate (d^{-1}) that is constant with age. Z is total mortality if losses due to advection or diffusion are assumed negligible.

The Pareto-type model was introduced by Hewitt et al. (1985). Like the linear model it has a single loss rate, but the rate changes exponentially with age instead of remaining constant.

(26) $$N_t = N_0 \left(\frac{t}{t_o}\right)^{-\beta}$$

where N_0 = density (m^{-3}) at t_0, β = mortality coefficient and t_0 = the youngest age (d) in a data set. Mortality at any age can be calculated as $Z_t = \beta\, t^{-1}$.

McGurk (1989) describes the advection-diffusion models used in this report. They partition the variance in population density into that due to advection, diffusion and mortality, rather than to a single loss rate. The most complex of the set of advection-diffusion models is

(27) $$N_{xyt} = \frac{C}{4\pi H \sqrt{K_x K_y t}} \exp\left[\frac{-(x-x_0-ut)^2}{4K_x t} - \frac{(y-y_0-vt)^2}{4K_y t} - Zt\right]$$

where N_{xyt} = density (number·km^{-3}) at distances x and y (km) from the origin and age t (d), C = number of newly-hatched larvae per unit volume at t = 0 d, H = depth (km) of the water layer in which larvae reside, K_x and K_y = coefficients of diffusion in the x- and y-axes (km^2·d^{-1}), x_0 and y_0 = distances from origin to hatch site along the x- and y-axes (km), u and v = rates of advection along x- and y-axes (km·d^{-1}), and Z = total mortality (d^{-1}) that is constant with age.

3.14.2 Egg-Larval Mortality

None of the herring larvae captured in this study were younger than 2 d old, therefore the daily egg-larval mortality, M_{el} (d^{-1}), that occurred between hatching of the eggs and the first date at which measurements of mean larval density could be obtained was estimated by comparing the total number of larvae in Auke Bay at the earliest age, n_2, with the total number of viable larvae that hatched, n_1. M_{el} was assumed to be constant with time because the rate at which it changed with time could not be measured. Thus,

$$M_{el} = \frac{-1}{t} \ln \left(\frac{n_2}{n_1} \right) \tag{28}$$

where t = time (d) between date of hatching and date of first estimate of mean larval density.

The total number of larvae at time t was calculated as

$$n_2 = N_o \cdot A \cdot H \tag{29}$$

where N_o = the density (m^{-3}) of herring larvae in Auke Bay predicted by a population model for t_0 the earliest age of the larval density data set, A = area (m^2) of Auke Bay, and H = depth (m) of layer in which herring larvae resided. The assumptions of equation (29) are:

1. All larvae are retained in Auke Bay. This assumption is necessary because, as is reported in section 10.2, there was not enough spatial variation in larval density to identify the margins of the distribution of larvae. It is supported by the arguments that: (a) the advection and diffusion rates of herring larvae hatching into sheltered embayments like Auke Bay are an order of magnitude lower than those for cohorts that hatch into exposed offshore waters (see section 10.1); (b) that Auke Bay possesses a counter-clockwise gyre of

surface currents that would tend to retain larvae in the Bay; and (c) that herring larvae may maintain themselves in Auke Bay by migrating vertically so as to take advantage of depth differences in current speed and direction (see section 10.1). This assumption is probably correct for cohorts in which the earliest age at which larval density was measured was only several d after hatching because the larvae were almost certainly still in Auke Bay at that age. The assumption would be less valid for cohorts with a longer time period between hatching and first measurement of larval density;

2. All larvae are retained within a vertical layer of depth H; and

3. There is no vertical or horizontal variation in the density of larvae within the Bay. These two assumptions are necessary because of the lack of data on the vertical distribution of herring larvae in Auke Bay and because no horizontal gradients of larval density were measured.

The total number of viable newly-hatched larvae was

$$n_1 = N_e \cdot a \cdot f_1 \cdot f_2 \qquad (30)$$

where N_e = mean density (m^{-2}) of eggs on the spawning ground, a = total area (m^2) of spawning ground, f_1 = fraction of eggs that survived exposure and predation, f_2 = fraction of surviving eggs that hatched viable larvae. The assumptions of equation (30) are:

1. All patches of eggs for each cohort were located and mapped. This is a reliable assumption for cohorts 2 and 3 because SCUBA survey showed that all spawning for these cohorts was restricted to the intertidal zone which was surveyed in detail by foot patrol;

2. There were no horizontal or vertical gradients of egg density on the spawning grounds. This assumption is appropriate because the highly patchy distribution of eggs meant that there were no significant correlations between the density of eggs and their position on the spawning beach; and

3. Egg mortality due to exposure and predation was uniform over the spawning ground. This assumption is supported by the argument that the spawning beds of cohorts 2 and 3 were too small (<250 m long) to have had significant spatial differences in exposure or predation mortality.

Substituting equations (29) and (30) into equation (28) gives an expression for daily mortality during the egg-larval period in terms of the seven parameters defined above

$$(31) \qquad M_{el} = \frac{-1}{t} \ln \left[\frac{N_0 \cdot A \cdot H}{N_e \cdot a \cdot f_1 \cdot f_2} \right]$$

The effects on M_{el} of variation in the assigned values of the seven parameters of equation (31) were examined by sensitivity analysis (section 10.3).

3.15 Statistical Analysis

All single linear regressions were predictive rather than functional regressions (Ricker 1973). Growth models, weight-length models and population models were fit to the data using non-linear regression. The advection-diffusion models were fit by first transforming them with natural logarithms because the transformed models provided more cases of convergence with lower residual sums of squares. The parameters of the population models were also re-cast in order to prevent exponential increases in their values that caused the non-linear regression program to cease functioning. For example, the coefficients of diffusion were estimated as $(4K)^{-1}$ rather than K.

Differences between cohorts of herring larvae in the relationships between otolith radius and fish length, and otolith ring number and age were tested using covariance analysis with dummy variables. For a linear regression of Y on X for n cohorts, n-1 dummy variables were inserted to test for differences in intercepts and another n-1 dummy variables were inserted to test for differences in slopes, e.g. for n=3 cohorts

$$Y = b_0 + b_1X + b_2g_1 + b_3g_2 + b_4g_1X + b_5g_2X$$

where g_1 = dummy variable with a value of 1 for cohort 1 and 0 for cohorts 2 and 3, g_2 = dummy variable with a value of 0 for cohort 1, 1 for cohort 2 and 0 for cohort 3, and b_0 to b_5 = coefficients estimated by multiple linear regression. If b_2 or b_3 are significant ($P<0.05$), then there are significant differences between cohorts in their intercepts, and if b_4 or b_5 are significant, then there are significant differences between cohorts in their slopes.

Response surface techniques were used to describe the relations between responses (e.g. predator concentration, specific growth rate, condition factor), and variables (date, age, prey concentration, and temperature). This involved fitting a linear polynomial

$$Y = b_0 + b_1X_1 + b_2X_2 + b_3X_1^2 + b_4X_2^2 + b_5X_1X_2$$

where Y = response, X_1 and X_2 are variables, and b_0 to b_5 = regression coefficients. Non-significant terms were rejected in a backwards stepping manner until a polynomial was found in which all terms were significant ($P<0.05$).

4. RESULTS-PHYSICAL AND BIOLOGICAL ENVIRONMENT

4.1 Temperature, Salinity and Water Density

Mean water temperatures, salinities, and densities for the upper 20 m of Auke Bay Monitor (ABM) station collected by APPRISE are presented in Appendix N, profile data for temperature at ABM collected by EPL are presented in Appendix O, and surface temperatures and salinities collected by the Auke Bay Laboratory are presented in Appendix P.

The combined data on surface water temperature is plotted against date in Fig. 3. Surface temperature rose from a minimum of 4.00°C on March 14 to a maximum of 17°C on August 25, the rise being punctuated by transient maxima and minima, the most obvious of which was a period of rapidly increasing temperature from April 17 to May 14, followed by declining or stable temperatures from May 14 to June 6. These data were used to calculate incubation times of herring eggs laid in the intertidal zone of Auke Bay and in an analysis of the relationship between the dates of first spawning and mean water temperature in Auke Bay.

The same temporal pattern is more clearly evident in the mean temperature of the upper 20 m shown in Fig. 4. These data were used in analyses of the relationships between growth and condition and environmental variables.

Mean salinity of the upper 20 m was constant at about 30.4 ppt from March 14 to May 7, and then it declined rapidly to a minimum of 26.82 ppt by June 1 in response to freshwater inflows from heavy rains (Fig. 4). Water density (sigma-t) followed a similar trajectory with date, being constant at about 24.0 from March 14 to May 7 and then declining rapidly to a minimum of 21.0 on June 1. The water column became progressively more stratified with date as are shown by profiles of density for the May 19 to June 14 period (Fig. 5).

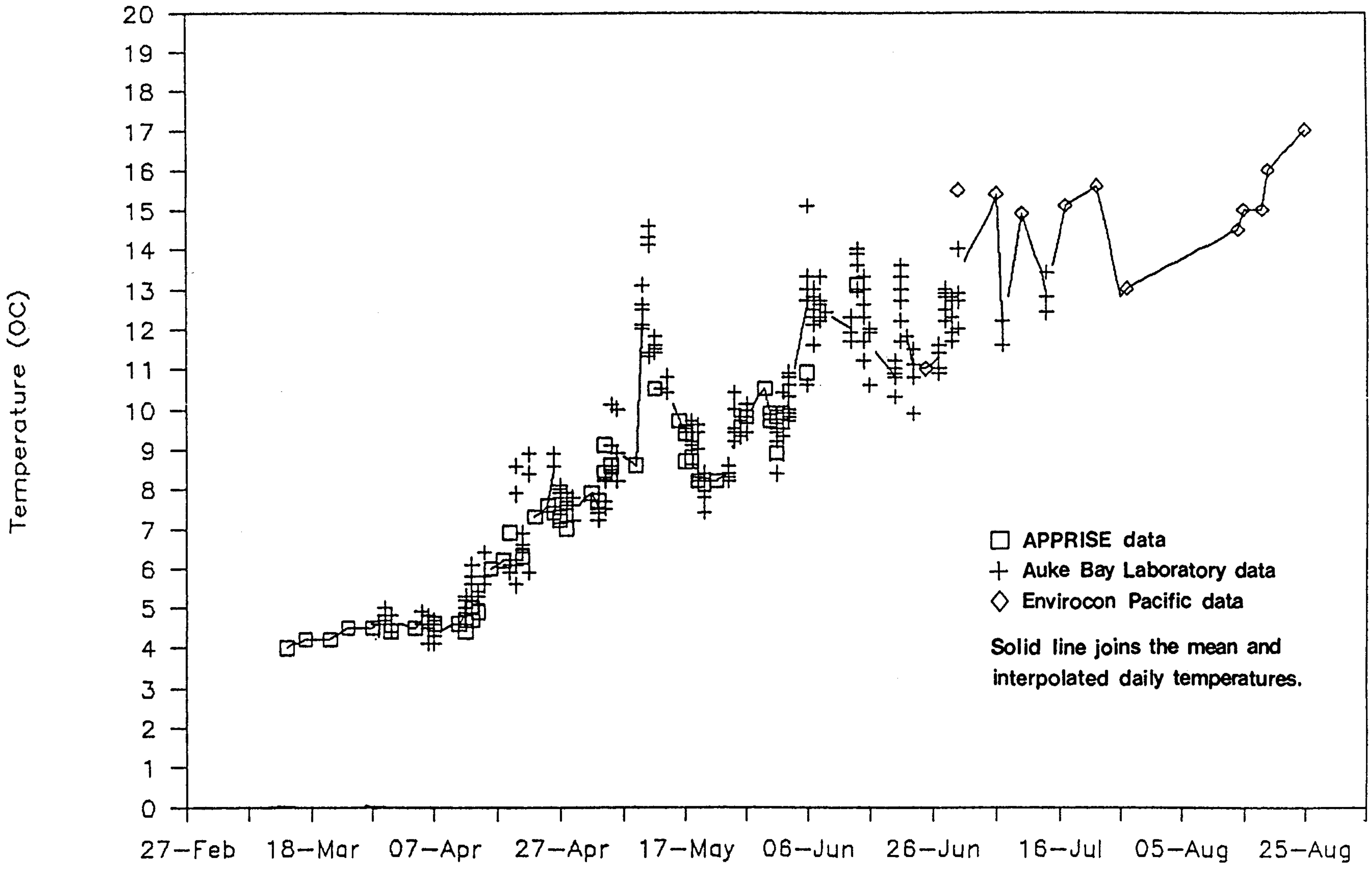


Figure 3: **SURFACE WATER TEMPERATURES IN AUKE BAY IN 1988**

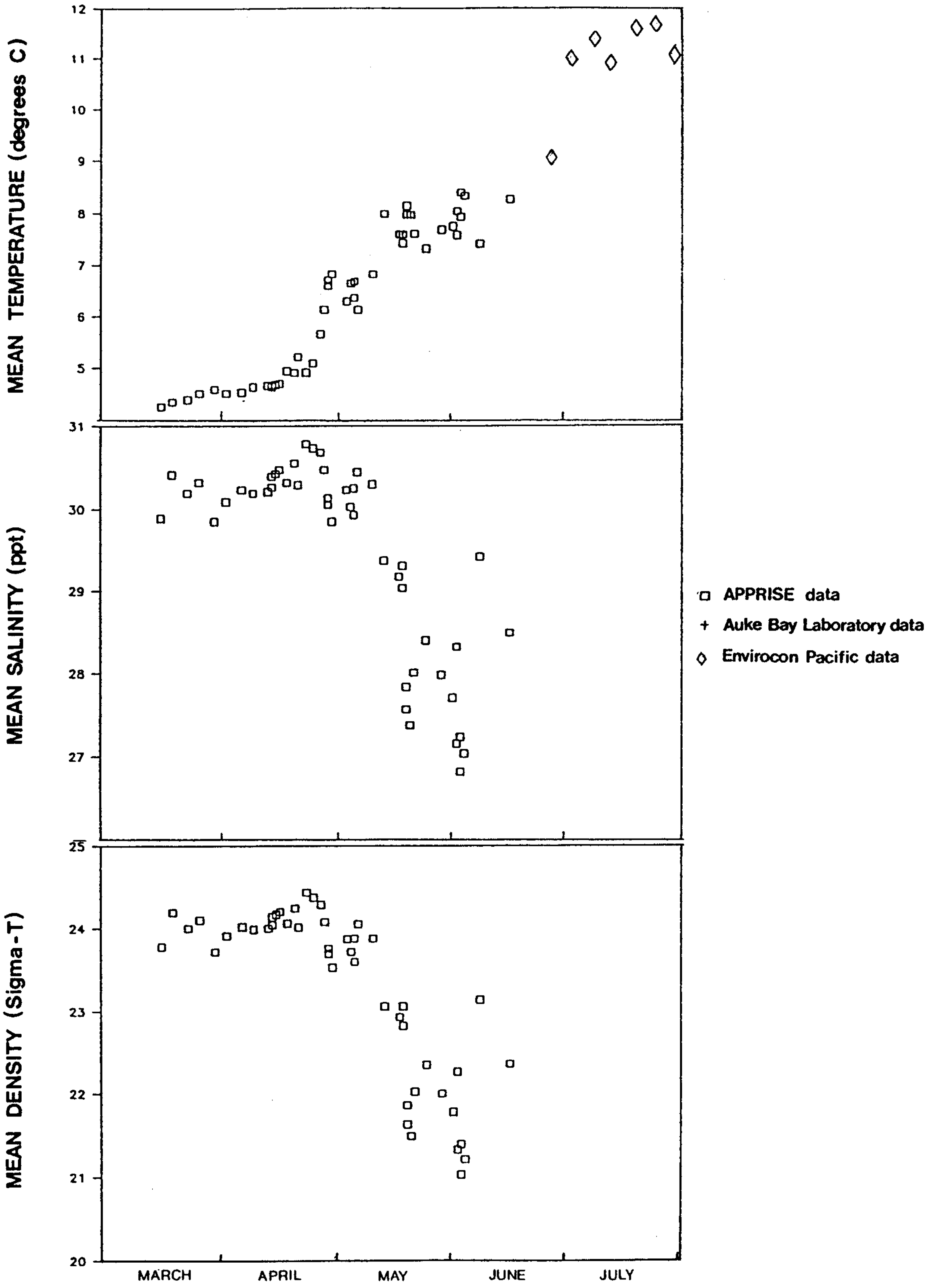


Figure 4: MEAN TEMPERATURE, SALINITY AND DENSITY IN THE UPPER 20m OF THE WATER COLUMN

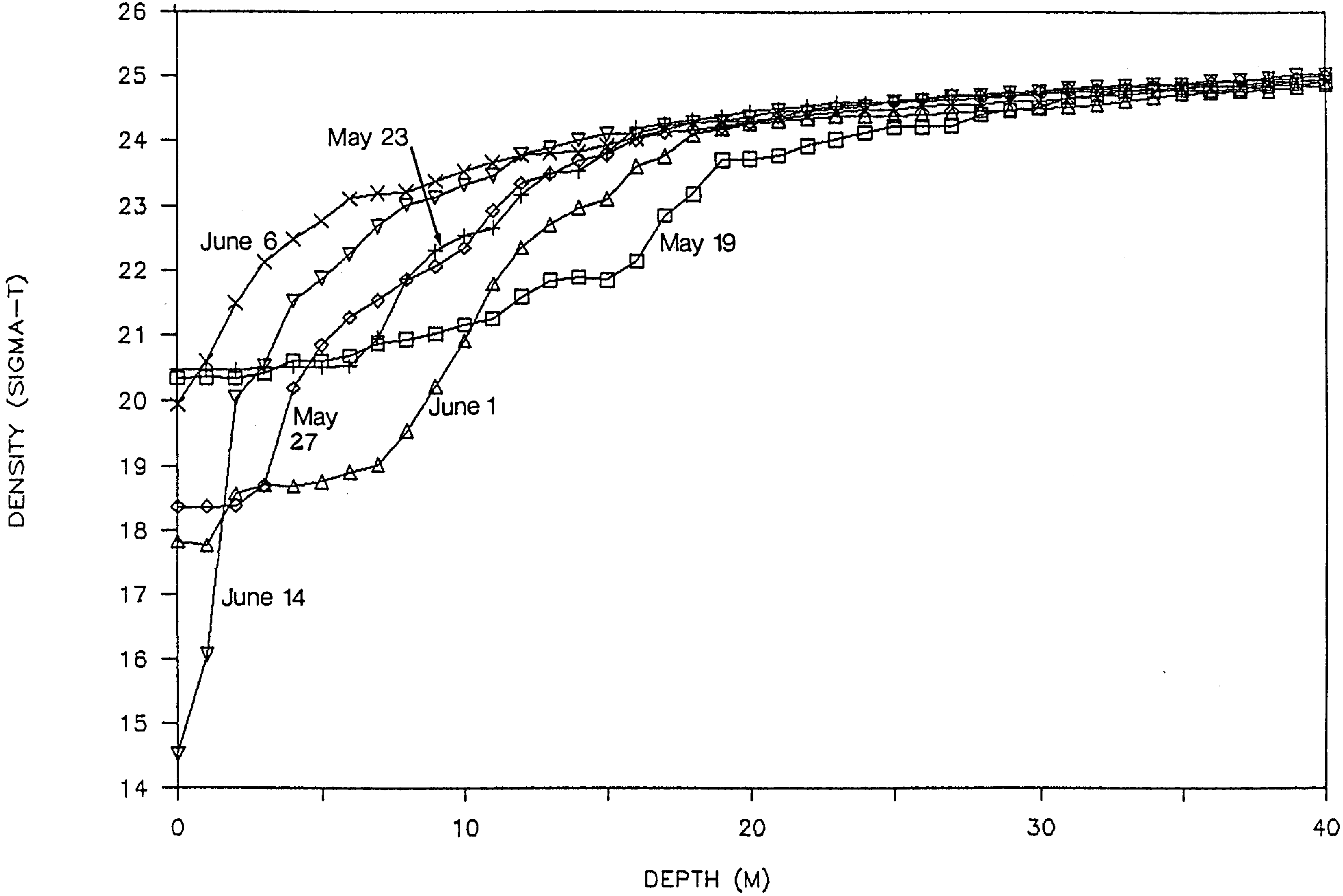


Figure 5: PROFILES OF WATER DENSITY (sigma-t) FOR THE UPPER 40m OF THE ABM STATION SHOWING INCREASING STRATIFICATION OF THE WATER COLUMN FROM MAY TO JUNE

4.2 Concentrations of Prey and Predators

Concentrations of the 19 components of the prey field of herring larvae are listed in Appendix K and plotted against date of capture in Fig. 6. Mollusc veligers and copepod nauplii had the highest average concentrations and harpacticoid copepods and small fish eggs had the lowest average concentrations. Prey concentrations were assigned to 6 separate length classes of herring larvae because the prey field changes with size of larvae (Appendix K, Fig. 7). The most striking feature of the mean prey concentrations is a U-shaped relationship with date; it decreased from a peak on May 27 to a minimum on June 10, and then increased to a second peak on June 20.

Concentrations of jellyfish, Parathemiso spp., and Sagitta elegans in Auke Bay are listed in Appendix M and plotted against date of capture in Fig. 8. Mean total concentrations of predators ranged from 0.9 to 34,027.7 $mg \cdot m^{-3}$ with a geometric mean concentration of 150.2 $mg \cdot m^{-3}$. Jellyfish comprised an average of 97.6% (SE=5.3, n=15) of the total concentration of predators at all dates. Table 1 shows that, apart from several 100 mm diameter Staurophora mertensi captured in mid-July, the jellyfish captured in the 165 µm mesh tows were relatively small; the modal preserved diameter was only 8 to 10 mm. Table 1 also shows that 36% of the total number of jellyfish were too badly damaged during capture to identify their species. These unidentified jellyfish consisted of fragments of large jellyfish, so the size distribution shown in Table 1 may underestimate the actual size distribution in Auke Bay.

Figs. 7 and 8 show that the concentrations of prey of herring larvae and the concentrations of their jellyfish predators were synchronous over the May 21 to June 25 time period. This suggests a functional response of jellyfish concentrations to concentrations of their zooplankton prey. Alternatively, the ratio of jellyfish to zooplankton concentrations may have been constant at all times and the variation in concentration of both components of the

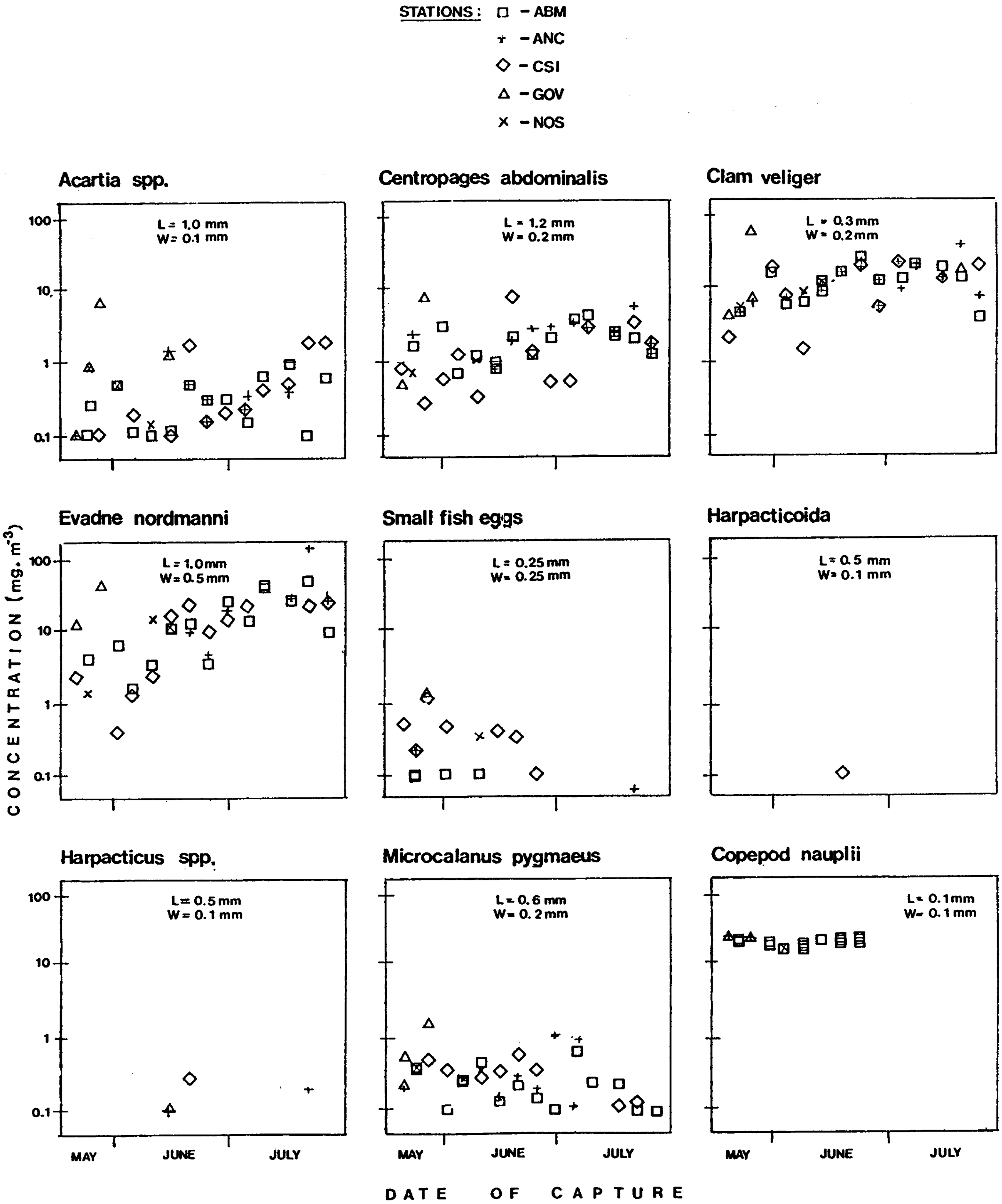


Figure 6: CONCENTRATIONS OF PREY OF HERRING LARVAE

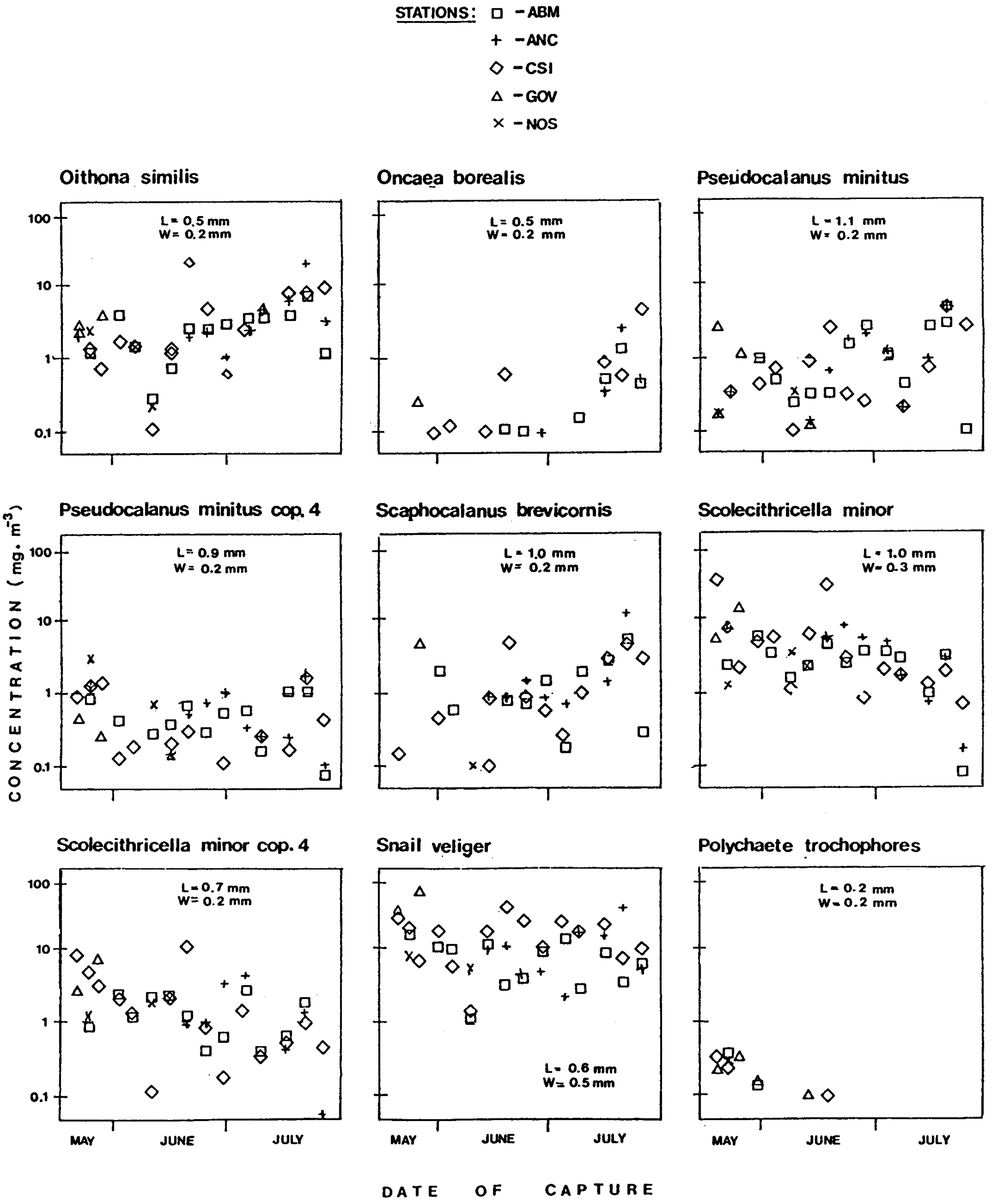


Figure 6 (cont.): **CONCENTRATIONS OF PREY OF HERRING LARVAE**

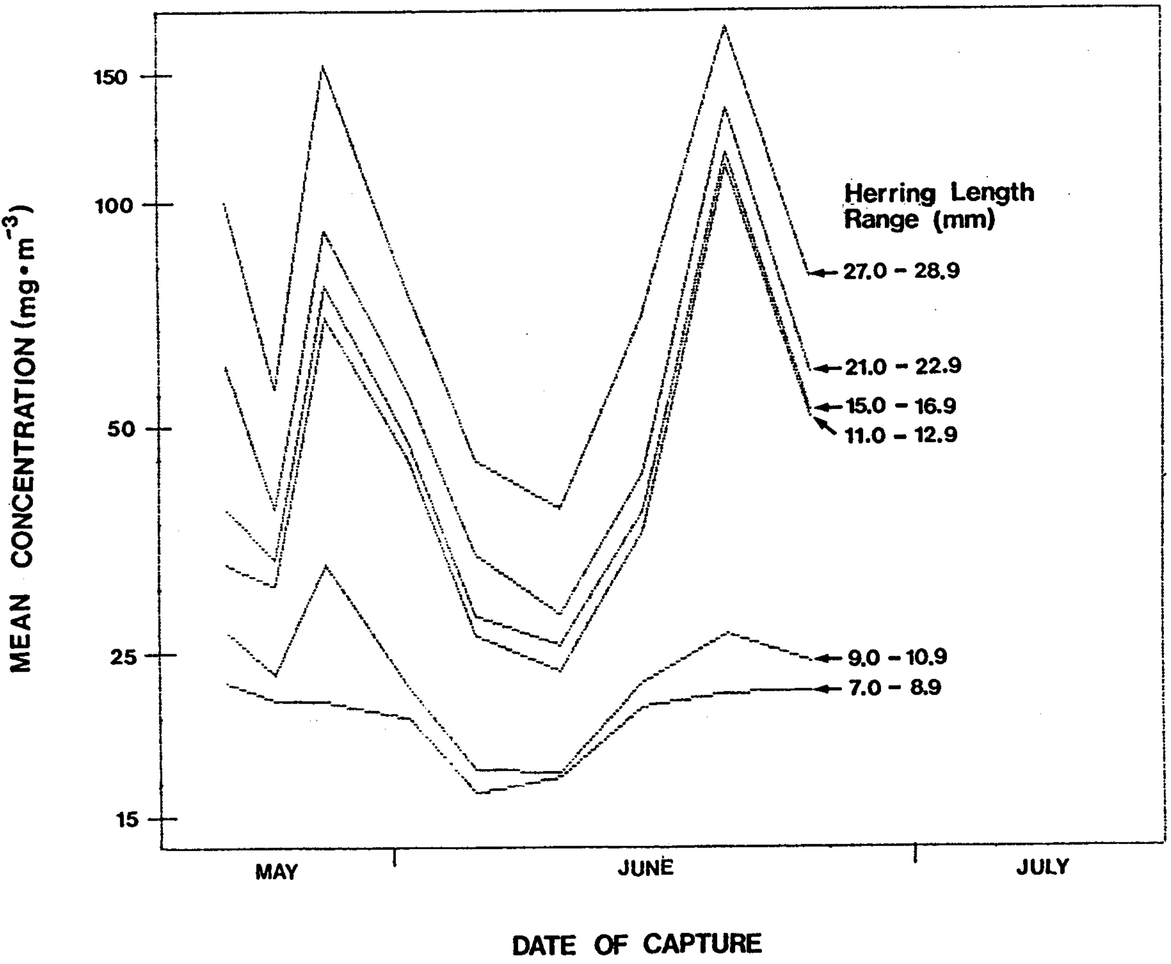


Figure 7: MEAN CONCENTRATION OF PREY FOR 6 LENGTH CLASSES OF HERRING LARVAE

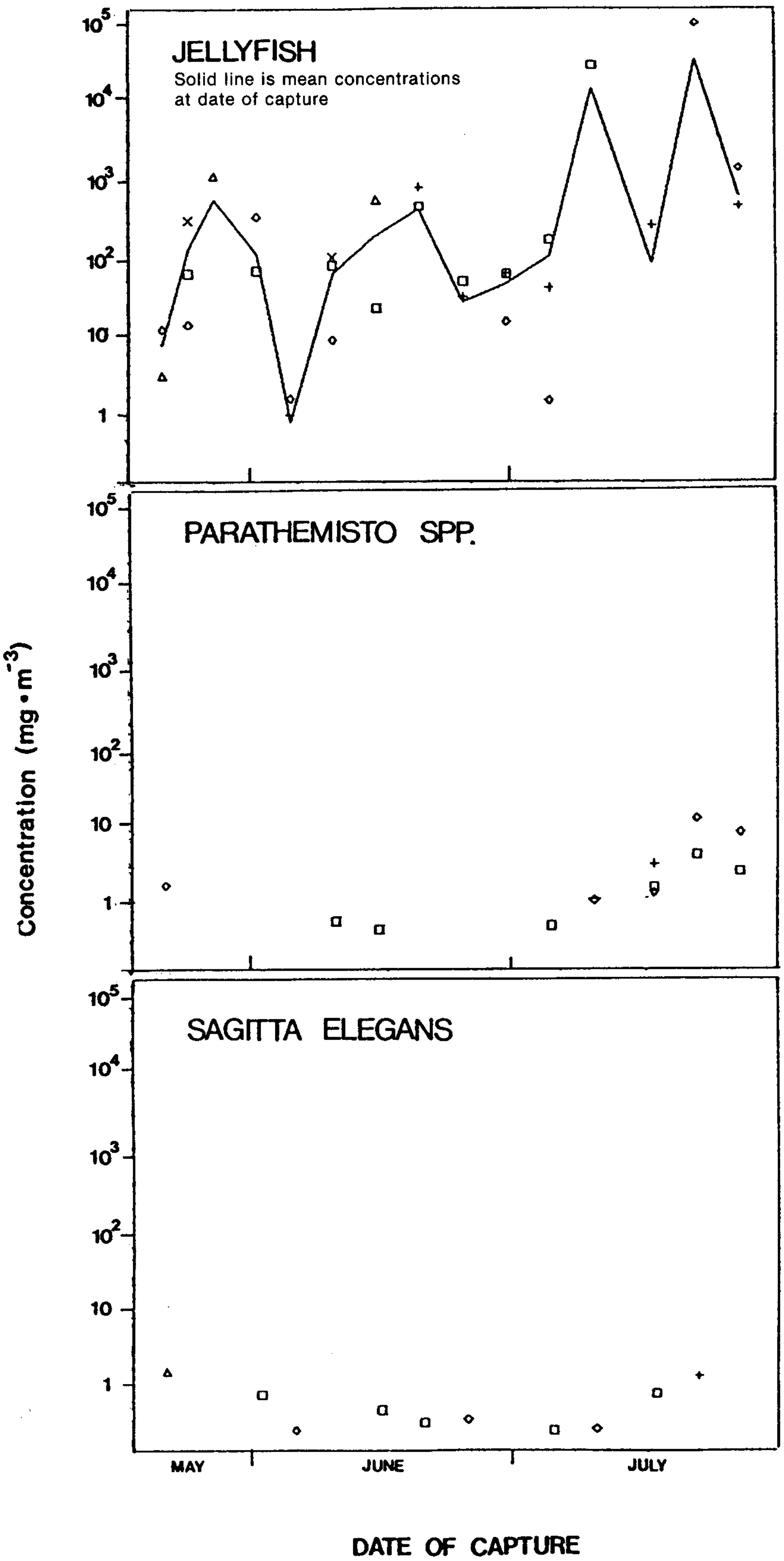


Figure 8: PLOTS OF CONCENTRATIONS OF PREDATORS OF HERRING LARVAE (symbols same as Fig. 6)

TABLE 1

Time and size distribution of jellyfish captured with 165 μm mesh nets.

		Number at Date																
	Mean Bell Diameter	May			June							July						
Species	(mm)	21	24	27	1	5	10	15	20	25	30	5	6	10	17	22	27	Total
Hybocodon prolifer	3		1				1											2
Halitholus spp.	3	1				1											1	3
Rathkea octopunctata	3							1				1						2
Sarsia spp.	8						1	2	1		3		1	1			1	10
Tiaropsis multicirrata	10			1			1		2	1	1				1		1	8
Mitrocomella sinuosa	12		1				1											2
Eperetmus typus	15														1			1
Cyanea spp.	16				1				1				1					3
Aequorea victoria	20							1	1								2	4
Staurophora mertensi	100													1		1		2
Damaged medusae	-	2	5	1	1		3		5	1	1		1				1	21
Total		3	7	2	2	1	7	4	10	2	5	1	3	2	2	1	6	58

Note: dashes indicate no data.

plankton was caused by the movements of different water masses into or out of the Bay. Response surface analysis was used in order to determine what proportion of the variation in jellyfish concentration was correlated with concentrations of prey for herring larvae (functional response) and what proportion was correlated with date (water movements or other external variables). Concentrations of prey and predators at individual sampling stations were used, rather than mean concentrations at date, in order to increase the size of the data set. For the same reason, total prey concentrations minus the mean concentration of copepod nauplii at date were used because this allowed the extension of the data set from June 25 to July 27. Only records with non-zero jellyfish concentrations were used in order to avoid using the ln(X+1) transformation of jellyfish concentration. This meant the elimination of 11 of 40 records. The maximum amount of variation in jellyfish concentration was explained by the interaction of date and prey concentration

(32) $$Y = -2.021 + 9.653 \times 10^{-3} X_1 X_2$$

$$r^2 = 0.28,\ n = 29,\ P = 0.003$$

where Y = ln[jellyfish concentration (mg·m^{-3})], X_1 = Julian date, and X_2 = ln[prey concentration (mg·m^{-3}) for the 165 µm mesh samples]. This equation indicates that prey concentration and the unknown environmental factors subsumed by date were both responsible for significant proportions of the variation in jellyfish concentrations. Partial correlation coefficients of Y with X_1 ($r = 0.40$), and X_2 ($r = 0.32$) and X_1 with X_2 ($r = 0.06$) indicate that date and prey concentration were equally important explanatory variables. The positive correlation coefficient for prey concentration supports the hypothesis that jellyfish aggregate at sites with relatively high concentrations of prey. Thus, habitat of herring larvae that contains high concentrations of prey also contains relatively high concentrations of predators.

5. DISCUSSION-PHYSICAL AND BIOLOGICAL ENVIRONMENT

The March to May period of 1988 was one of the warmest that has been recorded in Auke Bay during the past 14 years; Table 11 shows that for the five years (1975, 1976, 1986, 1987 and 1988) in which herring larvae were studied in Auke Bay, the mean surface water temperatures over the March to May period in 1988 were, with the exception of the first 2 wk in April, generally 0.3 to 1.3°C higher than in previous years. These higher temperatures led to an early date at onset of the spring phytoplankton bloom (Ziemann et al. 1989). Mean concentrations of prey for young herring larvae, primarily copepod nauplii, were also high in the May to June period of 1988 relative to the previous three years (Paul and Coyle 1986, 1987, 1988, 1989). However, there were significant differences in the concentration of prey for herring larvae of all length classes between late May and early and mid-June, 1988.

In summary, the habitat in Auke Bay was favorable for rapid growth of herring larvae. If the critical period hypothesis is correct, and survival of young fish larvae is directly related to successful feeding and high growth rates, then survival of herring larvae in Auke Bay in 1988 is predicted to be high relative to previous years. Also, survival of cohorts of herring that hatched during periods of high prey concentration in 1988 is predicted to be higher than that of cohorts that hatched during periods of low prey concentration in the same year. This study cannot test the first hypothesis because survival rates of herring larvae in previous years have yet to be calculated from APPRISE data. Instead, this study tests the critical period hypothesis by comparing growth and survival between separate cohorts of herring that hatched in 1988. This study also tests the hypothesis that survival of herring larvae is determined by predation as well as by food-limitation.

6. RESULTS-DISTRIBUTION AND SURVIVAL OF HERRING EGGS

6.1 Spawning Locations and Timing

The major spawning of the Lynn Canal - Auke Bay herring stock occurred on April 30, 1988. Approximately 11.2 linear km of spawn was deposited on the shore from Bridget Cove 25 km north of Auke Bay to the mouth of Kowee Creek in Berners Bay (personal communication, D. Ingledue, ADFG, Douglas, Alaska). Over the next 10 d minor spawnings of herring were also observed on the shores of Benjamin Island, 10 km north of Auke Bay.

At least 5 separate spawnings of herring occurred in Auke Bay in 1988 producing 5 distinct cohorts of herring larvae. Only the eggs of cohorts 2 and 3 were observed and mapped on the beaches (Figs. 9 and 10). The eggs of the first, fourth and fifth cohort were not observed, but their dates of spawning and hatching were estimated by a combination of back-calculation of the growth rates of the herring larvae and of back-calculation of egg development rates from average surface water temperatures. The spawning and hatching dates of all 5 cohorts are summarized in Table 10.

The parents of the second cohort were first observed in Auke Bay on April 30 by ADFG aerial surveyors and by local fishermen and boat owners. The fish concentrated at the head of the Bay underneath Fishermen's Bend and Dehart's marinas and the Government docks. On May 5 to 7 these fish spawned in the intertidal zone of the beach between Bay and Waydelich Creeks, about 100 m west of Fishermen's Bend docks (Fig. 10A). Spawning was first observed early on the morning of May 5 in Waydelich Creek and on the beach immediately east of the Creek (personal communication, Mabel Burford, Auke Bay). Spawning was next observed on May 7 near Bay Creek at the other end of the spawning beach (personal communication, D. Ingledue, ADFG, Douglas, Alaska). Apparently spawning swept along the beach from the eastern end to the western end over the 2 d period. Several days afterward the spawners left Auke Bay because they were no longer observed under the docks and they were no longer caught in gill nets slung underneath the docks by local fishermen.

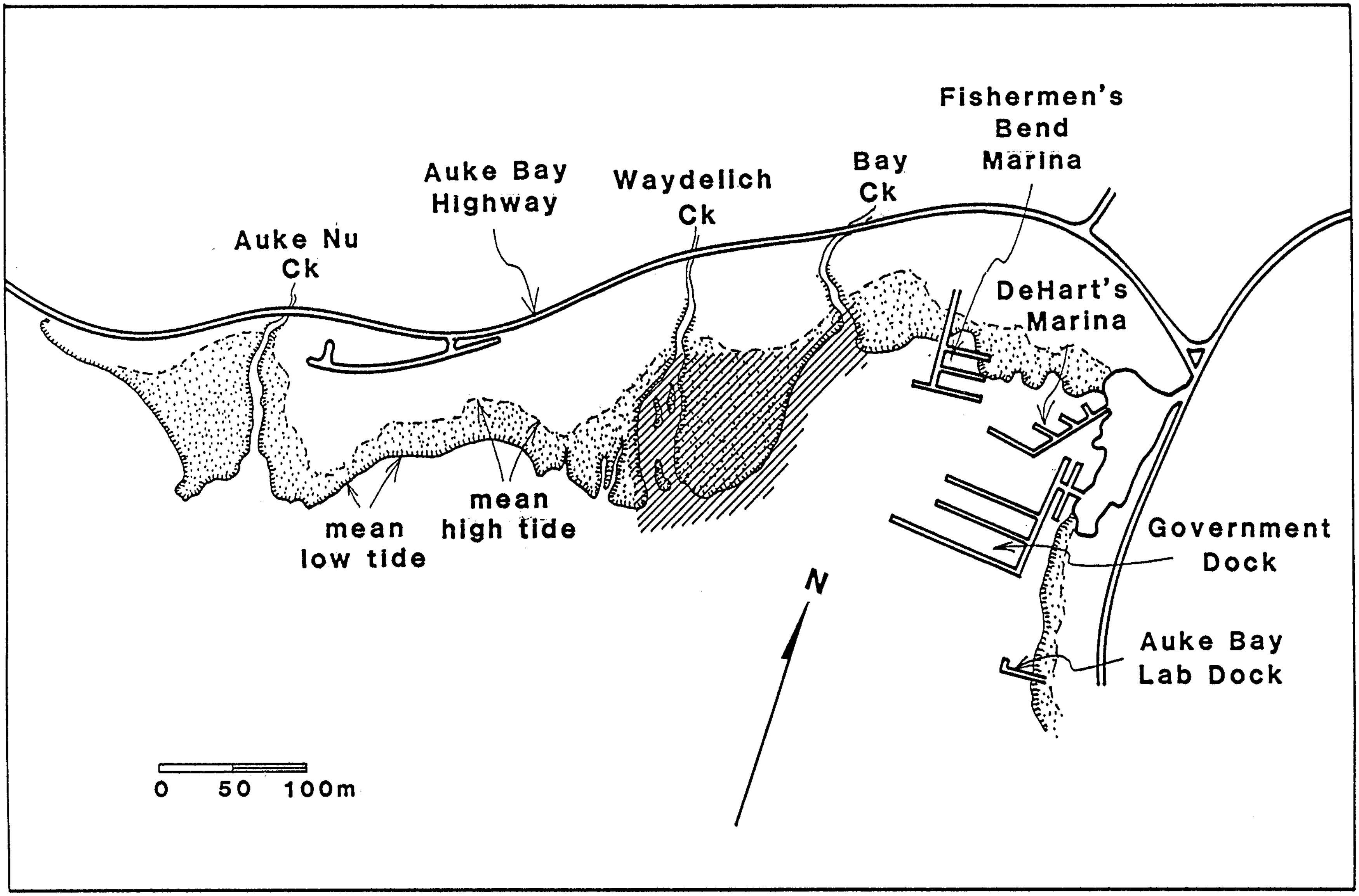


Figure 9: MAP OF NORTHERN SHORE OF AUKE BAY (hatched area of the intertidal zone indicates the location of spawning sites for cohort 2 and 3 herring)

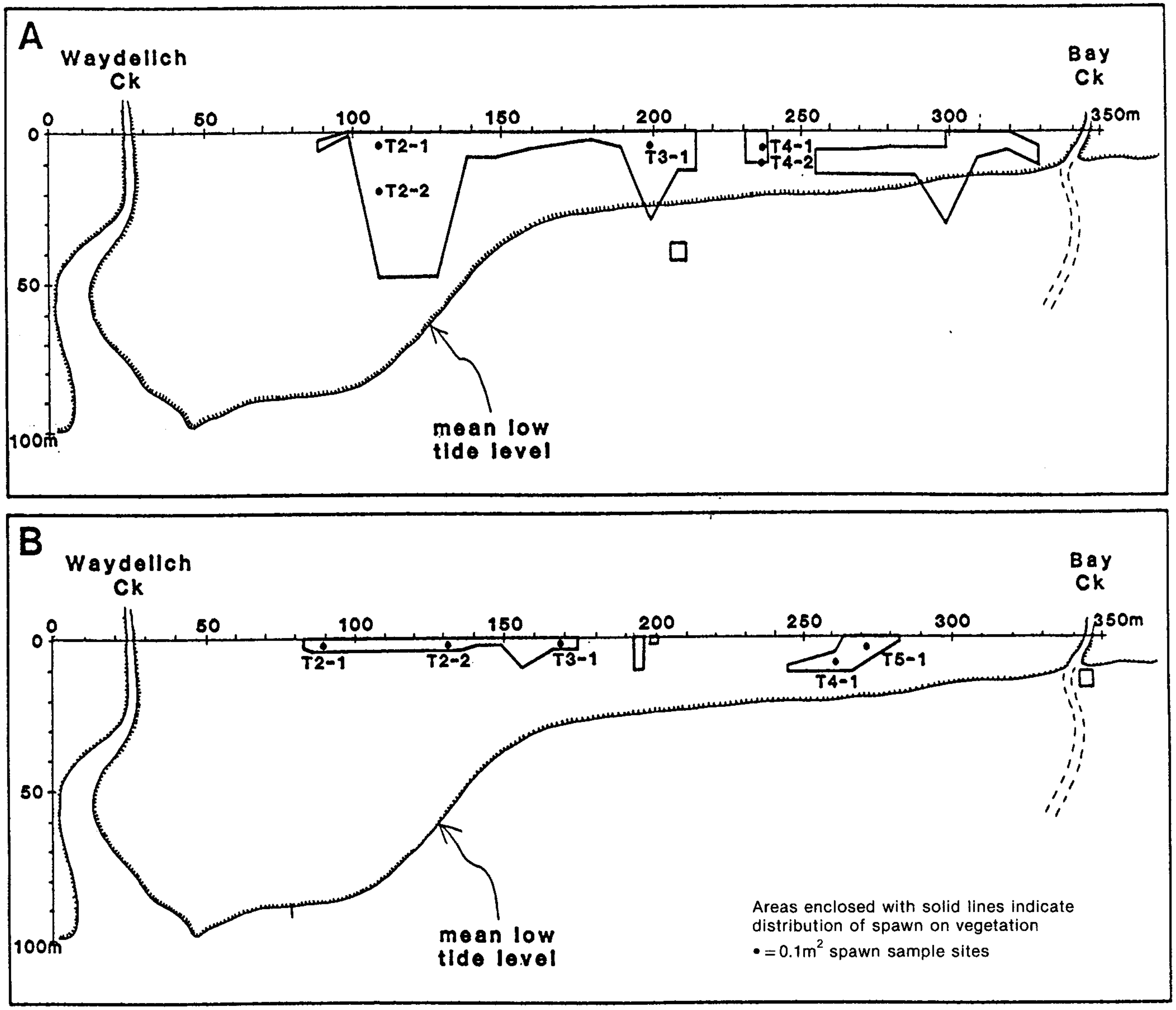


Figure 10: MAPS OF COHORT 2(A) AND 3(B) SPAWNING SITES IN THE INTERTIDAL ZONE OF THE NORTHERN SHORE OF AUKE BAY

The parents of the third cohort were seen by local residents on May 29 underneath Fishermen's Bend dock. The actual spawning event was not observed, but it must have occurred shortly after May 29 because the spawn was reported on June 5 (personal communication, Mabel Burford, Auke Bay, Alaska). This spawn was also laid on the beach between Waydelich and Bay Creeks, on the same patches of intertidal vegetation that held the eggs of the second cohort (Fig. 10B).

6.2 Egg Density and Number

The distribution of the eggs of the second and third cohorts on the beaches were mapped on May 18 and June 6, respectively. Eggs were laid on narrow strips of Fucus and Desmarestia within the upper 50 m of the intertidal zone. The strips covered a total length of about 250 m in each cohort. A SCUBA survey on May 18 found no eggs in the subtidal zone and no vegetation on which eggs could have been laid.

Density of cohort 2 eggs ranged from 80,400 to 994,500 m^{-2} with a mean (± 1 SD) of 508,100 (± 419,778) (Table 2). Cohort 3 eggs were almost twice as dense, ranging from 182,800 to 3,166,900 m^{-2} with a mean (± 1 SD) of 1,088,880 (± 1,204,758) m^{-2}. However, the high variances of the densities meant that the two means were not significantly different ($P>0.05$, Mann-Whitney U test) from each other. The high variances support the observation that egg deposition was highly patchy.

Cohort 2 eggs covered more than 4 times the area of cohort 3 eggs: 2949 m^2 compared to 662 m^2 (Table 3). Therefore, the estimated total number of cohort 2 eggs was twice as high as the estimated total number of cohort 3 eggs: 1,498 x 10^6 and 721 x 10^6, respectively.

TABLE 2

Egg density of herring cohorts 2 and 3.

								Number of Eggs					
								Subsample					
Date	Cohort	Sample Number	Meters from Origin	Meters from Upper Spawn Limit	Plant Type	Sample Wet Weight (g)	Sample Volume (ml)	A	B	Mean	SD	Total Eggs in Sample	Total Egg Density (m^{-2})
18 May 88	2	T2-1	110	5	Fucus	1031.9	750	746	581	663	117	99,450	994,500
18 May 88	2	T2-2	110	20	Fucus	411.2	100	428	375	402	37	8,040	80,400
18 May 88	2	T3-1	200	5	Desmarestia	662.9	350	415	313	364	72	25,480	254,800
18 May 88	2	T4-1	240	5	Fucus	448.5	450	686	1,185	1,026	224	92,340	923,400
18 May 88	2	T4-2	240	10	Fucus	234.5	150	1,028	888	958	99	28,740	287,400
												Mean	508,100
												SD	419,778
												n	5
06 June 88	3	T2-1	90	3	Fucus	658.1	550	3,058	2,700	2,879	253	316,690	3,166,900
06 June 88	3	T2-2	130	3	Fucus/ Desmarestia	588.6	550	967	654	810	221	89,100	891,000
06 June 88	3	T3-1	170	3	Desmarestia	421.0	250	1,651	1,863	1,757	150	87,850	878,500
06 June 88	3	T4-1	260	8	Fucus	120.0	100	1,006	822	914	130	18,280	182,800
06 June 88	3	T5-1	270	5	Fucus	193.6	200	780	847	813	47	32,520	325,200
												Mean	1,088,880
												SD	1,204,758
												n	5

Notes:
1. Origin is the intersection of upper limit of herring spawn with Waydelich Creek (Figs. 9 and 10).
2. All subsamples of 5 ml volume.
3. Number of eggs in sample = (volume of sample/5) x number of eggs in sub-sample.
4. Each sample taken from area of 0.1 m^2.
5. Number of eggs m^{-2} = number of eggs in sample/0.1 m^2.

TABLE 3

Estimated number and biomass of cohort 2 and 3 spawners and estimated number of newly-hatched larvae of cohorts 2 and 3.

	Cohort 2	Cohort 3
Mean egg density (m^{-2})	508,100	1,088,880
Area of spawn (m^2)	2,949	662
Number of eggs	1,498,386,900	720,838,560
Mean fecundity of female spawners	25,000	25,000
Number of female spawners	59,935	28,834
Ratio of male to female spawners	1:1	1:1
Number of male and female spawners	119,871	57,667
Average weight of spawning herring (g)	110	110
Biomass of spawners (kg)	13,186	6,343
Fraction of eggs lost during incubation	0.25	0.25
Number of newly-hatched larvae	1,123,790,175	540,628,920
Percent viable hatch	87.1	89.3
Number of viable larvae	978,821,242	482,781,626

Notes:

1. Mean egg density from Table 2.
2. Area of spawn from Figs. 10A and 10B.
3. Percent viable hatch from Alderdice and Velsen (1971).

6.3 Development Rates and Hatching Dates

Alderdice and Velsen's (1971) equation [equation (9)] relating the daily development of Pacific herring eggs to water temperature was used to predict hatching dates of cohorts 2 and 3 from the surface water temperatures measured in Auke Bay (Tables 4 and 5). Mean temperatures were calculated for dates on which several separate measurements were available. Dates for which no temperatures were available were estimated by interpolation between neighbouring dates. The eggs of cohort 2 are calculated to have hatched by May 19, 13 days after spawning on May 6 (Table 4), and the eggs of cohort 3 are estimated to have hatched by June 9, 11 days after an assumed spawning on May 29 (Table 5). These dates are increased or decreased by only 1 d if the lowest and highest temperatures at each date were used.

TABLE 4

Development rate of cohort 2 herring eggs.

	Surface Water Temperature (°C)			Egg Development Rate (%·d^{-1})			Cumulative Egg Development (%)		
Date	Mean	Low	High	Mean	Low	High	Mean	Low	High
06 May	9.0	8.2	10.0	6.599	5.926	7.482	6.599	5.926	7.482
07 May	8.8	8.8	8.8	6.428	6.428	6.428	13.027	12.354	13.910
08 May	8.7	8.7	8.7	6.343	6.343	6.343	19.369	18.696	20.252
09 May	8.6	8.6	8.6	6.258	6.258	6.258	25.628	24.955	26.511
10 May	12.5	12.0	13.1	9.895	9.389	10.518	35.523	34.344	37.029
11 May	13.3	11.3	14.3	10.730	8.700	11.815	46.253	43.044	48.844
12 May	11.4	10.5	11.8	8.797	7.941	9.190	55.050	50.985	58.034
13 May	10.5	10.5	10.5	7.941	7.941	7.941	62.991	58.926	65.975
14 May	10.6	10.4	10.4	8.034	7.848	8.222	71.026	66.775	74.198
15 May	10.1	10.1	10.1	7.573	7.573	7.573	78.598	74.347	81.770
16 May	9.7	0.7	9.7	7.213	7.212	7.212	85.810	81.559	88.982
17 May	9.4	8.7	9.6	6.946	6.343	7.123	92.757	87.902	96.105
18 May	9.3	8.7	9.7	6.859	6.343	7.212	99.615	94.245	103.317
19 May	8.7	8.2	9.6	6.343	5.926	7.123	105.958	100.171	110.440

Notes:

1. Development rate (%·d^{-1}) = $0.7648 + 0.4367T + 0.0235T^2$.

TABLE 5

Development rate of cohort 3 herring eggs.

	Surface Water Temperature (°C)			Egg Development Rate (%·d^{-1})			Cumulative Egg Development (%)		
Date	Mean	Low	High	Mean	Low	High	Mean	Low	High
29 May	10.3	10.3	10.3	7.756	7.756	7.756	7.756	7.756	7.756
30 May	10.5	10.5	10.5	7.941	7.941	7.941	15.697	15.697	15.697
31 May	9.8	9.7	0.9	7.301	7.212	7.391	22.998	22.909	23.088
01 June	9.2	8.4	9.8	6.771	6.091	7.301	29.770	29.000	30.389
02 June	9.9	9.3	10.4	7.391	6.859	7.848	37.161	35.859	38.237
03 June	10.2	9.7	10.9	7.664	7.212	8.317	44.825	43.071	46.554
04 June	11.0	11.0	11.0	8.412	8.412	8.412	53.237	51.483	54.966
05 June	11.8	11.8	11.8	9.190	9.190	9.190	62.427	60.673	64.156
06 June	12.6	10.6	15.1	9.998	8.034	12.717	72.425	68.707	76.873
07 June	12.4	11.6	13.0	9.793	8.993	10.413	82.219	77.700	87.286
08 June	12.6	12.2	13.3	9.998	9.590	10.730	92.217	87.290	98.016
09 June	12.4	12.4	12.4	9.793	9.793	9.793	102.010	97.083	107.809
10 June	12.3	12.3	12.3	9.692	9.692	9.692	111.702	106.775	117.501

Notes:

1. Development rate (%·d^{-1}) = $0.7648 + 0.4367T + 0.0235T^2$.

7. DISCUSSION-DISTRIBUTION AND SURVIVAL OF HERRING EGGS

The Auke Bay herring spawnings of 1988 were 2 orders of magnitude smaller in length than those that occurred around Bridget Point. This follows a trend of decreasing spawning in Auke Bay over the last 30 years. Table 6 shows that from 1953 to 1960 the majority of the Auke Bay stock spawned in Auke Bay, but since 1972 spawning has shifted north of Eagle River and Auke Bay has received only trace amounts of spawn or no spawn at all. The northward shift in spawning location has coincided with a decline in stock size, and with an increase in boat traffic in Auke Bay.

The 1988 Auke Bay spawnings also differ from the Bridget Point spawnings in the type of spawning substrate. The intertidal zone at the head of Auke Bay is dominated by Fucus and Desmarestia and the subtidal zone is too muddy to support vegetation. Thus, herring spawn only in the intertidal zone. In contrast, Blankenbeckler and Larson (1987) report that in 1983, 58% of the spawnings north of Eagle River were laid in the subtidal zone and only 42% in the intertidal zone. The average width of spawn off the beaches ranged from 20.0 to 38.6 m (Table 7). They also reported that 73% of the Auke Bay-Lynn Canal eggs were laid on large brown kelps, e.g. Laminaria, 23% were laid on Fucus and 3% were laid on Desmarestia.

Mean densities of herring eggs laid in Auke Bay in 1988 were higher than the mean densities measured for spawnings north of Eagle River. Blankenbeckler and Larson (1982, 1985, 1987) reported that the mean egg density of the Auke Bay-Lynn Canal stock in 1978, 1980 and 1983, measured for substrate that contained eggs, ranged from 117,000 to 874,238 m^{-2} (Table 7).

The number of spawning cohort 2 and 3 females was calculated by dividing the total number of eggs deposited in Auke Bay by a mean fecundity per female. Mean fecundity of herring in southeast Alaska ranges from 9,450 to 53,865 and depends strongly on the age and length of the female (Blankenbeckler and Larson 1982: Table 9). Modal lengths of southeast Alaska herring range from 191 to 220 mm and the corresponding average fecundities range from 22,585 to

TABLE 6

Linear kilometers of spawn and estimated biomass of the spawning population for the Auke Bay-Lynn Canal herring stock.

	Kilometers of Spawn				Biomass (10^6 kg)			
Year	AB	NE	SE	Total	Acoustic	Visual	Spawn	Survey
1953				15.19	-	-	-	-
1954				17.41	-	-	-	-
1955	13.33			22.59	-	-	-	-
1956	18.52			18.52	-	-	-	-
1957	23.89	15.19		52.04	-	-	-	-
1958	24.45			44.63	-	-	-	-
1959	20.00			20.00	-	-	-	-
1960	23.89			23.89	-	6.2	-	-
1961	-	-	-	-	-	-	-	-
1962	-	-	-	-	-	-	-	-
1963	-	-	-	-	-	-	-	-
1964	-	-	-	-	-	-	-	-
1965	-	-	-	-	-	-	-	-
1966	-	-	-	-	-	-	-	-
1967	-	-	-	-	-	-	-	-
1968	-	-	-	-	-	-	-	-
1969	-	-	-	-	-	-	-	-
1970				21.30	-	-	-	-
1971	-	-	-	-	-	-	-	-
1972	0.56	5.93	9.26	15.74	11.3	-	-	-
1973	0.00	18.33	1.30	19.63	2.7	-	-	-
1974	0.93	15.93	5.74	24.45	4.2	-	-	-
1975	2.32	13.70	4.17	20.19	6.8	-	-	-
1976	1.11	17.96	10.37	29.45	4.9	-	-	-
1977	0.56	17.41	0.00	17.96	6.2	-	-	-
1978	Trace	11.11	3.70	14.82	4.9	-	1.14	-
1979	0.93	8.80	0.93	10.56	2.1	1.8	-	-
1980	3.70	10.74	3.70	18.15	3.4	2.3	4.40	-
1981	0.56	16.11	0.37	17.04	3.0	4.5	-	-
1982	0.00	4.63	0.37	5.00	1.4	2.3	-	-
1983	Trace	11.11	0.00	11.11	1.6	-	0.50	-
1984	Trace	Trace	4.63	4.63	-	2.3	0.18	-
1985	0.00	9.26	0.19	9.45	2.1	1.6	-	-
1986	Trace	9.26	0.00	9.26	-	-	-	-
1987	Trace	4.63	Trace	4.63	-	1.6	-	-
1988	Trace	11.20	-	11.20	-	-	1.8	-

Notes:

1. Data from D. Ingledue (personal communication, Alaska Dept. Fish Game, Douglas, Alaska, USA)
2. AB = Auke Bay; NE = North of Eagle River; SE = South of Eagle River.
3. Dashes indicate no data.

TABLE 7

Spawn depth and width and average egg density for the portion of the Auke Bay - Lynn Canal herring stock that spawns north of Eagle River.

Year	Incubation temp. (°C)	Spawn depth (m) +	Spawn depth (m) -	Avg. width of spawn (m)	Avg. spawn density (m^{-2})	Source
1978	5-8	3.66	6.09	27.50	230,709	1
1980	5-8	3.04	7.61	38.63	874,238	1, 3
1983	7	2.13	9.14	20.00	117,000	2, 3
1984	8-9	0.61	11.58	---	---	4

Note:

1. 1 = Blankenbeckler and Larson (1982), 2 = Blankenbeckler and Larson (1985), 3 = Blankenbeckler and Larson (1987), 4 = Blankenbeckler (1987).
2. Dashes indicate no data.

29,415. Therefore, a mid-point fecundity of 25,000 was chosen for the calculations. This number is lower than the fecundity measured by Blankenbeckler and Larson (1982) for Lynn Canal spawners in 1978 (33,567) and 1980 (35,244), but higher than the fecundity measured by Blankenbeckler and Larson (1985) in 1983 (22,585). Using this number a total of 59,935 cohort 2 females and 28,834 cohort 3 spawners are calculated (Table 3). Assuming a sex ratio of 1:1, this is equivalent to 119,871 and 57,667 spawners, and assuming an average weight per spawner of 110 g, it is equivalent to spawning biomasses of 13,186 and 6,343 kg. These biomasses combined are approximately 1% of the biomass of the primary spawning north of Eagle River.

In order to estimate the number of viable larvae that hatched from these eggs it is necessary to know the mortality rate of herring eggs from predation, wave action and exposure. There is little consensus on the magnitude of predation mortality of herring eggs. Work done in the 1950's and 1960's in British Columbia (Outram 1958, Taylor 1964) and southeast Alaska (Montgomery 1958) produced loss rates ranging from 25% to 40%, but recent work on spawnings in southern British Columbia by Haegele et al. (1981) suggests that the loss from predation and storms is actually closer to 10% because most spawnings in that region are subtidal and only a small fraction of the total egg complement becomes exposed to air as a result of normal tidal cycles. The current practice of ADFG herring biologists in southeast Alaska is to assume a 25% loss of eggs unless extraordinary concentrations of predatory birds are observed, in which case a loss of 50% is assumed (Blankenbeckler and Larson 1982). The eggs deposited in Auke Bay in 1988 were exposed to the greatest possible risk because they incubated in the upper intertidal zone and were exposed for several hours in each tidal cycle. However, predation was probably light because no more than 20 birds were observed feeding on cohort 2 and 3 eggs at any time. Wave damage was also light because there were no storms during the incubation period. Therefore, assuming a loss of 25% over the incubation period, the number of newly-hatched cohort 2 and 3 larvae that entered Auke Bay on May 19 and June 9 was estimated to be 1,124 x 10^6 and 541 x 10^6, respectively (Table 3).

The percent of the hatching larvae that were viable can be estimated from the mean surface water temperatures and salinities over the incubation period using Alderdice and Velsen's (1971) model [equation (10)]. Mean (± 1 SD, n) temperatures and salinities were 9.14 (0.72, 9)°C and 26.26 (1.42, 7) ppt over the May 6 to 19 incubation period, and 9.96 (0.63, 7)°C and 23.05 (1.55, 7) ppt over the May 29 to June 9 incubation period. These translate to viable hatches of 87.1% and 89.3% for eggs of cohort 2 and 3, respectively. Therefore, the number of viable larvae that hatched into Auke Bay was 9.79×10^8 and 4.83×10^8 for cohorts 2 and 3, respectively (Table 3). These estimates were used to calculate egg-larval mortality rates.

8. RESULTS-GROWTH OF HERRING LARVAE AND JUVENILES

8.1 Number of Samples

A total of 140 samples of plankton were collected from Auke Bay between May 15 to July 27 (Appendix A). This consisted of 43, 20 and 77 samples collected with the 165, 333 and 505 µm mesh nets, respectively. The first 2 samples were taken on May 15 and subsequent samples were taken at intervals of 3 to 7 d until herring larvae were no longer captured by towed plankton nets. The last herring larvae was captured on July 27.

Nine samples of juvenile herring were taken in Auke Bay from August 14 to 25 (Appendix B). Eight of these samples were taken with a dipnet off the Government dock and 1 was taken by beach seining on the western shore of Spuhn Island by personnel of the Auke Bay Laboratory as part of their regular monthly sampling for salmonid fry. It was donated to this study by Alex Wertheimer (Auke Bay Laboratory, NOAA, Auke Bay). Collections of juveniles were taken as soon as they appeared in schools near the surface at the Government dock. I first observed them on August 14, but subsequent interviews indicated that they had appeared at the Auke Bay Laboratory dock 2 days earlier (personal communication, Bruce Wing, Auke Bay Laboratory, NOAA, Auke Bay). Attempts had been made since August 1 to capture juveniles with a purse seine set from the research vessel Envirocon IV, but no schools had been seen in Auke Bay until August 14. Juvenile sampling stopped after August 25 because the fish grew too large to catch them with a dipnet. The larger they grew, the deeper they swam and by August 25 they regularly swam below 1 m depth.

8.2 Number and Timing of Cohorts

The length frequency plots of the samples of larval and juvenile herring presented in Fig. 11 indicated that at least 5 cohorts hatched in Auke Bay in 1988. This is almost certainly the total number of cohorts in Auke Bay in

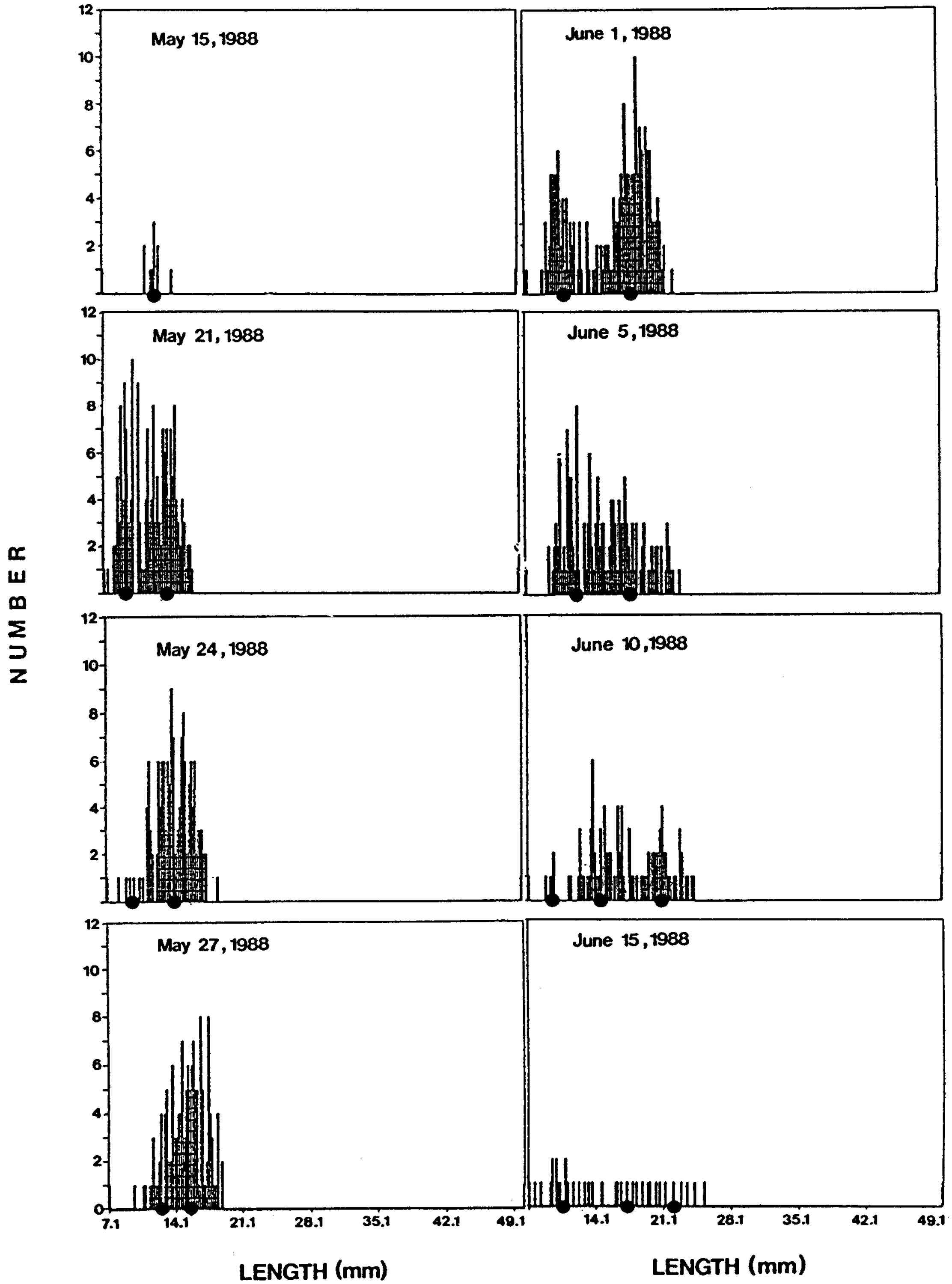


Figure 11: LENGTH FREQUENCIES OF HERRING LARVAE AND JUVENILES

NOTES: -five cohorts of herring are evident as modes
-mean lengths are indicated by closed circles

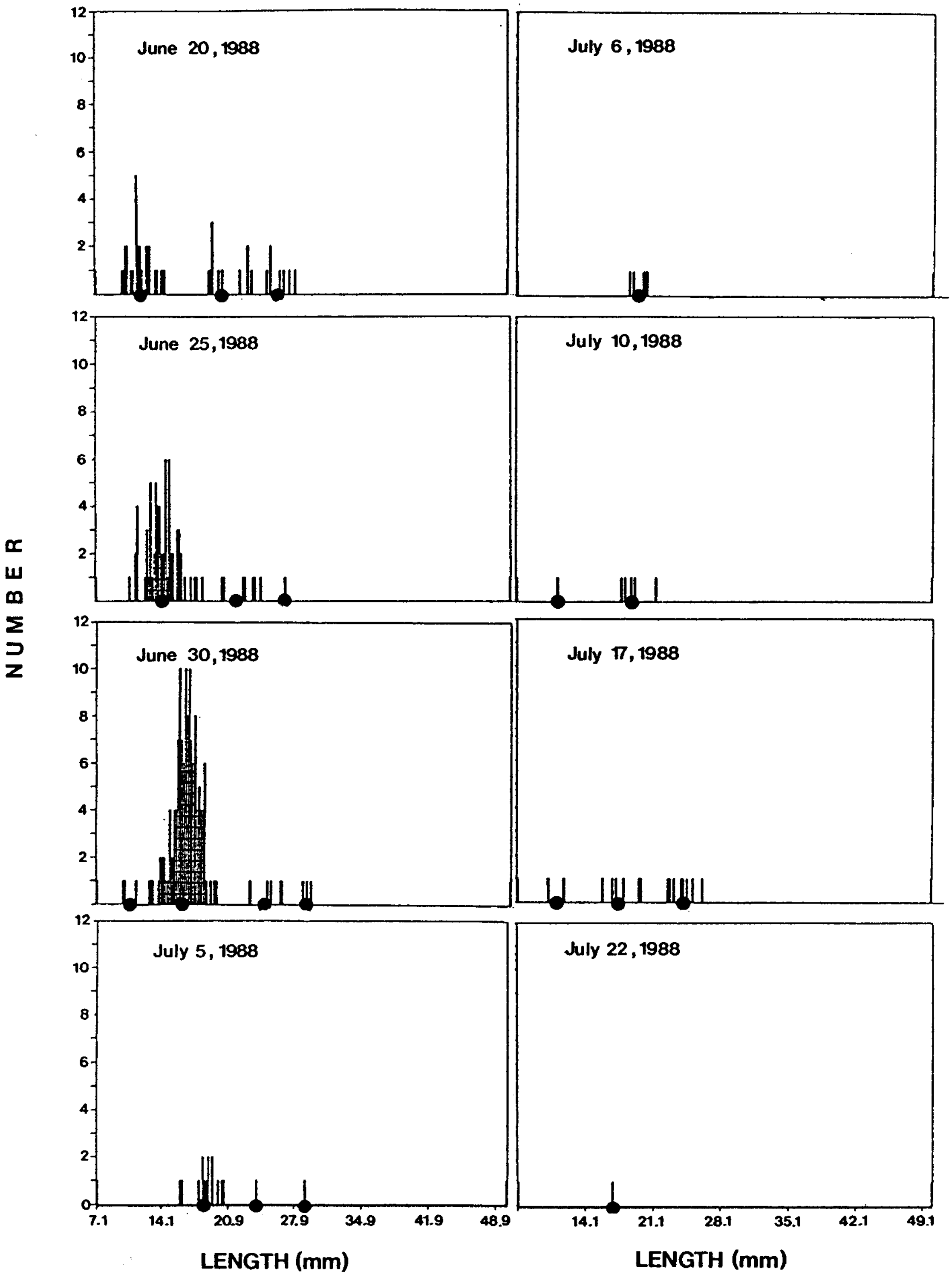


Figure 11(cont.): **LENGTH FREQUENCIES OF HERRING LARVAE AND JUVENILES**

NOTES: -five cohorts of herring are evident as modes
-mean lengths are indicated by closed circles

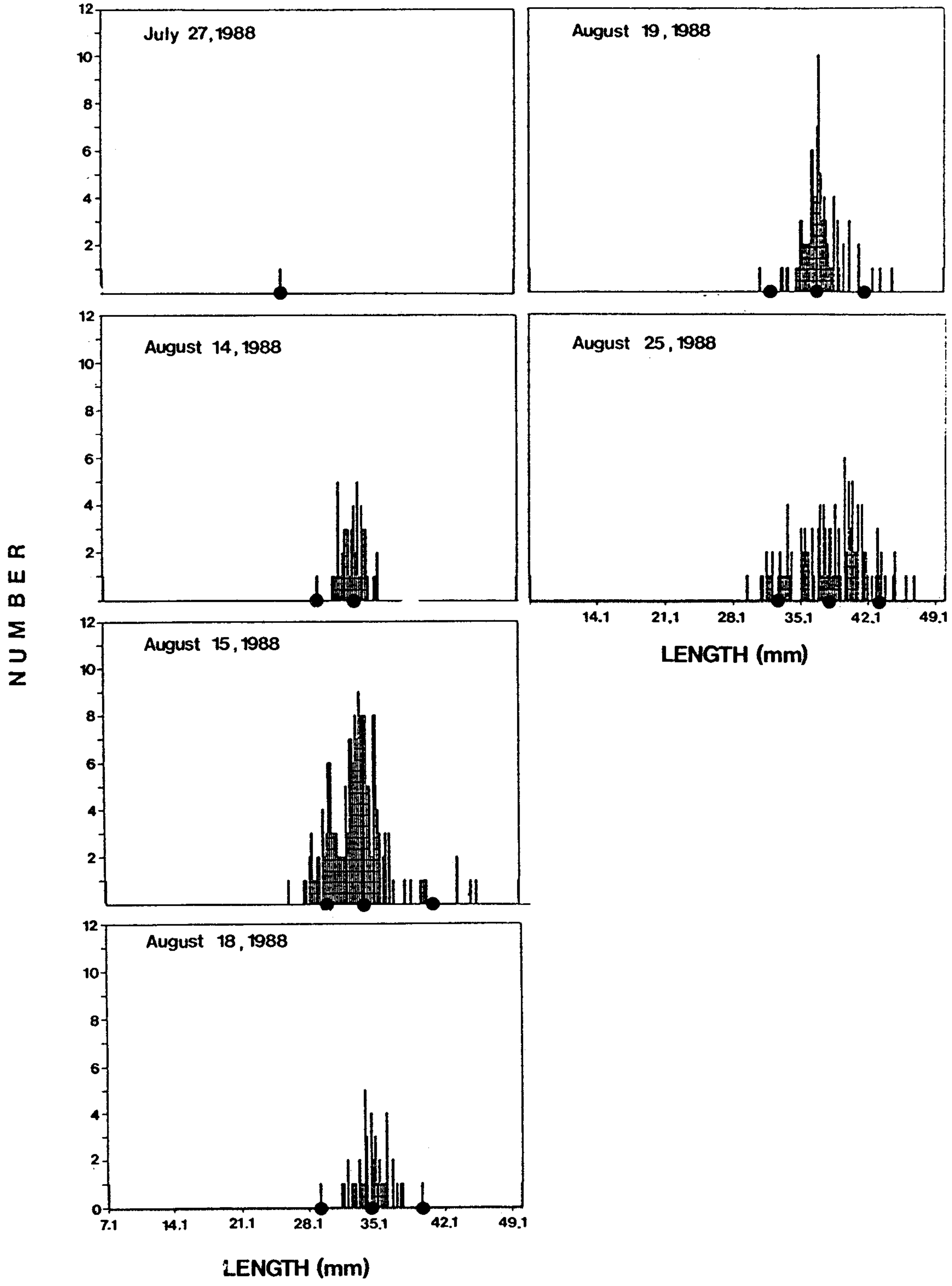


Figure 11(cont.): LENGTH FREQUENCIES OF HERRING LARVAE AND JUVENILES

NOTES: -five cohorts of herring are evident as modes
-mean lengths are indicated by closed circles

1988. It is unlikely that any other cohorts hatched before April because no large larvae were captured in the April plankton samples that were not clearly identified as cohort 1 larvae. It is unlikely that any other cohorts hatched in late July because spawnings at that late date are far outside the range associated with southeast Alaska: mid-January to June (Hay 1985). Only herring in Kotzebue Sound (Hay 1985) and in the Beaufort Sea (Ratynski 1983) are recorded as spawning in late July and August.

Spawning dates of cohorts 2 and 3 are known from ADFG aerial surveys and from personal communication with Auke Bay residents. Hatching dates of cohorts 2 and 3 were then forward-calculated from the spawning dates using average daily surface water temperatures in Auke Bay and Alderdice and Velsen's (1971) equation (Tables 4 and 5). The estimation of spawning and hatching dates of cohorts 1 and 4 proceeded in a reverse manner; hatching dates were back-calculated from the growth models presented in Fig. 12 and then spawning dates were back-calculated from hatching dates using average daily surface water temperatures and Alderdice and Velsen's (1971) equation (Tables 8 and 9). This procedure assumed that the average length of yolk sac larvae was the same for all 4 cohorts. The mean length (± 1 SD, N) of yolk sac larvae listed in Appendix C was 8.8 (± 0.3, 20). Herring larvae take an average of 5 d to completely resorb the yolk at 6 to 10°C (McGurk 1984b). Therefore, it was assumed that the hatching dates were 2.5 d previous to the dates at which length was predicted to have been 8.8 mm.

Table 10 shows that the mean (± 1SD) period of time between spawning events in Auke Bay in 1988 was 19.0 (± 3.8) d and that the mean (± 1SD) period of time between hatching events was 16.5 (± 4.6) d. The difference between the two means is not statistically significant ($P>0.05$, t-test). Table 10 also shows close agreements between the dates of spawning of cohorts 2 and 3 estimated from spawn surveys and the dates of spawning estimated from back-calculation from the hatching date predicted by the growth models. Close agreements also exist between the hatching dates of cohorts 2 and 3 forward-calculated from the spawning date, and the dates back-calculated from the growth models.

TABLE 8

Development rate of cohort 1 herring eggs.

	Surface Water Temperature (°C)			Egg Development Rate (%·d^{-1})			Cumulative Egg Development (%)		
Date	Mean	Low	High	Mean	Low	High	Mean	Low	High
06 May	9.0	8.2	10.0	6.599	5.926	7.482	100.000	100.000	100.000
05 May	8.9	8.4	10.1	6.513	6.091	7.573	93.401	94.074	92.518
04 May	8.1	7.5	9.1	5.844	5.362	6.685	86.889	87.983	84.945
03 May	7.5	7.2	7.7	5.362	5.127	5.521	81.045	82.621	78.261
02 May	7.0	7.0	7.0	4.973	4.973	4.973	75.683	77.494	72.740
01 May	7.8	7.8	7.8	5.601	5.601	5.601	70.710	72.520	67.767
30 April	7.6	7.6	7.6	5.441	5.441	5.441	65.109	66.920	62.166
29 April	7.5	7.2	7.8	5.362	5.127	5.601	59.668	61.479	56.725
28 April	7.6	7.0	7.0	5.441	4.973	4.973	54.306	56.351	51.124
27 April	7.8	7.2	8.1	5.601	5.127	5.844	48.865	51.378	46.151
26 April	8.5	7.4	8.9	6.175	5.283	6.513	43.264	46.251	40.307
25 April	7.6	7.6	7.6	5.441	5.441	5.441	37.089	40.968	33.794
24 April	7.4	7.4	7.4	5.283	5.283	5.283	31.648	35.527	28.353
23 April	7.3	7.3	7.3	5.205	5.205	5.205	26.365	30.243	23.070
22 April	7.7	5.9	8.9	5.521	4.159	6.513	21.160	25.038	17.865
21 April	6.5	6.3	6.9	4.596	4.449	4.897	15.639	20.879	11.352
20 April	7.0	5.6	8.6	4.973	3.947	6.258	11.043	16.430	6.455
19 April	6.2	5.9	6.9	4.376	4.159	4.897	6.070	12.483	0.197
18 April	6.2	6.2	6.2	4.376	4.376	4.376	1.694	8.324	-4.700
17 April	6.1	6.1	6.1	4.303	4.303	4.303	-2.682	3.948	-9.076
16 April	6.0	6.0	6.0	4.231	4.231	4.231	-6.985	-0.355	-13.379

Notes:

1. Development rate (%·d^{-1}) = $0.7648 + 0.4367T + 0.0235T^2$.
2. Hatching date estimated as May 6 from back-calculation of Gompertz growth curve.

TABLE 9

Development rate of cohort 4 herring eggs.

	Surface Water Temperature (°C)			Egg Development Rate ($\%\cdot d^{-1}$)			Cumulative Egg Development (%)		
Date	Mean	Low	High	Mean	Low	High	Mean	Low	High
25 June	11.0	11.0	11.0	8.412	8.412	8.412	100.000	100.000	100.000
24 June	11.0	11.0	11.0	8.412	8.412	8.412	91.588	91.588	91.588
23 June	11.0	9.9	11.5	8.412	7.391	8.895	83.176	83.176	83.176
22 June	11.8	11.8	11.8	9.190	9.190	9.190	74.764	75.785	74.218
21 June	12.7	11.7	13.6	10.101	9.091	11.050	65.574	66.595	65.091
20 June	10.8	10.3	11.2	8.222	7.756	8.604	55.473	57.504	54.041
19 June	11.0	11.0	11.0	8.412	8.412	8.412	47.251	49.748	45.437
18 June	11.2	11.2	11.2	8.604	8.604	8.604	38.839	41.336	37.025
17 June	11.4	11.4	11.4	8.797	8.797	8.797	30.235	32.732	28.421
16 June	11.5	10.6	12.0	8.895	8.034	9.389	21.438	23.935	19.624
15 June	12.4	11.7	13.3	9.793	9.091	10.730	12.543	15.900	10.235
14 June	13.5	13.0	14.0	10.943	10.413	11.485	2.760	6.809	-0.495
13 June	12.0	11.7	12.3	9.389	9.091	9.692	-8.193	-3.604	-11.979

Note:

1. Development rate ($\%\cdot d^{-1}$) = $0.7648 + 0.4367*T + 0.0235*T^2$.
2. Hatching date estimated as May 6 from back-calculation of Gompertz growth curve.

TABLE 10

Spawning and hatching dates of 4 cohorts of Auke Bay herring.

	Date of Spawning			Date of Hatching		
Cohort	Spawn Survey	Back-Calculation from Hatch Date	Interval Duration	Forward-Calculation from Spawning Date	Back-Calculation Growth Models	Interval Duration
1	-	April 18	-	-	May 6	-
2	May 6	May 7	18.5	May 18	May 19	12.5
3	May 29	May 30	23.0	June 9	June 10	21.5
4	-	June 14	15.5	-	June 25	15.5
		Mean	19.0		Mean	16.5
		SD	3.8		SD	4.6
		N	3		N	3

Notes:

1. Hatching dates of cohorts 1 and 4 were back-calculated from Gompertz growth curves assuming length at 8.8 mm is equal to hatching date plus 2.5 days; spawning date back-calculated from hatching date and average daily surface water temperatures in Auke Bay using Alderdice and Velsen's (1971) incubation-temperature relation.

2. Hatching dates of cohorts 2 and 3 forward-calculated from spawning dates and average daily surface water temperatures in Auke Bay using Alderdice and Velsen's (1971) incubation-temperature relation; spawning dates estimated by observation by ADFG overhead flights and reports of Auke Bay residents.

3. Dashes indicate no data.

8.3 Population Growth in Length

Herring larvae were corrected for shrinkage due to capture using Gompertz models (McGurk 1985b). No corrections to lengths were made for shrinkage due to fixation and preservation in formalin because formalin-preserved length is the standard to which all other lengths are adjusted. In the absence of experimental data on the effect of alcohol preservation on length of Pacific herring over the range of 9 to 45 mm, I compared mean lengths of pairs of formalin- and alcohol-preserved samples of herring larvae and juveniles of the same cohort captured on the same dates at the same stations within 4 h of each other. Forty six pairs of larval means and 7 pairs of juvenile means were taken from Appendix C and plotted against each other.

A linear regression of alcohol-preserved mean length of larvae on formalin-preserved mean length

(33) $Y = -0.133 + 1.044X$

$r^2 = 0.90$, $n = 53$, $SE_b = 0.047$, $P<0.001$

was highly significant, but the slope was not significantly higher than 1.0 ($P>0.05$). Despite this finding, I believe that adjustment of alcohol-preserved larvae to the formalin-preserved standard is necessary because there are more points above the line of equality than there are below it, and most authors who have examined the effect of alcohol on length of fish larvae in experimental conditions have found that it causes less shrinkage than formalin, e.g. McGurk (1984a). Therefore, the regression was rearranged as

Adjusted length = (measured length + 0.133)/1.044

and all alcohol-preserved larvae had their lengths recalculated with this equation as is shown in Appendix C.

Modified models of growth in length were fit to the lengths-at-date of Appendix C for cohorts 1, 2, 3 and 4 (Fig. 12). There were too few cohort 5 data to fit any kind of growth model. All of the models were highly significant, but the von Bertalanffy and logistic models explained less variance than either the Gompertz or the linear model so they were not considered any further. The Gompertz model best fit the length data of cohorts 1 and 3 and the linear model best fit the length data of cohorts 2 and 4.

In order to compare growth between the 4 cohorts. I assumed that growth was essentially linear from hatch to metamorphosis in all 4 cohorts. Since length at t_0 was set at 8.8 for all cohorts, the coefficient of growth of the linear model was used to make simple comparisons between the cohorts. Covariance analysis with dummy variables showed that there were no significant differences in the coefficient between any of the cohorts. The average value for all herring larvae and juveniles in Auke Bay in 1988 was 0.306 $mm \cdot d^{-1}$ (SE=0.003, N=1747).

8.4 Otolith Radius and Ring Number

The radii of the two sagittal otoliths, the number of rings in each otolith, and the widths of the outer four rings of each sagitta are listed in Appendix F. In order to calculate specific growth rates from the widths of the individual otolith rings it was necessary to develop a relationship between otolith radius and fish length. Covariance analysis with dummy variables showed that there were no significant differences between cohorts in their intercepts and slopes so a single linear regression of ln(radius) on fish length was calculated for the combined data of cohorts 1 to 4 (Fig. 13). This equation predicts that mean otolith radius is 11.8 µm at a fish length of 8.8 mm, the average length of yolk sac larvae before the deposition of the first ring. Rearranging the equation gives

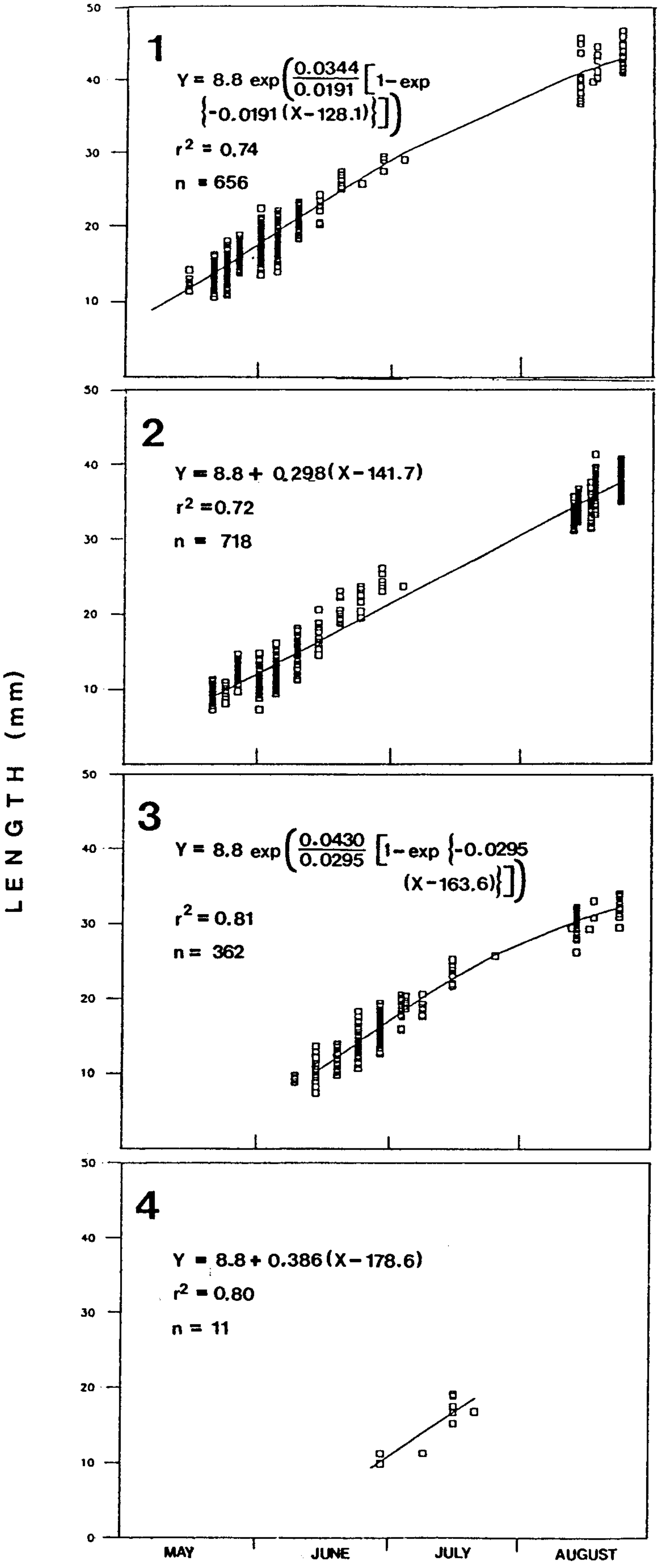


Figure 12

GROWTH IN LENGTH OF HERRING LARVAE AND JUVENILES OF COHORTS 1,2,3 AND 4

NOTE

Solid lines are Gompertz (cohorts 1 and 3) or linear (cohorts 2 and 4) growth models

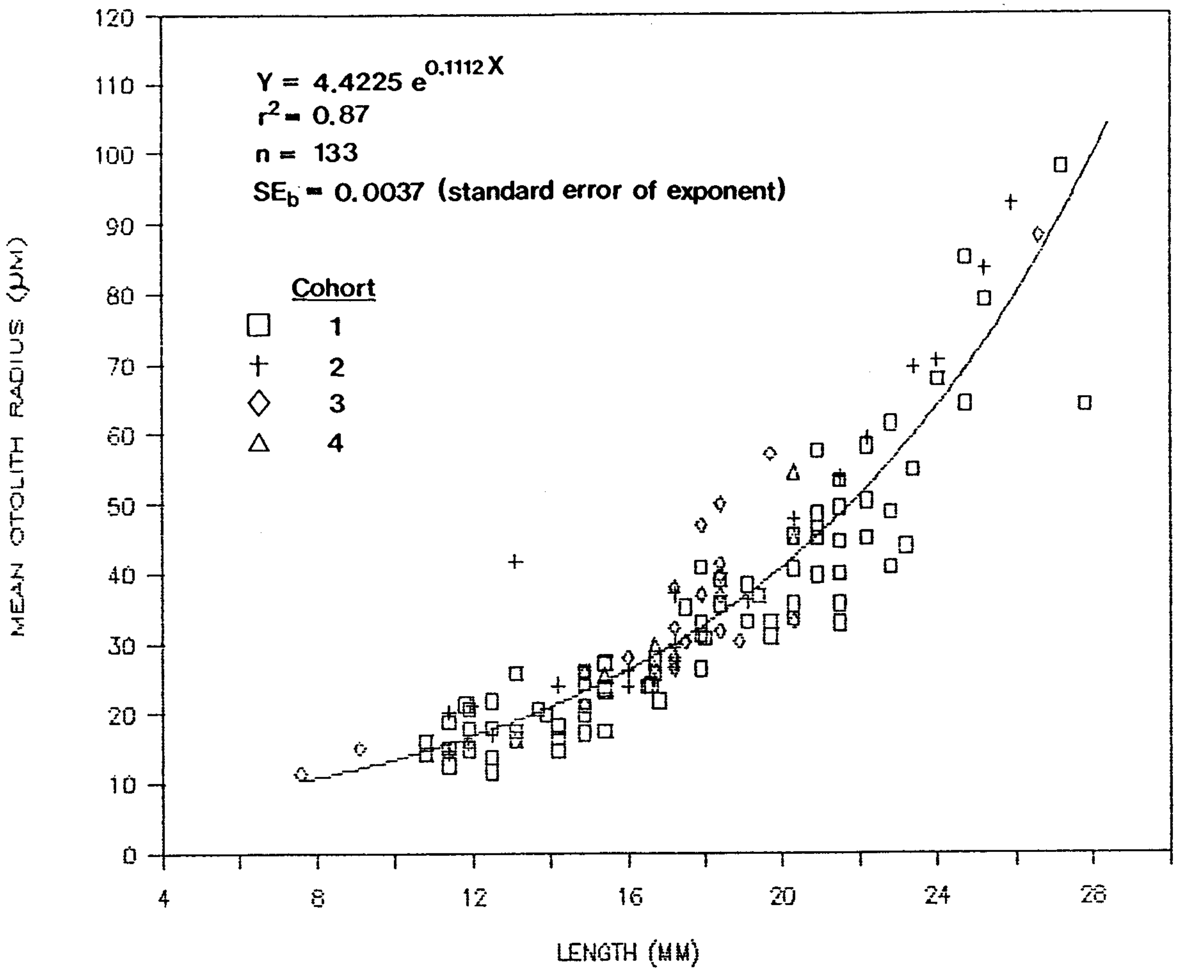


Figure 13: **REGRESSION OF MEAN OTOLITH RADIUS ON LENGTH OF HERRING LARVAE**

(34) $Y = 8.9928 (\ln X - 1.4867)$

where Y = fish length (mm) and X = otolith radius (μm).

Covariance analysis with dummy variables was also used to examine differences between cohorts in the relationship between otolith number and age. Age was defined as the number of days between the hatching date (back-calculated from the population growth curves) and the date of capture. There were no differences between cohorts, so a single regression was calculated

(35) $Y = -2.96 + 0.84X$

$r^2 = 0.73$, $n = 128$, $P<0.001$, $SE_b = 0.05$

where Y = mean number of rings for a fish, X = age (d), and SE_b = standard error of the ring deposition rate. The rate was not significantly ($P>0.05$, t-test) different from 1.0. Equation (35) predicts that the first ring was completely deposited at an average age of 5 d after hatch. A comparison of the mean number of rings at date of capture and the number of rings predicted from equation (35) for cohorts 1 to 4 shows (Fig. 14) a close agreement between measured and predicted ring number.

8.5 Weight-Length Relations

The logistic model provided the best fit to the weight-length data for cohorts 1 to 4 individually and for the combined data of cohorts 1 to 5. The 4 parameters of the logistic model are indistinguishable between cohorts, so only the fit to the combined data is shown in Fig. 15. This curve was used to calculate relative condition factor.

8.6 Specific Growth Rates

Specific growth rates calculated from the outermost rings in the sagittal otoliths are shown in Appendix F. They were highly correlated with each

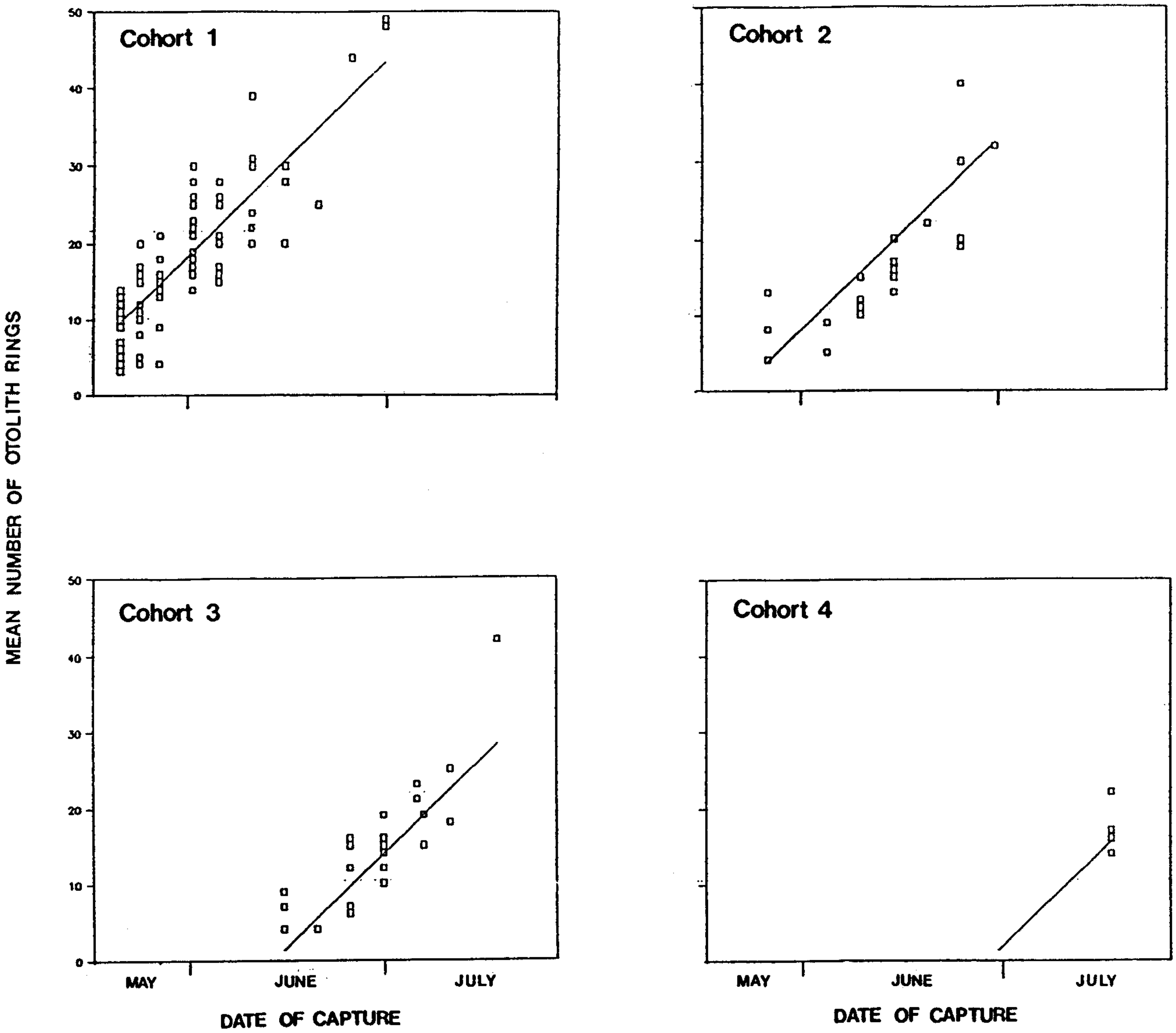


Figure 14 : **MEAN NUMBER OF OTOLITH RINGS PER FISH AT DATE OF CAPTURE**

NOTE: Solid lines are mean number of rings predicted from age of larvae using equation (35)

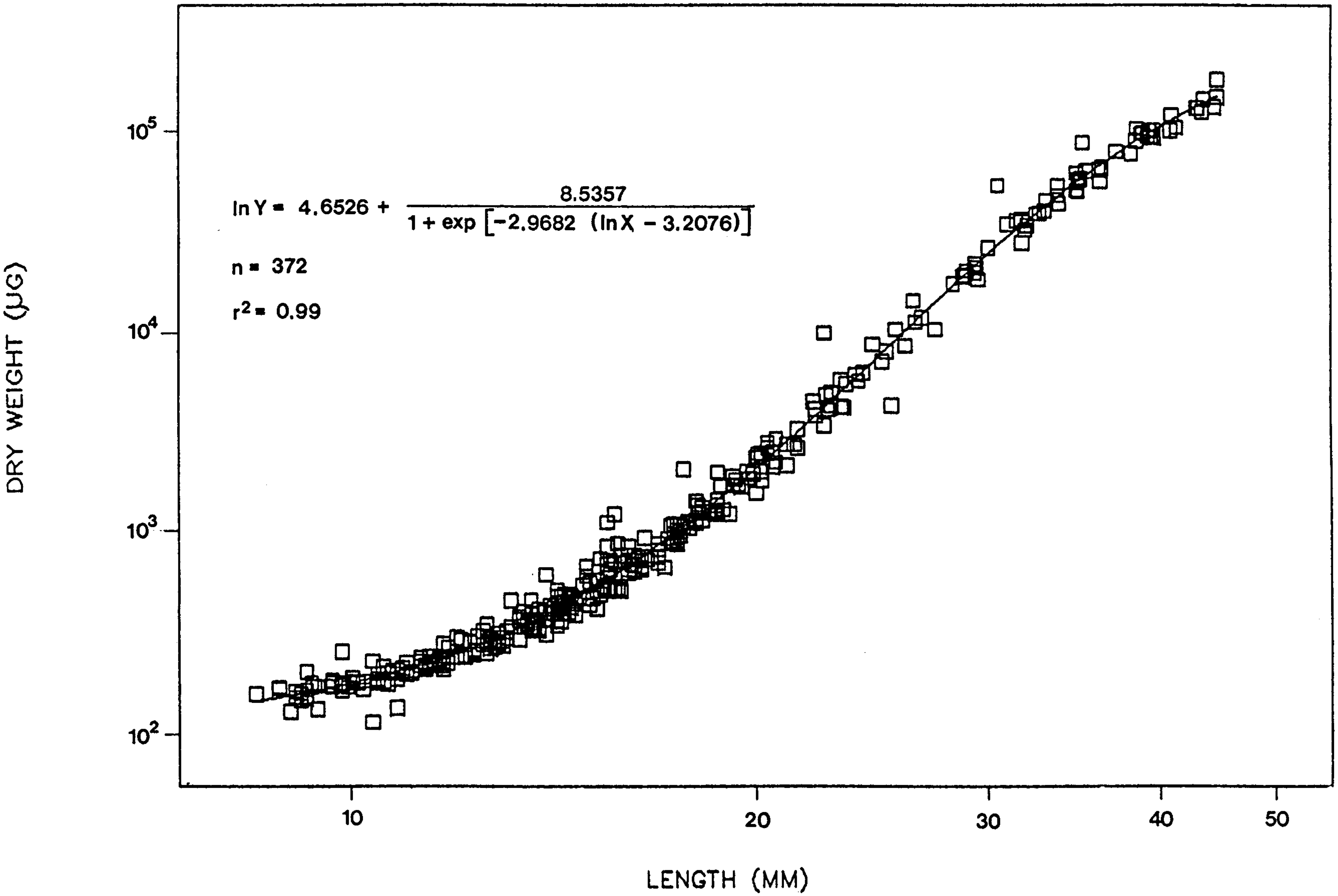


Figure 15 : LOGISTIC REGRESSION OF DRY WEIGHT ON LENGTH OF HERRING LARVAE AND JUVENILES OF COHORTS 1,2,3,4 AND 5 COMBINED

other ($r=0.90$ to 0.98), so only the growth rates calculated from the outermost ring, G_W, are used in the following analyses. The dome-shaped relationships between G_W and date of capture for cohorts 1 and 3 in Fig. 16 suggests the presence of a dome-shaped relationship between G_W and age similar to that reported by Oiestad (1983, cited by Kiorboe and Munk 1986) for Atlantic herring larvae. However, the apparent absence of such a relationship in cohort 2 suggests the presence of a second factor, perhaps a relationship between G_W and prey concentration similar to that reported by Kiorboe and Munk (1986) for Atlantic herring larvae. Response surface analysis identified the following equation as explaining the maximum variance of G_W with all-significant ($0.01<P<0.05$) coefficients

(36) $$Y = -1.8231 + 0.3919X_1 - 0.0062X_1^2 + 1.5820X_2$$
$$r^2 = 0.13,\ n = 108,\ P = 0.003$$

where $Y = G_W$ (%·d^{-1}), X_1 = age (d) of larvae and X_2 = ln[mean prey concentration (mg dry weight·m^{-3})]. Age and age^2 explained 9% of the variance in G_W and ln(prey concentration) explained the remaining 4%. The residuals of this equation were not significantly ($P>0.05$) correlated with mean temperature of the upper 20 m of the water column. Equation (36) predicts that G_W is maximal at an age of 32 d.

The absence of a significant relationship between G_W and temperature, and the low level of variance in G_W explained by age and prey concentration, was due to a lack of contrast in the environmental data. Mean temperatures of the upper 20 m of the water column from May 21 to June 25 fell within a narrow range of only 7.2 to 8.2°C (Fig. 4), and although mean prey concentrations ranged from 20.7 to 171.8 mg dry weight·m^{-3}, the increase in G_W over this range of prey concentrations that is predicted from laboratory rearing studies is only about 3%·d^{-1}. Fig. 17A compares G_W of Auke Bay herring larvae with that predicted by Kiorboe and Munk's (1986) regression model of G_W on ln(prey concentration) for Atlantic herring larvae; it is clear that G_W increases with prey concentration over the 20

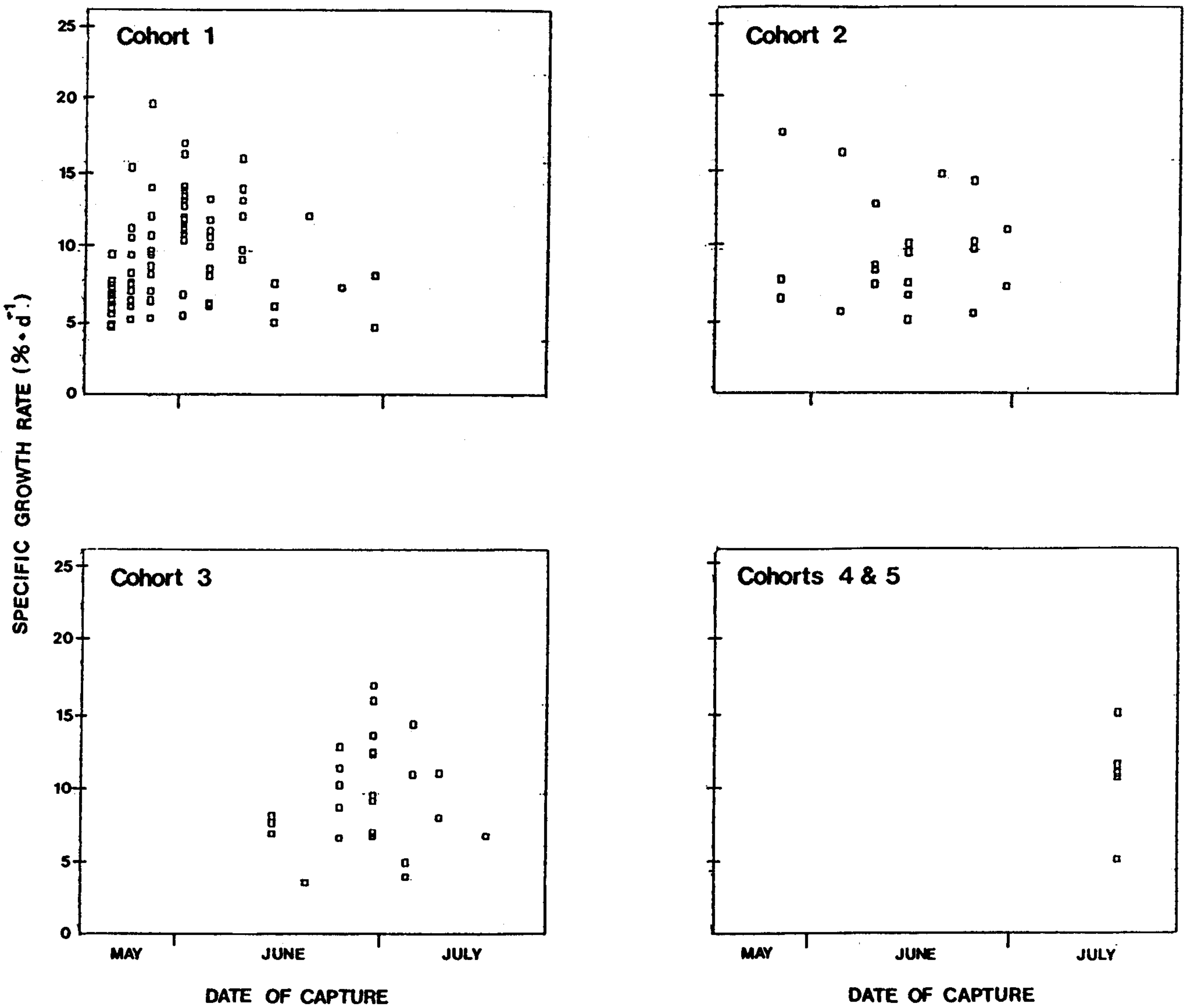


Figure 16: SPECIFIC GROWTH RATE OF HERRING LARVAE CALCULATED FROM THE WIDTH OF THE OUTERMOST OTOLITH RING AT DATE OF CAPTURE

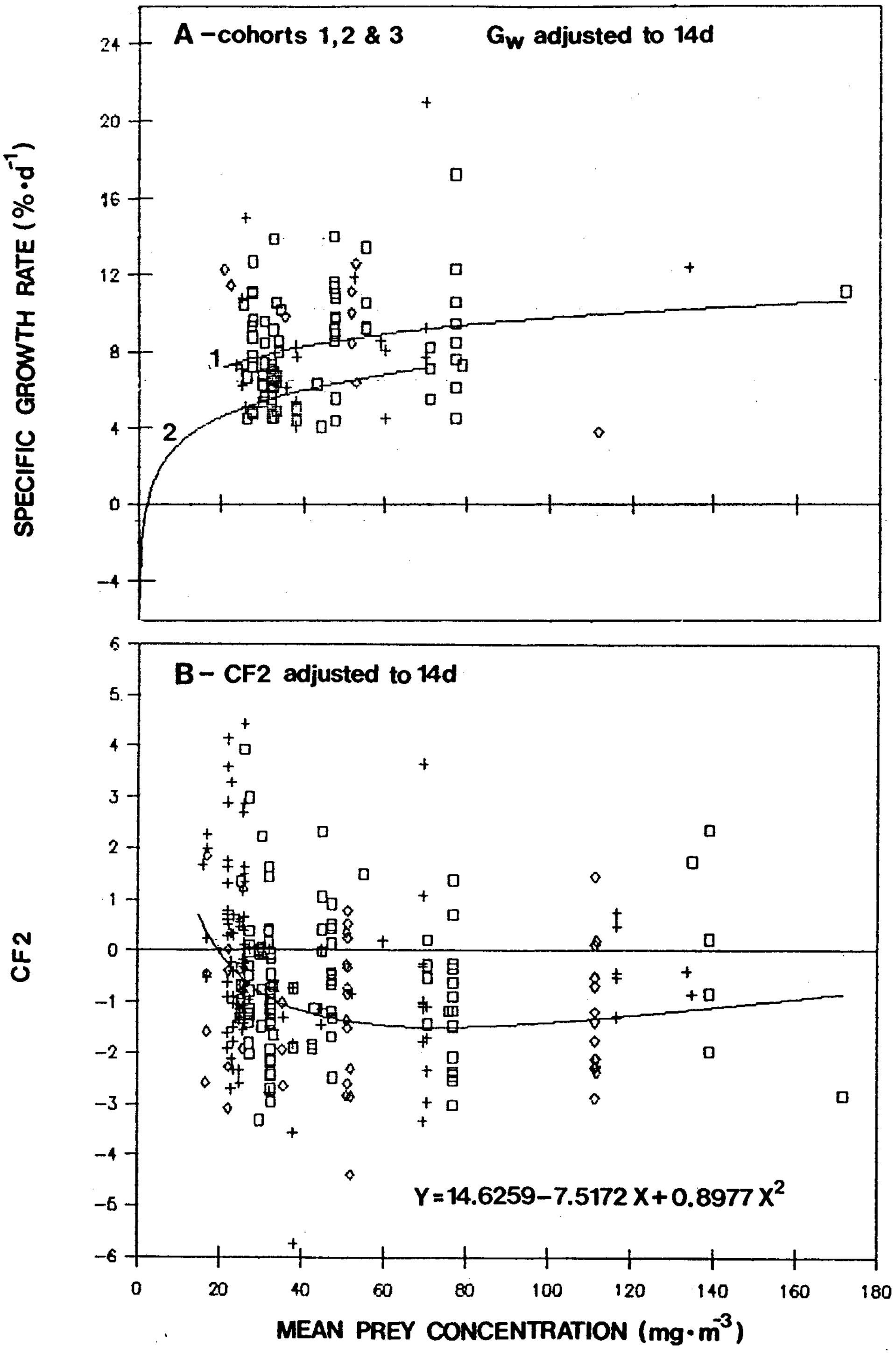


Figure 17. (A) Specific growth rates of herring larvae of cohorts 1, 2, 3 and 4 as a function of mean prey concentration at date. Symbols as in Fig. 13. Growth rates are adjusted to those expected of a 14 d old larva as explained in the text. Curve number 1 is specific growth rate predicted by equation (36) for a 14 d old larva. Curve number 2 is relationship reported by Kiorboe and Munk (1986) for laboratory-reared Atlantic herring larvae: Y=-1.36+2.00lnX. (B) morphometric condition factor CF2 as a function of mean prey concentration.

CF2 values adjusted to those expected of a 14 d old larva. Curve is CF2 predicted for a 14 d larva from equation (37).

to 170 $mg{\cdot}m^{-3}$ range at a much slower rate than it does over the 1 to 20 mg m^{-3} range.

In order to compare growth rates of Auke Bay herring larvae with those predicted by Kiorboe and Munk (1986) it was necessary to adjust the former to those of a 14 d old larvae because Kiorboe and Munk's (1986) model was developed from 1 to 3 week old fish. G_W was adjusted by multiplying it by the ratio of G_W predicted for an age of 14 d and prey concentration (X_2) by equation (36) to G_W predicted for age (X_1) and prey concentration (X_2) by equation (36). Over the prey concentration range of 20 to 70 $mg{\cdot}m^{-3}$ G_W of Auke Bay larvae was $2.3\%{\cdot}d^{-1}$ higher on average, than that predicted by Kiorboe and Munk's (1986) model, which suggests that Auke Bay herring larvae may have been feeding on high density patches of prey that were not measured by plankton tows that integrated the upper 30 m of the water column.

8.7 Condition

The two condition factors are listed in Appendix E. Response surface analysis indicated that there were no significant correlations between CF1 and age, ln(mean prey concentration) and mean water temperature. Therefore, this condition factor was not examined further.

Unlike CF1 there is substantial variation between cohorts in the trajectory of CF2 with date of capture (Fig. 18). The average condition of 0 to 10 d old larvae from cohort 2 was much lower (i.e. high CF2) than that measured for young larvae of cohorts 1 and 3. Since the mean date of hatch of cohort 2 (May 19) preceded the general decrease in concentration of prey that occurred between May 27 and June 10, this observation suggests a direct relationship between CF2 and prey concentration. Another factor to be considered is age, because CF2 clearly decreases with age in all cohorts.

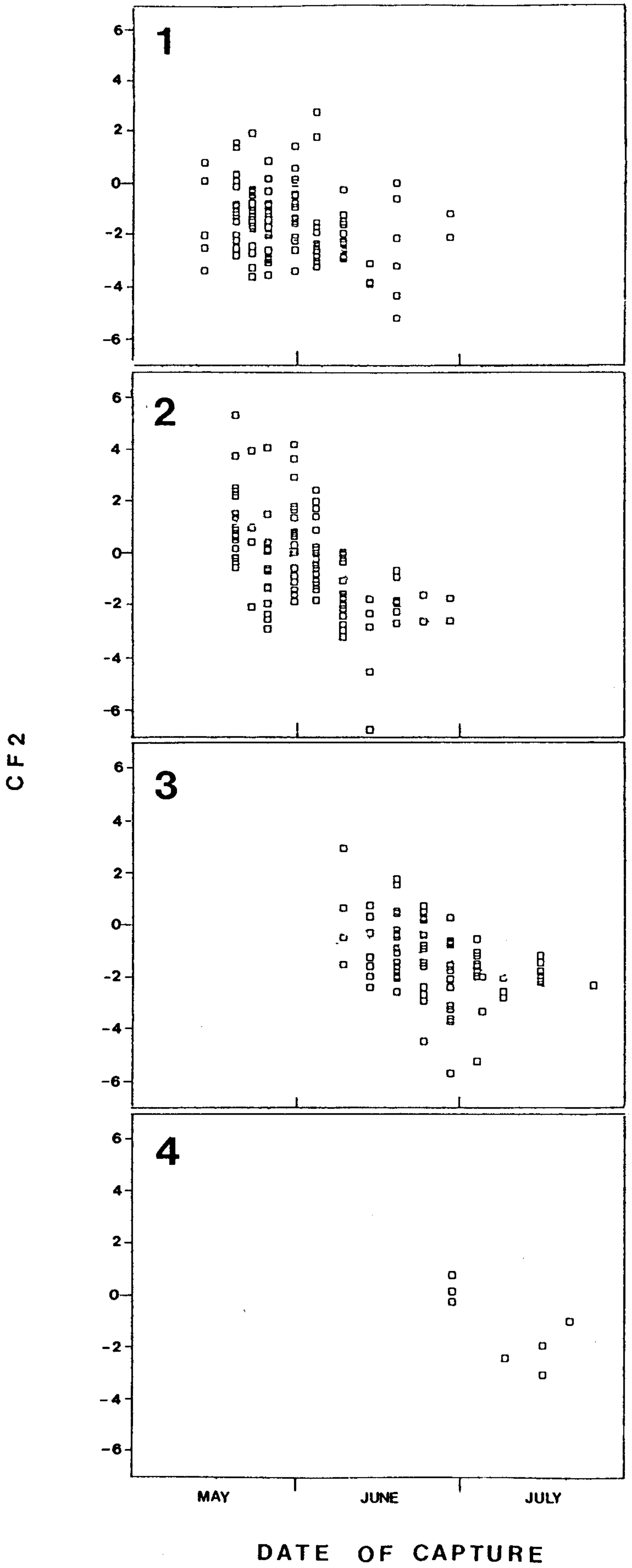


Figure 18

CONDITION FACTOR CF2 ON DATE OF CAPTURE FOR HERRING LARVAE OF COHORTS 1,2,3 AND 4

Response surface analysis of age, prey concentration, and water temperature identified the following equation as explaining the maximum variance in CF2 with all significant ($0.001<P<0.01$) coefficients

(37) $$Y = 15.6885 - 0.0759X_1 - 7.5172X_2 + 0.8977X_2^2$$
$$r^2 = 0.29,\ n = 261,\ P<0.001$$

where Y = CF2, X_1 = age (d), and X_2 = ln[mean prey concentration (mg dry weight$\cdot$m^{-3})]. Age accounted for 24% of the condition of CF2 and mean prey concentration accounted for the remaining 5% of the explained variation. CF2 was adjusted to an age of 14 d by adding to it the product of the coefficient for age of equation (37) and the difference between age and 19 d, i.e. 0.0759$\cdot$(age-14). These adjusted CF2's are plotted against prey concentration in Fig. 17B; CF2 is predicted by equation (37) to enter the starving class at prey concentrations below 21.6 mg$\cdot$m^{-3}.

9. DISCUSSION-GROWTH OF HERRING LARVAE AND JUVENILES

9.1 Number and Timing of Cohorts

The number of cohorts of Pacific herring identified in Auke Bay in 1988, 5, is the highest yet to be reported in one season at a single location. Jones (1978) reported only 2 cohorts per season in Auke Bay in 1975 and 1976, both Stevenson (1962) and McGurk (1987a, b) identified 3 separate cohorts per season of Pacific herring larvae in Barkley Sound, Vancouver Island, British Columbia, and Iizuka (1966) reported 2 cohorts per season in Akkeshi Bay, Hokkaido Island, Japan.

I attribute the difference in number of cohorts between this study and Jones' (1978) study to unknown biological factors, and not to problems related to sampling and data analysis. Jones (1978) sampled Auke Bay with plankton nets over the entire herring larvae season: from March 7 to August 28 in 1975 and from March to the end of July in 1976, so if there were more than 2 cohorts he would have captured them. Although he did not use length-frequency analysis to classify his larvae into cohorts, the standard deviations of the mean lengths of his larvae are similar to those calculated in this study, indicating that he classified his larvae at least as accurately as I did mine. Jones (1978) did not present his raw data in a form that would allow re-analysis using NORMPC.

Five cohorts of larvae per season are not uncommon in Atlantic herring. Lambert (1984) reviewed the evidence concerning larval cohort succession in this species and reported that 6 to 12 cohorts of Atlantic herring larvae were identified in catches from St. Mary's Bay, Nova Scotia, over a 7 mo period, and 3 to 8 cohorts from St. Georges' Bay, Nova Scotia, over a 6 mo period.

Maximum density of herring larvae in Auke Bay in 1988 occurred at or before May 25 (Table 11), which is the earliest date for maximum density that has

TABLE 11

Approximate dates of maximum density of Auke Bay herring larvae in relation to mean surface water temperature. The early date for 1988 is associated with higher temperatures.

Year	Date of Maximum Density of Herring Larvae	Surface Water Temperature (°C) Mar. 1-14 Mean	SD	n	Mar. 15-31 Mean	SD	n	Apr. 1-14 Mean	SD	n	Apr. 15-30 Mean	SD	n	May 1-14 Mean	SD	n	May 15-31 Mean	SD	n	Reference
1988	May 21	4.00	-	1	4.37	0.16	5	4.68	0.21	8	6.91	0.56	10	8.84	0.99	7	9.95	0.80	12	1
1987	June 2	-	-	-	4.05	0.24	4	5.53	0.12	3	5.39	0.49	6	7.60	0.86	3	8.34	0.76	4	2
1986	June 2	-	-	-	3.55	0.36	5	3.45	0.21	4	4.25	0.35	4	7.56	0.62	7	8.19	0.74	4	3
1976	June 1	-	-	-	-	-	-	2.90	0.80	2	5.30	1.60	3	5.20	0.10	2	6.50	0.50	2	4
1975	June 5	-	-	-	-	-	-	3.10	1.10	2	6.40	-	1	6.30	0.60	2	8.60	0.90	2	4

Note:

1. References: 1 = this study, 2 = Haldorson et al. (1988), 3 = Haldorson et al. (1987), 4 = Jones (1978).
2. Date of maximum density of herring larvae is an index of the date of first spawning.

ever been recorded in Auke Bay; it is at least 11 to 15 d earlier than the dates reported for 1975 and 1976 by Jones (1978), and 12 d earlier than the dates reported for 1986 and 1987 by Haldorson et al. (1987, 1988). This relatively early date of maximum density is associated with higher average surface water temperatures in April and May 1988 than in previous years, although there are no significant ($P>0.05$) correlations between dates of maximum density and mean temperatures for biweekly and monthly intervals from March 1 to May 31, probably because of low sample sizes. This observation is supported by Hay (1985), who reported highly significant inverse correlations between the mean time of spawning of Pacific herring in the Strait of Georgia and the mean surface water temperatures in March for the years 1951 to 1982. On average, an increase in mean March temperature of 1°C corresponded to a decrease in the mean date of spawning of 6 to 14 d in the Strait, a relationship that is similar to that observed in this study if one assumes that the date of first spawning and the date of maximum density of herring larvae are separated by a constant interval of time.

The mean (± 1SD) spacing in time between hatchings of herring cohorts in Auke Bay, 16.5 (± 4.6) d, is lower than the mean (± 1SD) spacing in time between hatchings of Pacific herring in Barkley Sound, Vancouver Island, reported by McGurk (1987a), 19.3 (± 8.5) d, and it is lower than the mean (± 1SD) spacing in time between hatchings of Atlantic herring reported by Lambert (1984), 17.5 (± 6.5) d. However, the mean (+1SD) spacing in time between spawnings of Auke Bay herring, 19.0 (± 3.8), is comparable with the latter two averages.

9.2 Growth in Length

The 4 major results of the analysis of population growth of Auke Bay herring larvae and juveniles: (1) linearity of growth in length over the larval stage; (2) average growth rates of 0.31 $mm\cdot d^{-1}$; (3) an increase in growth rate of larvae hatching later in the season; and (4) a decrease in growth rate of juveniles, have all been reported by previous authors for Pacific herring of Alaska, British Columbia, and Japan. Jones (1978) estimated growth rates of Auke Bay herring larvae of 0.35 $mm \cdot d^{-1}$ in 1975 and 0.30 and 0.50 $mm \cdot d^{-1}$ in 1976. He also reported that the growth rate of juveniles in 1976 slowed to 0.27 $mm \cdot d^{-1}$. Stevenson (1962) reported a growth rate of 0.30 $mm \cdot d^{-1}$ for a Barkley Sound, Vancouver Island, cohort hatching in March 1950 and a rate of 0.41 $mm \cdot d^{-1}$ for a cohort hatching in mid-April 1950. Iizuka (1966) reported rates of 0.21 and 0.32 $mm \cdot d^{-1}$ for herring larvae of Akkeshi Bay, Hokkaido Island, Japan. McGurk (1987a) reported linear rates of 0.36, 0.39, 0.40 and 0.41 $mm \cdot d^{-1}$ for larvae of Barkley Sound in 1981 and 1982. McGurk (1984b) summarized the literature on growth in length and weight of both Pacific and Atlantic herring larvae and reported that the growth rates of Atlantic herring larvae are similar to those of Pacific herring larvae, ranging from 0.16 to 0.43 $mm \cdot d^{-1}$.

9.3 Specific Growth Rates

This study is the first to measure recent growth rates of herring larvae from widths of otolith rings. It reports that approximately 9% of the variation in specific growth rate is due to a dome-shaped relationship between growth rate and age and 4% is due to an increase in growth rate with increasing prey concentration. The remaining 87% of the variation is due to natural variation in growth rate between fish and to errors of measurement.

The conclusion that the otolith radius - fish length relationship is the same for all 4 cohorts supports the conclusion that population growth rates were similar for all four cohorts. Reznick et al. (1989) and Secor and Dean (1989) recently reported that slower growing fish have larger otoliths than equal-sized, rapidly growing fish. Although they worked with guppies, Poecilia reticulata, and young striped bass, Morone saxatilis, respectively, they argued that the relationship is probably common to most species of fish including Pacific herring.

Daily ring formation in the otoliths of larval and juvenile fish appears to be a universal phenomenon (Campana and Neilson 1985). It has been reported in wild populations of Pacific herring larvae (McGurk 1987a) and in laboratory-reared populations of Atlantic herring larvae (Lough et al. 1982, Messieh et al. 1987). However, less-than-daily rates are also a common occurrence; they have been reported in populations of wild Pacific herring larvae by McGurk (1987a) and in laboratory-reared populations of Pacific herring larvae (McGurk 1984a) and Atlantic herring larvae (Geffen 1982, Lough et al. 1982, Campana et al. 1987). Two hypotheses have been advanced to explain this phenomenon: (1) the rate of ring deposition is directly related to the rate of growth of the fish and a threshold rate of growth must be exceeded before rings are deposited at a daily rate (Geffen 1982, McGurk 1984a); and (2) ring deposition is always daily, but rings deposited during periods of slow growth are too narrow to be resolved by light microscopy (Campana et al. 1987). These 2 hypotheses are not mutually exclusive and both have similar consequences for the practical application of otolith ring counts to ageing of herring larvae: the number of rings cannot be taken as an absolute index of age, but must be adjusted to take into account the apparent cohort-specific rate of ring formation. In this study an average rate of 0.84 d^{-1} was measured and subsequently used to convert ring widths to specific growth rates. This rate of ring deposition is close to that which would be expected from the average linear rates of growth in length. Both Geffen (1982) and McGurk (1984a) reported equations relating ring deposition rates and growth rates; their equations indicate that growth rates of 0.31 to 0.37 $mm \cdot d^{-1}$ should produce ring deposition rates of about 0.83 d^{-1}, which is similar to the rate measured in this study.

9.4 Condition

A comparison of the plots of CF2 on age given by McGurk (1986a: Fig. 1.12) for herring larvae of Bamfield Inlet, British Columbia, with the plots of CF2 on date of capture given in Fig. 18 of this report show similar ranges of CF2 values. The average CF2 of 3 separate cohorts of Bamfield Inlet herring larvae ranged from about 2.0 at hatch to -1.5 to -2.0 at an age of 30 d, and the ranges of CF2 for individual larvae were 4.0 to -4.0. The great majority of CF2 values for the Auke Bay study also fall within these ranges. The major difference between the 2 studies is that all 3 Bamfield Inlet cohorts had positive average CF2 values for the first 2 weeks after hatch, whereas only one of the 3 Auke Bay cohorts, cohort 2, followed such a trajectory. If we assume that CF2 is measuring the same aspect of condition in both Bamfield Inlet and Auke Bay herring larvae, then the condition of Auke Bay herring larvae was higher than that of Bamfield Inlet larvae, at least for cohorts 1 and 3.

9.5 Relationships of Growth and Condition to Environmental Factors

Population growth rates, specific growth rates, and condition factors indicate that herring larvae of cohorts 1, 3, and 4 grew fast and were in good condition compared to other populations of Pacific and Atlantic herring larvae. This was due to prey concentrations that were consistently higher than the average concentration that leads to slow growth and irreversible starvation. In contrast, the specific growth rates and condition factors of cohort 2 larvae indicate that they experienced significantly higher incidences of reversible and irreversible starvation. This is presumably the result of the fact that cohort 2 larvae spent the first 2 weeks of their lives in a prey field of lower than average concentration.

This evidence offers partial support for the hypothesis that growth and condition of Pacific herring is controlled by the concentration of prey. This qualified conclusion is necessary because the statistical correlations between specific growth rate and prey concentration, and between condition factor and prey concentration, are relatively weak, although they are statistically significant. The low correlations are due to a narrow range of environmental variability, and to the limited resolution of the techniques used to measure specific growth rate and physical condition.

If the critical period hypothesis is correct, and the primary agent of mortality of young herring larvae is irreversible starvation, then total mortality of young larvae of cohort 2 is predicted to be higher than that of cohorts 1, 3 and 4. A corrollary of the critical period hypothesis is that mortality due to predation is more important than starvation in the dynamics of cohorts 1, 3 and 4. These predictions are tested in section 10.0 by comparing total mortality of cohorts 1, 2 and 3 between each other and by searching for correlations between mortality, condition and predator concentration.

10. RESULTS-DISTRIBUTION AND SURVIVAL OF LARVAE

10.1 Cohort Densities

Numbers and densities of Pacific herring larvae captured in Auke Bay in 1988 are listed in Appendix D. Densities were calculated in 2 ways: directly from the number of herring larvae counted in each sample (Measured density), and corrected for the effect of net evasion (Corrected density). In this section, I examine the importance of 3 factors which may have biased estimates of larval density: (1) loss of alcohol-preserved larvae during storage of the unsorted plankton samples due to the decomposition of the larvae; (2) loss of larvae due to their extrusion through the meshes of the net; and (3) evasion of the towed plankton net by larger herring larvae..

In order to examine the first factor, 50 pairs of measured densities of formalin-preserved samples and alcohol-preserved samples taken at the same date and site were extracted from Appendix D. The ratios of the densities of formalin-preserved herring larvae to alcohol-preserved herring larvae of each pair were then transformed with natural logarithms in order to normalize the data (ln-transformation is used in all analyses of the density data in this study). The ln-transformed ratios were not significantly connected with date of capture ($P>0.05$) or mean length of each pair of samples ($P>0.05$). Therefore, the type of preservative did not warrant any correction of herring larvae density.

Plots of density of larvae against age for cohorts 3 and 4 (Fig. 22) suggest that extrusion of herring larvae through the 505 μm mesh may have been a factor responsible for an underrepresentation of larvae younger than 15 d old. There is no data available to test the hypothesis that extrusion of young herring larvae occurs in 505 μm mesh nets because there were no tows of the 333 and 505 μm mesh nets taken at the same date and station. However, there are density estimates for 10 pairs of 165 μm and 333 μm mesh nets taken at the same date and site in Auke Bay in 1988 (Appendix D). Ratios of the 333 density to the 165 density were ln-transformed and plotted against mean length. The data showed no trend, indicating that extrusion is not a factor influencing the measured densities of herring larvae in the 165 and 333 μm mesh catches.

Evasion of towed plankton nets by fish larvae has been shown to increase exponentially with length of larvae (Smith and Richardson 1977, Leak and Houde 1987, McGurk 1989). One method of correcting for this factor is to take advantage of the fact that evasion is usually lower during the night than during the day because the net is less visible to the larvae at night. The ratio of night to day densities at the same date and site can be used to adjust the densities measured by day tows. Six night tows were made in Auke bay in 1988 specifically for the purpose of generating a correction equation for net evasion. Separating the catches into cohorts gave 15 pairs of night/day densities (Appendix D). Plotted against mean length, the ratios clearly increase with length (Fig. 19). A linear regression of all of the ln-transformed ratio against length was significant ($0.01<P<0.05$), but this regression could not be used to adjust catches for net evasion because it predicted a ratio less than 1.0 at mean lengths below 12.4 mm, which means that densities of larvae with mean lengths less than 12.4 mm would actually be decreased rather than increased as a result of correction for net evasion. This result is due to the inclusion of 2 very low ratios derived from a single night tow: sample number 46. Without these 2 ratios and 2 other ratios calculated from sample number 46, the regression of ratios on mean length predicted positive ratios at all lengths greater than 8.8 mm and so it was chosen as the most appropriate equation. Rearranged as

(38) $Y = Y_o 0.5608\exp(0.1173X)$

where Y = corrected density (m^{-3}), Y_o = measured density (m^{-3}), and X = mean length (mm), it was used to adjust all day densities for net evasion. The densities of sample number 46 were corrected with this equation because it was reclassified as a day catch. Night catches were not adjusted for net

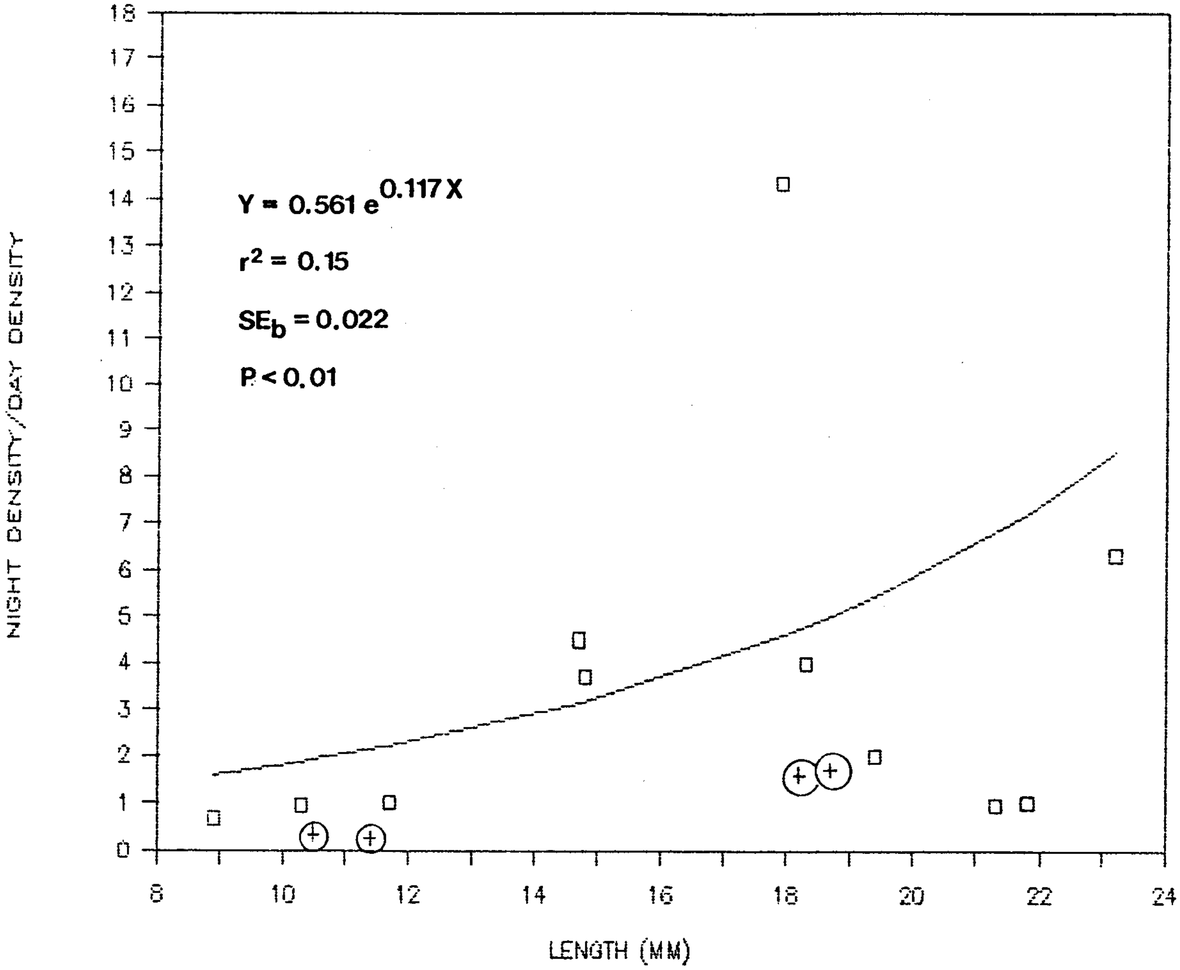


Figure 19: REGRESSION OF THE RATIO OF DENSITIES OF HERRING LARVAE CAUGHT AT NIGHT TO DENSITIES OF HERRING LARVAE CAUGHT DURING THE DAY ON MEAN LENGTH OF HERRING LARVAE (circled points were excluded from the regression)

evasion. Based on this equation, 63.5% of the available 8.8 mm long herring larvae, 30.7% of the available 15 mm long herring larvae and 5.3% of the available 30 mm long herring larvae were captured by day plankton net tows. These numbers are conservative compared to those calculated by other authors. For example, McGurk (1989) calculated that 68.6% of available 8.8 mm long herring larvae, 12% of available 15 mm long herring larvae and 0.2% of available 30 mm long herring larvae in were captured in day tows of a 481 µm mesh net in Barkley Sound, British Columbia. Leak and Houde (1987) calculated that 6.2% of available anchovy larvae, Stolephorus purpureus, 8.8 mm long and 0.3% of available anchovy larvae 15 mm long were captured in day tows of a 333 µm mesh net in Hawaiian waters.

10.2 Advection, Diffusion and Patchiness

No significant ($P>0.05$) rates of advection were calculated from the change in position of the centroids of each cohort with date of capture because the centroids did not consistently move in one direction (Fig. 20). Instead, the centroids tended to remain between station ABM ($y=1.54$ km) and CSI ($y=4.84$ km) on the y-axis. No coefficients of diffusion were calculated because no correlations were found between spatial variance of larval density, s_{xy}^2, Julian date of capture, and age of larvae. These results indicate that herring larvae were retained in Auke Bay instead of being transported offshore. This conclusion was employed in the calculation of egg-larval mortality rates of cohorts 2 and 3, and as an assumption underlying the population models used to estimate total mortality of cohorts 1, 2 and 3.

Examination of spatial patchiness at date for cohorts 1, 2, 3 and 4 shown in Fig. 21 suggested a positive relationship between patchiness and date of capture, as well as a curvilinear relationship between patchiness and age of larvae for each cohort. This was confirmed with response surface analysis; the equation that explained the maximum amount of variation in Lloyd's patchiness index with all-significant coefficients ($P<0.05$) was

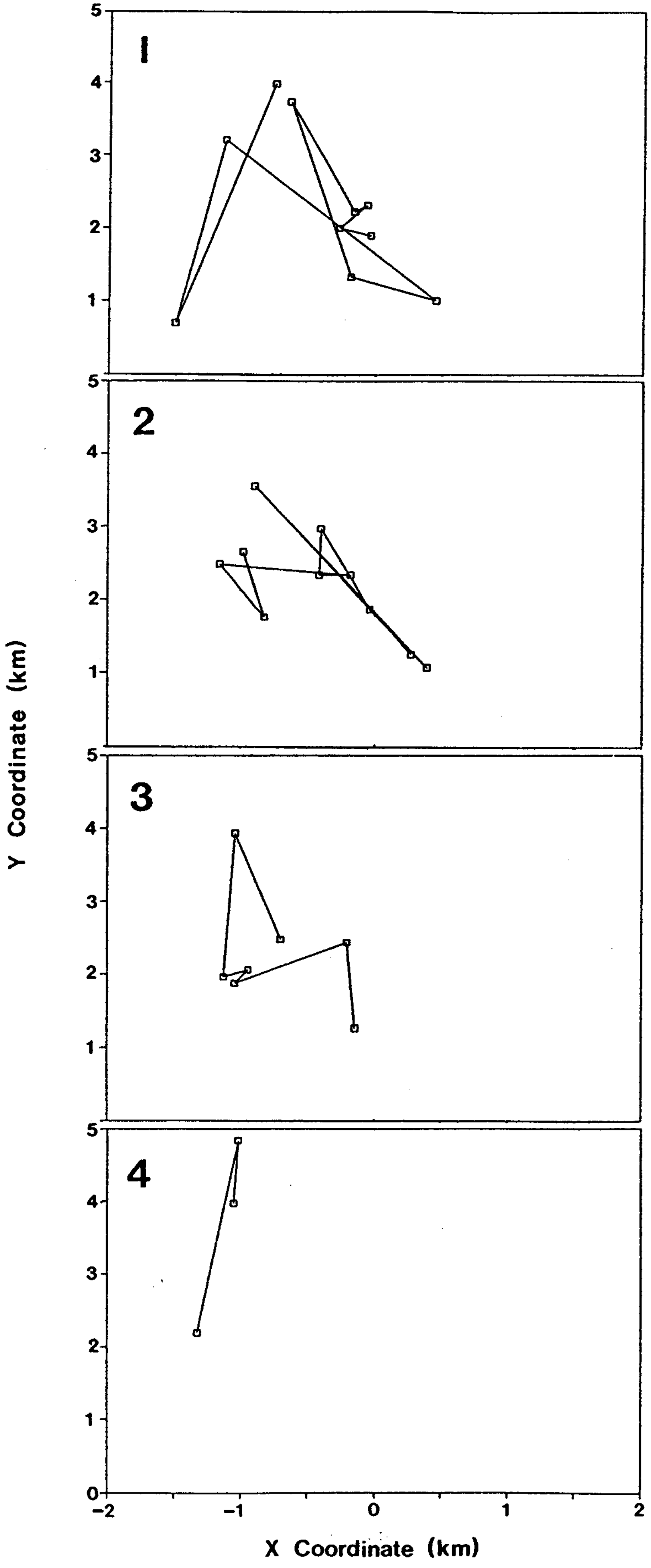


Figure 20

CENTROIDS OF COHORTS 1,2,3 AND 4 AT EACH SAMPLING DATE AND X-Y COORDINATES (no offshore movement is apparent)

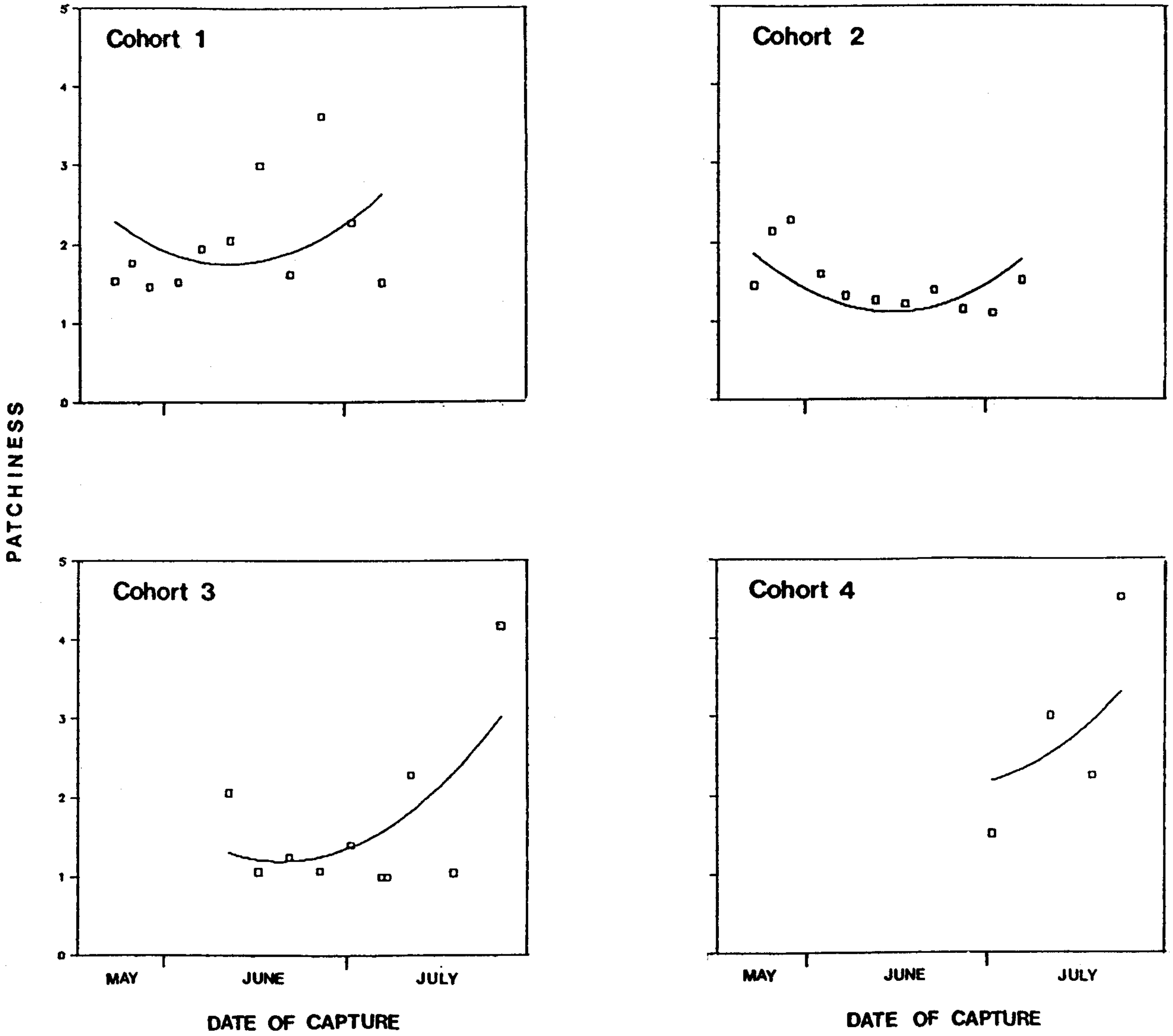


Figure 21: SPATIAL PATCHINESS ON DATE OF CAPTURE FOR HERRING LARVAE OF COHORTS 1,2,3 AND 4

NOTE: Solid lines are patchiness predicted from age of larvae and date of capture with equation (39)

(39) $$Y = 58.2650 + 0.3620X_1 - 0.7226X_2 + 1.612x10^{-3}X_1^2 + 2.29x10^{-3}X_2^2 - 2.506x10^{-3}X_1X_2$$
$$r^2 = 0.45, n = 36, P = 0.002$$

where Y = patchiness, X_1 = age (d) of larvae, and X_2 = Julian date of capture. A curvilinear relationship between patchiness and age was expected from previous studies of patchiness of fish eggs and larvae (Smith 1973, Hewitt 1981, McGurk 1987b), but the significant effect of date suggests that one or more environmental factors that varied with date also affected spatial patchiness of herring larvae in Auke Bay.

The roles of 6 factors: mean temperature of the upper 20 m of the water column, mean total prey concentration, mean total predator concentration, adjusted mean predator concentration, and the average dry weight of the larvae, in controlling patchiness were examined by substituting them for date in an analysis similar to that of equation (39). All factors, including patchiness and age, were ln-transformed because it was assumed that they acted multiplicatively. Partial correlation analysis showed that ln(weight) (r=0.27) and ln(adjusted predator concentration) (r=0.24) had the highest correlation coefficients, with all other factors having coefficients ranging from 0.01 [ln(prey concentration)] to -0.14 [ln(temperature)]. Response surface analysis of the former 2 variables gave the following equation

(40) $$Y = 5.76x10^{-2} + 5.42x10^{-3}X^2 + 1.18x10^{-2}X_2^2$$
$$r^2 = 0.42, n = 35, P = 0.0002$$

where Y = ln(patchiness), X_1 = ln[dry weight (ug)], and X = ln[adjusted mean predator concentration ($mg \cdot m^{-3}$)].

10.3 Mortality

A Pareto-type model provided the best fit to the density data of cohorts 1 and 2 (Fig. 22). None of the 3 population models gave an adequate description of the cohort 3 and 4 densities because they gave ecologically unreasonable parameter values: negative Z for the linear and Pareto models and extraordinarily high Z and negative K_x for the advection-diffusion model. I truncated the data set of cohort 3 so that it contained only the descending right-hand side of the catch curve, i.e. only densities that were 20 d or older, and re-analyzed this partial data set. This procedure is standard practice for the analysis of catches of fish the youngest and smallest members of which are too small to be fully catchable by the gear or who live in a different habitat from the older and larger members of the population (Ricker 1975). The Pareto model explained the highest amount of variance of this partial data set.

Egg-larval mortality, M_{el}, was calculated from equation (31) to be 0.93 d^{-1} over ages 0 to 1 d of cohort 2, and 0.12 d^{-1} over ages 0 to 19 d of cohort 3 (Fig. 23). Sensitivity analyses of equation (28) were performed in order to assess the amount of error involved in these calculations. They involved changing each of the eight parameters separately in equation (31) by ±5% and ±25% and calculating the percent change in M_{el}. In both cohorts 2 and 3, a +5% to -5% and a +25% to -25% change in each of the parameters N_0, A and H led to only a -2.5% and a -12.5% to +12.5% change in M_{el}, respectively. However, a +5% to -5% and a +25% to -25% change in t led to -4.8 to +5.3% and a -20.0 to +33.5% change in M_{el}, respectively. Therefore, M_{el} was most sensitive to t, the number of days between the mean date of hatching and the first date at which larval density could be estimated. Fortunately, this parameter was measured with relatively little error; both forward- and backward-calculation of the hatching date from the range of surface water temperatures did not alter the hatching date by more than 1 d (section 6.3). Thus a maximum probable error of ±30% of M_{el} for both cohorts 2 and 3 is appropriate (Fig. 23).

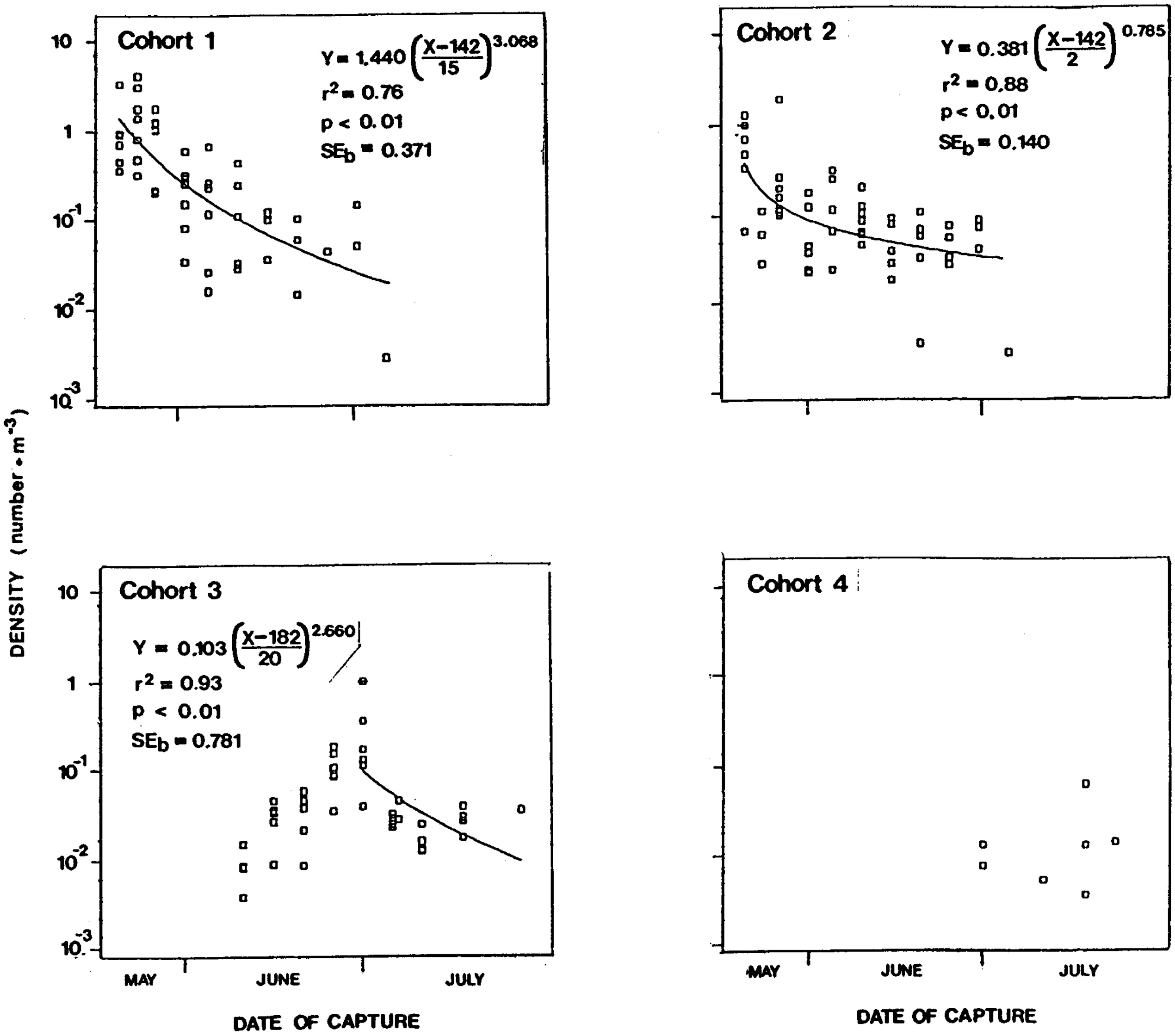


Figure 22 : REGRESSIONS OF DENSITIES OF HERRING LARVAE ON DATE OF CAPTURE

SOLID LINES ARE PARETO-TYPE POPULATION MODELS: $N_t = N_o\,([JD-a]/t_o)^b$

where: N_t = density (m^{-3}) at age t(d)

N_o = density at age t_o

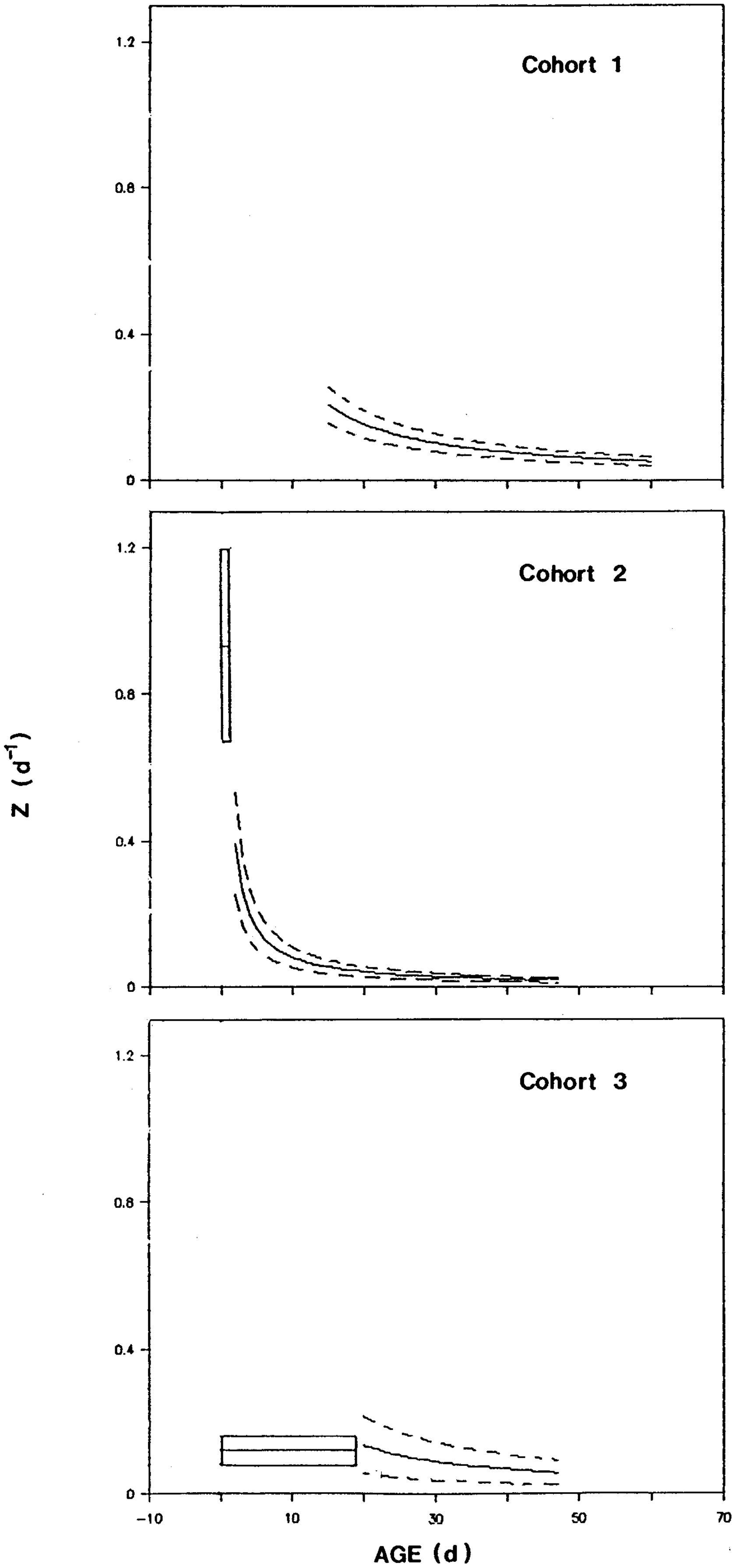
JD = Julian date at capture

a = Julian date at hatch

t_o = youngest age in a data set

b = mortality coefficient

Figure 23 TOTAL MORTALITY (solid lines) AND EGG-LARVAL MORTALITY (boxes enclose ±30% CONFIDENCE LIMITS OF TOTAL MORTALITY



Two trends are clear in the plots of total mortality on age: first, the mortality of newly-hatched 0 to 10 d old larvae was about 6 times higher in cohort 2 than in cohort 3; and second, the mortality of cohort 2 larvae older than 10 d was half the magnitude of that in cohorts 1 and 3. Six factors: age (t) and mean dry weight (W) of the larvae, the mean total (P) and adjusted (Padj) concentrations of predators, mean CF2 condition, and spatial patchiness (p), were examined in order to assess their role in controlling mortality rate. All variables including Z were ln-transformed; 1 was added to age because of 2 cases of 0 age, and 10 was added to CF2. Partial correlation analysis

	lnZ	ln(t+1)	lnW	lnP	lnPadj	ln(CF2+10)	lnp
lnZ	1.00						
ln(t+1)	-0.39	1.00					
lnW	-0.11	0.43	1.00				
lnP	-0.03	0.10	0.21	1.00			
lnPadj	-0.14	-0.10	-0.32	0.94	1.00		
ln(CF2+10)	0.09	-0.37	-0.38	0.40	-0.24	1.00	
lnp	0.30	-0.11	0.34	-0.04	0.12	-0.03	1.00

showed that Z was most highly correlated with age, followed by patchiness, the adjusted concentration of predators, and weight of the larvae. Total concentration of predators and mean CF2 condition were weakly correlated with Z. When all 6 variables were used in a multiple regression only age was selected as significant.

(41) $Z = 0.5273(\text{age}+1)^{-0.62}$

$r^2 = 0.54$, $n = 33$, $P<0.001$, $SE_b = 0.10$

When age was excluded from the analysis, and only body weight of the larvae and their patchiness were included, as a test of the mortality-patchiness hypothesis (McGurk 1986b), then response surface analysis identified the following equation as explaining the most variation in lnZ with all-significant coefficients.

(42) $$Z = 0.9549W^{-0.40}\ p^{\ 0.81}$$

$$r^2 = 0.46,\ n = 33,\ P = 0.0001,\ SE_W = 0.0819,\ SE_p = 0.3646$$

Equation (41) predicted higher Z at ages 0 and 1 for cohort 2 than was predicted by equation (42), but neither equation predicted the lower average Z in older larvae of cohort 2.

11. DISCUSSION-DISTRIBUTION AND SURVIVAL OF LARVAE

11.1 Advection and Diffusion

The absence of significant advection and diffusion of herring larvae out of Auke Bay supports the hypothesis that herring larvae were retained in Auke Bay. The retention area of the Auke Bay herring larvae was at least as large as Auke Bay because larvae were found between Coghlan and Spuhn Islands, but it may not have been very much larger than Auke Bay because many of the highest densities of herring larvae measured in Auke Bay were taken at ABM station in the middle of the Bay. This is not the distribution expected if larvae were being swept out of Auke Bay, but it is the pattern expected if the herring larvae were being retained within Auke Bay.

In order for the centroid of the Auke Bay spawnings to have remained within Auke Bay, i.e. to have traveled less than 5 km between hatching and the age of onset of schooling behaviour at 25 d (Marliave 1980, McGurk 1987b), the average advection rate must have been less than or equal to 5 $\text{km}\cdot(25\ \text{d})^{-1}$ or 0.2 $\text{km}\cdot\text{d}^{-1}$. This is similar to an advection rate of 0.15 $\text{km}\cdot\text{d}^{-1}$ estimated by McGurk (1989) for Pacific herring larvae that hatched in Bamfield Inlet, British Columbia. Both Auke Bay and Bamfield Inlet are sheltered from strong offshore currents that could transport fish larvae large distances in short time periods, so it is not unreasonable to expect that Auke Bay herring larvae would have advection rates of similar magnitude to those of Bamfield Inlet herring larvae. The same reasoning predicts that herring larvae that hatch from open unsheltered coasts, or which hatch into offshore waters from eggs laid on the continental shelf, should be advected at rate much higher than 0.2 $\text{km}\cdot\text{d}^{-1}$. This is what has been observed for Atlantic herring larvae that have been studied in offshore waters, their advection rates are an order of magnitude higher than those measured in Bamfield Inlet, ranging from 1 to 3 $\text{km}\cdot\text{d}^{-1}$ on Georges Bank (Wright and Lough 1979, cited by Munk et al. 1986) to 3.4 to 9 $\text{km}\cdot\text{d}^{1}$ in the North Sea and off the west coast of Scotland (Munk et al. 1986, Heath and

MacLachlan 1987, Heath and Rankine 1988). However, not all patches of Atlantic herring larvae have been found in offshore waters of unidirectional current flow. Heath et al. (1987) reported the retention of a patch of Atlantic herring larvae for at least 2 wk in inshore waters of the Pentland Firth on the northern coast of Scotland due to the formation of a gyre in that area. Larvae in areas further offshore from the Firth were rapidly dispersed due to coastal currents.

The expected diffusion rates of herring larvae in Auke Bay can be calculated using a simple relationship between the radial velocity of dispersal of a cohort of herring larvae, v $(\mathrm{km \cdot d^{-1}})$, the coefficient of radial diffusion, K $(\mathrm{km^2 \cdot d^{-1}})$, and the coefficient of mortality, Z $(\mathrm{d^{-1}})$. Okubo (1980) showed that for a population dispersing radially according to a one-dimensional form of equation (27), i.e.

$$(43) \qquad N_{xt} = \frac{C}{4\pi HKt} \exp\left[-\frac{x^2}{4Kt} - Zt\right]$$

where N_{xt} is density $(\mathrm{km^{-3}})$ at position x (km) and time t (d), an isocline of constant density travels away from the centroid at a rate of

$$(44) \qquad v = \frac{x}{t} = \pm 2K\left(\frac{1}{2t} - Z\right)^{\frac{1}{2}}$$

which rapidly converges to

$$(45) \qquad v = \pm\, 2(KZ)^{\frac{1}{2}}$$

as t goes to infinity. This can be rearranged as

$$(46) \qquad K = \frac{1}{Z}\left(\frac{v}{2}\right)^2$$

In this case, v is calculated on the assumption that most young larvae are retained in Auke Bay, i.e. $v = 0.2\ km\cdot d^{-1}$. Z is taken as the slope of a linear regression of ln(larval density) on age or date: 0.10 and 0.05 d^{-1} for cohorts 1 and 2, respectively. Thus, K of Auke Bay herring is calculated from equation (46) to range from 0.1 to 0.2 $km^2\cdot d^{-1}$. If the "retention area" is set at 10 km, instead of 5 km, then $v = 0.4\ km\cdot d^{-1}$ and K is predicted to range from 0.4 to 0.8 $km^2\cdot d^{-1}$. This range of diffusivities includes those reported by McGurk (1989) for Pacific herring larvae in Bamfield Inlet: 0.08 to 0.48 $km^2\ d^{-1}$. These diffusivities are among the lowest measured for fish eggs and larvae, due probably to the enclosed nature of Bamfield Inlet that reduced wind- and wave-generated mixing of the upper water layer and due also to the relatively small area of Bamfield Inlet. Okubo (1971) has shown that the diffusivity of dye particles in the sea increases exponentially with scale as larger scale eddies are incorporated.

Since both Auke Bay and Bamfield Inlet are relatively small and sheltered embayments, it is not unreasonable to conclude that herring larvae that hatched into them have similar diffusivities. This reasoning predicts that herring larvae in offshore waters should have much higher diffusivities and this is indeed the case. Munk et al. (1986) reported horizontal diffusion coefficients of 18.41 and 2.94 $km^2\cdot d^{-1}$ for the long and short axes, respectively, of a patch of Atlantic herring larvae in the Buchan area of the North Sea, and Heath and MacLachlan (1987) reported horizontal diffusion coefficients ranging from 0.5 to 10.0 $km^2\cdot d^{-1}$ for a patch of Atlantic herring larvae off the western coast of the Outer Hebrides Islands.

In summary, the rates of advection and diffusion expected under the assumption that herring larvae were retained in Auke Bay are similar to those measured by McGurk (1989) for small cohorts of herring larvae that hatched in the protected waters of Bamfield Inlet. This analysis suggests that the retention area of Auke Bay herring was not much larger than the Bay itself. There are two possible mechanisms for retention of herring larvae in Auke Bay: a counter-clockwise gyre of surface currents, and diel vertical migration of the larvae. Surface currents are important to the distribution of Pacific herring larvae because the larvae aggregate in the upper 20 m of the water column (Stevenson 1962, Robinson 1988). However, vertical migration of larvae in order to take advantage of different current speeds and directions at different depths has also been implicated as a retention mechanism in Atlantic herring in estuaries (Fortier and Leggett 1983) and off continental shelves (Stephenson and Power 1988). Both Stevenson (1962) and Robinson (1988) reported that Pacific herring larvae were aggregated in surface waters during daylight hours and sank lower in the water column during periods of darkness. This is a migration pattern similar to that exhibited by non-osmerid fish larvae in Auke Bay. Haldorson et al. (1988) reported that the larvae of six species of fish in Auke Bay actively migrated vertically in two distinct patterns: eulachon and capelin larvae rose to the surface at night and descended during the day, but all other species including walleye pollock, Theragra chalcogramma, rock sole, Lepidopsetta bilineata, flathead sole, Hippoglossoides elassodon, and northern smoothtongue, Leuroglossus schmidtii, sank at night and rose to the surface in the morning. Regardless of which type of migration pattern they exhibited, all six species returned to the depth strata, usually 5 to 15 m deep, with the highest concentration of copepod nauplii as soon as light intensity was high enough in the early morning to allow visual feeding. This evidence suggests that herring larvae in Auke Bay may have been exposed to different current speeds and directions as they moved through each diel cycle of vertical migration.

11.2 Mortality

This study is the first to describe total mortality of herring larvae as an age-dependent phenomenon. All previous reports have described the mortality of Pacific and Atlantic herring larvae as constant (Das 1968, Dragesund and Nakken 1971, 1973, Graham and Chenoweth 1973, Lough et al. 1981, Henderson et al. 1984, Graham and Townsend 1985, Munk et al. 1986, Heath and MacLachlan 1987, McGurk 1989).

The fact that cohort 2 hatched into a period of relatively low prey concentration, and that in the 0 to 10 d age period it had the lowest specific growth rates and CF2 condition and the highest total mortality, strongly suggests a link between prey concentration, growth and mortality. However, this linkage is not supported by a statistical analysis of mortality rate; the high egg-larval mortality rate of cohort 2 is not well explained by any variable except age.

12. GENERAL DISCUSSION

In this section I discuss the results of this study with special reference to the two hypotheses presented in the Introduction. First, I discuss the evidence supporting the hypothesis that was tested in this study: the idea that growth and fitness of larval herring is controlled by food production in their rearing area. Second, I briefly discuss the evidence supporting the two associated hypotheses underlying this study: the ideas that growth and fitness limits survival in larval herring, and that survival in the larval stage is the primary determinant of year-class success. Finally, I discuss the implications of this study for future research on the early life history of Pacific herring in Alaska.

12.1 Growth-food Production Hypothesis

The answer to the primary question of this study: what is the relationship between growth and fitness of herring larvae and environmental conditions in Auke Bay? Is that about 9% of the variation in specific growth rate is due to age and 4% is due to variation in prey concentration, and that 24% of the variation in condition factor is due to age and 5% to prey concentration. Prey concentration was not a major factor affecting growth and condition because it was relatively high over the sampling season.

An interesting result of this study is the fact that it confirms the validity of Kiorboe and Munk's (1986) relationship between specific growth rate and prey concentration. This suggests that experimental work on laboratory-reared herring larvae can be extended to natural ecosystems.

This study supports the results reported for studies of the condition of Atlantic herring larvae. In general, the relationship between condition and prey concentration is positive but weak, indicating that larvae are not food limited. Blaxter (1971) compared condition ($W \cdot L^{-3}$) of Atlantic herring larvae from the Firth of Clyde with the biomass of zooplankton that was retained on a 208 µm silk mesh and which had been previously identified as prey from gut contents analysis. He reported that there was an inverse relation between condition and biomass, and concluded that this counter-intuitive result may have been caused in part by the unreliability of this simple index of condition and also by the difficulty of accurately measuring biomass of prey. Cohen and Lough (1983) measured the feeding rates (prey per gut), prey preferences, morphological condition (primarily body height/length ratios), and mortality of Atlantic herring larvae of the Georges Bank-Nantucket Shoals area. They reported that condition and feeding rate of larvae was greater in the 1976 season than in 1974 or 1975, and that mortality was lowest in 1976, which suggests a link between condition and mortality, but they did not find any significant correlations between condition, feeding rates or feeding preferences, and prey biomass or prey type as measured by 165 µm and 333 µm mesh nets. Townsend et al. (1986) reported that relative condition of Atlantic herring larvae of the eastern Gulf of Maine was weakly correlated with concentrations of zooplankton as measured by 80 and 505 µm mesh nets. Condition was highest in recently hatched larvae collected from the northeastern Gulf, it fell considerably in larvae collected from more southwestern waters, and then it rose slightly in larvae collected from the most southwestern point of the sampling area. The western area of the Gulf had higher concentrations of zooplankton, and as larvae were assumed to be transported in a southwesterly direction from their hatching sites, this pattern was interpreted as a positive response of larval condition to increased zooplankton densities.

12.2 Growth-mortality Hypothesis

The hypothesis that growth and fitness of fish larvae limits their survival is one of the 3 major assumptions justifying this study. The other 2 assumptions are a link between food production and growth, which has been discussed above, and a link between larval mortality and year-class success. Despite its crucial importance in the chain of logic that leads from growth of larvae to year-class strength, there is little empirical evidence to support an inverse relationship between growth and mortality in wild populations. There is a direct positive correlation between growth and mortality between species, as Ware (1975) first demonstrated, but this relationship is most likely due to underlying negative relationships between population parameters and body weight. Petersen and Wroblewski (1984) and McGurk (1986b) have shown that mortality of fishes, including fish larvae, decreases with body weight to a power between 0.2 and 0.5, and growth rates of all organisms decrease with increasing body size because of the well-known inverse relationship between specific metabolic rate (rate per unit weight) and body size. This study shows that total mortality decreased with weight to the power of 0.40, and it offers partial support to the mortality-patchiness hypothesis by showing that mortality is weakly, but significantly, correlated with spatial patchiness of Pacific herring larvae.

There are few intra-specific comparisons of growth and mortality in larval fishes and none of them report an inverse correlation between growth and mortality. McGurk (1984b) compared pairs of growth and mortality estimates for wild populations of Pacific and Atlantic herring larvae and found no relationship. Graham and Townsend (1985) reported a correlation between growth and mortality of 7 cohorts of Atlantic herring larvae from coastal waters of Maine, but the correlation was positive.

There is also little empirical support for a relationship between physical condition and larval mortality. This study found no reliable evidence of a link between CF2 conditions and mortality of herring larvae in Auke Bay. This conclusion is similar to one reported by McGurk (1989). He reported that the trajectory of CF2 condition with age was similar for 2 cohorts of Pacific herring larvae captured from Bamfield Inlet; but one cohort had a total mortality rate 3 times higher than the other, indicating that mortality was a multi-factor process and that factors other than starvation, presumably predation, dominated the population dynamics of at least 1 of the 2 cohorts.

Westernhagen and Rosenthal (1981) measured condition ($W \cdot L^{-3}$) of Pacific herring larvae from Departure Bay, British Columbia, in 1974 and 1976, and concluded that there were significant differences between years in the number of poorly-conditioned fish: at any length the 1974 fish had better condition than the 1976 fish. However, Westernhagen and Rosenthal (1981) noted that recruitment of adult herring to the Strait of Georgia stock resulting from the 1974 year-class was only half that of the 1976 year-class, a result opposite to that expected from the condition factor data. Chenoweth (1970) reported that relative condition of Atlantic herring larvae overwintering in the Booth Bay area of the Maine coast from 1965 to 1968 was lowest in 1965, a winter in which mortality was unusually high. Vilela and Zijlstra (1971) reported the condition ($W \cdot L^{-3}$) of Atlantic herring larvae from central and southern North Sea was not correlated with an index of recruitment to the adult stock 3 years later. The positive link between morphological condition, feeding rate and mortality of Atlantic herring larvae from Georges Bank reported by Cohen and Lough (1983) has been discussed above.

Hewitt et al. (1985) conducted a study similar to that reported by McGurk (1989), but dealing with the causes of death of northern anchovy, Engraulis mordax, larvae in the California Bight. They reported a similarly complex relationship between condition and mortality: predation was the major source of mortality in yolk sac larvae, but as yolk was absorbed and larvae began to feed, starvation became a significant source of mortality. As the larvae further developed, starvation rapidly declined and predation again became the dominant source of mortality.

In summary, it is self-evident that starving or slow-growing fish larvae will suffer higher mortality from disease, parasites and predators than well-fed and fast-growing larvae, but there is little reliable evidence to demonstrate the operation of this principle in wild populations of fish larvae. Instead, mortality appears to be a multi-factor process with starvation being only one of the factors.

Stevenson (1962) concluded that the principal cause of death of Pacific herring larvae that hatched from the northwestern shore of Barkley Sound, British Columbia, was their passive transport by inshore water currents to the open sea. This was based on the observation that the greatest concentration of newly-hatched larvae was found in inshore waters, and as they were carried seaward the numbers decreased at an approximately constant rate. Stevenson (1962) did not examine the factors directly causing death in offshore waters, but he suggested that death may be caused by the high salinity of the open sea.

Alderdice and Hourston (1985) reviewed the field and experimental evidence on the effects of salinity and temperature on survival of Pacific herring eggs and yolk sac larvae and concluded that the upper boundary of larval tolerance to salinity is 27.5 to 31.7 ppt, which is near the lower end of the range of salinities commonly encountered in offshore waters of British Columbia. They also examined the distribution of herring larvae in the Strait of Georgia, where surface salinities are generally 27 to 28.6 ppt and found that larvae from offshore areas of the Strait were actively feeding and growing. They concluded that the usual surface salinities and food supply in the open waters of the Strait were not a dominant influence on larval survival, and suggested that the disappearance of larvae in the Strait as largely the result of predation.

Predation is undoubtedly a major factor in the mortality of Pacific herring larvae; they are preyed upon by many species of fish (Brodeur et al. 1987), including adult and juvenile herring (Hourston and Haegele 1980, Hourston et al. 1981), and pelagic invertebrates (Stevenson 1962, Westernhagen and Rosenthal 1976, Arai and Hay 1982). Predation has been implicated as the most important agent of mortality in wild Atlantic herring larvae (Moller 1984).

12.3 Larval Mortality-recruitment Hypothesis

If the growth/condition-mortality relationship is an important component of the recruitment process, then its action must occur as the presence or absence of catastrophic mortality during the 2 to 3 week period after absorption of the yolk. This is Hjort's (1914) 'critical period' hypothesis, which has guided so much research in larval fish ecology this century. However, there is no unanimity in the scientific community on the validity of the critical period paradigm. Several reviews of the hypothesis have been conducted over the past 30 years, and none have found convincing evidence for the existence of catastrophic mortality during the first-feeding stage as reflected by a sharp break in a plot of population density with age (Marr 1956, May 1974, Dahlberg 1979). None of the catch curves reported for Pacific (Stevenson 1962, Iizuka 1966) or Atlantic (Das 1968, Lough et al. 1981, Henderson et al. 1984) herring larvae have the discontinuities that are expected from the critical period hypothesis. The catch curves reported in this study for Auke Bay herring larvae show that mortality decreases steadily with age, but the highest mortalities are predicted to occur during the yolk sac stage and not the first-feeding stage.

Peterman et al. (1988) reported the first test of Hjort's (1914) hypothesis for northern anchovy. They compared the abundance of anchovy at the egg, yolk-sac larval and 19-d old larval stage with the abundance of 1 year old recruits and found no significant relationships. Their review of the scientific literature on the reported correlations of fish egg and larval abundance with abundance of recruits produced diverse results; some stocks showed significant correlations and others did not. They noted that the closer the abundance samples were taken in time, the more likely a significant correlation is to exist.

In conclusion, this study has shown that herring larvae of Auke Bay grew at a high rate throughout the May to June, 1988, season because high densities of prey were available in the upper 30 m of the water column. This finding is consistent with laboratory studies of the growth-prey density relationship of herring larvae. This study has also shown that mortality of herring larvae in Auke Bay varies between cohorts and changes rapidly with age, but that there are no clear links between environmental conditions and those changes in mortality.

The relevance of this kind of study to the problem of understanding the recruitment mechanisms of Pacific herring depends on a chain of logic whose basic assumptions are scientifically controversial. The questions involved in studying recruitment are so profound that their answers cannot realistically be expected for many decades. Therefore, even if the results of the study are accepted as establishing a link between growth and prey concentrations, so much else would remain to be done in order to relate growth to mortality and mortality to recruits that we must expect variation in year-class strength of Alaska herring to remain unexplained for a considerable time to come.

13. PLAN FOR BERING SEA STUDY

13.1 Objectives

I recommend that future studies of young herring in the Bering Sea focus on measuring the population dynamics of young herring, as well as measuring the interaction between growth and prey density. The following section explains the rationale underlying this recommendation.

The Auke Bay study has shown that growth of wild herring larvae is only weakly limited by food. Although this study is a successful first step, it is not certain that it will contribute substantially to our ability to predict year-class size from environmental conditions during the early life history stage if, as some researchers have argued, food supply is only one of a suite of factors that together control recruitment. It is entirely possible that non-trophic factors such as offshore dispersal or predation are just as important to survival as prey density. It may be more scientifically productive to shift the focus of future investigations from the growth-prey concentration question to questions of the roles of offshore dispersal and predation.

In conclusion, I recommend 3 significant differences in the basic study plan based on the Auke Bay experience. The Bering Sea study should include:

1. **A strong component of population modelling in order to obtain accurate estimates of mortality and dispersal.**

Rationale

If year class strength is established during the early life history stage of Pacific herring, then the primary factor responsible is mortality. Growth has a less direct influence on recruitment, but its magnitude may serve as an index of year-class success. Therefore, it is necessary to design future studies so that they may accurately measure mortality rate and how it changes with age and size of herring.

Few species of commercial fish are more amenable to population modelling than Pacific herring. The eggs beds are discrete and easily located in the intertidal zone, thus the origin of each cohort of larvae can be identified and the dispersal of larvae way from the egg beds can be measured with more accuracy than is possible for species that spawn in the pelagic zone. Herring larvae and juveniles tend to remain in the same estuaries and coastal embayments in which they hatched, thus allowing a relatively accurate assessment of population size. The combination of accurate estimates of dispersal and a relatively small larval retention zone means that it is possible to calculate accurate and reliable estimates of larval mortality by subtracting dispersal from total loss rates.

Advection-diffusion modelling of populations of fish larvae is rapidly becoming the standard practice in early life history studies. Such models have recently been used to estimate dispersal and mortality of Atlantic herring larvae in the North Sea (Munk et al. 1986, Heath and MacLachlan 1987), Pacific herring larvae in Barkley Sound, Vancouver Island (McGurk 1989), plaice larvae in the North Sea (Talbot 1977), haddock eggs on Browns Bank, Nova Scotia (Koslow et al. 1985) and capelin larvae in Newfoundland (Taggart and Leggett 1987a, 1987b).

2. **A sampling protocol designed in advance of the sampling season in order to satisfy the data requirements of a population model designed in advance of the study.**

Rationale

A suitable population model should be designed in advance of the sampling season by experts in the field of statistical or computational modelling of dispersal processes in aquatic systems in consultation with biologists experienced in sampling larval herring. Data requirements of the model should be used to plan the number of plankton stations and their locations, and the number of tows at each station.

It is a generally accepted principle that a sampling program designed in advance to answer specific questions will answer these questions more successfully than a sampling program onto which is applied an ad hoc analysis. Several versions of advection-diffusion models are available in the fisheries/oceanography literature. The choice of a model appropriate to herring larvae in the Bering Sea should be done by an expert in the field after a careful review of the subject.

Questions to be answered by this review include:

(1) is an analytical model sufficient or is it necessary to build a hydrodynamic model of the study site?

(2) What is the simplest and most convenient method by which physical data on currents can be integrated with data on the distribution of herring larvae?

(3) must population rates, i.e. mortality, advection, and diffusion, be assumed to be constant with age or to change at a constant rate with age, as they were in the Auke Bay study, or can they be calculated as time-varying rates in order to follow ontogenetic and seasonal changes in population parameters?

3. The study should include searches for the locations and dates of the spawning sites and measurements of the abundance and survival of the eggs.

Rationale

Three reasons support extending the program objectives to cover the distribution, abundance and dynamics of the egg stage:

(1) egg mortality may play a role in year-class success because substantial natural mortality occurs during the egg stage and this mortality may be highly variable between spawning beaches and between years;

(2) herring eggs are highly vulnerable to oil pollution of the intertidal zone; and

(3) estimates of the location and density of newly-hatched larvae are a check on the validity of any model of larval population dynamics.

Optional Component of Study Plan

The study may include a program for collecting information on the feeding rates and prey types and sizes of herring larvae and juveniles, and how these variables change with size of herring and with season.

Rationale

Although the study of the food of herring larvae and juveniles collected in southern British Columbia waters provided a reasonably accurate template of the prey field of herring larvae in Auke Bay, it may not be an adequate template for herring larvae and juveniles feeding in the Bering Sea because of the differences in available types of prey between the 2 ecosystems. If this component is considered sufficiently important to warrant doing, then the study should (1) employ short duration (<60 s) plankton hauls to shallow depths (20 m) to reduce the probability of voiding of guts; and (2) include sufficient resources of time and manpower to allow the collection of at least several hundred non-zero guts.

13.2 Study Site

This section presents 2 recommendations on the desirable characteristics of the study one.

1. **The study should be done in a region which has consistently received large amounts of spawn, defined as greater than 2.5 linear km of spawn, over the last decade.**

Rationale

Although it is certainly possible to conduct research on the early life stages of herring hatched from 'trace' spawnings, as the Auke Bay study has demonstrated, studies on larger spawnings are desirable for 2 reasons. First, large spawnings will ensure that there will be sufficient biological material. Second, the dynamics of populations hatched from large egg beds may be different from the dynamics of populations hatched from small beds because of density-dependent effects on growth, condition, dispersal and survival. The importance of density-dependence in the early life history of Pacific herring in Alaska may be assessed by comparing the population parameters of large cohorts hatched in the Bering Sea with the population parameters of the relatively small cohorts that hatched in Auke Bay in 1988. A spawning of 2.5 km long is recommended because it is an order of magnitude larger than the 2 spawnings that were observed directly in Auke Bay in 1988.

2. **The array of plankton sampling stations should extend a minimum of 10 km from the hatch sites in both of the 2 horizontal dimensions.**

Rationale

The Auke Bay study has shown that a transect extending 5 km from the hatch site is not long enough to define the retention area of even a 'trace' spawning. Locating the margins of the retention area is essential because it generates sufficient spatial contrast in population density to allow the accurate measurement of advective and diffusive transport of the larvae. This information on dispersal can be removed from the total rate of loss of larvae to give an accurate estimate of mortality. A minimum distance of 10 km along each side of an x-y grid is recommended because it is sufficient to cover the dimensions of a patch of young larvae, but is small enough for all stations to be visited at least once within a 10 h period of daylight.

13.3 Technical Recommendations

This section presents brief discussions of 2 technical matters arising from the Auke Bay study that may be relevant to a future Bering Sea study.

1. Net Extrusion

The problem of extrusion of small herring larvae through the meshes of plankton nets must be examined in order to accurately measure population density. I recommend conducting a series of paired tows of 165, 333 and 505 µm plankton nets at the same sites at the same date at least 3 times over the sampling season. Comparison of the catches of the different mesh nets would allow correction of the measured densities for net extrusion.

2. Density of Microzooplankton

The Auke Bay study showed that small water pumps with small diameter intake hoses do not produce reliable estimates of the densities of microzooplankton, primarily copepod nauplii, that are the main prey of first-feeding herring larvae. Although more powerful pumps may solve the evasion problem, a simpler course of action is to adopt the technique used by the APPRISE team: a large volume open and closing bottle which is dropped to the desired depth.

3. Growth Rate

The validity of otolith ring analysis should be checked by using a second and independent method of measuring recent growth rates. I recommend RNA/DNA analysis.

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LETHAL AND SUBLETHAL EFFECTS OF THE WATER-SOLUBLE FRACTION OF COOK INLET CRUDE OIL ON PACIFIC HERRING (*CLUPEA HARENGUS PALLASI*) REPRODUCTION

by

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Final Report

Outer Continental Shelf Environmental Assessment Program

Research Unit 661

1986

ACKNOWLEDGMENTS

This study was partially funded under a contract with the Alaska Outer Continental Shelf Environmental Assessment Program (OCSEAP), which is managed by the National Oceanic and Atmospheric Administration, U.S. Department of Commerce through an interagency agreement with the Mineral Management Service, U.S. Department of the Interior. Additional funding was supplied by U.S. Department of Commerce, National Oceanic and Atmospheric Administration, National Marine Fisheries Service, Northwest and Alaska Fisheries Center, Auke Bay Laboratory Habitat Investigations.

EXECUTIVE SUMMARY

The proposed sale of continental shelf leases for petroleum development in Bristol Bay, Alaska, is generating concern about the possible effects on valuable fishery resources, such as Pacific herring (_Clupea harengus pallasi_), in the area. Herring from Bristol Bay are marketed primarily for roe (exported to Japan for human consumption) and are an important prey of several commercially valuable fishes. The inshore spawning strategy of herring makes them particularly vulnerable to the effects of an oil spill. Spawning adults congregate at sites where they and their maturing gonads could be exposed to spilled oil, which could harm their reproductive success. Spawned eggs, and larvae, would have to survive and grow in an oil-contaminated environment.

Using the water-soluble fraction (WSF) of Cook Inlet crude oil, we studied effects of lethal and sublethal exposures on prespawn adult Pacific herring, eggs, yolk-sac larvae, and feeding larvae as well as on hatching success of eggs from exposed adults. We studied also the effects of feeding oil-contaminated prey to herring larvae. The results of our study are summarized:

* Prespawn adult herring exposed to WSF had a 2- and 12-day LC_{50} (the median concentration that killed 50% of the herring) of 2.3 parts per million (ppm) aromatic hydrocarbons.

* Eggs of adults exposed 12 days to 1.6 ppm had normal hatching success.

* Eggs exposed 2 days to 5.3 ppm had normal hatching success; eggs exposed 12 days had an LC_{50} of 1.5 ppm.

- Yolk-sac larvae exposed ≤6 hours to 6.0 ppm survived; yolk-sac larvae exposed from 16 hours to 6 days had LC_{50}'s of 2.8 to 2.3 ppm.
- Feeding larvae exposed 7 days had an LC_{50} of 1.8 ppm, and 21 days, 0.36 ppm.
- Tissue (muscle, liver, testes, and mature and immature ovaries) uptake of hydrocarbons in adult herring was rapid, but equilibrium was not reached in 10 days of exposure.
- Muscle tissue generally accumulated the highest levels of hydrocarbons; immature ovarian tissue accumulated almost two times the levels found in mature ovarian tissue.
- In adults, initial depuration was rapid but slowed after 24 hours, and 10% of the hydrocarbons were still present after 7 days of depuration in clean water. Hydrocarbon levels after 14 days were not significantly higher than control levels.
- Uptake in larvae was more rapid than in adults and reached equilibrium within 4 hours. Retention was less in larvae than adults, and after 24 hours, only 2% of the ^{14}C-labeled naphthalene remained in larval tissues.
- Growth of larvae was significantly reduced after 7 days of exposure to 0.3 ppm, and reductions were greater after longer exposures and higher concentrations.
- Growth of larvae was not significantly reduced by a diet of oil-contaminated prey.

We conclude that the life stage at which the reproductive success of Pacific herring is most likely to be impaired by oil is feeding larvae: Larvae are killed by shorter exposures and lower concentrations than are the eggs or the adult reproductive products or the adults themselves. We conclude also that even if oil is present at levels too low to threaten the survival of herring, the fisheries could be impacted because the rapid bioaccumulation of oil hydrocarbons in the edible muscle and ovarian tissues could make the herring unmarketable.

TABLE OF CONTENTS

Page

INTRODUCTION

The Pacific herring (Clupea harengus pallasi) is an important prey species and supports the valuable commercial fisheries in the coastal waters of Alaska. Effects of oil pollution are of particular concern because of the inshore spawning strategy of herring. Each herring stock spawns near shore within a restricted natal range in spring. Adults typically congregate for several weeks near prospective spawning sites while their reproductive organs mature, then they spawn en masse over a period of a few days. Herring spawn in 0-20 m depths on almost any available substrate (Jones 1978; Carlson 1980). Larvae hatch after approximately 20 days at Alaska spring temperatures (5-8°C) and live off yolk reserves for about a week prior to initial feeding. Larvae are weak and drift passively in waters near the spawning areas for several months before they transform into juveniles (Jones 1978).

Oil pollution in the spawning habitat could contaminate adult herring and their gonads or harm the spawn and larvae. Because herring spawn en masse, entire stocks and year classes are vulnerable to oil pollution at the time of spawning.

Herring have been fished in Alaska since 1882, but until 1970, the fishery was for a high-volume and low-priced product of salted herring, fish meal, fish oil, or bait. Beginning about 1970, demand by Japan for herring roe caused a resurgence of the fishery. Gonads (roe) of mature females immediately prior to spawning, and the spawned eggs, are highly valued in foreign markets, and the wholesale price of salted roe and eggs is more than $6.00 per pound, higher than the wholesale price for chinook salmon (Oncorhynchus tshawytscha) ($2.10 in 1983) or salmon eggs

($3.10 per pound in 1983) (Alaska Department Fish and Game 1984). The 1983 wholesale value of herring products from Alaska was $67 million.

Although studies on the effects of contaminants on reproductive processes in fish are rare, sensitivities of herring eggs and larvae to crude oil have been examined (Kühnhold 1974; Eldridge et al. 1977; Linden 1978; Cameron and Smith 1980). Most fish larvae are relatively sensitive to oil, but eggs are usually more resistant (Rice 1985). In contrast to eggs and larvae, little attention has been directed at the pollution effects on gamete formation, mainly because of difficulties in capturing, transferring, and holding mature adults in quantities sufficient to ensure valid statistical results. In one such study on Pacific herring, Struhsaker (1977) demonstrated adverse effects of benzene, a toxic and highly soluble component of crude oil, on developing ova, embryos, and larvae. Short-term (48-hour) benzene exposures (800 parts per billion (ppb)) decreased survival of ova in the gonads and also of resulting spawn. Struhsaker (1977) concluded that spawning fish are a very sensitive life stage. Her study received considerable attention, partly because viability of ova in the gonads was reduced at parts per billion concentrations and also because no similar studies had been done. However, benzene effects may not be representative of effects of exposure to the water-soluble fractions (WSF's) of crude oil, a more likely environmental scenario.

Even if not immediately toxic, hydrocarbons from an oil spill in the habitat of spawning herring may be accumulated by gonads and spawned eggs and, thus, affect their marketability. Detection of hydrocarbons in the habitat may lead to displacement of mature adults to less suitable spawning locations.

The objectives of our study were to determine 1) the LC_{50} for prespawning adult Pacific herring exposed to WSF of Cook Inlet crude oil; 2) uptake and depuration of aromatic hydrocarbons in gonads, liver, and muscle tissue of mature herring; 3) survival and viability of eggs spawned from adult herring exposed to WSF; 4) survival and viability of herring eggs and newly hatched (yolk-sac) larvae exposed to WSF; and 5) survival, growth, and hydrocarbon accumulation of feeding larvae exposed to WSF or fed WSF-contaminated food.

METHODS

Test Animal Collections

Mature adult Pacific herring (Clupea harengus pallasi) for adult herring exposures and for artificial spawning in the egg tests were caught by a standard commercial fishery purse seine near Juneau, Alaska, in 1984 and 1985. Fish were held in 1,000 L fiberglass tanks containing low salinity (15°/₀₀) running water for the first 5 days. Salinity was gradually increased during the next 5 days to 30°/₀₀. Holding herring in low salinity water minimizes hemorrhaging due to scale loss, by reducing osmotic stress. Nets were never used to transfer fish because they cause massive scale loss; all fish transfers were in buckets with water. Mortality was less than 1% during holding periods.

Naturally spawned herring eggs were collected from the Kahshakes fishery near Ketchikan, Alaska, in March 1985 and from Auke Bay in early June 1984 and 1985. Substrate for collected eggs was Fucus distichus. Larvae hatched from these eggs were used in the yolk-sac and feeding larvae experiments.

Dosing and WSF and Tissue Analyses

The WSF of Cook Inlet crude oil was supplied by a flow-through, WSF generator (Moles et al. 1985) that dripped 10 L/minute of Auke Bay seawater through a continuously replenished 40 cm layer of Cook Inlet crude oil. The resulting WSF was collected from below the slick and pumped into head tanks after the dispersed oil floated out. WSF and dilution water were delivered to test containers by appropriate manifold systems. Flow rates of WSF and of dilution water were held constant for each test group to maintain stable concentrations during the exposure periods. See Appendix for details of exposures of each life stage to WSF.

Aromatic hydrocarbon levels in WSF's of crude oil were determined by gas chromatography of methylene chloride extracts of WSF samples. All glassware and containers used in processing the samples were cleaned with detergent and water, then rinsed twice with distilled hexane. Samples (750 ml) of WSF were transferred from appropriate head tanks or exposure containers by small-bore siphon into a graduated cylinder. Methylene chloride used for the extractions was spiked with a known quantity of 1,3,5 triisopropyl benzene as an internal standard: Each sample was transferred to a 1-1 separatory funnel and extracted by 25 ml methylene chloride (shaken by hand 1 minute and allowed to settle 5 minutes). This procedure was repeated for a total of 50 ml collected in glass vials and frozen. Analyses were performed by a Hewlett-Packard[1] model 5880A gas chromatograph equipped with a 12 m fused silica dimethyl silicone capillary column and a flame ionization detector. The

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[1] Reference to trade names does not imply endorsement by the National Marine Fisheries Service, NOAA.

N_2 carrier gas was held at 70 kPa inlet pressure. Temperature of the inlet, outlet, and detector was held at 250°C. The injection volume was 1 μl. The column temperature program was as follows: 20°C for 2 minutes, followed by a temperature ramp of 10°C/minute to a final value of 200°C. Concentrations of individual aromatic hydrocarbons in the samples were determined by the internal standard method. Concentrations are reported in parts per million (ppm) aromatic hydrocarbons. Our WSF's were dominated by mononuclear aromatic hydrocarbons (about 95%); dinuclear aromatic hydrocarbons constituted about 5% (Table 1).

Aromatic hydrocarbon levels in tissues were determined by gas chromatography of hexane extracts of tissue samples digested in sodium hydroxide. All implements and containers that came in contact with the samples were glass or Teflon and were cleaned with detergent and water, rinsed twice with distilled hexane, then baked at 440°C for 8 hours. Tissues were dissected from freshly killed herring and immediately frozen in glass jars with Teflon-lined lids. Samples were thawed just before processing and weighed in tared 500 ml screw-cap Teflon centrifuge tubes. To each tube, we added 10 ml 10N NaOH, 2 ml hexane, and 0.1 ml internal standard (a known quantity of 1,3,5 triisopropyl benzene). The tubes were heated 3 hours at 70-80°C, shaken well once each hour, then cooled to room temperature. Next, 5 ml 10% NaCl and 10 ml hexane were added to each tube, samples were centrifuged at 10,000 rpm for 10 minutes, and the supernatant hexane was aspirated into a 50 ml flask. This procedure was repeated three times for a total of 30 ml collected. Two to 5 g of Na_2SO_4 was added and allowed to stand at

Table 1.--Distribution of individual aromatic hydrocarbons in water-soluble fraction (WSF) of Cook Inlet crude oil and in tissues of mature female Pacific herring (Clupea harengus pallasi) after 6 days of exposure to 1.2 ppm aromatic hydrocarbons (mean of three samples). Concentrations are in parts per million and were measured by capillary column gas chromatography. Asterisk indicates benzene was probably present in significant concentrations in tissues but eluted out with the solvent and could not be determined precisely.

	Mature ovary		Muscle		WSF	
Compound	Mean	%	Mean	%	Mean	%
Benzene	*		*		.550	45.8
Toluene	9.443	20.4	2.965	6.7	.377	31.4
Ethyl benzene	2.582	5.6	.746	1.7	.044	3.7
m- and p-xylene	6.399	13.8	1.584	3.6	.107	8.9
o-xylene	3.596	7.8	1.064	2.4	.065	5.4
Cumene	.879	1.9	.441	1.0	.008	.7
Mesitylene	.733	1.6	.449	1.0	.005	.4
n-propylbenzene	.581	1.3	.519	1.2	.006	.5
P-cymene	.256	.6	.161	.4	.004	.3
Naphthalene	3.722	8.1	4.069	9.1	.020	1.7
2-methylnaphthalene	2.787	6.0	6.264	14.1	.025	2.1
1-methylnaphthalene	2.540	5.5	4.969	11.2	.008	.7
2,6-dimethylnaphthalene	.308	.7	1.277	2.9	.009	.7
Total mononuclear aromatics	38.064	82.4	25.028	56.2	1.140	94.9
Total dinuclear aromatics	8.149	17.6	19.473	43.8	.061	5.1
Mono- and dinuclear aromatics	46.213	100.0	44.501	100.0	1.201	100.0

least 10 minutes. Samples were decanted into 50 ml pear-shaped flasks, evaporated to 2 ml on a rotary evaporator, then layered onto a silica column (5 g silica in hexane in 0.8 mm column). The aliphatic fraction was washed out with 14 ml hexane, and the aromatic fraction, with 18 ml hexane/methylene (4:1). The aromatic fraction was evaporated to 1 ml on a rotary evaporator, transferred to a 1.8 ml gas chromatograph vial with a Teflon-lined septum, and frozen until gas chromatograph analyses. Analyses were performed by a Hewlett Packard model 5880A gas chromatograph equipped with a 12 m fused silica dimethyl silicone capillary column and a flame ionization detector. The N_2 carrier gas was held at 70 kPa inlet pressure. Temperature of the inlet, outlet, and detector was held at 250°C. The injection volume was 1 μl. The column temperature program was as follows: 30°C initial temperature for 1 minute, 5°C/minute temperature ramp for 2 minutes, 10°C/minute temperature ramp for 21 minutes, and final temperature at 250°C for 12 minutes. Concentrations of individual aromatic hydrocarbons were determined by the internal standard method.

Short-term uptake (0-4 hours) and depuration (0-24 hours) in larvae and prey were measured with liquid scintillation techniques using ^{14}C-labeled naphthalene. Labeled naphthalene dissolved in acetone was added to seawater and stirred 15-20 minutes before larvae or the prey, *Artemia* nauplii, were added. Initial concentration of naphthalene was 0.33 (0.10 to 0.66) ppm. Herring larvae (20-100) were placed in 2 cm x 15 cm glass tubes with fine mesh-net bottoms. Tubes were drained and transferred quickly from clean water to labeled solutions. *Artemia* nauplii were washed onto plankton netting, then resuspended in the labeled solution. Labeled naphthalene was recovered by filtering samples through paper or glass fiber filters. Filters were then cut into small pieces and digested 24-48 hours in 5 ml tissue solubilizer (Soluene). A 10 ml scintillation cocktail (Dimilume) was then added as diluent. A 1 ml subsample in additional 10 ml Dimilume was counted with a liquid scintillator.

Adult Herring Toxicity, Uptake, and Depuration

The LC_{50} of adult herring was determined by an acute bioassay in a flow-through exposure system. Six groups of 12 fish were exposed to different WSF concentrations in six 600 L tanks, and their survival was monitored. Exposure levels in all subsequent, sublethal tests (Appendix) were selected as percentages of the 12-day LC_{50} but are reported in parts per million.

Uptake of hydrocarbons by adult herring was measured in two series of flow-through, WSF exposures representing short-term (2-day) and long-term (10-day) exposures. Groups of adult herring were exposed either 2 days to 0, 18, 43, 45, or 55% of the LC_{50} of WSF of Cook Inlet crude oil or 10 days to 0, 14, 18, or 30% of the LC_{50}.

In the depuration phase of this study, herring were exposed 4 days to 30% of the LC_{50} of WSF, then placed in clean, flowing seawater for 14 days. All tests were in 800 L fiberglass tanks with appropriate WSF and dilution water (flow rate, 8 L/minute). Tissues (muscle, liver, testes, and mature and immature ovaries) were sampled during and after exposure to WSF and were analyzed for aromatic hydrocarbon content. Values reported are means of tissue samples from three fish.

At 2 and 12 days, ovaries of six fish from the 1.6 ppm exposure group and ovaries of six control fish were examined to determine whether ovarian tissues and egg development were affected by WSF exposure.

Gonads, Eggs, and Yolk-Sac Larvae

Adult fish with mature gonads were exposed, before artificial spawning, to WSF's for 2 or 12 days; eggs were exposed within 5 minutes after spawning and fertilization to WSF's for 2 or 12 days; and yolk-sac larvae were exposed within 24 hours after hatching to WSF's for various periods from 20 minutes to 60 days. Each treatment was replicated at least three times (Appendix).

All eggs exposed as gonads or as fertilized eggs, and unexposed eggs (controls), were held in identical incubators. The incubators were 28 cm long X 15 cm diameter PVC pipe fitted with clear Plexiglas bottoms. Seawater (plus WSF for the exposures) was delivered at 50 ml/minute into these incubators by peristaltic pumps, and exited through four screened ports near the bottom of each incubator. Temperature fluctuations were minimized, and water levels maintained, by standing each incubator in a bucket that was bathed in circulating seawater. Slides of fertilized eggs were suspended within the incubators in plastic and stainless steel slide holders. The holders hung by monofilament line from an apparatus that raised and lowered the slides slowly (6 times/minute).

Eggs were observed daily. The day after hatching was first observed, we began counting eggs at 2-day intervals. Numbers of dead eggs, unhatched live eggs, and hatched eggs (empty egg cases) were recorded.

Gonad (Adult) Exposures

Mature adult herring were exposed either 2 or 12 days to WSF concentrations up to 1.6 ppm, 75% of the LC_{50}. From each WSF exposure, six females were used for artificial spawning and three males for artificial fertilization. Eggs from each female were squeezed (in a single layer of two rows) onto two glass microscope slides (45-130 eggs/slide). Eggs were fertilized by dipping them into a suspension of fresh milt in seawater. These eggs were transferred to incubators and held until hatching.

Egg Exposures

Herring eggs obtained from unexposed adults by artificial spawning and fertilizing (as described above) were transferred on slides to incubators where they were exposed for 2 or 12 days to WSF concentrations of 0.8 to 5.3 ppm. After exposure, eggs were moved to incubators supplied with clean seawater and held until hatching.

Yolk-Sac Larvae Exposures

Naturally spawned eggs were held in clean, flowing seawater until hatching. Within 24 hours after hatching, yolk-sac larvae were exposed from 20 minutes to 6 days to WSF. After 6 days, unfed larvae absorb their yolk and begin to die of starvation.

The 6-day WSF exposures of yolk-sac larvae used the same type of incubator as did egg exposures. About 30 larvae were in each incubator, and three incubators were used for each concentration. Larvae receiving shorter exposures were held in 2 cm ID glass tubes that had nylon screen bottoms and were suspended in the incubators. Triplicate tubes, each holding eight larvae, were used in each concentration. Larvae exposed

<6 days were placed in clean, flowing seawater for the remainder of the 6-day period. All larvae were checked after 24 hours of exposure or at the end of exposure period or both and were checked again when they were 6 days old. They were counted and classified as swimming, not swimming, or dead.

Feeding Larvae and Oil-Contaminated Prey Exposures

Larvae hatched from Kahshakes and Auke Bay herring eggs were used in the feeding larvae exposures. Kahshakes eggs were incubated at 6-7.5°C in test chambers or in 600 L fiberglass tanks supplied with flowing seawater until the majority hatched. Auke Bay eggs began hatching upon arrival in the laboratory. These larvae were maintained in 600 L fiberglass tanks until they were transferred to test chambers, where all larvae were held 17-18 days before tests began.

Larvae were fed rotifers (*Brachionus* spp.), then were gradually shifted to the larger *Artemia* nauplii. These prey items have been used successfully to rear larvae in other studies (Struhsaker et al. 1974; Eldridge et al. 1977). Rotifers were reared on cultured *Stephanoptera* spp. in 20 L plastic buckets. Rotifers were harvested every 2-3 days, washed onto a net, then resuspended in clean seawater or on algae in seawater. *Artemia* cysts were incubated for 3 days in 20 L plastic buckets in seawater with vigorous aeration.

The test chambers were identical for exposures to WSF or oil-contaminated prey. Larvae were reared and tested in 40 L black circular fiberglass chambers with concave bottoms. Seawater (28°/₀₀) and food were introduced at 0.7 L/minute through a diffuser chamber (height, 5 cm; diameter, 8 cm) designed to keep the bottom clean and create a gentle upwelling in the tanks. Overflow water exited through a 363 micron sleeve stretched over an 8 cm diameter standpipe protector at the surface center. In WSF tests, seawater was delivered to controls, and seawater and WSF were delivered to exposure tanks from head tanks to Teflon mixing funnels at the head of each manifold. Overflow water filled an external water jacket that minimized temperature fluctuations. A simulated diel environment of a 16-hour photoperiod and 15-minute "sunrise" and "sunset" periods was maintained with fluorescent lights. Tanks were treated as needed with erythromycin to control bacterial growth.

In contaminated prey tests, some of the _Artemia_ nauplii, which were harvested daily, were poured into conical nylon nets and exposed for 16 hours to WSF (0-5.5 ppm). Nauplii exposed to the lower WSF concentrations were fed directly to herring larvae, whereas nauplii in the highest WSF concentration were filtered and resuspended in clean seawater immediately before they were fed to the larvae.

In exposures to WSF and oil-contaminated prey, larval observation methods were identical. Mortality of feeding larvae was calculated indirectly. Direct observations of mortality were impossible because of large tank volumes, high larval abundance, waste food, and rapid decomposition after death. Mortality was estimated also from the number of larvae per liter remaining at the end of the experiment and was adjusted relative to controls. Mortality was estimated also from tank bottom subsamples when most or all larvae stopped swimming. These two estimates agreed closely.

Feeding status was easily determined: Food could be viewed through the transparent, larval integument without larvae being disturbed. The presence or absence of food in the gut was observed during collection for other measurements, or visually from above. Larvae were observed at the same 24 predetermined nodes in each chamber. In WSF tests, recovery potential of larval feeding was measured by observing feeding frequencies after exposing larvae to 0.9 ppm WSF for 2, 4, or 8 days. We also starved controls for 8 days, then measured their feeding recovery potential for comparison.

Hydrocarbon uptake by predator and prey was measured by gas chromatography after 0, 1, 2, 4, and 16 days of exposure. Larvae were collected early in the morning before the first feeding to reduce possible effects of contaminated prey on the analysis. Larvae were captured, filtered onto a fine mesh net, rinsed with seawater, weighed, and frozen until analysis. Artemia nauplii were collected for tissue analysis immediately after removal from the WSF. Nauplii were also sampled to determine the rates of hydrocarbon loss before and after they entered the herring test tanks. Artemia nauplii were filtered through 100 micron plankton net, rinsed, and stored until analysis.

Short-term uptake (0-4 hours) and depuration (0-24 hours) in larvae and prey were measured using ^{14}C-labeled naphthalene as described earlier.

Measurement of larval growth required several steps. Twenty to 25 living larvae were collected weekly from each tank, placed in 20 ml glass scintillation vials, and preserved with Dietrich's solution. Samples were allowed to equilibrate at least 1 month before measurement. Preserved specimens were arranged on a petri dish and photographed against a black background. Negatives were enlarged 8-10 X, and each specimen was traced onto a sheet of paper. Tracings were analyzed with a digital pad to determine notochord lengths. To correct length measurements for fixative effects, random samples of living larvae were measured directly with an eyepiece micrometer, photographed, and then preserved for subsequent measurement.

Mathematical and Statistical Analyses

Median concentrations causing death (LC_{50}) and swimming or feeding inhibition (EC_{50}) were determined by logit analysis (Finney 1952; Berkson 1957) or by Spearman-Kärber techniques (Hamilton et al. 1977). Correction for control response (Abbott 1925) was applied as necessary. Tukey's *a posteriori* multiple comparison tested differences between responses of dosed groups and controls, or Scheffé's test (Scheffe 1953) compared several groups simultaneously. Unless stated otherwise, all results are defined as statistically significant at $P < 0.05$. To control type I error in time series data, values were tested at 0.05/n, where *n* was the number of sets of comparisons in a series.

RESULTS

Adult Herring Exposures

The acute toxicity (LC_{50}) of WSF of oil to adult herring was 2.3 ppm after 2 days and throughout 12 days of exposure (Table 2). All mortalities occurred within the first 36 hours.

Uptake of aromatic hydrocarbons into tissues was rapid, and by 24 hours, concentrations were 20-35 ppm in herring exposed to 0.6 ppm (Fig. 1). Uptake was affected by exposure times and concentrations and by tissue types. Tissue uptake continued throughout the 10-day period (Fig. 1), indicating tissue equilibrium with the WSF concentrations

Table 2.--Sensitivity of several life stages of Pacific herring (*Clupea harengus pallasi*) exposed to water-soluble fractions (WSF) of Cook Inlet crude oil for 2, 6, 12, or 21 days. Mortality of gonads and of eggs was defined as failure to hatch.

Stage	LC_{50} (ppm) ± 95% CI			
	2 days	6 days	12 days	21 days
Ripe adults	2.3 ± 0.4	2.3 ± 0.4	2.3 ± 0.4	--
Gonads	>1.6	>1.6	>1.6	--
Eggs	>5.3	--	1.5 ± 0.1	--
Yolk-sac larvae	3.2 ± 1.0	2.3 ± 0.2	--	--
Feeding larvae	--	2.0 ± 0.2	0.9 ± 0.1	0.36 ± 0.1

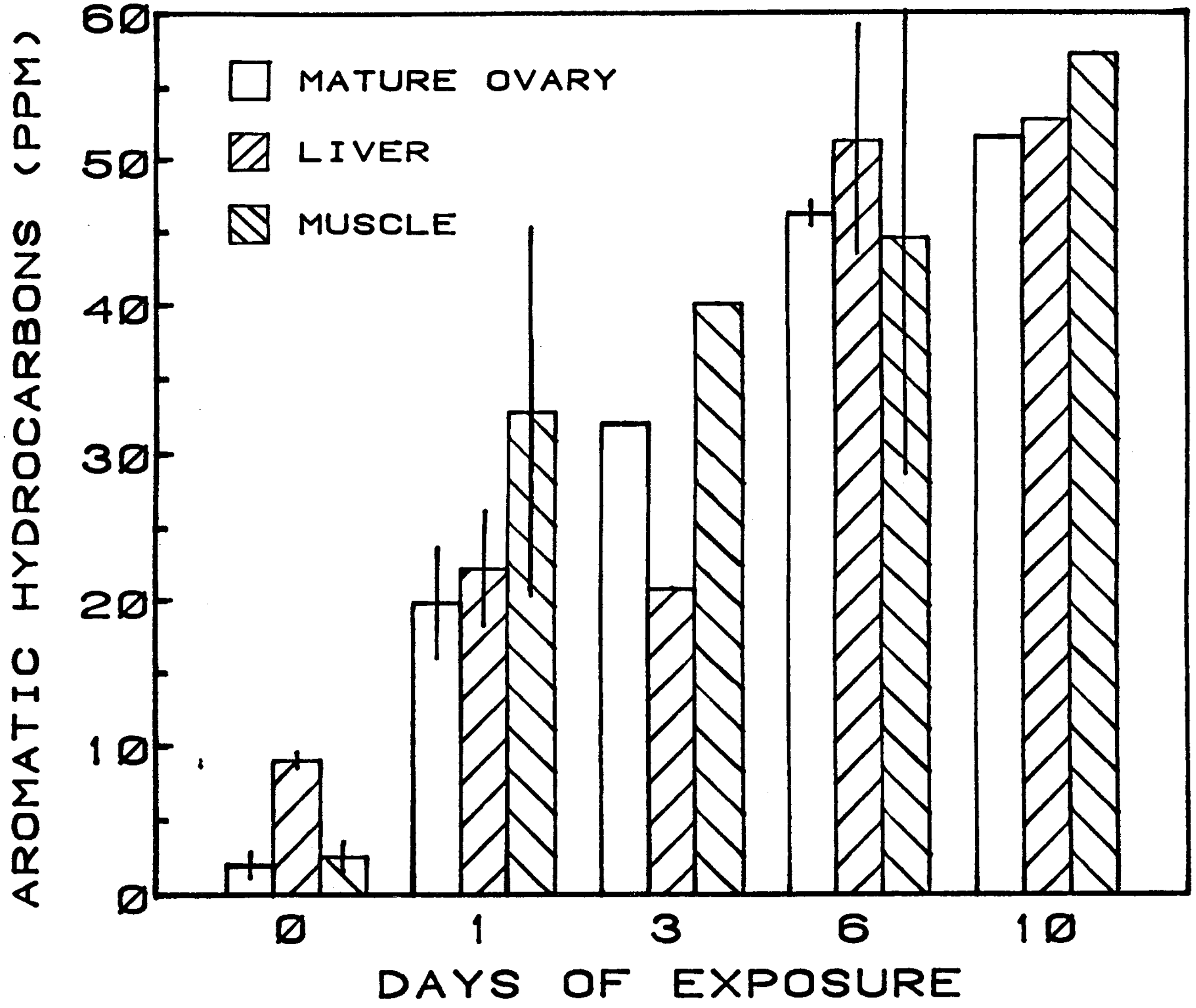

Figure 1.--Accumulation of aromatic hydrocarbons in tissues of adult Pacific herring (*Clupea harengus pallasi*) during 10 days of exposure to 0.6 ppm water-soluble fraction (WSF) of Cook Inlet crude oil. Vertical bars = standard error.

takes longer than 10 days. Tissue concentrations were influenced directly by exposure concentrations (Fig. 2). Muscle tissue usually accumulated the highest concentrations (Figs. 1, 2); testes and liver tissues generally had the lowest concentrations. Immature ovarian tissue consistently accumulated more than did mature ovarian tissue (Fig. 3). After 48 hours, immature ovarian tissue from fish exposed to 1.2 ppm WSF accumulated 120 ppm compared with 75 ppm for mature ovaries.

The distribution of aromatic hydrocarbons in the WSF was dominated by monoaromatic hydrocarbons (95%), and concentrations of larger compounds declined in approximate proportion to their solubilities (Table 1). In contrast, the distribution of aromatic hydrocarbons in tissues was not as simple. Monoaromatics dominate in the ovarian tissue, but in muscle tissue, the concentrations of diaromatic compounds were nearly equal to monoaromatics. Concentration differences between tissues and WSF demonstrate that lipophilic tissues can bioconcentrate larger aromatic hydrocarbons, even though their concentrations in the WSF are relatively low. Polyaromatic hydrocarbon concentrations were highly variable in tissues of exposed and control fish; therefore, quantification of uptake in the experimental animals was impossible. However, because polyaromatics have low water solubility, virtually none occur in the WSF. All the polyaromatic hydrocarbons in herring tissues are almost certainly of biogenic origin. Differences in distribution of aromatic compounds between ovarian and muscle tissues are probably caused by differences in the lipid content of the tissues, in the access to the tissues by the blood, and in the ability to metabolize and remove hydrocarbons from tissues.

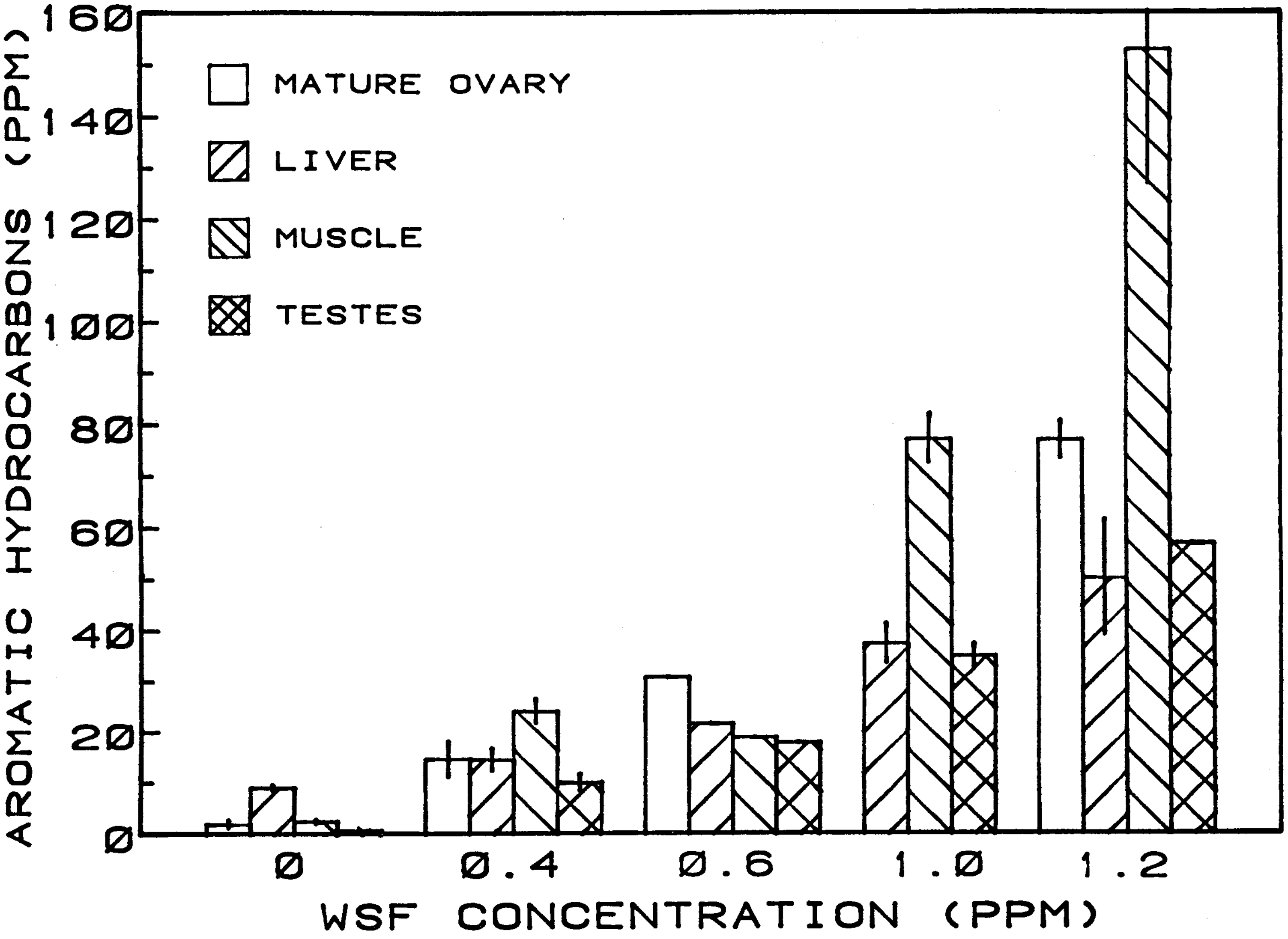

Figure 2.--Concentration of aromatic hydrocarbons in adult Pacific herring (*Clupea harengus pallasi*) tissues after 48-hour exposure to different levels of water-soluble fraction (WSF) of Cook Inlet crude oil. Vertical bars = standard error.

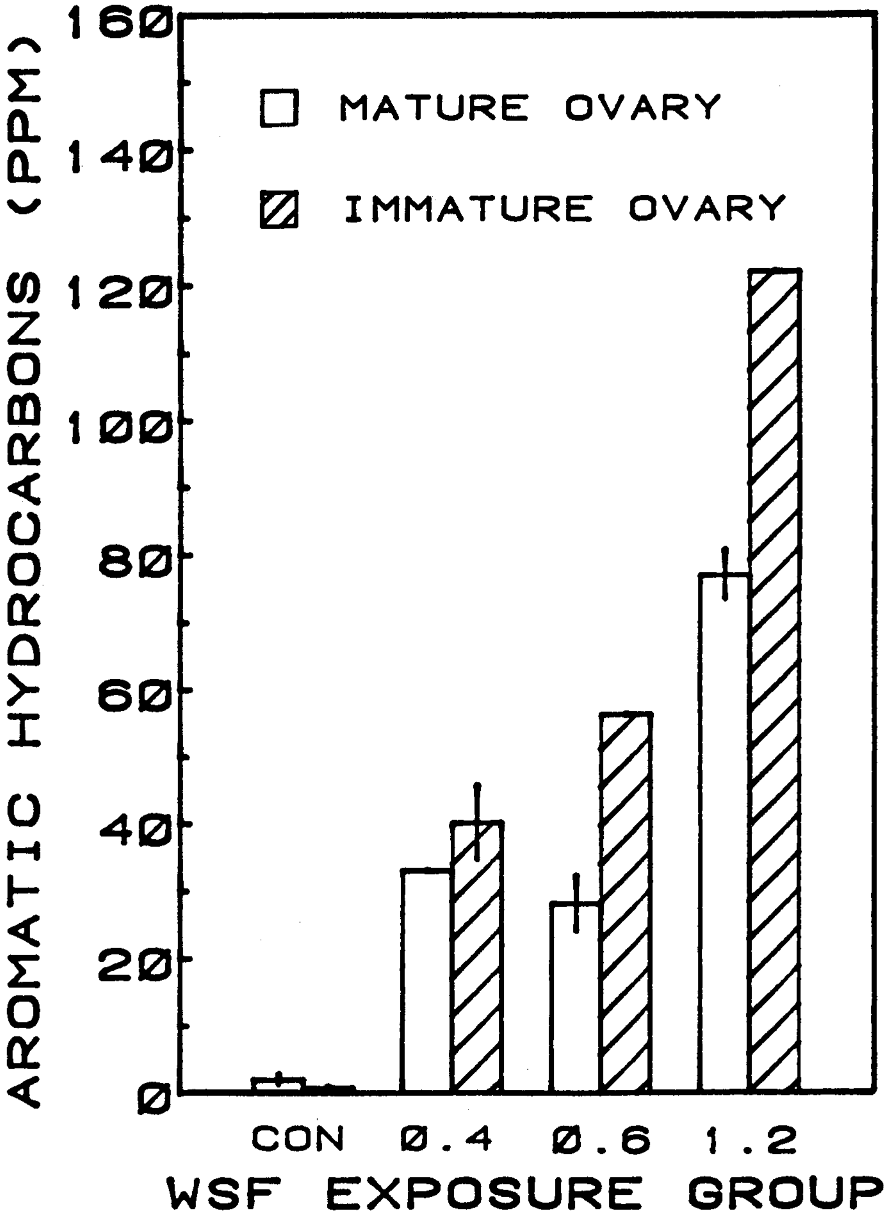

Figure 3.--Accumulation of aromatic hydrocarbons in mature and immature ovaries of prespawning Pacific herring (Clupea harengus pallasi). CON = control group; vertical bars = standard error.

Depuration was rapid in muscle and ovarian tissues during the first 24 hours in clean water; about 50% of the hydrocarbons were lost (Fig. 4). Depuration was much slower after the initial 24-hour period. Two more days were required to lose 50% of the remaining hydrocarbons, and another 50% was lost between Day 4 and 7. By Day 14, hydrocarbon levels in muscle and ovarian tissues were not significantly higher than levels in tissues of unexposed fish.

WSF exposures to prespawn adult herring did not damage ovaries: All exposure groups appeared normal. There was no evidence of increased number of dead eggs, of atretic follicles, or effect on egg sizes.

Gonad (Adult), Egg, and Yolk-Sac Larvae Exposures

There was no effect on survival of spawn from oil-exposed, mature adults (Fig. 5). Hatching success of eggs spawned from adult herring that were exposed to WSF for 12 days varied between 78 and 85% and did not differ significantly from controls. The highest concentration tested was 1.6 ppm, 75% of the LC_{50} for adult herring (85% of the herring survived at this exposure). If the adults survived oil exposure, hatching rates were normal.

Relatively long-term (12-day) WSF exposures of artificially spawned eggs affected hatching rates (Fig. 5), whereas short-term (2-day) exposures did not affect hatching rates. Eggs exposed 2 days to WSF concentrations as high as 5.3 ppm hatched at rates between 78 and 81%, and rates were not significantly different between exposed or control eggs. In contrast, eggs exposed 12 days hatched at rates between 0 and 84% and had an LC_{50} of 1.5 ppm aromatic hydrocarbons (Table 2).

Yolk-sac larvae exposed to WSF ≤ 6 hours were less affected than the larvae exposed ≥ 16 hours. Larvae exposed ≤ 6 hours to 6.1 ppm aromatic

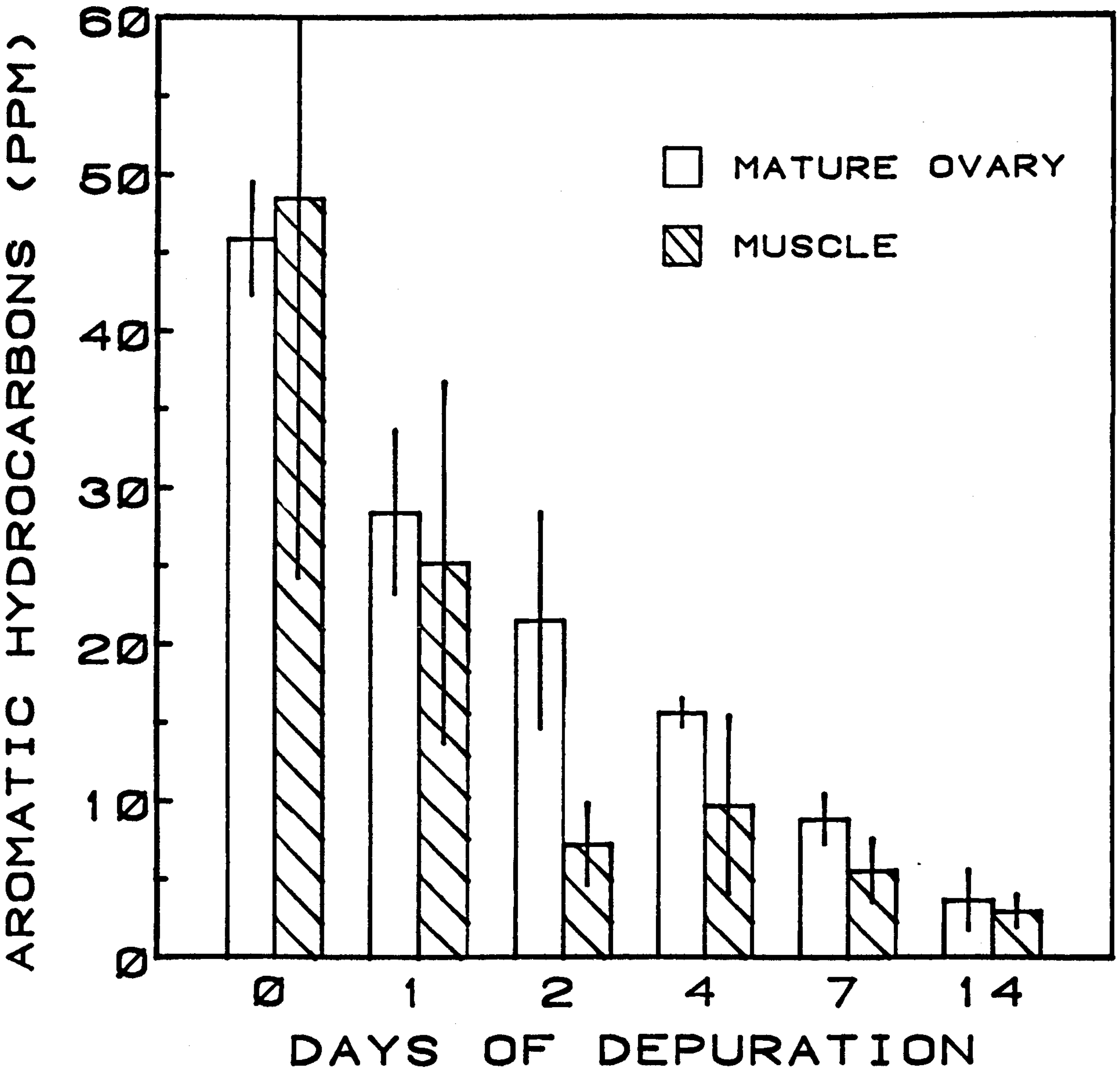

Figure 4.--Depuration of aromatic hydrocarbons from adult Pacific herring (*Clupea harengus pallasi*) previously exposed 96 hours to 0.6 ppm water-soluble fraction (WSF) of Cook Inlet crude oil. Vertical bars = standard error.

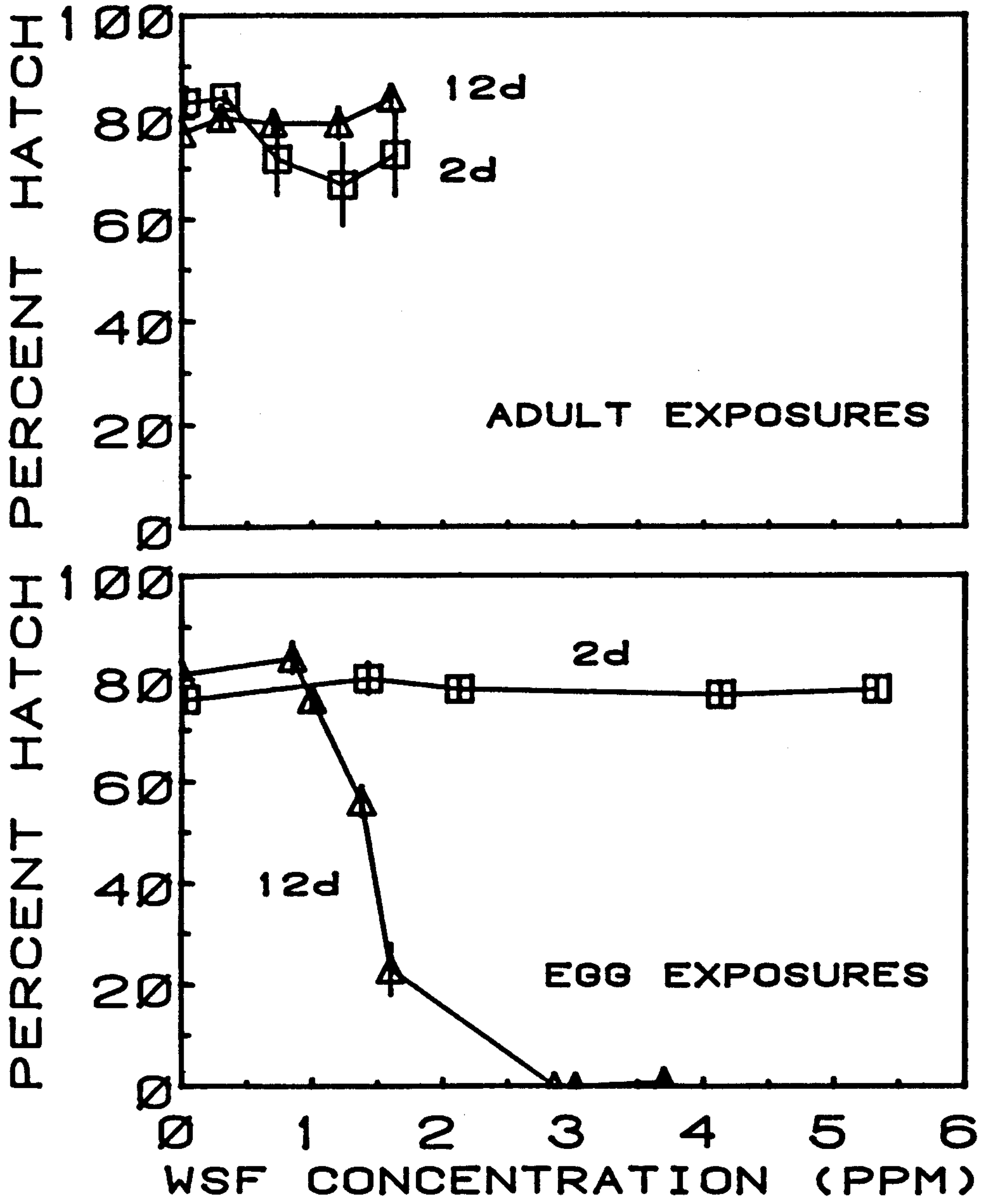

Figure 5.--Percent hatch of Pacific herring (Clupea harengus pallasi) eggs from adults exposed 2 or 12 days to water-soluble fraction (WSF) (1.6 ppm, 75% of the LC_{50}, was the highest WSF concentration used in the adult exposures), and percent hatch of artificially spawned and fertilized eggs exposed 2 or 12 days to WSF. Vertical bars = standard error.

hydrocarbons (the highest concentration tested) survived. Six hours of exposure to 4.8 ppm caused swimming failure in 57% of larvae, and 6.1 ppm caused 71% swimming failure, but the effect was transitory: Larvae regained swimming ability within 24 hours after exposure. Larvae exposed $\geq$16 hours had an LC_{50} of 2.8 ppm (95% CI = ±0.6), and larvae exposed $\leq$6 days had an LC_{50} of 2.3 ppm (95% CI = ±0.2) (Fig. 6).

Feeding Larvae and Contaminated Prey

Survival, feeding, and growth of herring larvae were affected by direct exposure to WSF. Oil-contaminated prey had a much smaller influence than did direct exposure to aromatic hydrocarbons: Larval survival was eventually reduced by the most contaminated prey, but feeding rates and growth were little affected.

Direct exposure to WSF caused high larval mortality. The LC_{50} dropped from 1.85 ppm WSF on Day 7 to 0.36 ppm on Day 21 and remained unchanged through Day 28 (Fig. 7). WSF concentrations >0.8 ppm were fatal within 3 weeks. Herring fed contaminated prey had higher survival rates than did larvae exposed directly to WSF. The most contaminated prey (59 ppm initial tissue concentration) caused a significant (*P* = 0.94) fraction, 51%, of the larvae to die relative to controls (Fig. 8), and after 3 weeks, effects of these contaminated prey were equivalent to effects seen in 0.3 ppm WSF exposure. Larvae that survived the indirect exposures appeared robust. Survival in control groups was above 90% throughout the study (Fig. 8).

Larval swimming was inhibited by exposure to WSF before death occurred (Fig. 7). Swimming was inhibited more rapidly as doses increased. For example, larvae stopped swimming and settling occurred

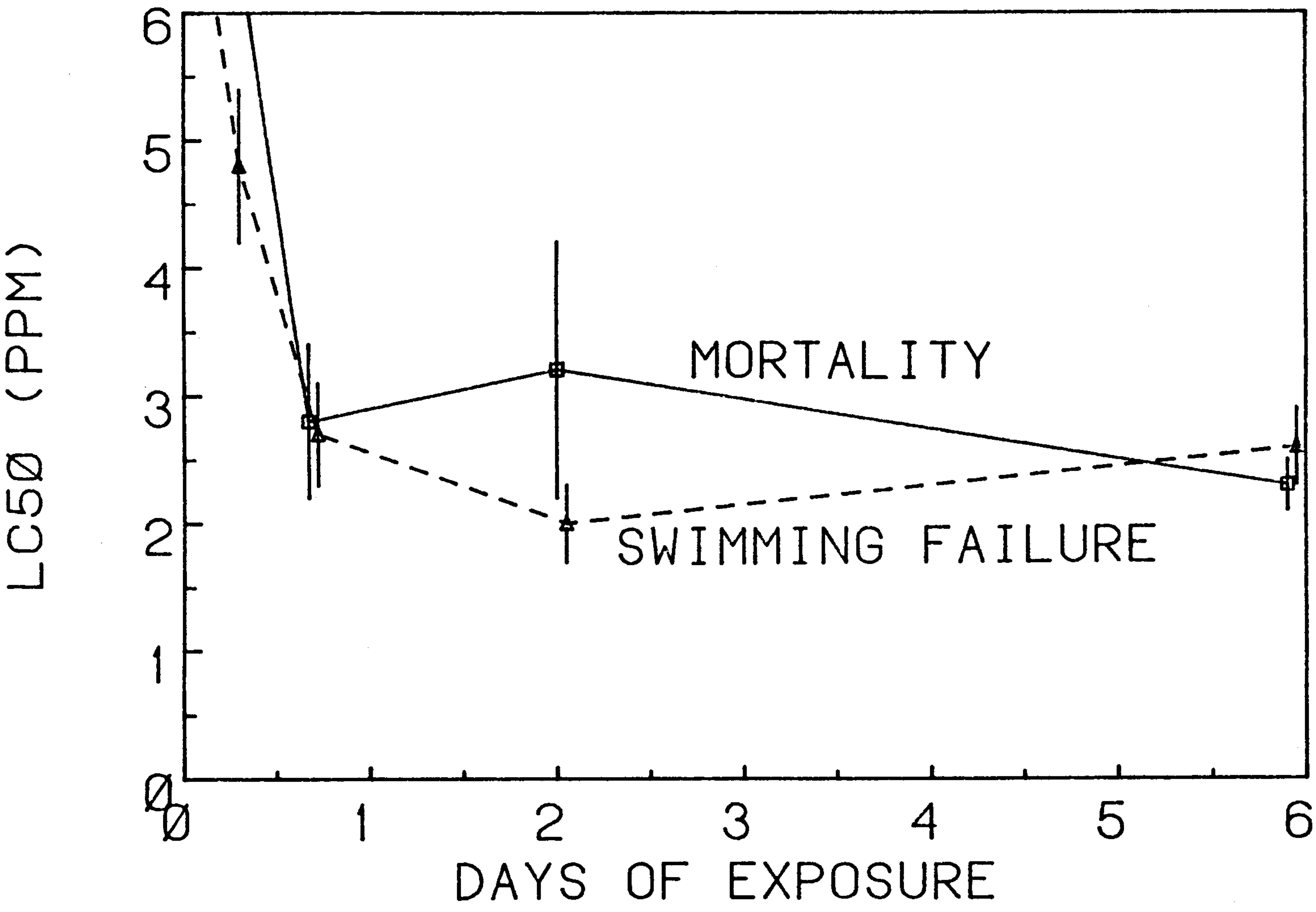

Figure 6.--Effect of exposure to water-soluble fraction (WSF) Cook Inlet crude oil on Pacific herring (*Clupea harengus pallasi*) yolk-sac larval mortality (LC_{50}) and swimming ability (EC_{50}). Vertical bars = 95% confidence intervals

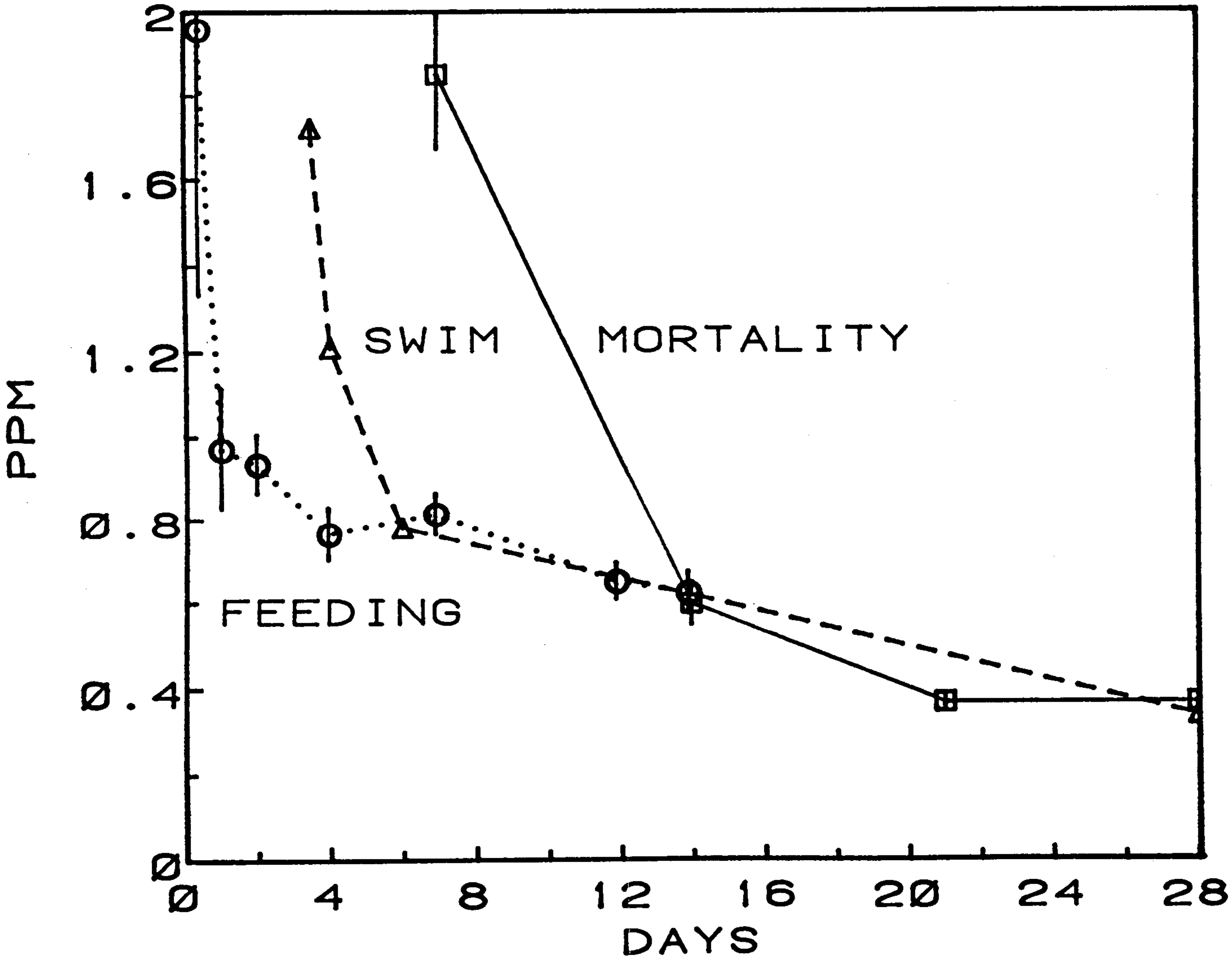

Figure 7.--Effect of exposure to water-soluble fraction (WSF) of Cook Inlet crude oil on feeding Pacific herring (Clupea harengus pallasi) larval mortality (LC_{50}) and swimming ability and feeding (EC_{50}). Vertical bars = 95% confidence intervals.

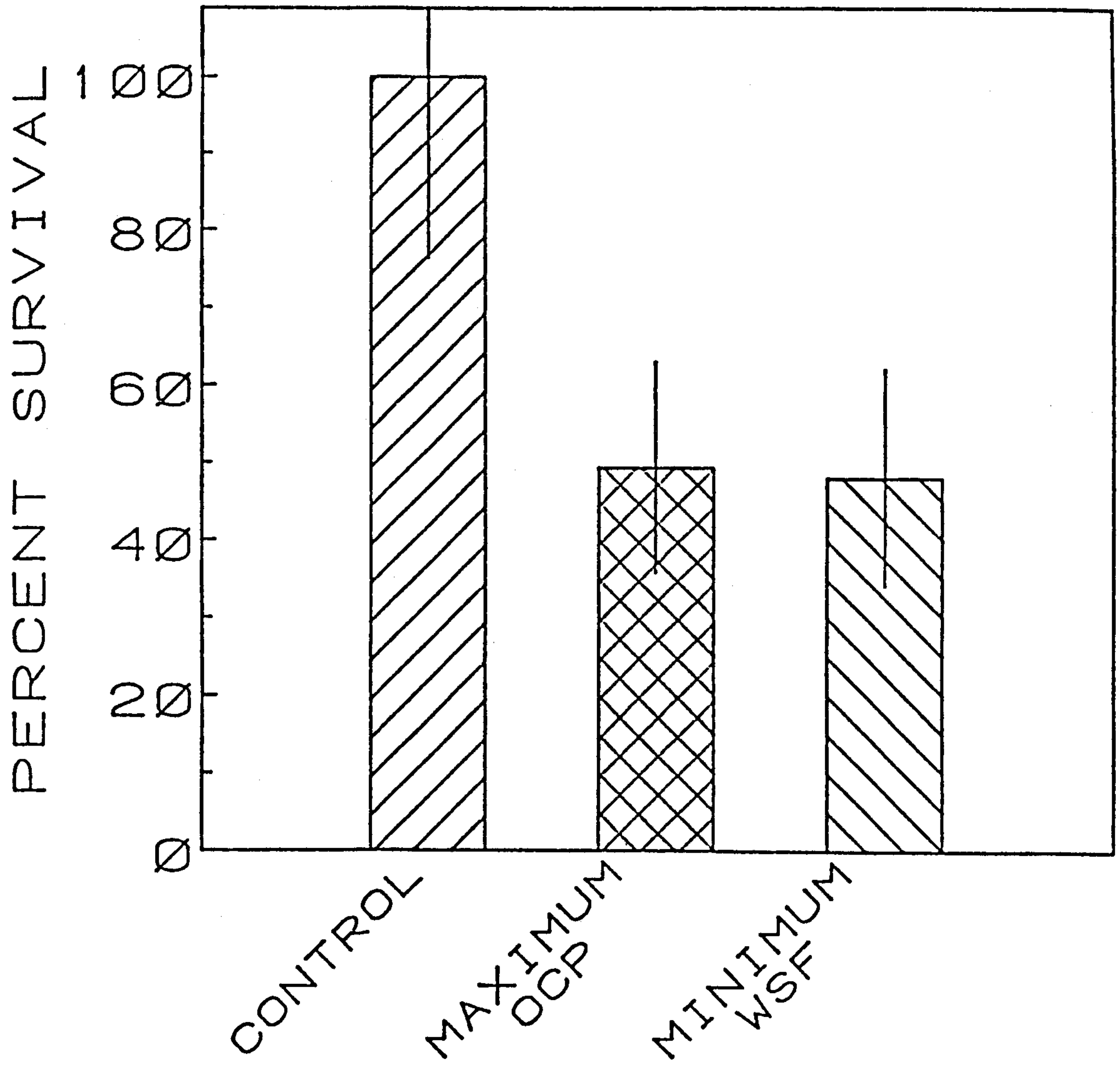

Figure 8.--Survival of Pacific herring (Clupea harengus pallasi) control larvae and of larvae exposed 16 days to maximum oil-contaminated prey (OCP) doses (59 ppm initial tissue concentration) or to minimum WSF doses (0.3 ppm). Vertical bars = ±1 standard error.

in about 3.5 days at 1.7 ppm WSF, whereas settling occurred in about 6 days at 0.9 ppm. Mortality and swimming inhibition were inseparable after larvae had been exposed >14 days (Fig. 7). Eating oil-contaminated foods did not cause noticeable swimming inhibition in larvae. Swimming ability of the prey, *Artemia* nauplii, was reduced by exposure to highest WSF concentrations.

Feeding frequencies were significantly reduced by exposure to WSF before swimming ability was reduced or significant mortality occurred (Fig. 7). Concentrations causing half the larvae to cease feeding decreased to 2.0 ppm WSF after 9 hours, 1.0 ppm on Day 1, 0.8 ppm on Day 4, and 0.7 ppm on Day 12. Feeding frequencies at 0.9 ppm decreased significantly within half a day, continued to decline rapidly (Fig. 9), and ceased within 10 to 14 days of exposure. Feeding frequencies decreased at concentrations as low as 0.5 ppm. Contaminated food had no effect on feeding frequencies; daily feeding rates never differed significantly from controls (Fig. 9).

Larvae that survived exposure to 0.9 ppm WSF resumed feeding when transferred to clean water, but increased exposure times sharply reduced survival (Fig. 10). Feeding frequencies, measured after 2, 4, and 8 days of exposure, increased rapidly once WSF dosing stopped (Fig. 10). The longer the larvae were exposed to WSF, the more rapidly survivors tended to resume feeding. However, increases in the exposure times sharply reduced larval survival ($Y^{\frac{1}{2}} = 10.01 - 0.71x$; $r^2 = 0.89$; Fig. 10). After 8 days of exposure, only 16% of the larvae survived; of these, 89% resumed feeding. Reductions in feeding frequencies after 12 days of exposure correlated with larval mortality measured at 3 weeks ($r^2 = 0.94$, $F = 222$, 1,15 d.f., $P < 0.001$; Fig. 11).

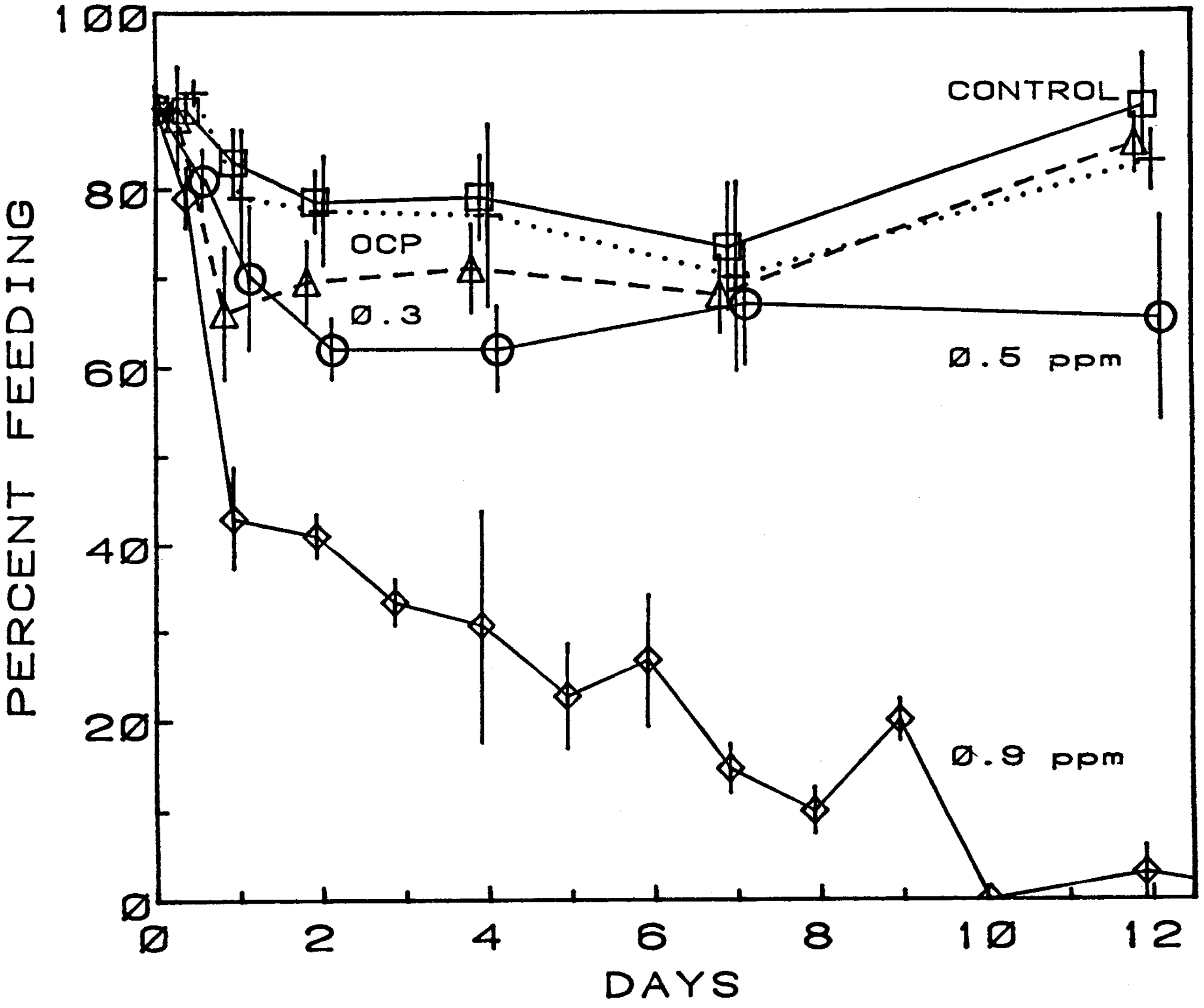

Figure 9.--Feeding frequency of Pacific herring (Clupea harengus pallasi) larvae exposed to water-soluble fraction (WSF) of Cook Inlet crude oil and larvae fed oil-contaminated prey (OCP). Vertical bars = standard error.

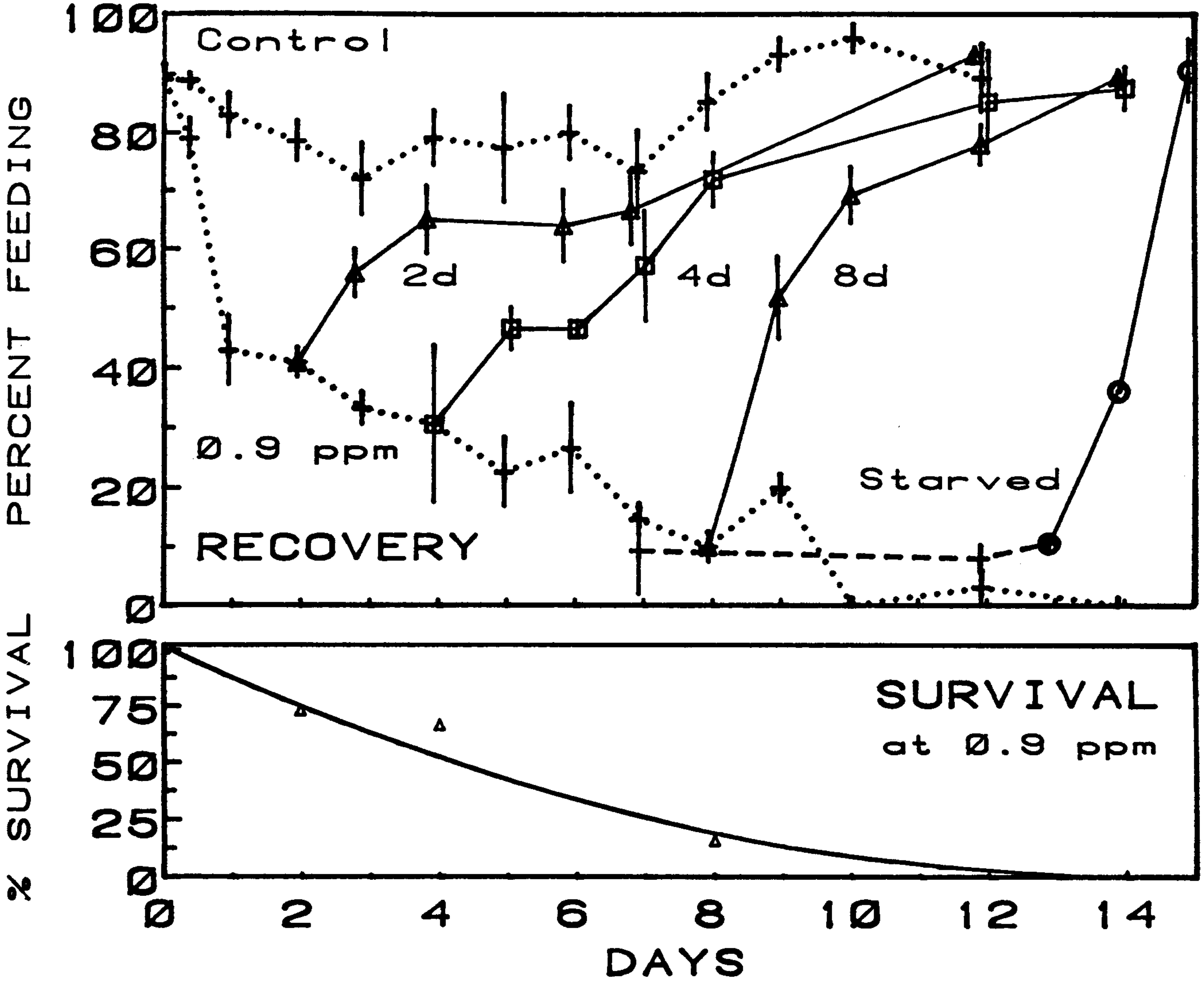

Figure 10.--Recovery of feeding response and survival of Pacific herring (*Clupea harengus pallasi*) larvae after exposure to 0.9 ppm water-soluble fraction (WSF) for various time periods. Vertical bars = standard error.

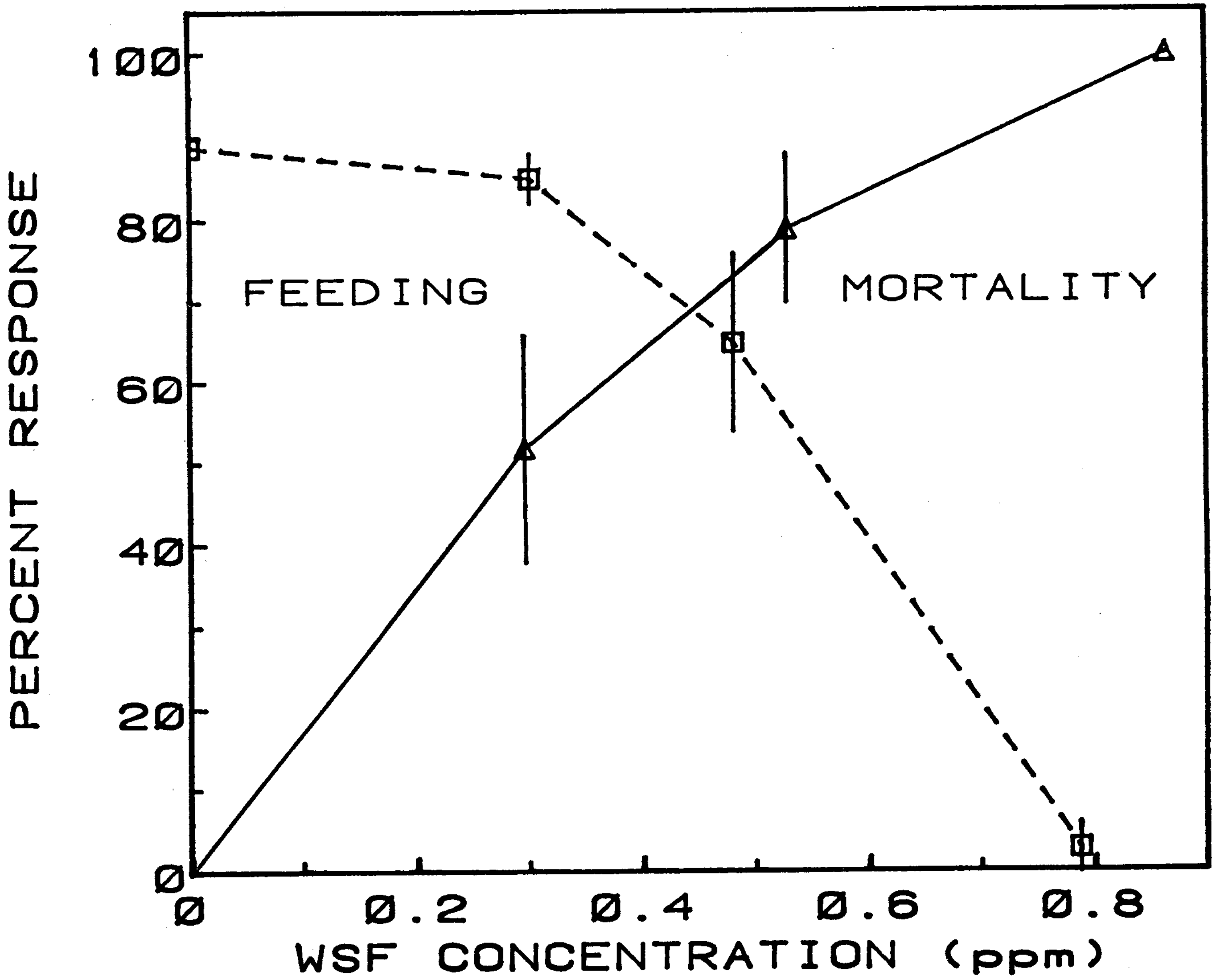

Figure 11.--Relationship of feeding frequency and mortality in Pacific herring (*Clupea harengus pallasi*) larvae. Feeding frequencies were determined after 12-day exposure to water-soluble fraction (WSF), and mortality, at 21-day exposure. Vertical bars = standard error.

Growth (notochord length) in feeding herring larvae was strongly inhibited by WSF exposure, but not by indirect exposure (Fig. 12). After 1 week of exposure, concentrations >0.7 ppm reduced the growth rate. After 2 weeks, the lowest WSF dose (0.3 ppm) also caused significant reductions. Growth became negative at concentrations >1.2 ppm during the first week and at 0.8 ppm during the second week. At these concentrations, mortality was 100% within 3 weeks.

Herring larvae and their prey exchanged hydrocarbons rapidly with surrounding water. Herring larvae accumulated radio-labelled naphthalene faster than did Artemia nauplii, but the nauplii retained a greater proportion of the ^{14}C-naphthalene (Fig. 13). Tissue concentrations of larvae reached equilibrium after 1 hour, and of Artemia nauplii, 10 hours. Depuration of ^{14}C-naphthalene was also rapid (Fig. 13). However, a substantial fraction (18%; standard error = 0.6) of the carbon-14 did remain in Artemia nauplii but did not remain in herring larvae (2%; standard error = 0.3) after 24 hours. This result indicates naphthalene was either trapped in lipid-rich tissues or metabolized and permanently incorporated in nauplii tissues. Virtually no carbon-14 was permanently incorporated into larval tissues.

Herring larvae accumulated hydrocarbons when exposed to WSF, but larvae fed contaminated prey did not accumulate hydrocarbons to detectable levels. Bioaccumulation of WSF was low (0.9-2.1). For example, larvae exposed to 0.3 ppm WSF accumulated 0.3 ppm aromatic hydrocarbons.

Although larvae feeding on contaminated prey had hydrocarbon concentrations that were not detectable, the concentrations in prey were

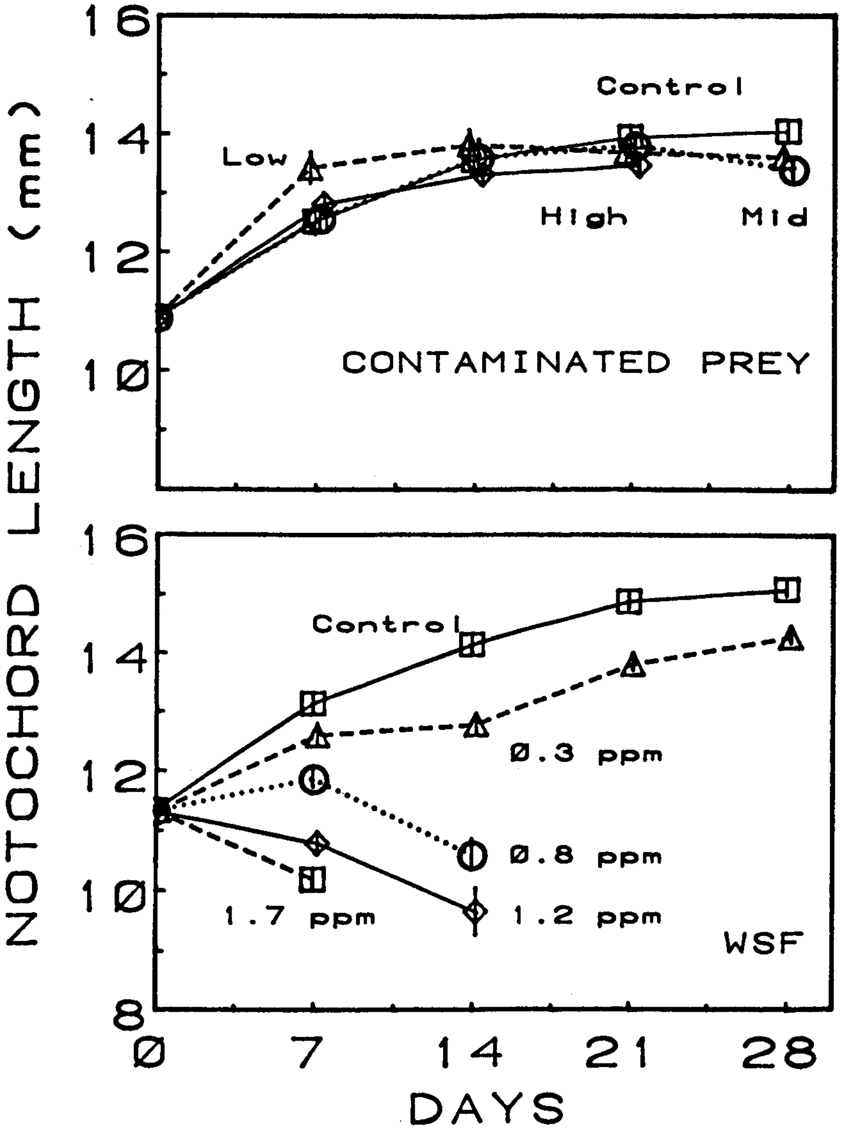

Figure 12.--Influence of water-soluble fraction (WSF) exposure and oil-contaminated prey (OCP) on growth of Pacific herring (*Clupea harengus pallasi*) larvae. Vertical bars = standard error.

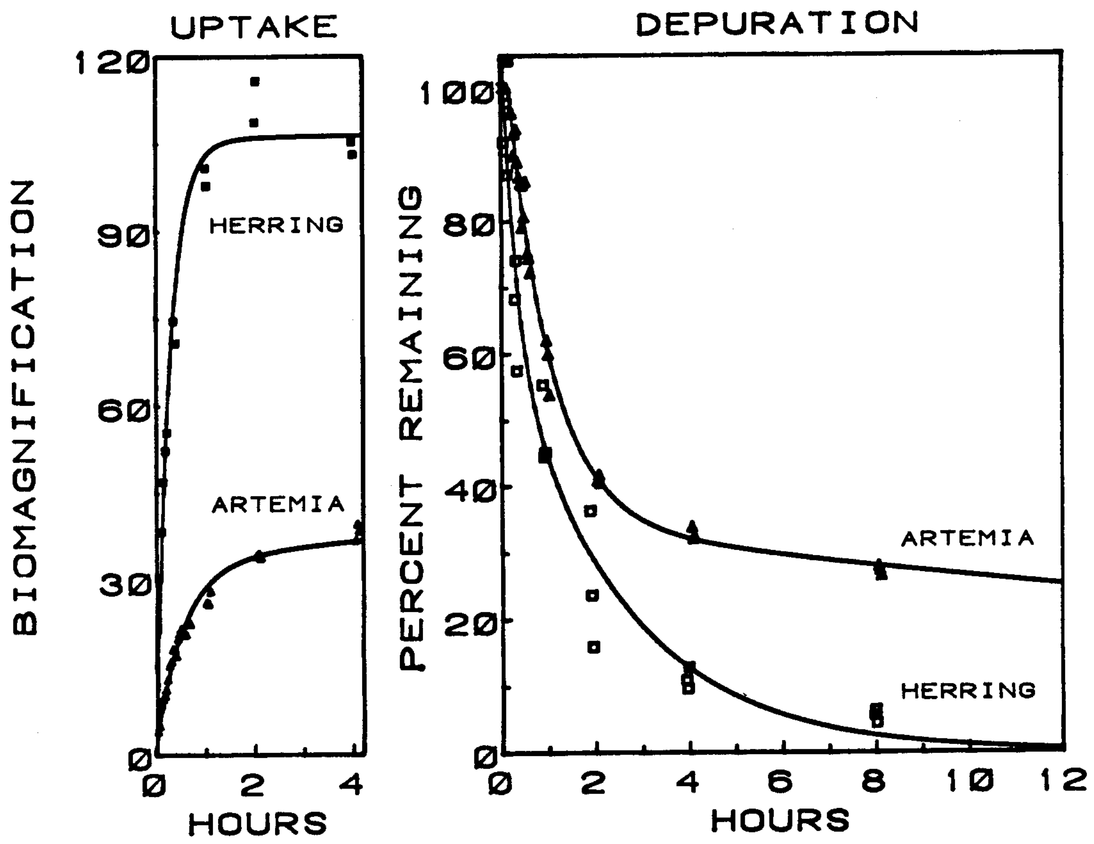

Figure 13.--Uptake and depuration of radio-labelled naphthalene by Pacific herring (Clupea harengus pallasi) larvae and their prey, Artemia nauplii. Vertical bars = standard error.

easily measured. In the most contaminated food group, aromatic hydrocarbon concentrations in Artemia nauplii tissues averaged 59 ppm at the end of exposure (Table 3) but dropped rapidly during holding and circulation in experimental tanks (Fig. 14). Average tissue concentrations at the time of consumption could not be determined precisely because of multiple feeding times (six per day), variable larval hunger, and imprecise knowledge of nauplii residence time (<8 hour). At the time of consumption, we estimated that 2-100% of the aromatic hydrocarbons remained in nauplii tissues and averaged about 14% (8.6 ppm).

Table 3.--Concentrations of aromatic hydrocarbons (mono- and di-aromatic) in Artemia nauplii that were fed to Pacific herring (Clupea harengus pallasi) larvae. WSF = water-soluble fraction of Cook Inlet crude oil; S.E. = standard error.

Dose group	n	WSF exposure (ppm)	Tissue concentration (mean ppm ± S.E.)	Biomagnification
Control	6	0.00	0.0 ± 0.10	-
Low	5	0.23	1.4 ± 0.53	6.1
Medium	5	0.72	6.8 ± 0.63	9.5
High	14	5.52	58.8 ± 9.54	10.7

DISCUSSION

Adult Herring

All tested herring tissues (muscle, liver, testes, and immature and mature ovaries) accumulated aromatic hydrocarbons. Continued accumulation, without reaching equilibrium, through Day 10 suggests that

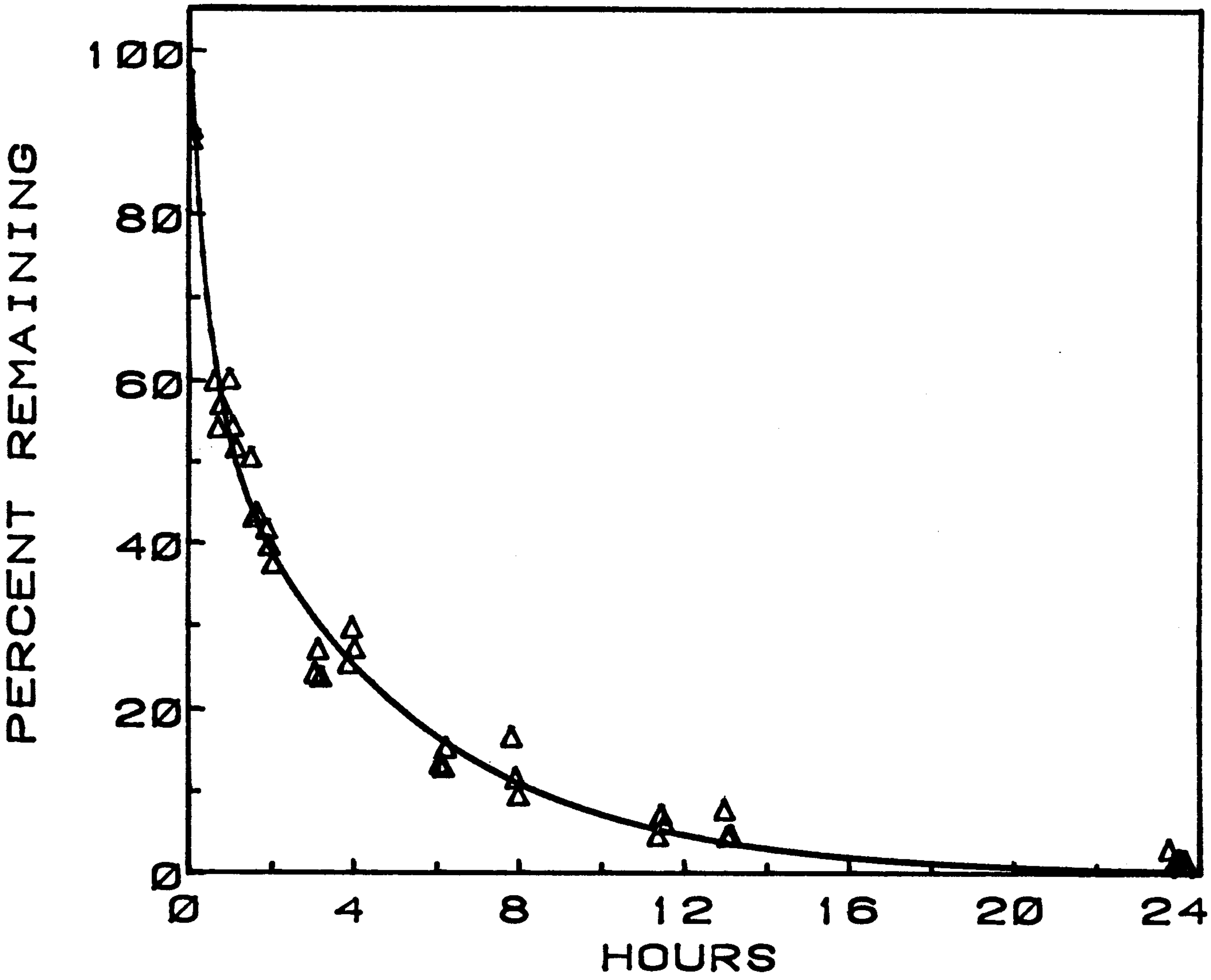

Figure 14.--*Artemia* nauplii depuration of radio-labelled naphthalene before they were fed to Pacific herring (*Clupea harengus pallasi*) larvae. Vertical bars = standard error.

higher concentrations would be reached if exposure times were longer. All tissues, including ovary, depurated hydrocarbons, but depuration after 24 hours was slow.

The pattern of continuous accumulation of hydrocarbons through Day 10 is different from that in pink salmon (O. gorbuscha) fry exposed to Cook Inlet WSF (Rice et al. 1977). Pink salmon reach equilibrium rapidly (24-48 hours), and tissue concentrations return to background levels by 96 hours, even while the fish remain in the WSF. Pink salmon actively metabolize and excrete hydrocarbons at rates faster than incoming rates after 24 hours. In adult herring, prolonged accumulation of hydrocarbons is probably the net result of two primary factors: high lipid concentrations in their tissues and the lack of aromatic hydrocarbon metabolism because of reproductive condition. The lengthy time without reaching equilibrium concentrations in the tissues suggests that hepatic aryl hydrocarbon hydroxylase (AHH) activity was low. Findings of other investigators (Walton et al. 1978; Spies et al. 1985) suggest that suppression of basal AHH activity in prespawn marine fish is a common occurrence, and that AHH is not inducible during late stages of gonad maturation (Walton et al. 1983). Adult herring in the prespawning condition have not been actively feeding for weeks, and their ability to metabolize and excrete aromatic hydrocarbons may be different during the summers when they are actively feeding and not in a reproductive mode.

Although aromatic hydrocarbons accumulated in herring tissues, particularly developing ovarian tissue, survival of ova and hatching success of spawn were not adversely affected. Our results contrast with those of Struhsaker (1977) who found that ova survival and hatching success decreased after 48-hour exposures to benzene. The two studies had two major differences: toxicants and stocks of fish.

The most obvious difference between the two studies--toxicants--probably did not cause the differences in survival of ova and hatching success of spawn. Struhsaker (1977) exposed adult herring to 0.8 ppm benzene, and our WSF dose of 1.6 ppm aromatic hydrocarbons contained about 0.7 ppm benzene. In our study, 12 days of exposure should have been long enough for adverse effects on ova and on hatching success to become evident.

The factor most responsible for the observed differences between the two studies is probably the source of the two stocks of herring. Struhsaker (1977) captured herring in San Francisco Bay, where pollutant levels from a wide variety of sources are considered to be threatening to some fish and shellfish populations (Whipple et al. 1981). Hatching success of herring eggs from adults collected in San Francisco Bay was about 25% less than that of eggs from stocks collected outside the bay (Struhsaker et al. 1974). This reduction was attributed to differences in accumulated pollutants from the more polluted bay (Struhsaker 1977). Herring in our study were collected in pristine waters in remote areas of southeastern Alaska, and the viability of the spawn was consistently high. Thus, poor viability of herring eggs in the study by Struhsaker (1977) probably resulted from the combined effects of benzene exposure along with the pollutant load accumulated from San Francisco Bay.

Gonads, Eggs, and Yolk-Sac Larvae

If mature adult herring survive WSF exposure, their eggs survive and develop. For 12 days, at least, the body of the adult protects its gametes from injury. Spawned eggs resist damage by WSF for at least 2 days but are killed by exposure to concentrations >1.5 ppm for over 12 days. In contrast, yolk-sac larvae can be killed in relatively short exposures, only 16 hours at $\geq$2.4 ppm.

Other studies on herring eggs exposured to WSF of crude oil or to selected monoaromatics have shown increased mortality and increased frequency of abnormalities in the embryos and larvae (Linden 1978; Smith and Cameron 1979; Vuorinen and Axell 1980). These crude oil studies were static, and fouling complications caused by bacteria and diatoms were reported by Smith and Cameron (1979). We did not observe any abnormalities, but extensive examination was not done. Abnormalities may have become evident if the tests had ended after yolk absorption occurred rather than at hatching.

Feeding Larvae and Contaminated Prey

Larval survival was reduced by contaminated prey and by direct WSF exposure, which was much more toxic. Highly contaminated prey (about 59 ppm initial tissue concentration) caused about half the herring larvae to die in 21 days, but the surviving larvae appeared robust. Contaminated prey did not affect larval feeding and swimming. The vigor of larvae fed contaminated prey may have been due to a prophylactic effect of the oil, i.e., low concentrations of oil improved tank hygiene by killing bacteria and ciliates.

Although herring larvae were killed by low WSF concentrations (21-day LC_{50}, 0.36 ppm), they reacted more slowly to the toxicant than did another pelagic species (*Theragra chalcogramma*) in a similar study (Carls unpubl. data). Herring larvae exposed to 1.7 ppm did not cease swimming for 3-4 days. In contrast, the swimming ability of T. chalcogramma larvae exposed to 1.2 ppm WSF of oil was reduced within 4 hours (Carls unpubl. data).

Prey contamination probably contributed to WSF effects during direct exposure, but direct toxicity was more significant. Larvae exposed to WSF in our study were also exposed to contaminated prey because uncontaminated prey accumulated hydrocarbons rapidly in tissues after entering dosing chambers as food. Prey remaining several hours in the lowest (0.3 ppm) WSF dose would probably accumulate hydrocarbon concentrations equivalent to the lowest contaminated prey dose. No WSF exposure concentrations were great enough for prey to accumulate maximum (5.5 ppm) contaminated prey doses. Maximum contaminated prey doses caused mortality equivalent to minimum WSF doses.

Direct exposure to WSF reduced larval feeding, but the mechanism is obscure. Larvae exposed to 0.9 ppm WSF often continued to exhibit strike behavior, including those individuals with empty guts. Strike speed and agility appeared uninhibited. Reductions in feeding were found in herring larvae (Struhsaker et al. 1974) and in striped bass (Morone saxatilis) larvae exposed to benzene (Eldridge et al. 1981), in pink salmon juveniles exposed to naphthalene and WSF (Moles and Rice 1983), and in adult coho salmon (Oncorhynchus kisutch) exposed to WSF (Folmar et al. 1981). In our study, feeding reductions were not permanent because surviving larvae rapidly resumed feeding in clean water. Feeding frequencies were sensitive, easily measured indicators of toxicant effect. Changes in feeding predicted mortality and growth.

Starvation alone does not explain WSF-induced mortality. Although feeding rates declined rapidly in WSF treatments, larval survival (40%)

after 8 days' starvation was much better than after direct exposure to 0.9 ppm WSF (16%) for the same time period. Furthermore, starved larvae resumed feeding more rapidly than did WSF-exposed larvae.

Growth of control larvae was not a linear function, but leveled off at about 1.4 cm. At the higher temperature (7.9°C vs. 6.4°C), feeding frequencies declined at 12 days when larvae were 1.25 cm; these declines correlated with asymptotic growth. We postulate that we reached our limit of ability to provide suitable nutrition in spite of an excess of food being available to the larvae. Other researchers found similar reductions in growth rate. Some marine larvae (e.g., plaice) are able to grow through metamorphosis on rather small prey (Brachionus spp.) but have depressed growth, whereas growth in other species, e.g., Pacific mackerel (Scomber japonicus), slows and few larvae survive to metamorphosis (Hunter 1984).

Exposure to hydrocarbons reduced growth. Direct exposure caused rapid, dramatic reductions, whereas dietary sources resulted in slow, small reductions. Growth was sharply reduced by WSF exposures and was significantly affected at sublethal concentrations (0.3 ppm). Reductions in growth, particularly at the high concentrations, were primarily due to reductions in feeding. In other studies, growth of larval herring was reduced by dissolved benzene, and corresponded with reduced feeding (Struhsaker et al. 1974). Growth of pink salmon alevins (Rice et al. 1975) and juveniles was reduced at least partially by reduced feeding (Moles and Rice 1983). Reductions in growth at sublethal exposures may also be due to changes in metabolic rate. For example, oxygen consumption and breathing rates of pink salmon fry exposed to toluene and naphthalene increased immediately upon exposure (Thomas and Rice 1979). Respiration of Fundulus heteroclitus embryos exposed to WSF increased briefly but was depressed after prolonged exposure (Sharp et al. 1979). Embryonic activity, a measure of respiration, was initially increased by exposure to dissolved light oils and then later depressed (Linden 1978).

Contaminated prey inhibited growth only at very high concentrations and after long exposures. Other studies have also demonstrated that oil-contaminated prey affect growth and require time for the effects to become visible. Growth of pink salmon fry was reduced by a diet of contaminated Artemia nauplii at hydrocarbon levels that would be lethal as WSF (Schwartz 1985). Chinook salmon (Oncorhynchus tshawytscha) gut tissue was damaged when exposed to dietary hydrocarbons (Hawkes et al. 1980), energy reserves in trout (Salmo spp.) were depleted, and growth was reduced (Hawkes 1977). In our study, hydrocarbons present in prey were partially depurated before consumption; nauplii in the pink salmon study were eaten rapidly before significant depuration could occur (Schwartz 1985).

The difference in rate of effects between WSF and contaminated food is caused by the large difference in hydrocarbon accumulation rates. Hydrocarbon accumulation in larval tissues is rapid if the WSF exposure is direct, reaching maximum levels in about 1 hour. Accumulation of hydrocarbons through contaminated food takes a long time, if it occurs at all, because larvae eat only a fraction of their body weight per day. Hydrocarbons taken up from prey in 1 day are lost the next. Net accumulation from prey can occur only if the absorbed hydrocarbons are trapped in the lipid-rich tissues and are not metabolized or excreted. The high surface area of larvae permits depuration into the clean surrounding water because most hydrocarbons in the WSF, particularly the monoaromatic hydrocarbons, are not tightly bound in the lipids. Eventually, contaminated prey can affect larvae, but the low rate of hydrocarbon accumulation takes a long time before effects are evident.

Depuration of hydrocarbons by prey tends to obscure exact dose significance but emphasizes the importance of hydrocarbon loss by prey in the real world. Hydrocarbons present in prey were partially depurated before consumption. Artemia nauplii depurated WSF hydrocarbons rapidly (2% retention after 24 hours). Brachionus spp. depurated naphthalene rapidly during the first 2 hours, but depuration was much slower thereafter (33% retention after 24 hours). Other investigators have also observed rapid depuration of hydrocarbons from zooplankton: Coonstripe shrimp (Pandalus hypsinotus) zoeae depurated 97% in 1 day, (Brodersen unpubl. data), Calanus helgolandicus depurated 35-85% in 1 day (Corner et al. 1976), and Euchaeta japonica depurated 60% in 1 day and about 80% in 2 days (Lee 1975). Generally, crustaceans depurate hydrocarbons rapidly (Anderson et al. 1974). Small amounts of hydrocarbons are often retained by zooplankters (e.g., Euchaeta japonica and Calanus helgolandicus) for long periods, but after 1 day, much of the remaining hydrocarbons may be as metabolites (Lee 1975; Corner et al. 1976).

Contaminated prey in natural environments is not the major avenue of toxicant exposure for herring larvae. Because prey and predator inhabit the same planktonic environment, both would be simultaneously exposed to the same levels of WSF contamination. Concentrations required to significantly contaminate prey (about 6 ppm) are directly and more rapidly lethal to herring larvae. Since prey (and predator) rapidly exchange hydrocarbons with their environment, prey cannot accumulate significant quantities of hydrocarbons days or weeks in advance and then adversely affect larvae that hatch after the contaminant is gone.

Probable Effects of Oil on Fisheries

Catastrophic oil spills such as from the Amoco Cadiz (March 1978) on the north coast of Brittany in France and from the grounding of the Metula in the Strait of Magellan (August 1974)--both in temperate, subarctic regions--can result in the complete destruction of adjacent intertidal and subtidal floral and faunal communities. Accumulated crude oil in intertidal areas will persist and its effects seen for many years (Glémarec and Hussenot 1982; Gundlach et al. 1982). Incubating herring eggs would be vulnerable in this type of a situation.

Although oil in the water column in the vicinity of a spill may be more transitory, Calder and Boehm (1981) show a drop from >1,000 μg/l oil-in-water (9 days after the grounding of the Amoco Cadiz in Aber Wrac'h estuary) to 60 μg/l 48 days later. Initial concentrations may well be within the range to impact herring, particularly the sensitive larval stages. Potential impacts of WSF from an oil spill in an area where herring spawn can be predicted from our study. Concentrations of 1.6 ppm aromatic hydrocarbons or more will kill some adult fish; however, if the oil dissipates before the surviving fish spawn, the resultant eggs probably will not be affected. If oil remains in the water column for no more than 2 days after spawning, eggs should develop normally and successfully hatch. If the eggs are subjected to 1.5 ppm or more for 12 or more days, at least half of them will fail to hatch. Unless there was a large oil spill or a chronic discharge of oil, it is unlikely that WSF concentrations would be high enough or would persist long enough to damage herring eggs. Although herring eggs are more tolerant of WSF than are larvae, they are more vulnerable to oil stranded in the intertidal zone where herring spawn. Direct contact with beached oil could lead to massive mortalities from suffocation or toxicity effects.

In contrast to herring adults and eggs, herring larvae are affected rapidly by exposure to low concentrations of WSF. Yolk-sac larvae can be killed by WSF in a matter of hours. If oil is present at a concentration of >2.8 ppm for <16 hours there will be significant mortalities. Feeding larvae cease to eat after 7 days at exposure concentrations as low as 0.4 to 0.7 ppm, which leads to mortalities several days later. Herring larvae are fragile and, like most marine fish larvae, are poor swimmers and have low survival rates even in unpolluted environments. Larval survival has been considered one of the determinant of year-class strength in Pacific herring (Lasker 1985; Smith 1985). Herring population levels could be affected through impact on the more sensitive larval stage.

Considering the aromatic hydrocarbon load in ovarian tissue and the slow rate of depuration, it is surprising we saw no increase in dead ova or in poor hatching of spawn from exposed adults. No effects on viability of spawn from exposed mature adults were detected: If the adults survived, the spawn hatched. Reproduction is usually considered a life stage sensitive to pollutants, but there are several possible reasons why that sensitivity was not evident in our study. One is developing ova and embryos may be resistant to or tolerant of the accumulated aromatic hydrocarbons, which are sequestered primarily in the lipid portion of the eggs rather than in actively growing embryonic tissues. Thus, the developing embryos, as they slowly consume yolk for energy and tissue growth, may have to tolerate only low levels of hydrocarbons. Passive depuration eventually rids the yolk of the hydrocarbons, possibly before any significant amount of damage occurs. A second possibility is damage does occur, but the yolk-sac larvae do not require full use of all their structures and tissues until after yolk absorption. Subtle deformities, particularly cellular damage, that are not evident at hatching may limit survival after yolk absorption.

Accumulation of aromatic hydrocarbons in herring tissues indicates an oil spill could have an effect on the herring fishery, even though direct evidence of an effect on reproduction is lacking. An oil spill at a spawning site could contaminate the roe in adults, making it unmarketable for human consumption. Because mature roe is harvested immediately before spawning, waiting for depuration to occur may not be practical: These fish may spawn before depuration has been completed.

CONCLUSION

Several life stages of Pacific herring were exposed to WSF of Cook Inlet crude oil. Direct effects on the reproductive process were not observed: If adult herring survived oil exposure, the resulting spawn hatched. Eggs were more resistant than adults to 2-day exposure but were more sensitive than adults to 12-day exposures. However, eggs spawned in the intertidal zone could be heavily impacted by stranded oil at low tides. Larvae were the most sensitive life stage observed.

The presence of oil longer than 16 hours in larval rearing habitats could devastate an entire year class. Growth of larvae was decreased at WSF concentrations as low as 0.3 ppm aromatic hydrocarbons.

Herring fisheries could also be impacted by an oil spill through uptake of hydrocarbons into muscle and developing ovarian tissues. Accumulated hydrocarbons and slow depuration rates may result in unmarketable fishery products and fishery closures.

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APPENDIX

Table A.--Experimental conditions for exposures of Pacific herring (Clupea harengus pallasi) to the water-soluble fraction of Cook Inlet crude oil. This study was conducted by the Habitat Investigation Laboratory Unit, Auke Bay Fisheries Laboratory in 1984 and 1985.

Stage exposed	Exposure time	Parameters measured	Exposure concentrations (mean ppm aromatic hydrocarbons)	Individuals per concentration (No.)
Adult	12 days	Mortality (LC50)	0, 0.33, 0.68, 1.2, 2.7, 3.3	12 adults
Adult	48 hours (samples @: 0, 6, 12, 24, 48 hours)	Uptake in liver, muscle, testes, immature & mature ovary	0, 0.33, 0.63, 1.0, 1.2	Three adults per sample[a] (nine per sample time to supply all tissues)
Adult	10 days (samples @: 0, 24 72, 144, 240 hours)	Uptake in liver, muscle, testes, immature & mature ovary	0, 0.28, 0.39, 0.61	Three adults per sample[a] (nine per sample time)
Adult	4 days (samples @: 0, 24 48, 96, 168, 336 hours)	Depuration from muscle, mature ovary	0, 0.69	Three adults per sample[a] (six per sample time)
Gonad (mature adult)	2 days	Hatching success of eggs	0, 0.24, 0.54, 0.93, 1.47	575-750 eggs; eggs from six fish on 12 slides in three incubators[b]
Gonad (mature adult)	12 days	Hatching success of eggs	0, 0.38, 0, 70, 1.18, 1.55	575-750 eggs; eggs from six fish on 12 slides in three incubators[b]
Eggs	2 days	Hatching success	0, 1.36, 2.07, 4.10, 5.30	575-750 eggs; eggs from three fish on 12 slides in three incubators[b]

Table A.--Continued.

Stage exposed	Exposure time	Parameters measured	Exposure concentrations (mean ppm aromatic hydrocarbons)	Individuals per concentration (No.)
Eggs	12 days	Hatching success	0, 1.00, 1.38, 2.86 3.70	575-750 eggs; eggs from four fish on eight slides in two incubators[b]
Eggs	12 days	Hatching success	0, 0.85, 1.60, 3.02	575-750 eggs; eggs from four fish on twelve slides in three incubators[b]
Yolk-sac larvae	40 minutes 2 hours 6 hours[c]	Mortality Swimming	0, 0.24, 0.49, 1.16 2.21, 3.04, 4.81 6.11	18-20 larvae in three tubes in one incubator[b]
Yolk-sac larvae	16 hours[c]	Mortality Swimming	0, 0.22, 0.42, 1.04 2.21, 2.60, 3.90	13-19 larvae in three tubes in one incubator[b]
Yolk-sac larvae	12 days	Mortality Swimming	0, 0.24, 0.42, 1.05 2.08, 2.67, 4.09	17-20 larvae in three tubes in one incubator[b]
Yolk-sac larvae	6 days[c]	Mortality Swimming	0, 0.25, 0.44, 1.15 2.12, 2.91, 4.23	76-108 larvae in three incubators[b]
Feeding larvae	28 days	Mortality Swimming Feeding Growth	0, 0.3, 0.78, 1.21 1.72	>4000 larvae in four tanks
Feeding larvae	21 days	Mortality Swimming Feeding Growth	0, 0.3, 0.53, 0.86	>8,000 larvae in four tanks

Table A.--Continued.

Stage exposed	Exposure time	Parameters measured	Exposure concentrations (mean ppm aromatic hydrocarbons)	Individuals per concentration (No.)
Feeding larvae	28 days OCP[d]	Mortality Swimming Feeding	Prey exposed to 0, 0.28, 0.82, 6.29 OCP[d] tissue levels = 0, 1.4, 6.8, 59 ppm	>2,000 larvae in four tanks

[a] Many adult herring were exposed to ensure finding three males, three immature females, and three mature females (externally alike) at each sampling period.

[b] Additional individuals and replicates were used for control groups.

[c] All yolk-sac larvae tests were monitored 6 days, regardless of exposure time to WSF. Larvae were placed in clean, flowing seawater following exposure.

[d] OCP = Oil-contaminated prey (Artemia nauplii).

NEARSHORE FISH SURVEY IN THE WESTERN BEAUFORT SEA: HARRISON BAY TO ELSON LAGOON

by

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Final Report
Outer Continental Shelf Environmental Assessment Program
Research Unit 631

June 1983

TABLE OF CONTENTS

INTRODUCTION

Prior to the development of the petroleum industry, fisheries surveys in the Alaska Beaufort Sea were few and limited in scope. Most of these early surveys (Murdock 1885, Bean 1891, Anderson 1951, Wohlschlag 1954, McPhail 1966) provided new range extensions and some described new species; however, the areas covered were limited to large rivers, deltas and subsistence fishing grounds. More recent fisheries surveys (Kogl and Schell 1974, Bendock 1979a, Craig and Haldorson 1981, Craig and Griffiths 1981, Griffiths and Gallaway 1982, Gallaway and Britch 1983) have increased the understanding of anadromous fisheries resources in the Beaufort Sea, especially those areas east of the Colville River. These studies have been stimulated in part by the high petrochemical interests in areas of the mid- and eastern Beaufort, especially near Prudhoe Bay. More recently an accelerated lease-sale program initiated by the current administration in the Department of Interior has shifted interest to areas west of Prudhoe Bay encompassing the nearshore areas between Harrison Bay and Point Barrow. Fisheries studies in this area are limited.

Frost et al. (1978) conducted marine demersal fish surveys in offshore waters of the Beaufort Sea, Hablett (1979) conducted a two-year fisheries survey of lakes, streams and rivers within the NPR-A including several sites near the Beaufort coast; and Craig and Griffiths (1981) surveyed areas of Harrison Bay near Thetis and Eskimo islands (Figure 1). These surveys provided significant new fisheries information for selected areas of the western Beaufort Sea, however to date no broad synoptic surveys have been conducted in the nearshore estuarine and marine waters. Clearly a need existed for initial fisheries surveys in this area of the Beaufort Sea.

Study Area

The western Beaufort Sea, including areas from the Colville River delta to Barrow, encompasses several types of coastal habitat. Some

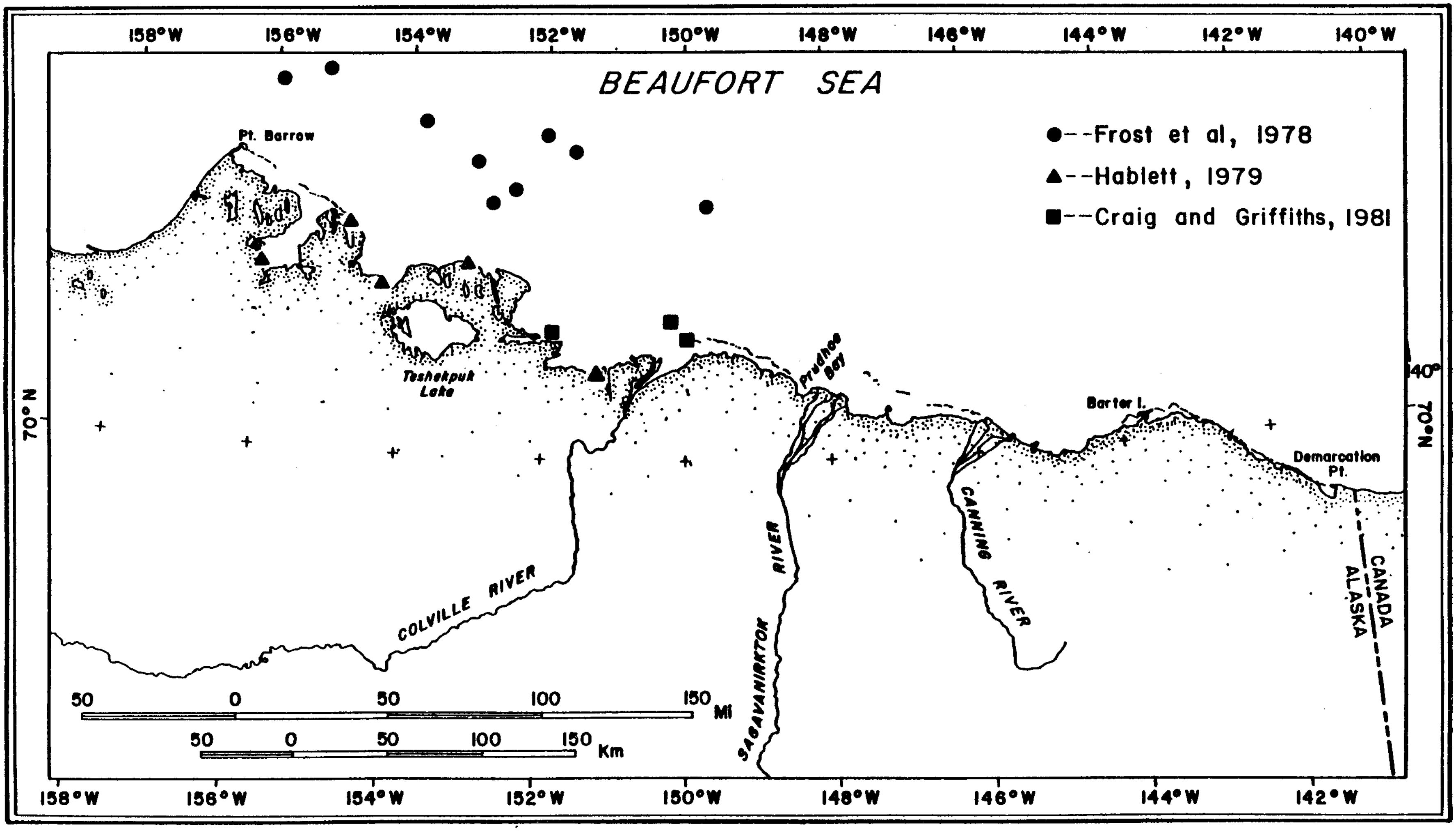

Figure 1. Sampling site locations in the western Beaufort Sea prior to the 1982 survey (after Frost et al, 1978; Hablett, 1979; Craig and Griffiths, 1981).

areas, such as Harrison Bay and Dease Inlet are typified as large protected embayments with variable but low salinities (Naidu and Mowatt 1975) usually resulting from breakup conditions and riverine influence (Walker 1974). Limited areas of this coastline including Elson Lagoon are lagoons protected by barrier islands. These lagoons, as others (Craig and Haldorson 1981), have variable salinities depending upon riverine input and meteorological conditions. Finally, areas such as Pitt and Pogik points represent unprotected shoreline. Dominant conditions here include variable, moderate to high salinities, relatively low water temperatures and frequent strong currents and high waves.

The western Beaufort coastline, when viewed as a whole and compared to the eastern Beaufort, contains fewer barrier island-protected lagoons but more large bays. These two areas also differ in coastal zone habitat. The western Beaufort is influenced by several slow-flowing, tundra rivers (e.g., Colville, Meade and Ikpikpuk rivers) and numerous smaller tundra streams. Comparatively, streams and rivers in the eastern Beaufort are montane in origin, and have relatively clean and fast flowing water. Many of these streams are spring fed and provide over-wintering habitat (Craig and McCart 1974, Craig 1977). The western Beaufort zone also contains numerous small and large tundra lakes, including Teshekpuk Lake, which may provide overwintering habitat for whitefish. To date the role that this large lake plays in influencing coastal fisheries is unknown.

METHODS

Fish sampling in the western Beaufort Sea was conducted from 23 July to 7 August 1982. Fish were captured in gill nets 30.5 m long and 1.8 m deep with three equally-sized panels with mesh sizes of 2.5, 5.1 and 7.6 cm (stretched). The nets were buoyed and weighted such that the lead line would set on the bottom and the float line would be at or near the surface. Nets were set from shore and perpendicular to it with the largest mesh being the most seaward. Net set locations illustrated in Figure 2, were reached by float plane and the nets were set by wading offshore and anchoring the seaward end. On two occasions, when the water depths exceeded 1.3 m, the nets were set from the floats of the airplane as it taxied from shore. Nets were typically set for 24 h, however, several sets were longer due to inclement flying weather.

Originally a benchmark net was to be set and run daily at Cape Halkett, however, large quantities of peat in the nearshore area precluded effective gillnetting. An alternative site was selected at Eskimo Island. The survey progressed from east to west by first running the benchmark net, then running a second net which was then pulled and moved to a new location farther west. The following is a list of the net locations with a brief description of the site including map coordinates (Orth 1971):

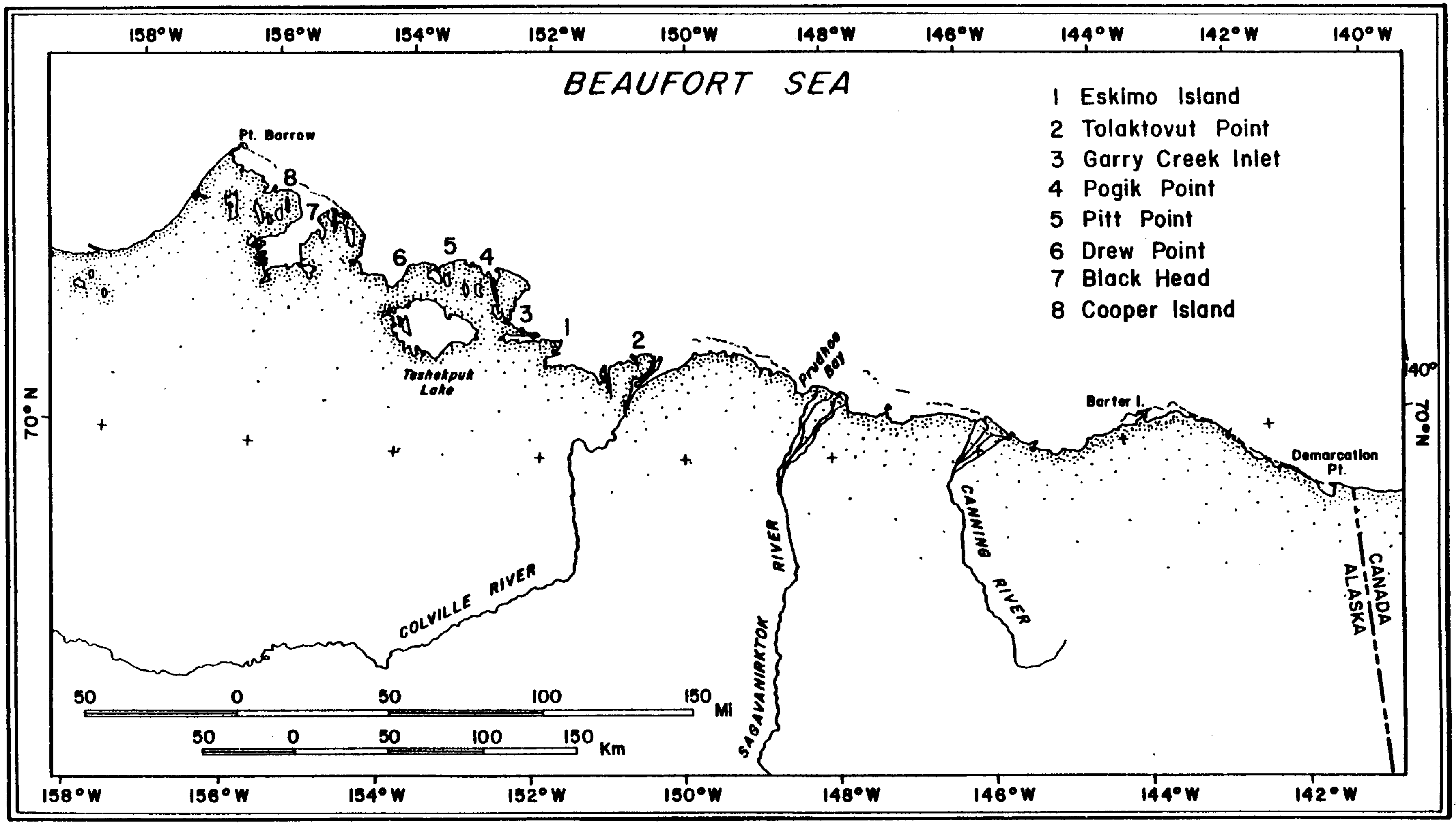

Figure 2. Sampling site locations for the 1982 western Beaufort Sea fish survey.

Site No.	USGS Name	Description
1.	Eskimo Island	70°34'N, 151°55'W. A vegetated island with a sandy shoreline. Net was set from the southwestern shore of the most easterly island.
2.	Tolaktovut Point	70°28'N, 150°54'W. A vegetated point with sandy/muddy substrate and numerous submerged peat mats. Net was set on the western side of the point.
3.	Garry Creek Inlet	70°38'N, 152°27'W. Net was set along the north shore of the inlet where it empties into Harrison Bay. The substrate was muddy and there was much water-borne peat.
4.	Pogik Point	70°54'N, 152°53'W. Net was set on the south side of the island. Substrate was sand and gravel. The initial set was on the north side and was snagged by ice.
5.	Pitt Point	70°55'N, 153°10'W. Net was set north from the beach at a location approximately 2 km west of Pitt Point.

6.	Drew Point	70°53'N, 153°56'W. Net was set from the point extending westward. The substrate was muddy and there was much water-borne peat.
7.	Black Head	71°04'N, 155°16'W. The net was extended westerly and set slightly offshore to avoid shallow areas with water-borne peat.
8.	Cooper Island	71°14'N, 155°42'W. The net was set on the lagoon side of a spit which extends south from Cooper Island. The substrate was sand and gravel.

Fish collections from each sampling station were categorized and enumerated by species and each fish measured (fork length) to the nearest 5 mm. The sex and state of maturity of pink salmon was also recorded. Salmon were considered ripe if sex products were readily extrudable. On two occasions, dissection was necessary to distinguish Bering cisco from the more abundant Arctic cisco.

Temperature, salinity and time of day was recorded when each net was set and again when they were pulled. Temperature was measured to the nearest 0.1°C with a hand-held calibrated thermometer and salinity was measured with an AO Model 10419 optical refractometer calibrated against a distilled water standard. Temperature and salinity data at each net location is presented in Appendix I.

RESULTS

During the 1982 western Beaufort Sea survey, a total of 1,201 fishes comprised of 13 species were caught (Table 1). Eight species including Arctic char, pink salmon, rainbow smelt and the Coregonid whitefish were anadromous; four species, capelin, fourhorn sculpin, Arctic flounder and saffron cod were marine; and one species, round whitefish, was freshwater. Anadromous fish catches were lead by least cisco (41.6%) following by Arctic cisco (24.9%). Marine species were dominated by fourhorn sculpin (94.2%) and followed by Arctic flounder (4.5%)

The total catch at Eskimo Island was of course higher since that net was run every day. Seven hundred forty-seven fish were caught during 9 netting efforts for an average catch of 83 fish per effort.

Species Accounts

The following accounts for the 13 species captured during this survey are taken from various sources in the scientific literature. These accounts provide a general overview of life history trends and distribution. The findings of this survey are discussed relative to these accounts. Emphasis is placed upon the more high profile nearshore anadromous fishes (Arctic cisco, least cisco, broad whitefish, humpback whitefish, Arctic char and pink salmon).

Arctic Cisco (*Coregonus autumnalis*)

The Arctic cisco ranks as one of the most important and abundant anadromous fishes of the nearshore Alaskan Beaufort Sea. This species is targeted by subsistence fisheries along the northern coastline of Alaska from Demarcation Point to Point Barrow. This species also helps support small commercial fisheries in the Colville Delta and near Point Barrow (Bendock 1979a).

Table 1. Total catch, percentages of total catch and percentages of group (anadromous, freshwater or marine) for each species at each station. Stations are numbered as follows: 1-Eskimo Island, 2-Tolaktovut Point, 3-Garry Creek Inlet, 4-Pogik Point, 5-Pitt Point, 6-Drew Point, 7-Black Head, 8-Cooper Island.

	Stations											
Species	1	2	3	4	5	6	7	8	Total	% of Total		% of Group
Arctic cisco	152		1	10	33	4		5	205	17.1		24.9
Least cisco	198		1	2	80	6	52	3	342	28.5		41.6
Arctic char	12	1			12			4	29	2.4		3.5
Broad whitefish	12	15	6		2		2		37	3.1	Anadromous	4.5
Humpback whitefish	36	1			2		26		65	5.4		7.9
Bering cisco					1	1			2	0.2		0.2
Pink salmon	10			1	18	5	16		50	4.2		6.1
Rainbow smelt	90		2						92	7.7		11.2
Round whitefish	1	1							2	0.2	Freshwater	100.0
Capelin								4	4	0.3		1.1
Fourhorn sculpin	222	40	5	2	11	11	41	23	355	29.6	Marine	94.2
Arctic flounder	15	2							17	1.4		4.5
Saffron cod	1								1	0.1		0.3
Total	749	60	15	15	159	27	137	39	1,201			

The range of this species includes northern Europe and Siberia and the western Arctic coast of North America. In the latter region the range extends from Bathurst Inlet, Northwest Territories, Canada, west to Point Barrow, Alaska (Scott and Crossman 1973, Morrow 1980).

The Arctic cisco is truly anadromous in behavior. Overwintering occurs in the brackish-water delta regions of the Colville (Alaska) and Mackenzie (Canada) rivers and a summer feeding dispersal from the deltas occurs at the onset of breakup of fast ice along the nearshore Beaufort Sea (Gallaway et al, in press). Spawning and early life histories have been reasonably well documented in the Mackenzie River system (Wynne-Edwards 1952, Hatfield et al. 1972, Stein et al. 1973, McLeod et al. 1979, O'Neal et al. 1981, Taylor et al. 1982). Upstream spawning migration occurs from late June through October with timing depending upon the distance up the Mackenzie the fish must move. The Liard River (1600 km upstream of the delta) is the furthest upstream tributary of the Mackenzie system known to support spawning populations of Arctic cisco and the peak run occurs here in September. Eggs are laid in the fall and a post-spawning downstream migration occurs with large numbers of spawned-out fish present in the Mackenzie Delta by early October. Eggs hatch the following spring and young of the year move downstream during breakup to spend the summer in the delta and nearshore regions.

It is notable that numerous fisheries investigations conducted on the Colville River system have failed to provide conclusive documentation of spawning populations of Arctic cisco in the system (Bendock 1979a, McElderry and Craig 1981, Craig and Griffiths 1981). Gallaway et al. (in press) summarized "these studies indicate that Arctic cisco likely do not penetrate the Colville River beyond Umiat (about 175 km upstream), are abundant only as far upstream as the Itkillik River (about 17.5 km) and few, if any, of these fish are in spawning condition." Also, the fall/winter commercial fishery conducted in the Colville Delta has failed to catch Arctic cisco in spawning condition or post-spawning condition although these fish would be expected to be vulnerable to the fishery if spawning occurred in the Colville River.

Gallaway contends that Arctic cisco in Alaska are representatives of a Canadian stock from the Mackenzie system. If this is the case, it appears that a portion of the young Arctic cisco dispersing westward from the Mackenzie system are picked up and distributed by the prevailing east to west longshore currents along the Alaskan Beaufort Sea coast. Following the summer feeding dispersal, overwintering in Alaska occurs in the deltaic regions of the Colville River and possibly other large rivers of the North Slope. The summer after attaining sexual maturity, males at seven years and females at eight years (Craig and Haldorson 1981), these fish apparently leave the Alaskan coastline, returning to natal waters of the Mackenzie system to spawn.

Invertebrates are the principal food of Arctic cisco. In Simpson Lagoon mysids (Mysis litoralis and M. relicta) accounted for 70-87% of their summer diet, whereas a single species of amphipod (Pontoporeia affinis) was found to be the major prey eaten in winter (Craig and Haldorson 1981). Additional groups important to the diet of Arctic cisco include copepods, larval fish, chironomid larvae and polychaetes.

Arctic cisco were the second most abundant anadromous fish in gillnet catches of the nearshore western Beaufort Sea. A total of 205 were captured, representing 17.1% of the overall catch and 24.9% of the anadromous fish caught. Length frequency data are presented in Figure 3.

Least Cisco (Coregonus sardinella)

The least cisco is one of the most widely distributed fishes of Alaska. It is present in most streams and lakes north of the Alaska Range and can be found in brackish, nearshore waters from Bristol Bay to the Arctic coast. On the north slope numerous streams west of and including the Colville River support anadromous and resident populations of least cisco. However, they are not found in drainages between the Colville and Mackenzie rivers although the Mackenzie drainage supports a substantial population. Hablett (1979) found that after ninespine stickleback, least cisco were the most widespread and numerous fish

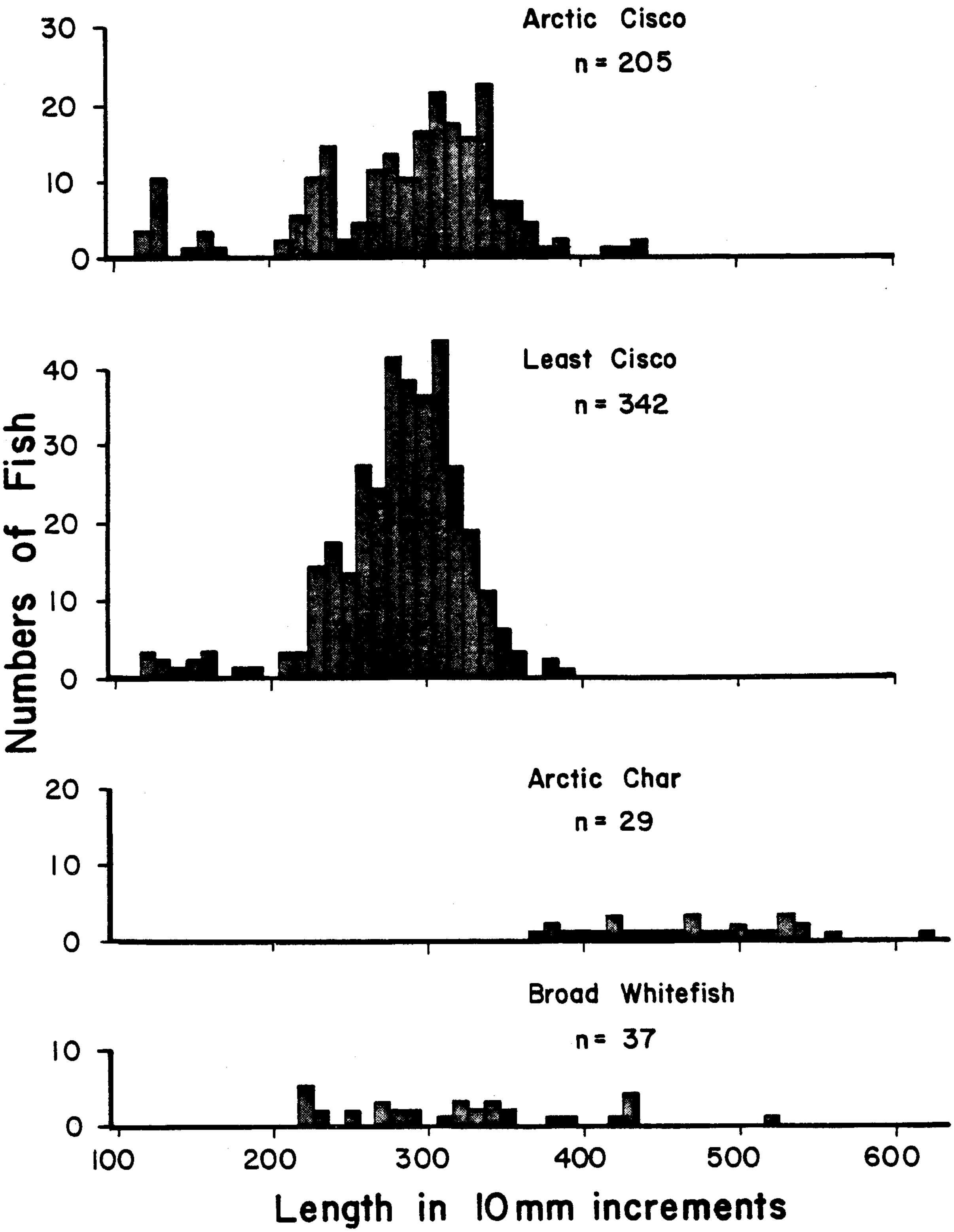

Figure 3. Length-frequency histograms for Arctic cisco, least cisco, Arctic char and broad whitefish.

encountered during stream and lake surveys of the NPR-A (within an approximate 300 km radius of Pt. Barrow). Least cisco were also the most abundant fish caught during fall gillnet sampling of the lower Colville drainage (McElderry and Craig 1981).

Overwintering occurs in brackish waters associated with river deltas. A wide salinity tolerance has been noted in overwintering least cisco which have been collected in salinities from 18 to 32 o/oo in the Colville Delta to as low as 0.2 o/oo in nearshore coastal waters off the Mackenzie River (Craig and Haldorson 1981). As breakup commences anadromous least cisco move into the nearshore zone of the Beaufort coast to feed. However, this summer dispersal is not as extensive as that observed for Arctic char or Arctic cisco.

Spawning presumably occurs in September or October in the Colville drainage. Least cisco in or nearing spawning condition were collected in the lower 60 km of the Colville downstream of Ocean Point in the delta and in several coastal lakes during late August and September (McElderry and Craig 1981). Eggs are released and fertilized over gravel and sand substrate where they remain through the winter. Hatching begins in spring and fry move downstream to deeper, slower water.

Age at maturity ranges from 6 to 7 years for males and 7 to 10 years for females. Few individuals live more than 13 to 14 years, however, fish to 18 years were captured in Simpson Lagoon during 1977 (Craig and Haldorson 1981), and specimens to 26 years are reported from Victoria Island, Northwest Territories (Scott and Crossman 1973).

During the summer months fish collected in Simpson Lagoon fed heavily on mysids (66 to 69% of their diet), however, during the winter months amphipods became the major prey group obtained in the Colville Delta (Craig and Haldorson 1981). Other food groups found to be of importance include copepods, larval fish and insects.

On the North Slope least cisco are captured in domestic fisheries aimed primarily at Arctic cisco. The more oily flesh of the latter makes it more sought after as food while least cisco is used as dog food. A fall and winter commercial fishery also exists in the Colville Delta in which approximately 30 to 70% of the catch is least cisco.

Least cisco were the most abundant anadromous species encountered during 1982 sampling efforts in the western Beaufort Sea. A total of 342 least cisco were caught in gillnets representing 28.5% of the overall catch and 41.6% of the anadromous species captured. The size distribution of least cisco are presented in Figure 3.

Arctic Char (Salvelinus alpinus)

The Arctic char is widely distributed throughout arctic waters of the northern hemisphere. It is present in rivers and coastal regions of northern Europe and Asia, the British Isles, Greenland and North America. This species exhibits two life history patterns: an anadromous pattern in which a seaward migration is undertaken and a non-anadromous pattern in which the fish remain and mature in streams or rivers (a second non-anadromous form is also recognized which is represented by isolated, landlocked populations in several Brooks Range alpine lakes). Although anadromous char are found along the entire North Slope coast they are generally associated with fast-flowing 'Mountain Streams' typical of many of the drainages of the eastern Beaufort Sea (Craig and McCart 1975).

Following a summer feeding dispersal in salt water, char return to streams in August and September to spawn and/or overwinter. The juvenile or immature fish entering streams to overwinter are preceded by mature adults returning to spawn. The latter specifically seek their natal streams at this time while immatures may overwinter in streams other than those of their origin.

Sexual maturity is first reached by males and females at 7 and 6 years, respectively, in anadromous char from the Anaktuvuk River (Bendock 1981). Spawning takes place from late August through November with most activity occurring in September and October. Redds are excavated in gravel substrates in regions of spring sources (Bain 1974, Bendock 1981 and Yoshihara 1973). The eggs are buried and remain in the gravel about 4 months until hatching. After hatching, the fry remain concealed in the gravel until the yolk sac is absorbed, emerging in May or June (Bain 1974 and Yoshihara 1973). The young remain in their natal stream for 2 to 5 years prior to their first migration to salt water. It appears that not all individuals within a population go to sea and that a greater percentage of females than males are anadromous (Bain 1974).

Young Arctic char feed primarily on aquatic insects and crustaceans during their residence in rivers (McPhail and Lindsey 1970, Morrow 1980 and Bain 1974). From Arctic char collected in salt and brackish water of the Beaufort Sea, mysids and amphipods were found to be the major prey species (Craig and Haldorson 1981 and Yoshihara 1973).

A total of 29 Arctic char were captured during the 1982 western Beaufort sampling, representing only 2.4% of the overall catch and only 3.5% of the anadromous fish catch. The size distribution of char is represented in Figure 3. No small juveniles were present in the collection which consisted of fish from 370 to 620 mm in length.

Broad Whitefish (*Coregonus nasus*)

The broad whitefish is distributed in the fresh and brackish waters of northern Siberia and the western arctic coast of North America. In the latter region, its range extends from the Kuskokwim River, Alaska, north to the Beaufort Sea and east to the Perry River, Northwest Territories (Morrow 1980, Scott and Crossman 1973). Although anadromous this species seldom ventures far from the brackish waters of estuarine areas.

Broad whitefish in the Beaufort Sea were found to be slow growing, late maturing and long lived (Craig and Haldorson 1981 and Bendock 1979a). From specimens collected in Simpson Lagoon maturity was found to be reached at an age of 9 to 14 years and individuals to 21 and 22 years old were collected.

Broad whitefish enter the Beaufort Sea during spring breakup to feed in the river deltas, shallow bays and lagoons of the nearshore regions through the summer (Bendock 1979a and Alt and Kogl 1973). In late August mature adults return to the Sagavanirktok River to spawn in deep pools in the delta area (Bendock 1979a). In the Colville River a large spawning migration occurs in the Umiat area (about 175 km upstream) in mid-August and spawning was observed farther upstream during September (Hablett 1979). Eggs are deposited in gravel where they remain until hatching the following spring. Hablett (1979) reports young-of-the-year and immature broad whitefish make extensive use of the overflow channels and oxbows connected to the Colville River. However, it appears that some of the fry migrate downstream, as ages 0, 1 and 2 were reported in fyke net catches in the brackish water of the Sagavanirktok Delta (Gallaway and Britch 1983).

Major food groups of the broad whitefish include chironomid larvae, amphipods, snails and bivalve mollusks (Bendock 1979a,b and 1979 and Morrow 1980).

The broad whitefish is considered one of the finer tasting of arctic fish and is the target species of a summer subsistence fishery conducted in the Colville River. In the lower reaches of this river broad whitefish were the fourth most abundant fish captured during fall gillnet sampling between 23 September and 15 November 1972 (Kogl and Schell 1974). This species contributes significantly to other subsistence fisheries along the Western Beaufort for example in subsistence catches observed near Atqasuk on the Meade River August 11, 1981 broad whitefish were found to be the most abundant fish taken (Craig and Schmidt 1982).

During the 1982 sampling, 37 broad whtiefish were caught accounting for 3.1% of the overall catch and 4.5% of the anadromous fish caught. The length frequency data is presented in Figure 3.

Humpback Whitefish (Coregonus pidschian)

The humpback whitefish falls within the '<u>Coregonus</u> <u>clupeaformis</u> complex' from which as many as three species are recognized. However, this is a source of considerable controversy as almost the only means of distinguishing them is by the modal number of gill rakers in large samples. Members of this complex are widespread throughout the northern regions of North America, being found in western Alaska from Bristol Bay north and east across most of Canada to New Brunswick and Labrador and south to the Great Lakes. Along the western Beaufort Sea the humpback whitefish is found in coastal lakes and all the major drainages east of Barrow to the Sagavanirktok River (Bendock 1979a and Hablett 1979). Bendock (1979a) considers the Colville River as the largest producer of humpback whitefish on the North Slope.

Life histories are not well understood for the anadromous Beaufort Sea populations presumably because it is not found in great numbers nor does it contribute appreciably to domestic fisheries in this region and has consequently not received much attention.

During the openwater season, humpback whitefish probably do not disperse far from the brackish waters of stream estuaries. Relatively few were captured in Simpson Lagoon (Craig and Haldorson 1981) and Bendock (1979a) found them sparsely distributed between the Colville and Sagavanirktok rivers with increasing numbers nearer the Colville.

An upstream migration has been observed at Umiat on the Colville River from mid-August to early September and spawning occurs from September to October from the delta to as far as 200 km upstream (Hablett 1979, Bendock 1979b, Kogl and Schell 1974). Following spawning a movement back into the lower reaches of the Colville was observed by Kogl and Schell (1974). Eggs are believed to hatch in late winter or early spring.

Age at maturity ranges from 4 to 6 years in Alaskan populations (Morrow 1980) and spawning most likely occurs every other year (McPhail and Lindsey 1970). In lakes of northern Canada fish as old as 28 years have been captured, however, the anadromous fish of the Beaufort Sea populations appear to be shorter lived with maximum ages ranging from 11 to 13 years (Kogl and Schell 1974, Hablett 1979 and Bendock 1979a).

Food habits of the humpback whitefish indicate bottom feeding. Major prey items of young fish are zooplankton while those of adults include bivalve mollusks, snails, chironomids and amphipods (Kogl and

Schell 1974, Alt 1979 and Morrow 1980). During spawning humpback whitefish were found to consume large quantities of their own eggs but amphipods comprised the major food item of overwintering fish in the lower Colville during October (Kogl and Schell 1974).

The humpback whitefish contributes to local subsistence fisheries although to a lesser degree than other anadromous fishes. Kogl and Schell (1974) found them to be the most abundant fish caught during sampling in the Colville Delta between 24 September and 15 November. However, Alt and Kogl (1973) state that they comprise only 10% of the summer subsistence catch and only 1% of the winter catch in the Colville River.

Humpback whitefish were the fifth most abundant fish captured during sampling efforts with a total of 65 representing 5.4% of the entire catch and 7.9% of the anadromous fish catch. Length frequency data is presented in Figure 4.

Bering Cisco (*Coregonus laurettae*)

The Bering cisco is found along western Alaska from Bristol Bay north and east to the Colville Delta. The distributions of Bering and Arctic cisco overlap between Pt. Barrow and the Colville River causing some confusion regarding identity.

The Bering cisco is very similar in appearance to the Arctic cisco from which it is most easily distinguished by fewer gill rakers on the lower portion of the first gill arch. The Bering cisco has 18-25 gill rakers here, whereas the Arctic cisco has 26-31 (Morrow 1980). Craig and Haldorson (1981) also noted that the Bering cisco appear somewhat stouter or thicker than Arctic cisco of the same length.

Little is known of the biology of the Bering cisco and what is known is chiefly from the Yukon and Kuskokwim populations. Spawning migration commences in spring however actual spawning presumably takes place in fall. Spawning behavior and choice of spawning grounds is unknown, although it is thought to take place in clearwater tributaries

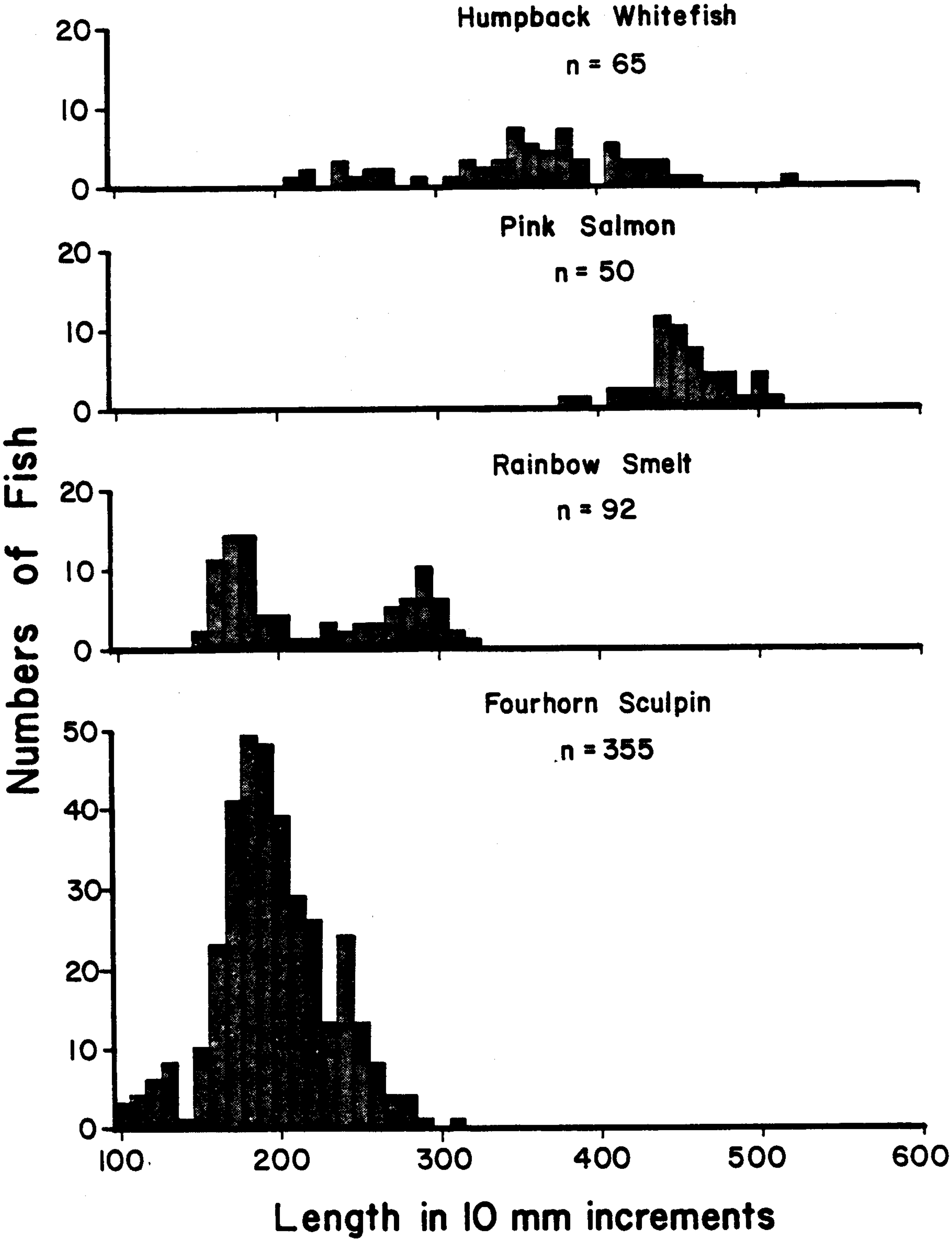

Figure 4. Length-frequency histograms for humpback whitefish, pink salmon, rainbow smelt and fourhorn sculpin.

of the rivers. Downstream migrations follow spawning and overwintering occurs in brackish or salt water in the river deltas.

Bering cisco feed primarily on crustaceans (amphipods) although larval fish (cottids) have also been reported in stomach contents (McPhail and Lindsey 1970 and Alt 1973).

Only 2 Bering cisco, one 370 mm and one 390 mm in length, were collected during the 1982 sampling efforts.

Pink Salmon (Oncorhynchus gorbuscha)

Pink salmon are found in most larger drainages of northwest Asia and North American north of 35° N latitude and which drain into the North Pacific and Arctic oceans. In North America the range extends from the Sacramento River, California, north to the arctic coast of Alaska and east to the Mackenzie River, Northwest Territories (Scott and Crossman 1973). Adult pink salmon are present in late summer along the entire Beaufort coastline and have been reported to enter the Meade, Chipp and Colville rivers (Hablett 1979, Bendock 1979a, Craig and Haldorson 1981).

By mid- to late-summer adult pre-spawners begin to appear along the coastline moving in an easterly direction. Adult pink salmon were captured in the Chipp river during the first week of August, 1977 (Hablett 1979) and they enter the Colville River during mid-August (Bendock 1979a, Craig and Haldorson 1981, Hablett 1979). Spawning occurs in the mainstream of the Colville River and possibly in the lower reaches of tributaries such as the Itkillik, Chandler and Anaktuvuk rivers (Bendock 1979a). Spawning probably occurs in North Slope drainages other than those listed above, however, the current knowledge of the region west of the Colville River is based on relatively few sampling efforts. Also, pink salmon do not exhibit as strong a homing instinct as other Pacific salmon and have been found spawning in streams up to 640 km from their natal streams (Morrow 1980).

Eggs are laid in redds dug in gravel. The eggs hatch during the winter however the alevins remain in the gravel, until the yolk sac is absorbed, emerging later in spring. After emerging from the gravel the fry begin moving downstream. They remain in the estuary for up to a month prior to moving offshore. Little is known of the movements undertaken during the 18 months the salmon spend at sea. It is likely the North Slope populations move westerly towards the Chukchi Sea and upon maturing at the age of 2 years the salmon then return to their natal streams to spawn in the fall.

Young-of-the-year probably do not feed significantly during the short period spent in natal streams but feed on copepods and other zooplankton in the estuary. As the fish grow, larger prey species become important including amphipods, euphausiids and fishes (Morrow 1980 and Scott and Crossman 1973).

The pink salmon is caught in subsistence fisheries along the Beaufort coastline and in the Colville River. Because of large year to year fluctuations in numbers of pink salmon (Bendock 1979) its importance in domestic fisheries varies.

A total of 50 pink salmon were caught which represented 4.2% of the overall catch and 6.1% of the anadromous fish catch. Length frequency data is presented in Figure 4. Except for 1 ripe male, the state of sexual maturity of the entire catch prior to 30 July was found to be green, however, from 30 July to 3 August, 18 of 24 salmon caught were determined to be ripe (see Appendix II).

Rainbow Smelt (<u>Osmerus mordax</u>)

The rainbow smelt is circumpolar in distribution ranging in the west Pacific Ocean from Korea and northern Japan north to the Arctic Ocean and west across northern Siberia and Europe. In North American it is found along the Eastern Pacific from Vancouver Island north to the Arctic Ocean and east to Cape Bathurst in the Canadian arctic and from Labrador to Virginia, including the Great Lakes watershed, along the Atlantic Ocean.

This anadromous smelt is a spring spawner. Through the winter rainbow smelt were found concentrated off the delta of the Colville

River until the first influence of meltwater at breakup. It was presumed that these fish migrated into the river at that time to spawn (Craig and Haldorson 1981). Typically rainbow smelt do not travel far upstream to spawn and have been observed spawning in brackish water near the mouths of streams (Morrow 1980). The minute young soon hatch and are carried downstream to the estuary. As they continue to grow, the young fish are found ranging farther into more saline waters, however, Morrow (1980) indicates that they do not range far from their natal streams.

Rainbow smelt reach maturity at 5 to 7 years and individuals to 15 years have been caught in Simpson Lagoon (Craig and Haldorson 1981).

Food of the young rainbow smelt include copepods, cladocerans and other zooplankton while adults feed on mysids, amphipods and small fish such as Arctic cod (Morrow 1980 and Craig and Haldorson 1981).

Rainbow smelt were the fourth most abundant fish in the western Beaufort collections with a total of 92 representing 7.7% of the overall catch and 11.2% of the anadromous fish catch. The size distribution of rainbow smelt depicts a bimodal curve with peaks at lengths of 180 mm and 290 mm (Figure 4).

Round Whitefish (Prosopium cylindraceum)

The round whitefish is an accidental visitor of the nearshore regions of the Beaufort Sea. This freshwater species is widely distributed across northeastern Asia and North America. The round whitefish spawns in fall. Northern populations tend to be slower-growing, longer-lived and later maturing than those from the southern parts of its range (Morrow 1980).

During periods of high runoff and resulting low nearshore salinities, the round whitefish is occasionally caught in the nearshore coastal zone (Bendock 1979a and Craig and Haldorson 1981).

Food of the round whitefish include snails, bivalves, aquatic insects and phytoplankton (Hablett 1979, Morrow 1980).

Round whitefish was the only freshwater species represented in the 1982 western Beaufort collections. Only 2 were captured during the sampling efforts with lengths of 150 and 270 mm.

Capelin (Mallotus villosus)

The capelin is a marine species which is relatively infrequently encountered along the Beaufort Sea coast. This fish is found in the North Pacific, North Atlantic and Arctic Oceans.

Capelin enter shallow waters to spawn during the summer. Near Pt. Barrow spawning occurred in late July and August during which time they were captured in dip nets by local residents for food. In Prudhoe Bay spawning occurred in mid-August (Bendock 1979a). Fish enter the surf zone along gravel beaches to lay adhesive eggs which stick to the gravels. Eggs hatch in 2 to 3 weeks.

Movements of capelin within the Beaufort Sea are poorly understood. Age at maturity may be 1 year and capelin do live to be 3 or more years (Hart 1973). Euphausiids and copepods have been observed in the food of specimens collected in British Columbia.

Only four capelin were collected during the present study and all of these were obtained at Cooper Island. Lengths ranged from 130 to 140 mm.

Fourhorn Sculpin (Myoxocephalus quadricornis)

The fourhorn sculpin is a marine species abundant along the Arctic coast from Norton Sound, Alaska, north and east across northern Canada to Greenland. During the openwater season on the Beaufort Sea coast these sculpin move into the shallow, nearshore brackish waters to feed, returning to deeper waters offshore of the barrier islands to overwinter and/or spawn.

Spawning occurs sometime between late November and late February in the vicinity of Simpson Lagoon. Females lay the entire batch of eggs in a single clump which is guarded by the male until hatching in spring.

In Simpson Lagoon populations maturity was reached 1 to 3 years earlier than in populations farther east from Nunaluk and Katovik Lagoons. Males reached maturity as early as 2 years and all were mature by 4 years while female sculpins matured between the ages of 4-6.

During the summer months, the diet of sculpins collected in Simpson Lagoon consisted almost entirely of crustaceans. Amphipods represented 81%, mysids 10% and isopods 6% of the total food consumed. In the winter isopods were the major prey species (60-78%) followed by amphipods 5-31% and fish eggs 5-9% (Craig and Haldorson 1981). Isopods and amphipods, were indicated as important prey species at other coastal locations as well.

Fourhorn sculpin were the most abundant fish in the 1982 sampling efforts along the western Beaufort Sea. A total of 355 fourhorn sculpin represented 29.6% of the overall catch and 94.2% of the saltwater fish. Length frequency data is presented in Figure 4.

Arctic Flounder (Liopsetta glacialis)

The Arctic flounder is distributed in coastal waters of the Bering and Chukchi seas north into the Arctic Ocean from Queen Maude Gulf in Arctic Canada west along the North American and Siberian coastline to the White Sea and Barents Sea (Morrow 1980).

Winter spawning occurs from January to March at which time the flounders move into shallow waters at depths of 5 to 10 m. Maturity is reached by age 4 or 5 years with some as early as 2 years (Morrow 1980).

Food items of Arctic flounder collected in Simpson Lagoon and Prudhoe Bay include amphipods, mysid, and isopods (Bendock 1979a and Criag and Haldorson 1981), and other prey include small mollusks and fishes (Morrow 1980).

This marine species is associated with shallow brackish coastal waters and apparently exhibits an offshore movement in the fall and an onshore movement in the spring (Morrow 1980).

Only 17 Arctic flounder were caught in the western Beaufort sampling effort, however, following fourhorn sculpin it is the second most abundant saltwater species, representing 4.5% of this group. Lengths ranged from 150 to 320 mm with most (82.4%) 200 mm or less.

Saffron Cod (Eleginus gracilis)

The saffron cod is present along the entire Beaufort Sea coast although it is not found in large numbers here. Spawning occurs from December to February at which time fish move into shallower nearshore water. The young hatch in spring and are planktonic for the first few months of their lives (Morrow 1980). Age at maturity is not known for Beaufort Sea populations but has been reported as 2 to 3 years in Siberian waters (Morrow 1980).

Saffron cod migrations are somewhat limited except for an onshore movement in fall and winter prior to spawning and the subsequent offshore movement to deeper summer feeding areas. It occasionally is found in rivers though seldom farther upstream than the influence of salt water.

Food items include fish, mysids, amphipods and polychaete worms (Morrow 1980 and Craig and Haldorson 1981).

Only 1 saffron cod 220 mm in length was collected during the 1982 sampling efforts.

Benchmark Location Catches (Eskimo Island)

Catches for each species at the Eskimo Island location are listed in Appendix III and graphically presented in Figures 5, 6 and 7. Catches assumed a great deal of variation throughout the survey period, however, several peaks in the CPUE values are apparent. Catches of some anadromous fishes and fourhorn sculpin were high during the early days of the survey on 25 and 26 July and again between 31 July and 3 August. Arctic cisco were the most abundant fish during the first days of the survey and least cisco and fourhorn sculpin dominated later in the survey. Humpback whitefish showed a relatively high abundance initially, as did Arctic char, however, abundance of these two species

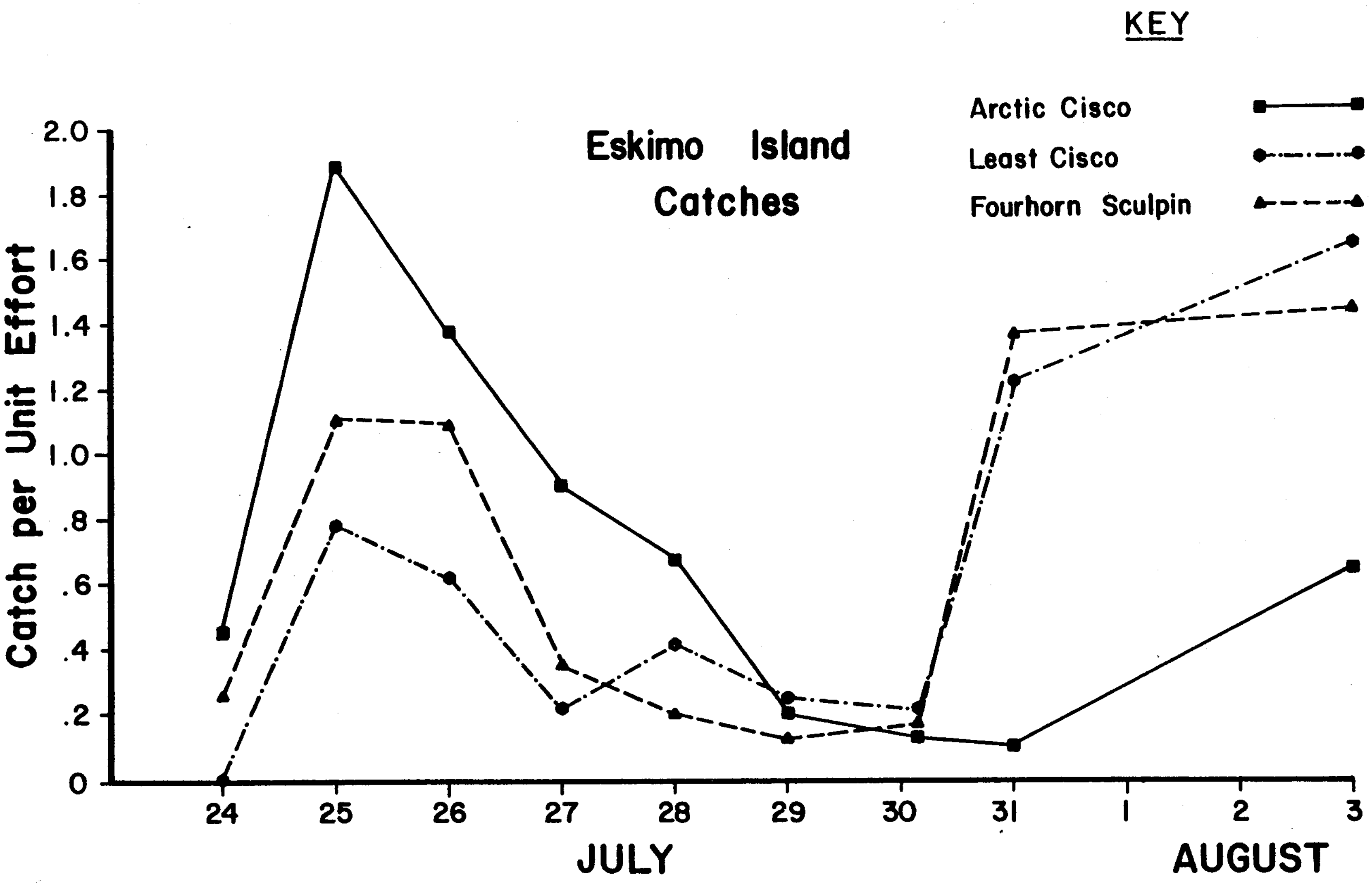

Figure 5. CPUE Values for Arctic cisco, least cisco and fourhorn sculpin at the Eskimo Island location.

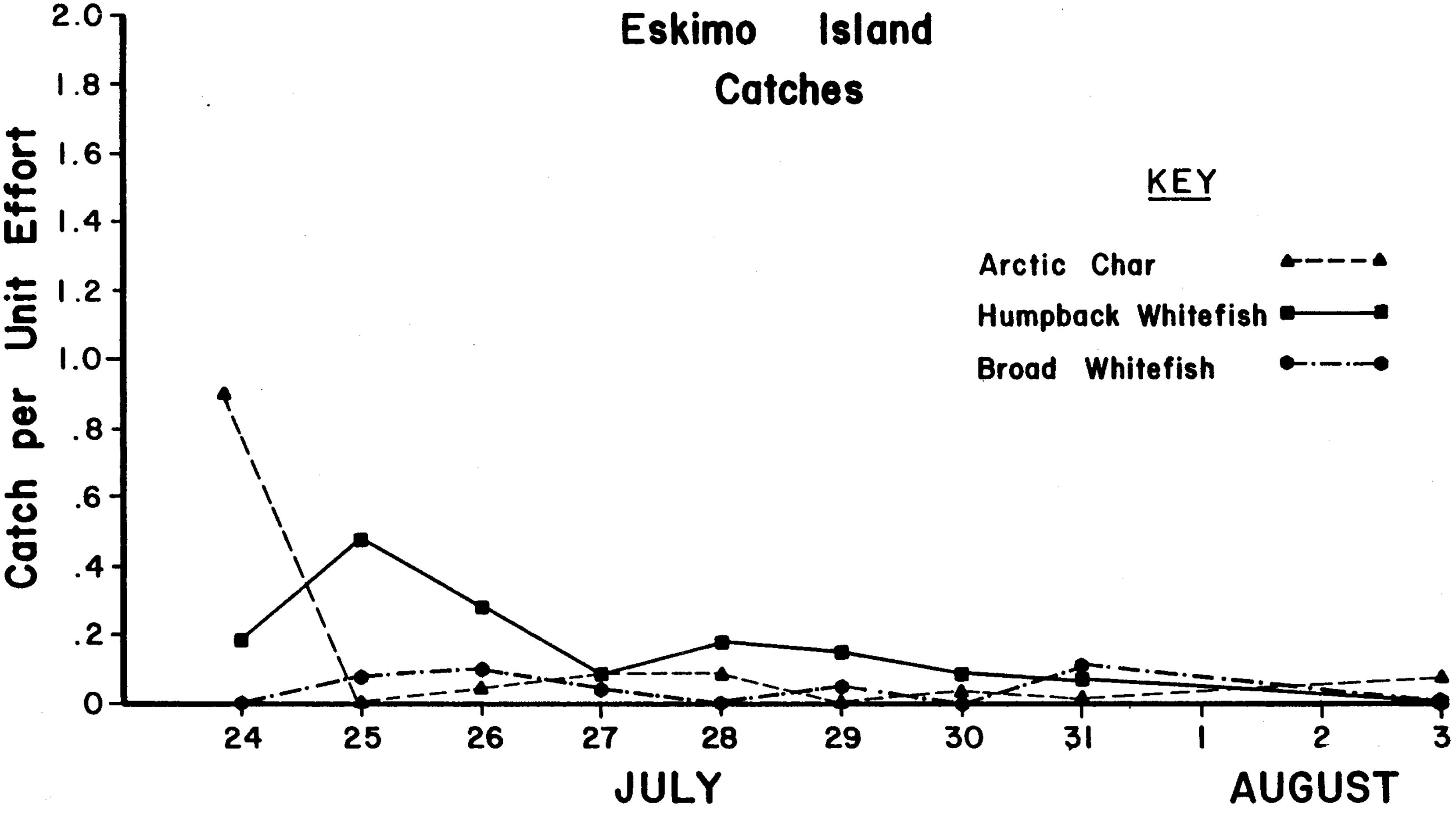

Figure 6. CPUE Values for Arctic char, humpback whitefish and broad whitefish at the Eskimo Island location.

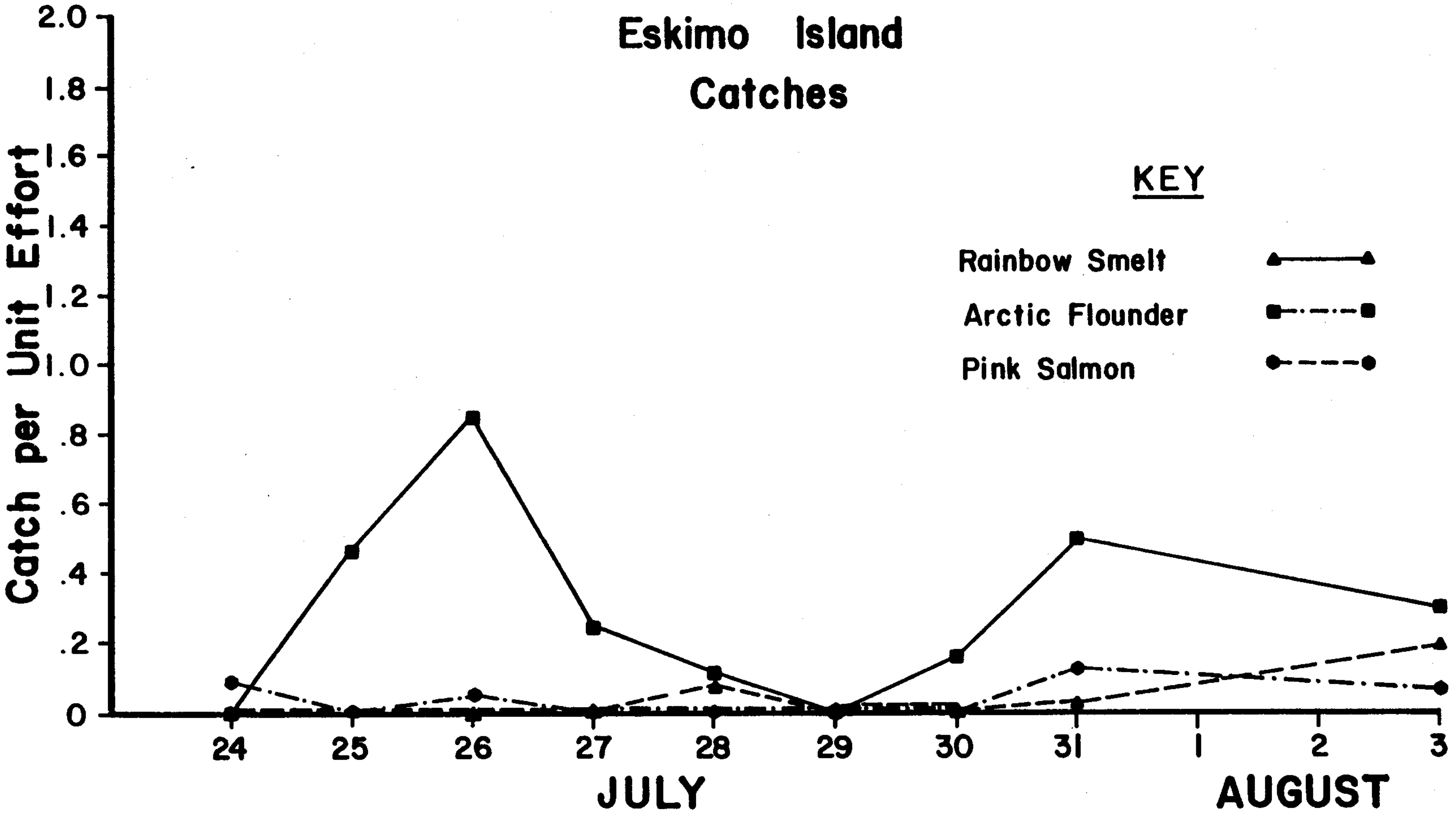

Figure 7. CPUE values for rainbow smelt, Arctic founder and pink salmon at the Eskimo Island location.

declined later in the survey. Catches of broad whitefish remained low during the entire survey. Rainbow smelt exhibited two peaks in abundance, one early in the survey and one later, that coincide with those of Arctic cisco and fourhorn sculpin and to some degree with that of least cisco. Abundance of pink salmon remained low throughout the survey. This species first appeared at the Eskimo Island location on 28 July, one day after it was documented at Pogik Point to the west (Appendix II). None of the salmon caught at that time were ripe, however, maturation seems to begin during this time frame since several of the later catches contained ripe salmon.

Figure 8 shows the catches at the Eskimo Island location pooled into anadromous and marine species and compared using CPUE values. The trend for anadromous fishes was similar to that for Arctic and least cisco (Figure 5) with peak catches at the beginning and end of the survey period and truncated catches during mid-survey. The pooled CPUE values for marine fishes showed a trend nearly identical to that of fourhorn sculpin. This result was not wholly unexpected since this species comprised 94.2% of the marine catch.

Temperature and salinity measurements taken at the Eskimo Island location showed trends similar to those of other studies (Craig and Haldorson 1981; Griffiths and Gallaway 1982; Gallaway and Britch 1983). Mean temperatures were generally higher early in the survey with the highest, 13.4°C, occurring on 25 July, thereafter steadily decreasing (Figure 9). Salinities steadily increased due primarily to the general lack of freshwater influence from melting sea ice and freshets.

To test whether CPUE value for each species are influenced by temperature or salinity, a least squares linear regression was performed. Results were tabulated for all species except saffron cod, capelin, round whitefish and Bering cisco. These species were omitted due to their low numbers. Linear regressions, y intercepts and correlation coefficients are given in Appendix IV. The CPUE values for two species, Arctic cisco and humpback whitefish, were significantly correlated ($p < 0.05$ and $p < 0.01$, respectively) with temperature; and CPUE values for least cisco and pink salmon were significantly

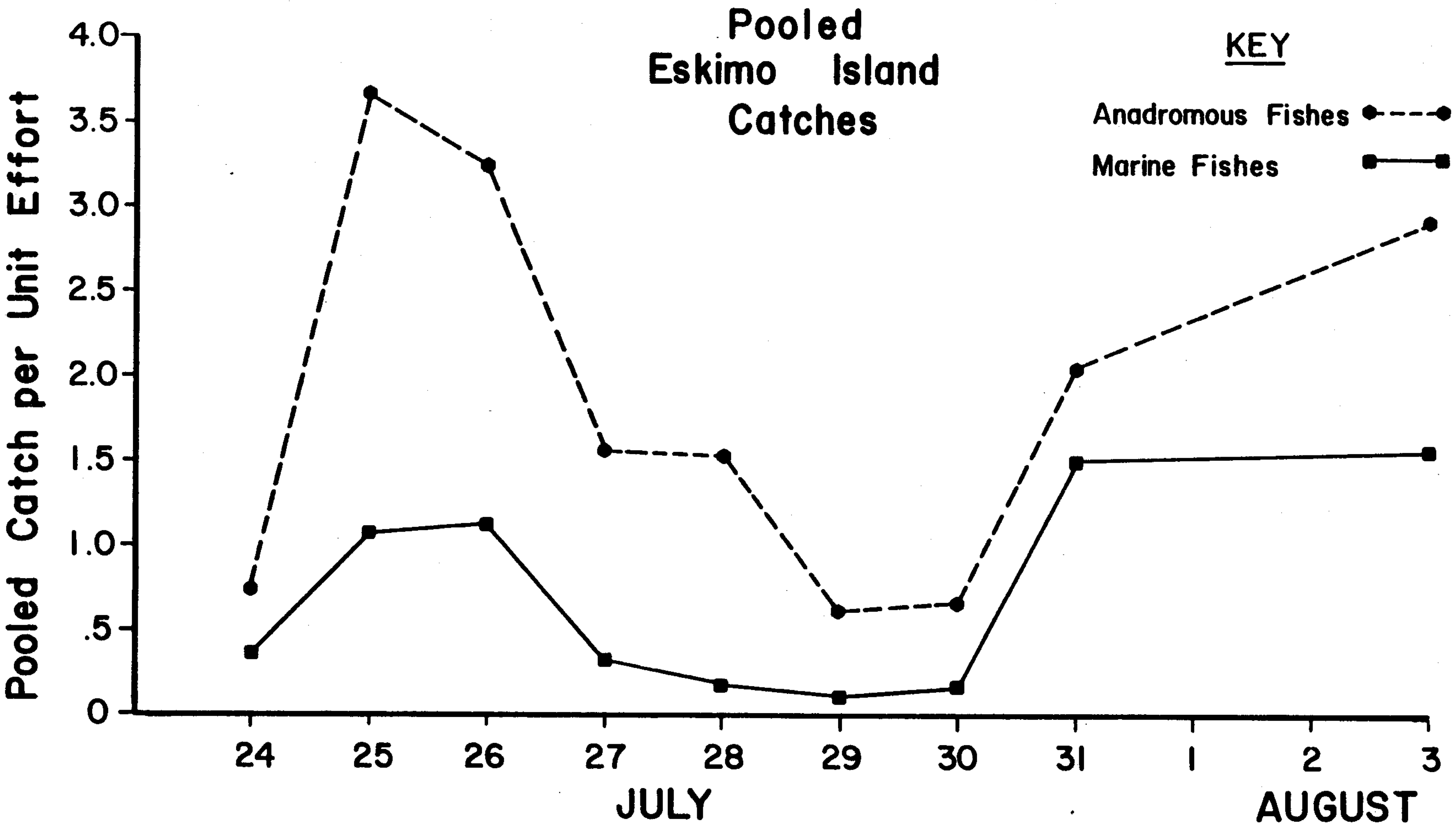

Figure 8. Pooled CPUE values for anadromous and marine fishes at the Eskimo Island location.

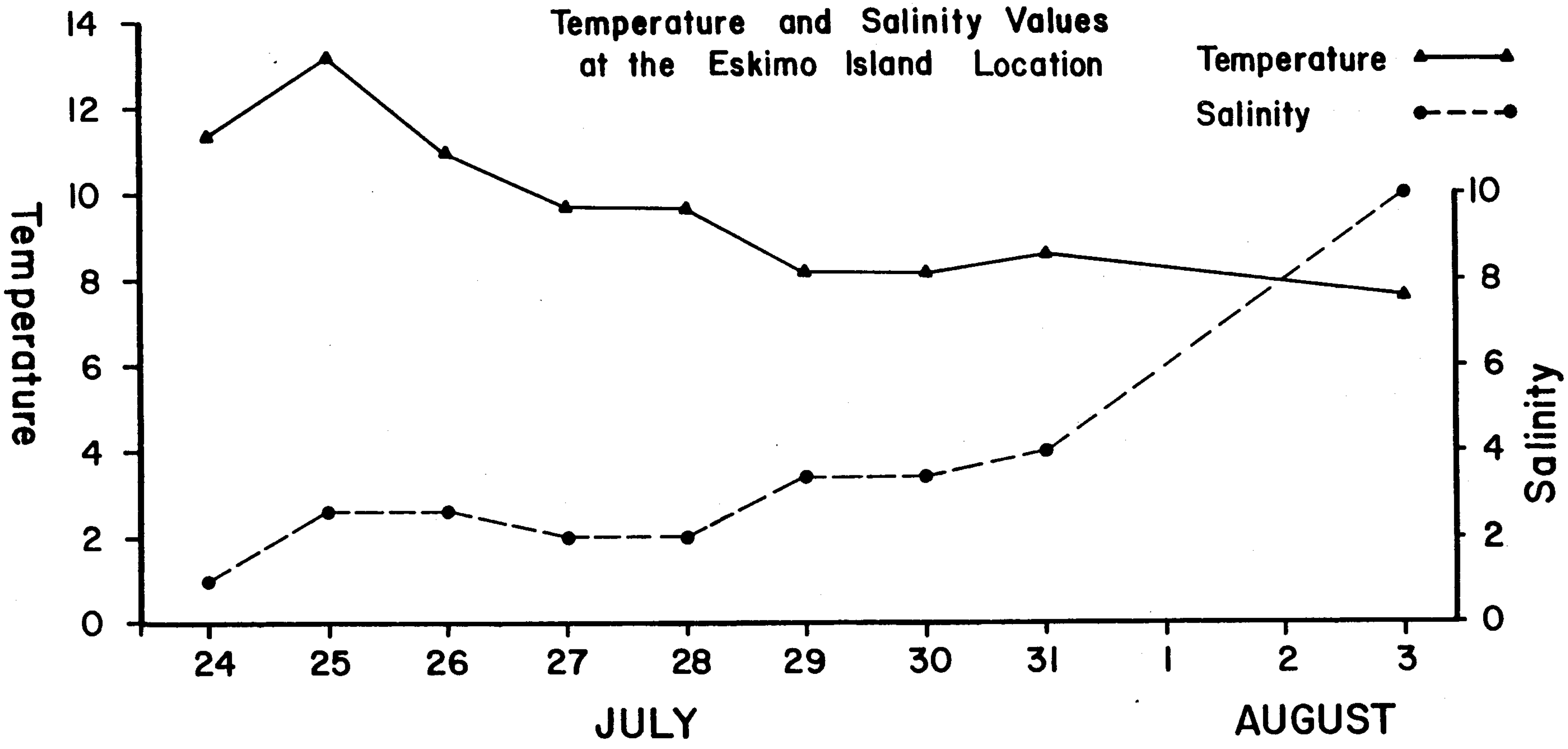

Figure 9. Mean temperature and salinity values taken at the Eskimo Island location.

correlated ($p < 0.01$) with salinity. The remaining species show no significant correlation with either temperature or salinity.

Single Survey Location Catches

Catches at the single survey locations, Tolaktovut Point, Garry Creek Inlet, Pogik Point, Pitt Point, Drew Point, Black Head and Cooper Island, are listed in Appendix III and presented graphically in Figures 10, 11, and 12. The CPUE data for the Eskimo Island location for 24 July have been included to provide temporal continuity of the sample dates and spatial continuity since the sample sites are presented east to west. CPUE values assume a great deal of variability due partially to the high variance associated with nearshore Arctic fishes and partially to the variance inherent in sampling different locations and consequently different habitat regimes. CPUE values for Arctic cisco reach their maximum on 28 July at Pitt Point with a smaller peak on 24 July at Eskimo Island. CPUE values for least cisco were greatest at Pitt Point and Black Head but relatively low elsewhere. Fourhorn sculpin, Arctic char and humpback whitefish CPUE values show a large degree of variation among locations but all species show peak abundance at either Pitt Point or Black Head or both. Broad whitefish show relatively small peaks at those two locations with their peak abundances occurring farther to the east at Tolaktovut Point and Garry Creek Inlet. Pink salmon first appeared at Pogik Point on 27 July when one green male was caught (Appendix II). Peak abundances occurred at Pitt Point when 18 green adults were caught and at Black Head when 4 green and 12 ripe adults were caught. The first ripe adults were caught on 29 July at Drew Point. The mean size of males was 458.55 mm (fork length); females averaged 426.67 mm.

Figure 13 illustrates the pooled CPUE values for both anadromous and marine fishes. The pooled CPUE values for anadromous fishes show two major peaks, one at Pitt Point and the other at Black Head. The Pitt Point anadromous fish catches were dominated by Arctic and least cisco comprising 76.3% of the catch and the Black Head catches were

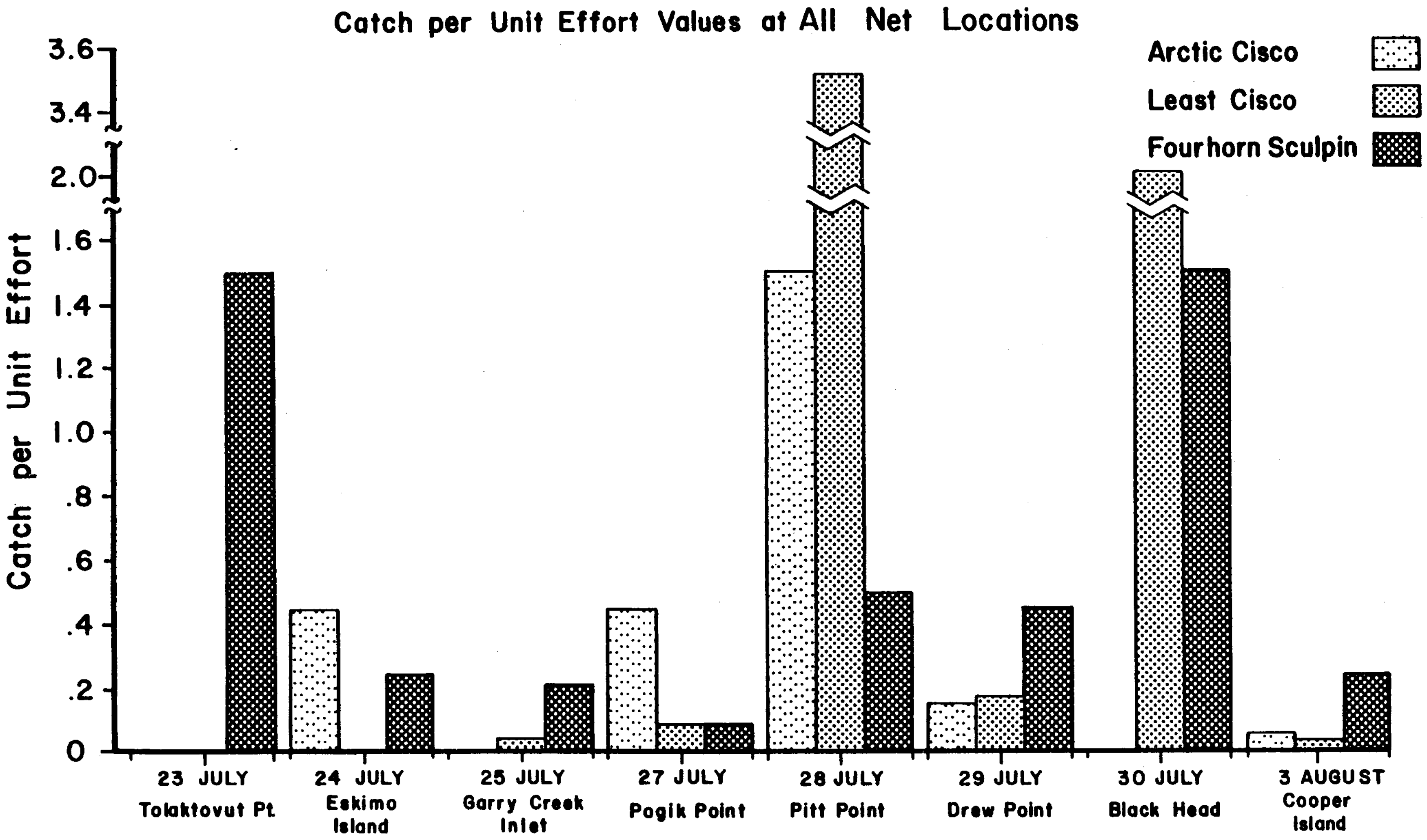

Figure 10. CPUE values for Arctic cisco, least cisco and fourhorn sculpin at all net locations. The catch at Eskimo Island on 24 July is used for continuity.

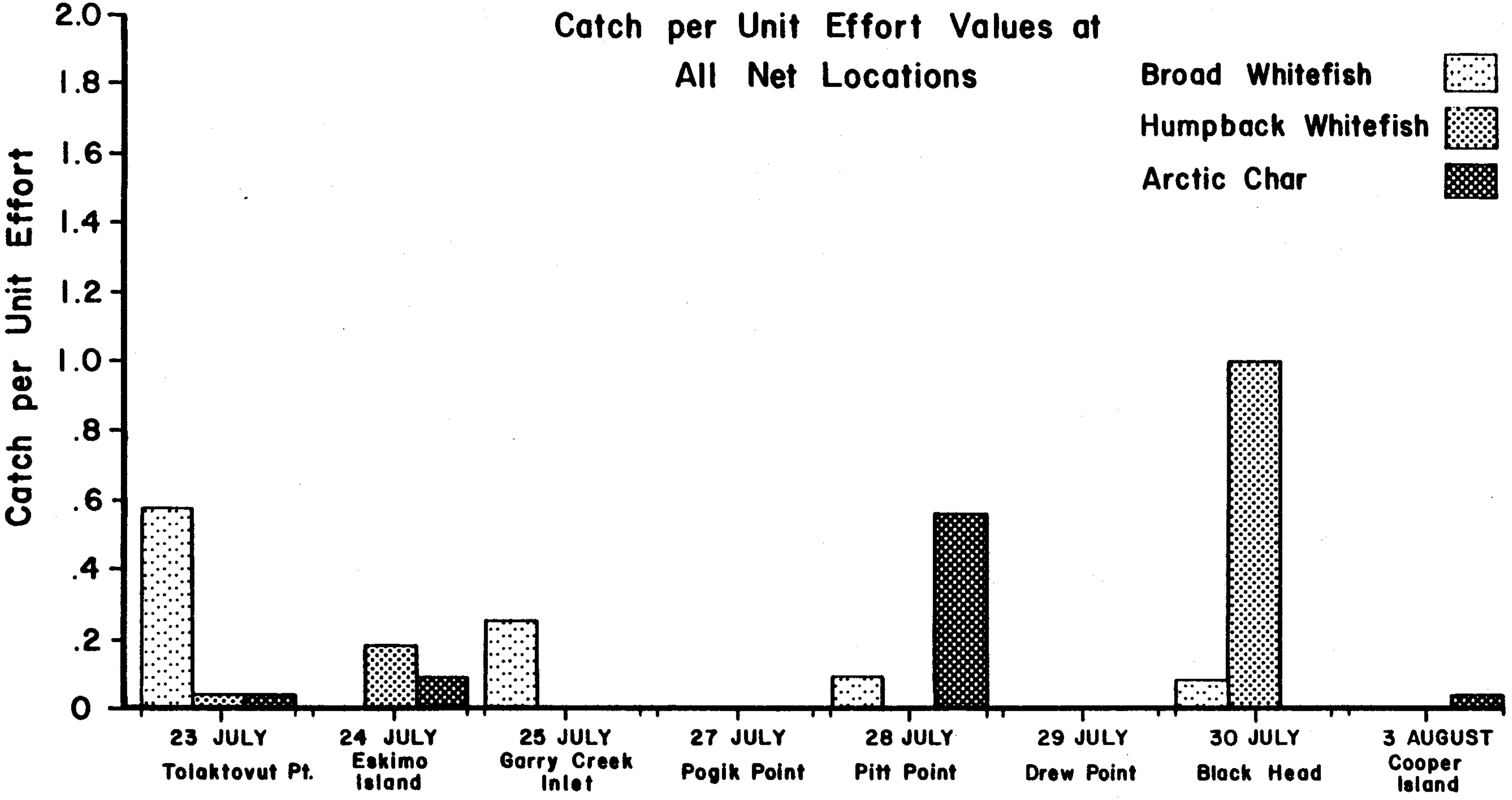

Figure 11. CPUE values for broad whitefish, humpback whitefish and Arctic char at all net locations. The catch at Eskimo Island on 24 July is used for continuity.

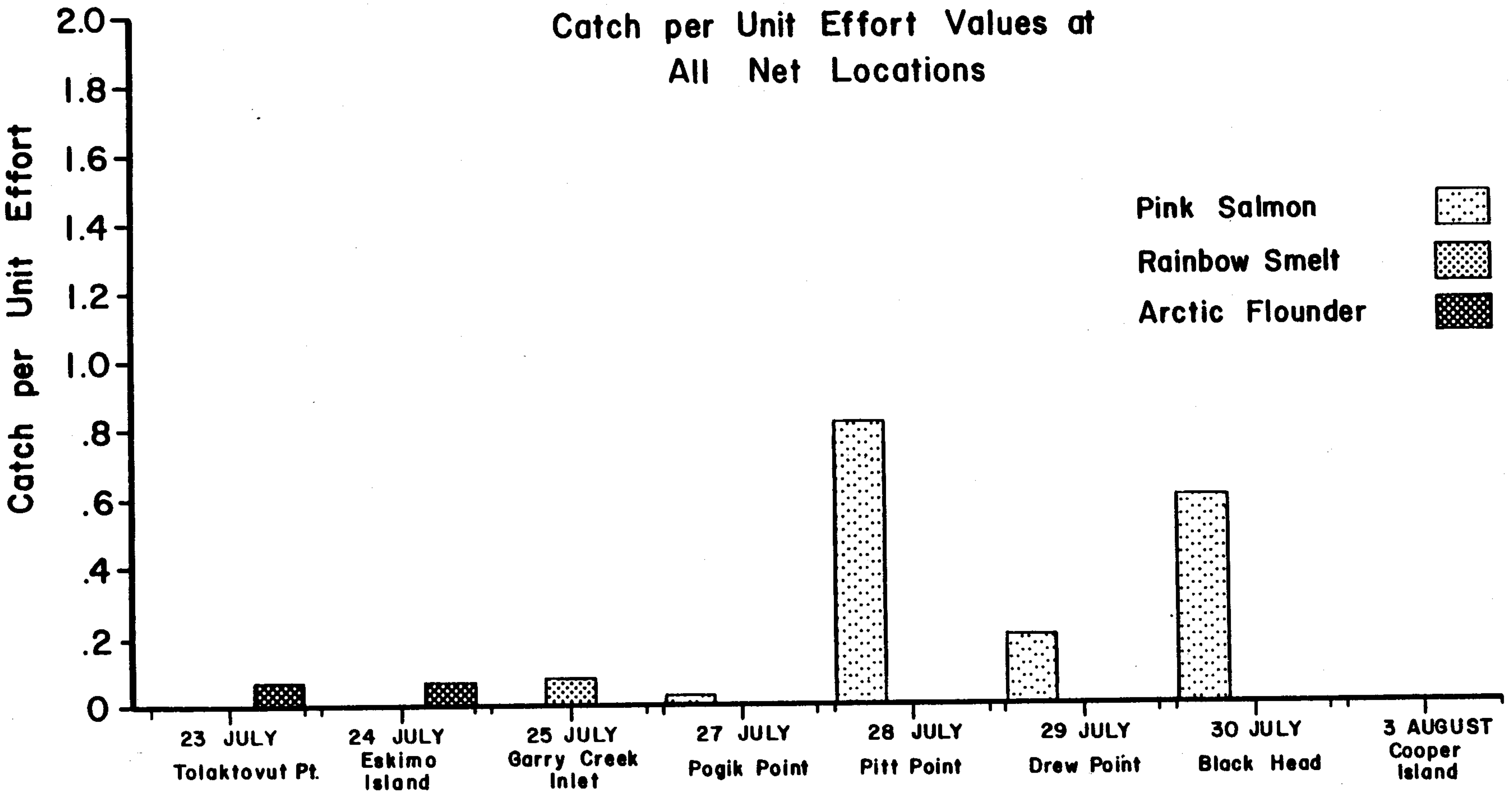

Figure 12. CPUE values for pink salmon, rainbow smelt and Arctic flounder at all net locations. The catch at Eskimo Island on 24 July is used for continuity.

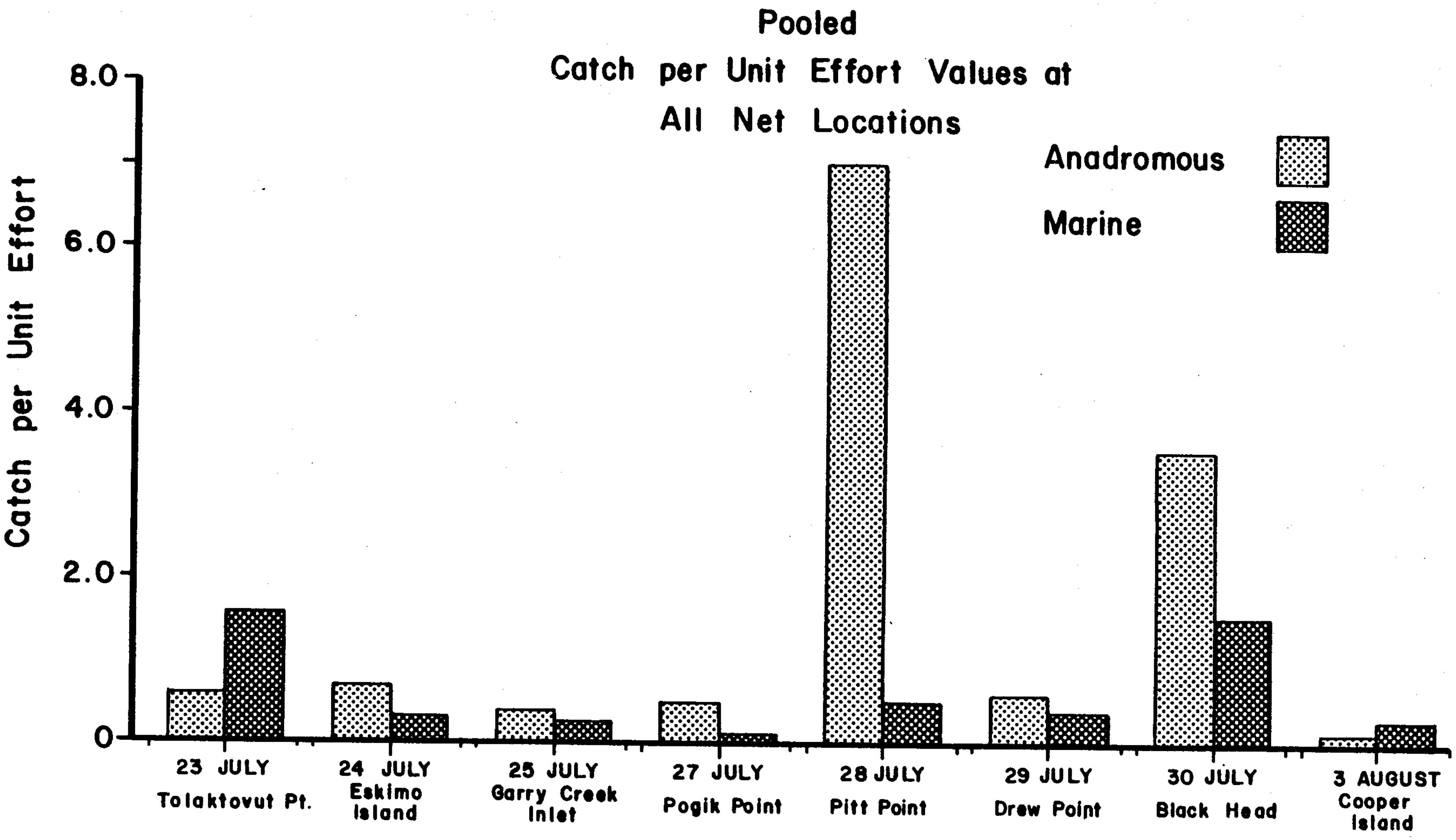

Figure 13. Pooled CPUE Values for anadromous and marine fishes at all net locations. The catch at Eskimo Island on 24 July is used for continuity.

dominated by least cisco and humpback whitefish comprising 81.3% of the catch (Table 1). Pooled CPUE values for marine fishes reach maximums at Tolaktovut Point and Black Head where fourhorn sculpin dominate the catches.

CPUE values for each species (except Bering cisco, round whitefish, capelin and saffron cod) were regressed separately upon temperature and salinity values at each station. The results including linear regressions, y intercepts and correlation coefficients are listed in Appendix V. None of the catches were significantly correlated with temperature or salinity illustrating the high variability usually associated with nearshore fisheries surveys (Craig and Haldorson 1981).

DISCUSSION

The species composition of catches along the Alaskan Beaufort coastline shows some degree of similarity as many of the same species continue to reappear in independent surveys. Species which tend to occur along the entire coast include the Arctic char, Arctic cisco, least cisco, fourhorn sculpin and Arctic flounder (Table 2).

The greatest disparity between catches of this and other studies occurs in the distribution and relative abundance of anadromous fishes, specifically among whitefishes. A greater number of whitefish species is found farther west along the coast as the distributions of broad and humpback whitefish are discontinuous east of the Sagavanirktok Delta, also the Bering cisco is believed to range only as far east as the Colville River. The relative abundance of Arctic cisco and Arctic char appears to decline from east to west as these fish represented greater percentages of the overall catch in virtually all studies conducted east of the present study.

The distributions of these anadromous fishes along the Beaufort Sea coast presumably reflects the east-west variation in physiography of the coastal regions and its subsequent effect on riverine habitat available for spawning, early life stages and overwintering. These physical differences in habitat type are largely a function of the proximity of

Table 2. A comparison of catch percentages by species of nearshore gillnet sampling along the Beaufort Sea coast (from Griffiths et al. 1975; Griffiths et al. 1977; Craig and Haldorson 1981; Griffiths and Gallaway 1982; Gallaway and Britch 1983; and Griffiths, LGL Ltd., pers. comm.)

Site Study (From West to East)	Present Study	Simpson Lagoon	Waterflood Causeway (Prudhoe Bay)	Sagavanirktok Delta	Kaktovik Lagoon	Angun and Beaufort Lagoons	Nunaluk Lagoon
Arctic cisco	17.1	56.3	28.7	44.3	19.8	37.1	55.6
Arctic char	2.4	14.2	39.6	17.7	9.6	37.8	21.1
Least cisco	28.5	11.6	21.4	12.2	1.5		2.5
Broad whitefish	3.1	3.8	0.2	13.3			
Humpback whitefish	5.4	2.2	0.1				
Bering cisco	0.2	1.0					
Rainbow smelt	7.7			0.2		0.7	
Pink salmon	4.2						
Coho salmon			0.1				
Chum salmon			*				
Round whitefish	0.2			0.1			
Arctic grayling							0.2
Inconnu							*
Fourhorn sculpin	29.6	9.2	9.4	11.6	67.8	24.1	18.9
Arctic cod		0.1	*	0.5	0.1		
Arctic flounder	1.4	0.4	*		0.5		1.5
Capelin	0.3	1.0			0.4	0.4	
Saffron cod	0.1		0.1	0.1			
Snail fish			0.1	0.1			
False sea scorpion					0.1		
n =	1201	781	2144	1577	729	278	1325

* = less than 0.1%.

the Brooks Range to the coast. To the east of the Colville River the continental divide (delineated by the Brooks Range) approaches to within 100 km of the coast, resulting in a relatively steep slope and narrowing of the Arctic Coastal and Arctic Foothills physiographic provinces (Payne et al. 1951). The streams of this region are typical of Mountain Streams as classified by Craig and McCart (1975). These fast-flowing, cold clearwater streams originate in the Arctic Mountain Province and are characterized by steep gradients, braided channels and spring sources are frequently associated with them. It is these which provide spawning and rearing habitat for Arctic char which Craig and McCart (1975) describe as the characteristic fish of Mountain and Spring Streams.

In contrast, west of the Colville River the continental divide lies 300 km from the coast. The gradual slopes of this region are drained by slow-moving, meandering Tundra Streams which are fed by tundra runoff from the broad Arctic Coastal and Arctic Foothills Provinces (e.g., Meade, Ikpikpuk and Topagoruk rivers). These rivers and associated coastal plain lake systems provide more suitable habitat for anadromous coregonids including the least cisco, broad and humpback whitefish.

It would follow that the two fish, Arctic char and Arctic cisco, more closely associated with features of the eastern coast would be more abundant in that area than in the west. The Arctic char associated with the mountain streams of the east coast and the Arctic cisco which is thought to reproduce only in the Mackenzie River are found to present a smaller percentage of the overall catches to the west. Concurrently, the three whitefish, humpback whitefish, broad whitefish and least cisco, which do not migrate as extensively and are more closely associated with the tundra streams of the western Beaufort coast represent a greater percentage of the overall catches to the west than to the east (where, indeed, the humpback and broad whitefish are not present in some collections).

The distribution of marine fishes shows a marked degree of similarity from east to west with the slight disparity among catches probably due to differential efforts and location of sample sites.

Fourhorn sculpin consistently dominate the nearshore catches, however, when high salinity, low temprature conditions persist toward the end of the open water season, there is often a large influx of Arctic cod (Griffiths and Gallaway 1982; Gallaway and Britch 1983). Other relatively abundant marine species found in nearshore catches are Arctic flounder, saffron cod, capelin and snail fish.

The length-frequency histograms for the two ciscos show a bimodal distribution especially in the case of Arctic cisco (Figure 3). This distribution is similar to the findings of Griffiths and Gallaway (1982). The small Arctic cisco size cohort captured during this study probably consists of a combination of age groups. Craig and Haldorson (1981) reported age 1 fish as having a mean length of 112 mm (range 65-145 mm) and age 2 fish as having a mean length of 155 mm (range 129-188 mm). The length-frequency histogram for least cisco also shows a small size cohort which corresponds to age 2 fish with a mean length of 126 mm (range 95-154) and age 3 fish with a mean length of 154 mm as reported by Craig and Haldorson (1981). The length-frequency histograms for the remaining species show no obvious size cohort segregation except for rainbow smelt. This species appears to have two size cohorts, one averaging about 175 mm, the other about 280 mm. Using the results reported by Craig and Haldorson (1981) the smallest cohort probably consists of age 3 through age 6 fish and the larger cohort consists of age 6 through age 15 fish.

Arctic char captured during this survey fell within the size range documented in other surveys along the Beaufort coastline, however, they were distinctly skewed toward the larger sizes. Gillnets generally have a sampling bias toward larger char as seen in the results of the Simpson Lagoon study (Craig and Haldorson 1981). Their gill net catches ranged in size from 180 to 720 mm while the catches of the present study ranged from 370 to 620 mm using gill nets of similar mesh. The reasons for this dispariy are unclear, however, one possible explanation may be that the Arctic char in the western Beaufort are the larger members of the populations which are more capable of swimming greater distances from spawning and overwintering rivers to the east.

Catches at the Eskimo Island locations (Figures 5, 6, and 7) showed a high degree of variation both between species and between sample dates. This variation was not wholly unexpected since numerous other short surveys show a similar high variation. This variation may be confounded by a fishes temperature-salinity preference and by the seasonal timing of migration. During short surveys, such as the present study, these compound variables are difficult to completely separate, however, some patterns do appear. Considering only the Eskimo Island catches, the CPUE values for Arctic cisco and humpback whitefish were significantly correlated with temperature and the CPUE values for least cisco and pink salmon were significantly correlated with salinity. The former correlation seems entirely reasonable in light of the recent experimental research done by Fechhelm et al. (1983) which showed a temperature preference of Arctic cisco to be about 15° C. Presumably humpback whitefish follow a similar preference, however, the critical experiments have not been done. The unexpected positive correlation of least cisco and pink salmon CPUE values may be due to a timing-of-migration effect rather than to temperature-salinity preference. This seems plausible at least for the salmon since the major migratory pulse of this species did not occur until 28 July, a time when salinities generally begin to increase at the end of the open water season (Appendix I).

Catches at the other net locations (Figures 10, 11, and 12) also show a high degree of variability and CPUE values for each species at all locations were not significantly correlated with either temperature or salinity (Appendix V). Aside from the previously discussed sources of variation, temperature-salinity preference and timing of migration, these histograms also reflect a locational variation where one site may be more or less favorable depending upon factors such as proximity to rivers or food resources, protection from turbulence and suspended peat sediments, etc. Protected areas where CPUE values were high (Black Head and to some extent Tolaktovut Point) may represent favorable habitat supporting larger densities of fish; on the other hand unprotected areas with high CPUE value (Pitt Point) may represent poor habitat through which fish were rapidly moving and consequently were being captured in large number. This dilemma can only be sorted out by employing either long term studies with passive gear (gill nets, fyke nets) or shorter term studies with active gear (trawls, seines).

Prospectus

Often when relatively new areas are investigated many questions arise from both the results of the investigation and from the experience of dealing with a new area. The western Beaufort is indeed a new area, not merely an extension of the well-researched mid- and eastern-Beaufort coasts. It contains several habitats not represented in the east. The two large bays, Admiralty and Smith bays and the semi-enclosed bay, Harrison Bay, are unequalled elsewhere in the Alaskan Beaufort. The western Beaufort also contains a large lagoon, Elson Lagoon, and numerous tundra streams and rivers providing fish access to the numerous coastal plain lakes including Teshekpuk Lake, the largest in Arctic Alaska. The riverine systems that drain into the Beaufort differ, with montane streams to the east and tundra streams to the west. These differences may provide habitat distinctions which would presumably affect the distribution and abundance of the various fish species.

Observing these differences a list of research needs is presented. This list is based upon recognized informational gaps and upon scientific curiosity. The list is presented below.

- The western Beaufort contains three large bays, Admiralty, Smith and Harrison bays, and a large lagoon system, Elson lagoon. What is the influence of riverine input on the temperature, salinity and turbidity regimes of these systems and how does this affect indigenous fish distribution and movements?

- What is the role of Teshekpuk Lake and other large tundra lakes in providing overwintering and spawning habitat for anadromous fishes?

- The distribution, timing of migration and abundance of several species of anadromous fish in the western Beaufort are poorly understood. Species included are Bering cisco, humpback whitefish and broad whitefish. Additionally, little is known of the distribution of out-migrating pink salmon smolt and subsequent juvenile stages spent in salt water.

- Little is known of the abundance of off-shore marine fishes or their distribution in relation to boulder patches or ice edges.

- Little is known of the temperature-salinity preferences of near-shore anadromous fishes. To date only one species, Arctic cisco, has been the subject of temperature-salinity preference studies (Fechhelm et al. 1983).

- What is the role of unprotected shoreline (e.g., Pitt Point) in influencing anadromous fish migration? Do fish migrate quickly through these areas or is there no difference between these and protected areas? How would causeway construction on unprotected shoreline affect local migration patterns.

- What will be the ramifications of cumulative industrial development upon near shore habitat, trophic dynamics and resource utilization including commercial and subsistence fishing?

ACKNOWLEDGMENTS

The authors thank Jim Helmericks who piloted the float plane, helped pick nets and offered freely his suggestions and his Arctic expertise. Without his help this survey would have strained to reach its objectives. We also thank Teena Helmericks and the younger members of the Helmericks family for their logistic and moral support.

Thanks is also extended to Rosa Meehan of the U.S. Fish and Wildlife Service for her assistance in picking nets and performing other odious tasks associated with fisheries surveys.

The completion of this report was facilitiated by Evelyn Kimbrough who typed and helped edit the first draft, and Betsy Sturm who performed all the drafting and lettering.

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Appendix I. Temperature and salinity data. Physical data was taken when the net was set and again when the net was pulled. Both values are given along with the mean value.

Date	Location	Temperature (°C)			Salinity (ppt)		
		In	Out	Mean	In	Out	Mean
23 July	Tolaktovut Point	10.0	10.5	10.3	0	0	0
24 July	Eskimo Island	10.8	12.2	11.5	0	2	1
25 July	Eskimo Island	12.2	14.5	13.4	2	3	2.5
25 July	Garry Creek Inlet	11.2	12.0	11.6	2	2	2
26 July	Eskimo Island	11.5	9.5	10.5	3	2	2.5
27 July	Eskimo Island	9.5	10.0	9.8	2	2	2
27 July	Pogik Point	9.0	10.0	9.5	12	10	11
28 July	Eskimo Island	10.0	9.3	9.7	2	2	2
28 July	Pitt Point	9.0	4.0	6.5	5	18	11.5
29 July	Eskimo Island	9.3	7.0	8.2	2	5	3.5
29 July	Drew Point	4.2	4.3	4.3	19	16	17.5
30 July	Eskimo Island	7.0	9.2	8.1	5	2	3.5
30 July	Black Head	7.1	10.0	8.6	12	7	9.5
31 July	Eskimo Island	9.2	8.0	8.6	2	6	4
3 August	Eskimo Island	8.0	7.1	7.6	6	14	10
3 August	Cooper Island	4.2	8.0	6.1	29	24	26.5

Appendix II. Pink salmon capture data.

Date	Location	No.	Length	Sex	Condition
27 July	Pogik Point	1	440	M	Green
28 July	Eskimo Island	1	455	F	Green
		1	510	M	Green
28 July	Pitt Point	1	390	F	Green
		1	405	F	Green
		1	420	M	Green
		1	430	F	Green
		1	435	F	Green
		2	440	M	Green
		1	440	F	Green
		1	445	M	Green
		1	450	M	Green
		2	460	M	Green
		2	465	M	Green
		2	470	M	Green
		1	475	M	Green
		1	495	M	Green
29 July	Drew Point	1	435	M	Green
		1	460	M	Green
		1	475	M	Ripe
		1	475	M	Green
		1	495	M	Green
30 July	Black Head	1	380	F	Green
		1	410	M	Green
		1	430	M	Ripe
		1	435	M	Green
		1	435	F	Ripe
		1	440	M	Ripe
		1	445	F	Green
		1	445	M	Ripe
		1	445	F	Ripe
		3	450	M	Ripe
		1	460	M	Ripe
		1	475	M	Ripe
		1	490	M	Ripe
		1	495	M	Ripe
31 July	Eskimo Island	1	450	M	Ripe
3 August	Eskimo Island	1	420	F	Ripe
		1	440	F	Ripe
		1	440	M	Ripe
		1	445	M	Green
		2	460	M	Green
		1	495	M	Ripe

Males mean length = 458.55 mm, S.D. = 22.54, n = 38
Females mean length = 426.67 mm, S.D. = 23.39, n = 12

Appendix III. Survey schedule of net locations including species, number caught, percentage of catch, hours set and catch per unit effort (CPUE).

Date	Location	Species	No. Caught	% of Catch	Hours Set	CPUE
23 July	Tolaktovut Point	Humpback whitefish	1	1.7	25.75	0.039
		Broad whitefish	15	25.0		0.583
		Arctic char	1	1.7		0.039
		Round whitefish	1	1.7		0.039
		Fourhorn sculpin	40	66.7		1.553
		Arctic flounder	2	3.3		0.078
			60			
24 July	Eskimo Island	Arctic cisco	10	41.7	22.00	0.455
		Humpback whitefish	4	16.7		0.182
		Arctic char	2	8.3		0.091
		Fourhorn sculpin	6	25.0		0.273
		Arctic flounder	2	8.3		0.091
			24			
25 July	Eskimo Island	Arctic cisco	43	39.1	23.00	1.870
		Least cisco	18	16.4		0.783
		Humpback whitefish	11	10.0		0.478
		Broad whitefish	2	1.8		0.087
		Fourhorn sculpin	25	22.7		1.087
		Rainbow smelt	11	10.0		0.478
			110			
25 July	Garry Creek Inlet	Arctic cisco	1	6.7	23.25	0.043
		Least cisco	1	6.7		0.043
		Broad whitefish	6	40.0		0.258
		Fourhorn sculpin	5	33.3		0.215
		Rainbow smelt	2	13.3		0.086
			15			

Appendix III (continued)

Date	Location	Species	No. Caught	% of Catch	Hours Set	CPUE
26 July	Eskimo Island	Arctic cisco	27	31.4	19.50	1.385
		Least cisco	12	14.0		0.615
		Humpback whitefish	5	5.8		0.256
		Broad whitefish	2	2.3		0.103
		Arctic char	1	1.2		0.051
		Rainbow smelt	17	19.8		0.872
		Fourhorn sculpin	21	24.4		1.077
		Arctic flounder	1	1.2		0.051
			86			
27 July	Eskimo Island	Arctic cisco	21	46.7	23.50	0.894
		Least cisco	5	11.1		0.213
		Humpback whitefish	2	4.4		0.085
		Broad whitefish	1	2.2		0.043
		Arctic char	2	4.4		0.085
		Fourhorn sculpin	8	17.8		0.340
		Rainbow smelt	6	13.3		0.255
			45			
27 July	Pogik Point	Arctic cisco	10	66.7	23.00	0.435
		Least cisco	2	13.3		0.087
		Pink salmon	1	6.7		0.043
		Fourhorn sculpin	2	13.3		0.087
			15			
28 July	Eskimo Island	Arctic cisco	16	38.1	24.00	0.667
		Least cisco	10	23.8		0.417
		Humpback whitefish	4	9.5		0.167
		Arctic char	2	4.8		0.083
		Pink salmon	2	4.8		0.083
		Rainbow smelt	3	7.1		0.125
		Fourhorn sculpin	5	11.9		0.208
			42			

Appendix III (continued)

Date	Location	Species	No. Caught	% of Catch	Hours Set	CPUE
28 July	Pitt Point	Arctic cisco	33	20.8	21.25	1.553
		Least cisco	80	50.3		3.767
		Humpback whitefish	2	1.3		0.094
		Broad whitefish	2	1.3		0.094
		Bering cisco	1	0.6		0.047
		Arctic char	12	7.5		0.565
		Pink salmon	18	11.3		0.847
		Fourhorn sculpin	11	6.9		0.518
			159			
29 July	Eskimo Island	Arctic cisco	5	27.8	24.50	0.204
		Least cisco	6	33.3		0.245
		Humpback whitefish	3	16.7		0.122
		Broad whitefish	1	5.6		0.041
		Fourhorn sculpin	3	16.7		0.122
			18			
29 July	Drew Point	Arctic cisco	4	14.8	24.25	0.165
		Least cisco	6	22.2		0.247
		Bering cisco	1	3.7		0.041
		Pink salmon	5	18.5		0.206
		Fourhorn sculpin	11	40.7		0.454
			27			
30 July	Eskimo Island	Arctic cisco	4	16.7	27.50	0.145
		Least cisco	6	25.0		0.218
		Humpback whitefish	2	8.3		0.073
		Arctic char	1	4.2		0.036
		Rainbow smelt	5	20.8		0.182
		Fourhorn sculpin	5	20.8		0.182
		Saffron cod	1	4.2		0.036
			24			

Appendix III (continued)

Date	Location	Species	No. Caught	% of Catch	Hours Set	CPUE
30 July	Black Head	Least cisco	52	38.0	26.00	2.000
		Humpback whitefish	26	19.0		1.000
		Broad whitefish	2	1.5		0.077
		Pink salmon	16	11.7		0.615
		Fourhorn sculpin	41	29.9		1.577
			137			
31 July	Eskimo Island	Arctic cisco	8	3.0	75.75	0.106
		Least cisco	93	34.3		1.228
		Humpback whitefish	5	1.8		0.066
		Broad whitefish	6	2.2		0.079
		Arctic char	2	0.7		0.026
		Round whitefish	1	0.4		0.013
		Pink salmon	1	0.4		0.013
		Fourhorn sculpin	106	39.1		1.399
		Rainbow smelt	39	14.4		0.515
		Arctic flounder	10	3.7		0.132
			271			
3 August	Eskimo Island	Arctic cisco	18	13.9	28.50	0.632
		Least cisco	48	37.2		1.689
		Arctic char	2	1.6		0.070
		Pink salmon	7	5.4		0.246
		Fourhorn sculpin	43	33.3		1.509
		Rainbow smelt	9	7.0		0.316
		Arctic flounder	2	1.6		0.070
			129			
3 August	Cooper Island	Arctic cisco	5	12.8	98.50	0.051
		Least cisco	3	7.7		0.031
		Arctic char	4	10.3		0.041
		Fourhorn sculpin	23	59.0		0.234
		Capelin	4	10.3		0.041
			39			

Appendix IV. Linear regressions, y intercepts and correlation coefficients for CPUE values at the Eskimo Island location vs. temperatures and vs. salinity. Critical value at the 5% level is r = 0.666 and at the 1% level is r = 0.798, n = 9.

	Temperature	Salinity
Arctic cisco	slope = 0.2428 y intercept = -1.6465 r = 0.7620*	slope = -0.0360 y intercept = 0.8345 r = -0.1588
Least cisco	slope = -0.0771 y intercept = 1.3451 r = -0.2666	slope = 0.1682 y intercept = 0.0171 r = 0.8164**
Humpback whitefish	slope = 0.0687 y intercept = -0.5084 r = 0.9096**	slope = -0.0263 y intercept = 0.2495 r = -0.4895
Broad whitefish	slope = 0.0091 y intercept = -0.0495 r = 0.4075	slope = -0.0025 y intercept = 0.0491 r = -0.1814
Arctic char	slope =-0.0010 y intercept = 0.0584 r = -0.0503	slope = -0.0007 y intercept = 0.0515 r = -0.0507
Pink salmon	slope = -0.0190 y intercept = 0.2227 r = -0.4310	slope = 0.0272 y intercept = -0.0556 r = 0.8640**
Fourhorn sculpin	slope = 0.0092 y intercept = 0.5944 r = 0.0306	slope = 0.1262 y intercept = 0.2490 r = 0.5906
Rainbow smelt	slope = 0.0337 y intercept = -0.0219 r = 0.2241	slope = 0.0098 y intercept = 0.2709 r = 0.0921
Arctic flounder	slope = -0.0032 y intercept = 0.0692 r = -0.1194	slope = 0.0047 y intercept = 0.0219 r = 0.2486

Appendix V. Linear regressions, y intercepts and correlation coefficients for CPUE values for all net locations vs. temperature and vs. salinity for several species of fish. Critical value at the 5% level is r = 0.497, n = 16.

	Temperature	Salinity
Arctic cisco	slope = 0.0863 y intercept = 0.1084 r = 0.3292	slope = -0.0153 y intercept = 0.6442 r = -0.1841
Least cisco	slope = -0.1199 y intercept = 1.7900 r = -0.2795	slope = 0.0216 y intercept = 0.5624 r = 0.1587
Humpback whitefish	slope = 0.0297 y intercept = -0.1075 r = 0.2638	slope = -0.0044 y intercept = 0.1900 r = -0.1233
Broad whitefish	slope = 0.0208 y intercept = -0.1022 r = 0.3184	slope = -0.0077 y intercept = 0.1376 r = -0.3704
Arctic char	slope = -0.0155 y intercept = 0.2080 r = -0.2590	slope = 0.0021 y intercept = 0.0533 r = 0.1127
Pink salmon	slope = -0.0465 y intercept = 0.5476 r = -0.4228	slope = 0.0108 y intercept = 0.0549 r = 0.3087
Fourhorn sculpin	slope = 0.1095 y intercept = 0.4264 r = 0.1095	slope = -0.0114 y intercept = 0.7524 r = -0.1436
Rainbow smelt	slope = 0.0393 y intercept = -0.1776 r = 0.3517	slope = -0.0117 y intercept = 0.2568 r = -0.3312
Arctic flounder	slope = 0.0031 y intercept = -0.0020 r = 0.1655	slope = -0.0018 y intercept = 0.0389 r = -0.3057

GENETIC STOCK IDENTIFICATION OF SOCKEYE AND CHUM SALMON FROM BRISTOL BAY, ALASKA

by

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Final Report

Outer Continental Shelf Environmental Assessment Program

Research Unit 694

June 1989

ACKNOWLEDGMENTS

This study was funded by the Minerals Management Service, Department of the Interior, through an Interagency Agreement with the National Oceanic and Atmospheric Administration, Department of Commerce, as part of the Alaska Outer Continental Shelf Environmental Assessment Program.

We thank Gary Sonnevil and his staff (Service Fisheries Assistance Office, King Salmon) for collecting the Bristol Bay salmon used in this study. Lyman Thorsteinson (National Oceanic Atmospheric Administration) facilitated the entire study. Various employees of the Alaska Department of Fish and Game helped us in different aspects of this project. David Rutz and John Bigelow assisted with electrophoresis. Martha Ronaldson typed the manuscript.

ABSTRACT

To study the Pacific salmon that may be affected by oil and gas development in the North Aleutian Basin, Alaska, we have used electrophoretic methods of protein separation to genetically characterize stocks. In 1987, tissue samples were collected from eleven populations of sockeye salmon and four populations of chum salmon from Bristol Bay drainages. In the laboratory, we analyzed 50 gene loci from each collection to establish genetic baseline data. In comparisons to sockeye salmon sampled from the same drainages in previous years, we found no significant differences in allele frequencies. The genetic identities (Nei) among Bristol Bay sockeye salmon populations are high, all greater than 0.98. Few loci are variable, and only 2% of the total genetic variation is due to differences between populations. Bristol Bay chum salmon sampled have genetic identities of 0.97 or more. Divergence between chum stocks, at 4%, is twice that of sockeye salmon sampled. Computer simulations with maximum likelihood statistics and re-sampling procedures were used to estimate the composition of artificial mixed stocks made up from baseline data. For sockeye salmon, only a few stocks were accurately and precisely identified from mixtures. Chum salmon stocks were more precisely identified, with some bias among the geographically close Inner Bay stocks.

TABLE OF CONTENTS

INTRODUCTION

Offshore oil and gas lease sales proposed for the North Aleutian Basin have the potential to impact several life history stages and fisheries of Bristol Bay salmon. These concerns stem from the overlap of proposed leasing areas with major salmon migration pathways (Straty 1981; Thorsteinson and Thorsteinson 1984), the potential siting of onshore facilities near important rearing habitats for juvenile salmon (Thorsteinson 1984; Isakson et al. 1986), and a perception of diminishing resource availability and harvest incomes resulting from possible oil spills.

An appraisal of the risk to Pacific salmon from resource development in the North Aleutian Basin would be best addressed on a river by river (or stock) basis. This form of assessment requires that detectable differences exist between stocks of salmon from major drainages in the Bristol Bay region. Detectable stock differences can result from either genetic and/or environmental factors, and may be identifiable depending on the species of interest and the method of study.

Methods for identifying fish stocks include enumeration and comparison of various morphological and biological characters (e.g., scale and otolith growth patterns and parasite infestations). These types of markers can be affected by yearly fluctuations in the environment and must be standardized on an annual basis if population identification is desired (Ihssen et al. 1981). Using starch-gel electrophoresis, we can detect differences between individuals as a result of inherited genetic material not subjected to environmental perturbations. These differences have been shown to be stable characteristics within salmon populations (Grant et al. 1980; Utter et al. 1980; Beacham et al. 1985).

Genetic stock identification (GSI) is based on electrophoretically detectable differences in genotypic distributions among fish populations. The genotypic distributions result from allele frequency differences at protein-coding gene loci. For anadromous fishes, estimates of stock composition in a mixed fishery are derived by comparing genotypic distributions of a mixed-stock sample against samples taken from discrete freshwater populations (baseline data). The best fit estimates of various stock admixtures are determined by maximum likelihood analysis (Pella and Milner 1986). Genetic stock identification is being employed in the management of salmon stocks in the states of Washington and California, and in British Columbia.

Objectives

The objectives of this segment of the study are:

1) to collect electrophoretic gene frequency data from freshwater spawning populations of sockeye (*Oncorhynchus nerka*) and chum salmon (*O. keta*);

2) to describe the amount of interannual variation in allele

frequencies based on our work and two previous genetic studies of Bristol Bay salmon populations conducted in different years; and

3) to use this data as a reference baseline to assess whether sufficient detectable genetic divergence exists among populations of Bristol Bay sockeye and chum salmon to permit accurate stock compositon estimates in a mixed-stock fishery.

The identification of fish taken from potential development sites can aid in assessing the effects of resource development on specific stocks throughout Bristol Bay. The long range goal of this study includes genetic stock analysis for all five species of Pacific salmon that inhabit the Bristol Bay area.

MATERIALS AND METHODS

Sampling and Electrophoresis

Tissue samples from eleven populations of sockeye salmon and six populations of chum salmon were collected from drainages of Bristol Bay (Tables 1 and 2, Figure 1). Biologists from the U.S. Fish and Wildlife Service (Service) Fishery Assistance Office in King Salmon used nets to capture adult salmon during their freshwater spawning migration. Samples from these collection sites are thought to be representative of populations that are major contributors to the Bristol Bay sockeye and

Table 1.- Sockeye salmon collection sites, Universal Transverse Mercator (UTM) coordinates, sample size, and dates for the genetic stock identification study, Bristol Bay, Alaska.

Site	UTM coordinates			Number of fish	1987 collection date
	Zone	Latitude	Longitude		
Bear River	4W	6210625W	420625E	100	July 9
Brooks Lake					
Headwaters Cr.	4W	6484375N	671875E	34	August 14
Hidden Creek	5W	6485625N	328750E	33	August 14
Upatree Creek	5W	6488750N	336875E	33	August 15
Egegik River	4W	6437500N	625000E	100	July 7
Igushik River	4W	6545000N	483125E	100	July 10
Kvichak River	5W	6580000N	335000E	100	July 6
Naknek Lake					
Margot Creek	5W	6485000N	350000E	34	August 6
Idavain Creek	5W	6508125N	346250E	33	August 13
Brooks River	5W	6493125N	337500E	33	August 27
Nushagak River	4W	6530625N	574375E	100	July 3
Nelson River	4W	6176250N	368750E	100	July 11
Togiak River	4W	6548750N	423125E	100	July 15
Ugashik River	4W	6281875N	619375E	29	July 16
	4W	6281875N	619375E	71	July 18
Wood River	4W	6468250N	523750E	100	July 8
Total				1100	

chum salmon fisheries.

Individual fish were dissected for samples of muscle, liver, eye, and heart tissue, and the samples were placed in polystyrene test tubes.

Table 2.- Chum salmon collection sites, Universal Transverse Mercator (UTM) coordinates, sample sizes, and dates for the genetic stock identification study, Bristol Bay, Alaska.

Site	UTM coordinates			Number of fish	1987 collection date
	Zone	Latitude	Longitude		
Alagnak River	4W	6544375N	671875E	100	August 18
Herendeen Bay					
Portage Creek	4W	6176250N	395000E	34	August 21
Grass Valley	4W	6176250N	399375E	33	August 21
Lawrence Creek	4W	6178750N	399375E	33	August 21
King Salmon River					
unnamed tributary	4W	6450000N	662500E	4	July 13
Gertrude Creek	4W	6450000N	665000E	40	July 18
unnamed tributary	4W	6450000N	662500E	42	July 20
Gertrude Creek	4W	6450000N	665000E	14	July 25
King Salmon River					
Mother Goose Lake	4W	6342500N	598750E	100	July 28-30
Nelson River	4W	6183750N	367500E	50	August 21
Sapsuk Lake	4W	6176250N	368750E	50	August 22
Togiak River	4W	6569375N	431250E	98	July 27
Total				598	

The tissues were immediately placed on ice, then transported to King Salmon where they were frozen. The frozen samples were flown to the Alaska Fish and Wildlife Research Center laboratory in Anchorage where they were stored at -80°C prior to electrophoretic analysis.

We used horizontal starch-gel electrophoresis of genetically-encoded enzymes to detect differences between populations (Utter et al. 1974). Staining procedures follow the methods described by Aebersold et al. (1987) and Harris and Hopkinson (1976, 1977). The isozyme nomenclature

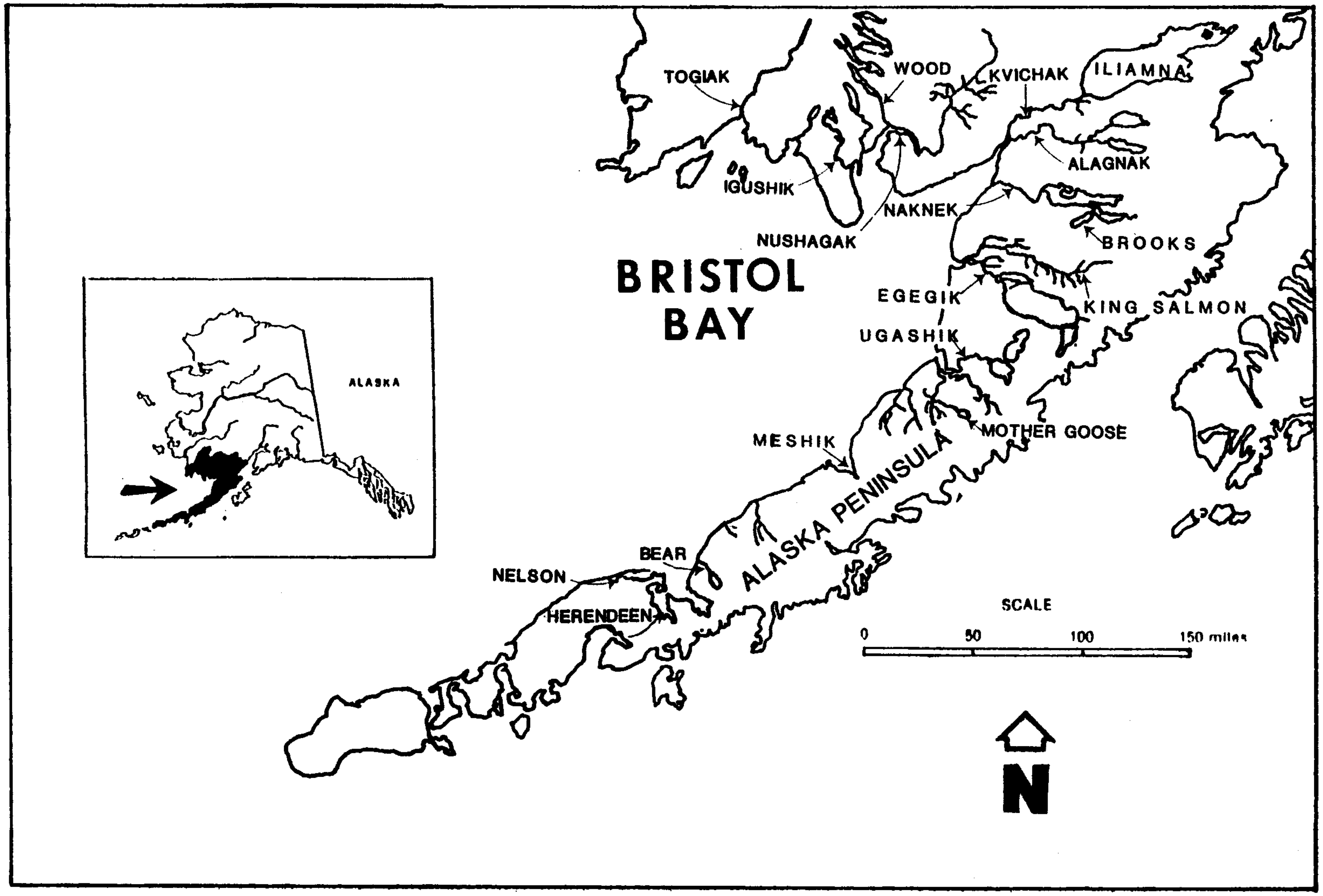

Figure 1. Bristol Bay and the Alaska Peninsula showing the locations sampled for chum and sockeye salmon.

and method of measuring allele mobilities are those of Allendorf et al. (1983). We examined 26 enzymes encoded by 50 presumptive gene loci using four gel buffers (Table 3).

Genotypic distributions

The electrophoretic genotypes for each individual were coded and gene frequencies at each locus were calculated. All polymorphic loci were tested for significant deviations from expected random-mating genotypic proportions (Hardy-Weinberg equilibria) using the chi-square analysis.

Allele frequency heterogeneity

A multiple simultaneous log-likelihood ratio statistic (G-test: Sokal and Rohlf 1981) was used to determine heterogeneity among all collections from each species. G-tests were then used to test for significant differences between allele frequencies of conspecific populations, pairwise. The significance level was adjusted using the correction of Cooper (1968) to reduce chance statistically significant results due to the number of pairwise tests.

Genetic variation

We used average heterozygosity per locus (H) and percentage of polymorphic loci (P) to measure electrophoretically-detectable genetic variation within the study populations. Assuming a population is in

Table 3.- Enzyme loci examined electrophoretically for 1987 Bristol Bay genetic stock identification study of sockeye and chum salmon with Enzyme Commission (E.C.) numbers (IUB 1984). Tissues are: M (muscle), L (liver), E (eye), and H (heart). Buffers include: AC (Clayton and Tretiak 1972) pH 6.1 to 6.8; EBT (Boyer et al. 1963) pH 8.6; TC (Schall and Anderson 1974) pH 5.8; RW (Ridgeway et al. 1970) pH 8.2. Loci in parentheses are duplicate pairs (isoloci).

Enzyme	E.C. number	Loci	Tissue	Buffer
Acid phosphatase	3.1.3.2	Acp1,2	H	TC,AC
Aconitate hydratase	4.2.1.3	Ah1	L	AC,TC
Adenosine deaminase	3.5.4.4	Ada1,2[a]	L,H	AC
Adenylate kinase	2.7.4.3	Ak	M	AC
Alanine amino transferase	2.6.1.2	Alat	M	AC
Aspartate aminotransferase	2.6.1.1	Aat(1,2)	M	EBT,AC
		Aat4	L	EBT,AC
Creatine kinase	2.7.3.2	Ck1,2	M	RW
		Ck5	E	RW
Esterase-D	3.1.1.1	Est-D	M,H	EBT
Fructose biphosphate aldolase	4.1.2.13	Ald1,2,3[b]	E	AC
Fumarate hydratase	4.2.1.2	Fh	H	TC
Glucose phosphate isomerase	5.3.1.9	Gpi(1,2)	M	RW
		Gpi3	E,M	RW
Glutathione reductase	1.6.4.2	Gr	L,H	AC
Glyceraldehyde phosphate dehydrogenase	1.2.1.12	Gap3,4	E	AC
α-glycerophosphate dehydrogenase	1.1.1.8	G3p1	M	AC,EBT
		G3p1,2,3[c]	H	AC,EBT
Guanine deaminase	3.5.4.3	Gda	L	AC
Isocitrate dehydrogenase	1.1.1.42	Idh1,2	H,M	AC
		Idh3,4	L	AC
Lactate dehydrogenase	1.1.1.27	Ldh1,2	M	RW
		Ldh4	L	RW
		Ldh3,4,5	E	RW
Malate dehydrogenase (NAD)	1.1.1.37	Mdh(1,2)[b]	L	AC
		Mdh(3,4)	M	AC
Malate dehydrogenase (NADP)	1.1.1.40	mMdhp1,2	M	AC
		Mdhp1	H	TC,AC
Mannosephosphate isomerase	5.3.1.8	Mpi	H	EBT

Table 3.- Continued.

Enzyme	E.C. number	Loci	Tissue	Buffer
Peptidase	3.4.11			
Leucyl-glycyl-glycine		Tapep	H,M	AC
Leucyl-tyrosine		Pep-LT[c]	L	AC
Phosphoglucomutase	2.7.5.1	Pgm2	M	RW
6-Phosphogluconate dehydrogenase	1.1.1.44	Pgdh	M,L	AC
Sorbitol dehydrogenase (Iditol)	1.1.1.14	Sdh1,2[b]	L	RW
Superoxide dismutase	1.15.1.1	Sod1[b]	L,H	RW,EBT
Triosephosphate isomerase	5.3.1.1	Tpi1,2	M	AC
		Tpi1,2,3,4	E	AC

[a] Polymorphic in chum, but poorly resolved.
[b] Deleted from chum baseline screen.
[c] Added to chum baseline screen.

polymorphic loci (P) to measure electrophoretically-detectable genetic variation within the study populations. Assuming a population is in random mating proportions, H is defined as the expected frequency of individuals heterozygous (having a variant) at a particular locus:

$$H = 1 - \sum_{i=1}^{n} p_i^2$$

where n equals the number of alleles and p_i equals the frequency of the $i^{\underline{th}}$ allele. The expected heterozygosity per individual per locus within each population was calculated by summing the single-locus heterozygosities and dividing by the total number of loci studied.

A locus that has its most common allele present in a frequency less than or equal to 0.99 is considered polymorphic. The percent of polymorphic loci (P) is determined by dividing the number of variable loci by the total number examined electrophoretically and multiplying by 100.

Genetic similarity

Genetic relatedness between populations was measured using the genetic identity (I) of Nei (1972). When two populations are electrophoretically indistinguishable, sharing the same alleles at all loci, their genetic identity is defined as 1.0. Complete genetic divergence (I= 0.0) is indicated by fixed allele substitutions at all loci. Genetic identity values represent the probability of sampling the same allele from two populations and are a normalized measure of genetic relatedness within or between species.

In this study, genetic identity values were calculated using only polymorphic loci, which overestimates the differences between populations. To graphically depict relationships between collections of salmon from Bristol Bay drainages, we used an unweighted pair-group clustering algorithm (UPGMA: Sneath and Sokal 1973). The clustering analysis calculates the averaged gene identity values between populations and produces a dendrogram based on the observed allelic similarity over all loci studied.

Gene diversity analysis

When measuring genetic divergence, the combined total variation of all stocks of a species in a region can be partitioned to determine how the variation is distributed within and between the stocks. We used two measures for determining the source of genetic variation. First, the hierarchical gene diversity analysis of Chakraborty (1980) partitions the total amount of genetic variation within a subdivided population:

$$H_T = H_S + D_{ST}$$

where H_T is the total gene diversity (heterozygosity) if all the samples are considered as a single randomly mating unit, H_S is the average heterozygosity within each subpopulation or stock, and D_{ST} represents that portion of genetic variation due to differences between subpopulations. The relative diversity represents the percent of total variation due to differences between stocks from different drainages.

For this hierarchical statistic, the eleven sockeye salmon collections from different drainages were each treated as different subpopulations within a larger geographic region (Bristol Bay). All six chum salmon collections were treated as separate subpopulations that were secondarily partitioned into areas of Bristol Bay. Herendeen Bay and Nelson Lagoon chum salmon collections represent the southwest area of Bristol Bay, based on both the genetic identity value and the geographical separation from the other subpopulations. The Togiak

River collection represents the northwest area of Bristol Bay. The King Salmon, Alagnak, and Mother Goose collections are both genetically and geographically close, and represent the geographic area of inner Bristol Bay. All the separate areas (southwest, northwest, and inner) were then compared at the highest hierarchical level.

Second, the coefficient of genetic divergence (G_{ST}) value of Nei (1973) was used as a normalized measure of differentiation among populations from different drainages. A value of 1.0 indicates complete genetic divergence among subpopulations. G_{ST} is estimated as $1 - (H_S / H_T)$.

Genetic stock identification

We tested the effectiveness of the GSI method on populations of Bristol Bay sockeye and chum salmon by constructing artificial mixed-fishery samples of known composition. Artificial mixtures were analyzed relative to baseline data using the maximum-likelihood estimate program provided by Sam Nelson and Jerome Pella (National Marine Fisheries Service, Auke Bay, Alaska). Standard deviations were calculated from re-samplings via a bootstrapping algorithum (Efron 1982).

First, a mixed-stock fishery was constructed for each species by pooling all individuals (from all drainages) into a single group. The ability of the GSI program to discriminate between stocks, each making an equal contribution, was tested by analyzing this known mixture with 200 re-sampling iterations.

Second, incremental mixed-stock simulations were used to determine the accuracy and precision of GSI estimates on a stock-by-stock basis. We constructed artificial mixed stocks by adding percentages of a given population to a mixture at 20% increments (from 0 to 100% as in Beacham et al. 1985). The remainder of the artificial mixed stock was constructed of equal contributions of data from the other populations. The GSI program was run 100 times on each mixture using bootstrap resampling. Standard deviations for the 100 estimates were used to evaluate the precision of each point estimate.

RESULTS

Sockeye salmon

Of the protein-coding loci studied, we found only four variable loci that could be reliably scored in sockeye salmon: Pgm2, Ldh4, Mdh1,2, and Mdh3,4. A polymorphic Alat muscle locus used by Grant (1980) was variable in our collections as well, but lacked sufficient resolution to be useful in our analysis. The allele frequencies for all polymorphic loci were calculated for each collection (Appendix A).

Genotypic distributions

The genotypic distribution of the loci studied do not deviate significantly from expected Hardy-Weinberg proportions with the exception of Pgm2 in Bear River sockeye salmon ($P<0.025$). The other two variable loci in this populations (Ldh4, Mdh1,2) show no departure from expected proportions so the samples were probably collected from a population mating at random.

MDH phenotypes are derived from duplicated gene pair with indistinguishable mobilities for the alleles at either locus. We treated each duplicate pair as two disomic loci to simplify the analyses; variant alleles were arbitrarily assigned to one locus.

Allele frequency heterogeneity

The multiple-simultaneous G-test analysis for heterogeneity of allele frequencies among all collections of Bristol Bay sockeye salmon indicate that there are sufficient differences that prohibit them from being pooled into a large homogeneous group ($P<0.001$). The pairwise G-tests support this hypothesis as 31 of 55 comparisons produced significant G-values (Table 4).

Electrophoretic data are available from two previous studies of Bristol Bay sockeye salmon. Based on the two variable loci that could be compared among collections (Ldh4, Pgm2). There are no significant allele frequency differences between Wood River fish collected in 1976 (Grant 1980) and those from this study ($P>0.05$). The same is true for fish collected from the Nushagak River in 1976 (Grant et al. 1980) and those we collected in 1987 ($P<0.05$). Wilmot et al. (1985) have data

Table 4.- Pairwise comparisons of allele frequency heterogeneity between sockeye salmon populations. G-values and degrees of freedom were summed over all variable loci that could be compared between populations. The probability values were adjusted to reflect multiple tests (Cooper 1968).

1	Nushagak	-										
2	Egegik	*	-									
3	Wood	*	ns	-								
4	Bear	**	**	ns	-							
5	Igushik	*	ns	ns	ns	-						
6	Nelson	*	ns	ns	*	ns	-					
7	Togiak	**	*	**	**	*	*	-				
8	Naknek	**	ns	**	**	*	ns	*	-			
9	Ugashik	ns	ns	ns	ns	ns	ns	ns	*	-		
10	Brooks	**	**	**	ns	**	**	**	**	**	-	
11	Kvichak	*	ns	ns	**	ns	ns	*	ns	ns	**	-
		1	2	3	4	5	6	7	8	9	10	11

* = $P<0.05$
** = $P<0.01$
ns = not significant

for 64 fish collected from the Brooks River in 1984. No significant allele frequency differences were detected for Pgm2 and Ldh4 when compared to 1987 spawners taken from the same area ($P>0.05$).

Genetic variation

Subpopulation heterozygosities (H_S) range from a low of 0.007 in Brooks Lake sockeye salmon to 0.015 in both Togiak and Naknek collections (Table 5). The average subpopulation heterozygosity over all

Table 5.- Heterozygosities for eleven populations of Bristol Bay sockeye salmon. Averaged, single-locus values for H within populations are listed with standard errors. Population heterozygosity (H_S) is based on a total of 50 loci. Average population heterozygosity was calculated by averaging H_S over all populations. P equals the proportion of loci that are polymorphic.

Population	Loci					
	Ldh4	Pgm2	Mdh1	Mdh3	P	H_S
Bear	0.095	0.308	0.049	0.000	0.060	0.009
Brooks	0.104	0.226	0.039	0.000	0.060	0.007
Egegik	0.226	0.403	0.010	0.000	0.060	0.013
Igushik	0.164	0.385	0.020	0.000	0.060	0.011
Kvichak	0.211	0.412	0.010	0.000	0.060	0.012
Naknek	0.314	0.424	0.030	0.000	0.060	0.015
Nelson	0.203	0.370	0.000	0.000	0.060	0.011
Nushagak	0.121	0.476	0.030	0.000	0.060	0.013
Togiak	0.248	0.380	0.030	0.077	0.080	0.015
Ugashik	0.172	0.399	0.020	0.020	0.080	0.012
Wood	0.104	0.385	0.000	0.000	0.060	0.010
Average	0.178	0.379	0.022	0.009	0.064	0.0116
S.E.	(0.070)	(0.065)	(0.016)	(0.023)	(0.080)	(0.002)

collections is 0.012.

The percent polymorphic loci (P) is either 0.060 or 0.080 for each population since only three or four loci out of 50 are variable (Table 5). The _Alat_ muscle locus was not used for these estimates as our data are incomplete.

Genetic similarity

Genetic identity estimates between population pairs exceed 0.980 and are based only on inclusion of polymorphic loci in the data base (Table 6). The mean identity estimate (I) over all comparisons is 0.996 ± 0.003. No allele substitutions were observed at any locus between any of the populations. The results of the cluster analysis of genetic similarity among the 11 Bristol Bay sockeye salmon populations is presented as a dendrogram (Figure 2).

Gene diversity analysis

Ninety-eight percent of the total gene diversity in Bristol Bay sockeye salmon is due to differences among individuals within populations (Table 7). On average, only 2% of this diversity can be attributed to differences between populations. The estimate of population differentiation, measured as G_{ST}, is 0.03.

Genetic stock identification

In the mixed fishery simulations with all populations of Bristol Bay sockeye salmon equally represented, the contributions of Egegik, Wood, Igushik, and Kvichak stocks are underestimated at zero even though each actually represented 9.1% of the artificial mixture (Figure 3, Appendix C). Nelson and Nushagak sockeye salmon are overestimated at 33.3% and 23%. Brooks, Bear, Naknek, and Ugashik contributions are 16.2%, 4.7%,

Table 6.- Matrix of Nei's (1972) gene identity values between 11 populations of Bristol Bay sockeye salmon.

1 Nushagak	-										
2 Egegik	.995	-									
3 Wood	.995	.998	-								
4 Bear	.989	.996	.998	-							
5 Igushik	.995	.999	1.000	.998	-						
6 Nelson	.993	1.000	.999	.998	1.000	-					
7 Togiak	.992	.999	.998	.996	.999	.999	-				
8 Naknek	.993	.999	.994	.991	.997	.997	.998	-			
9 Ugashik	.996	1.000	1.000	.997	1.000	1.000	.999	.997	-		
10 Brooks	.981	.993	.995	.999	.995	.996	.994	.987	.994	-	
11 Kvichak	.996	1.000	.999	.996	1.000	.999	.999	.998	1.000	.992	-
	1	2	3	4	5	6	7	8	9	10	11

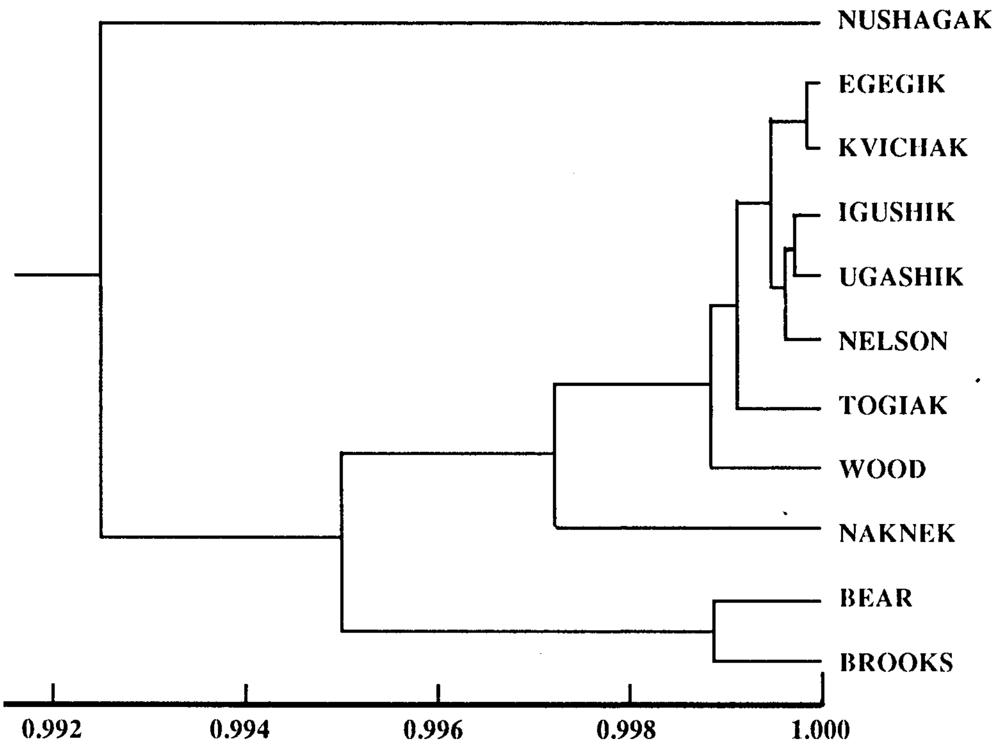

Figure 2.- Dendrogram depicting genetic relationships among 11 populations of Bristol Bay sockeye salmon. Clustering is based on unweighted averages of Nei's (1972) genetic identity values. The values in this table are based on polymorphic loci only.

Table 7.- Distribution of electrophoretically detectable gene diversity among 11 populations of Bristol Bay sockeye salmon. The absolute gene diversity averages are based on 50 gene loci (46 that are monomorphic).

Locus	Absolute gene diversity		Relative gene diversity (%)	
	Total (H_T)	Within populations (H_S)	Within populations	Between populations
Ldh4	0.182	0.178	98.0	2.0
Mdh1	0.022	0.021	99.3	0.7
Mdh3	0.009	0.008	97.0	3.0
Pgm2	0.386	0.379	98.0	2.0
Average	0.012	0.012	98.1	1.9
S.E.	(0.060)	(0.058)		

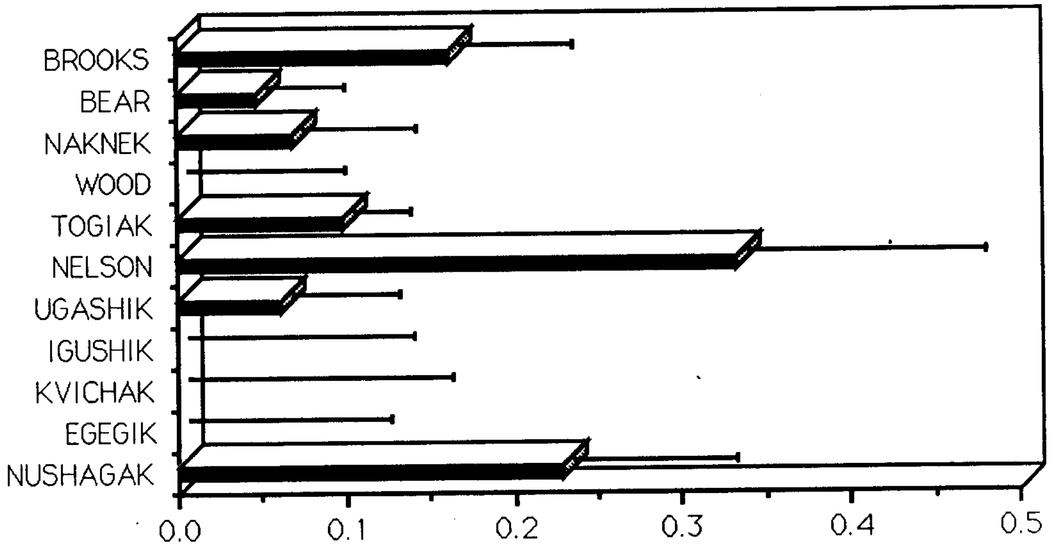

Figure 3.- Percent composition estimates for a mixed fishery (N = 1100) constructed from equal contributions of Bristol Bay sockeye salmon populations. Each population comprised 9.1% of the simulated fishery. Error bars represent one standard deviation calculated from 200 bootstrap resampling iterations.

6.9%, and 6.1%, respectively. The estimated contribution of Togiak River sockeye salmon (9.9%) is the most accurate.

From the incremental stock identification simulations, Bear, Brooks, Naknek, and Nushagak sockeye have the most accurate estimates and the smallest standard deviations (Figure 4). Composition estimates for populations within that cluster on the dendrogram above 0.999 (Egegik, Igushik, Kvichak, Nelson, and Ugashik) are generally poor and have large standard deviations. Togiak and Wood sockeye salmon cluster close to the major group on the dendrogram, but are distinguishable from each other in a mixed fishery due to polymorphism at the Mdh3,4 locus in the Togiak stock.

Chum salmon

Twelve variable loci were scored in chum salmon (Appendix B).More enzyme systems are variable (e.g. Gda, Ada1, Mdh1, and Mdh2), but could not be reliably scored. Duplicated loci [i.e. Aat(1,2); Mdh(3,4)] were treated as previously described for sockeye salmon, with variation arbitrarily assigned to one locus of the pair.

Genotypic distributions

Only the genotypic distribution at the Idh3 locus in Alagnak chum salmon deviates significantly from random mating proportions ($P<0.001$). The other variable loci scored in the Alagnak collection

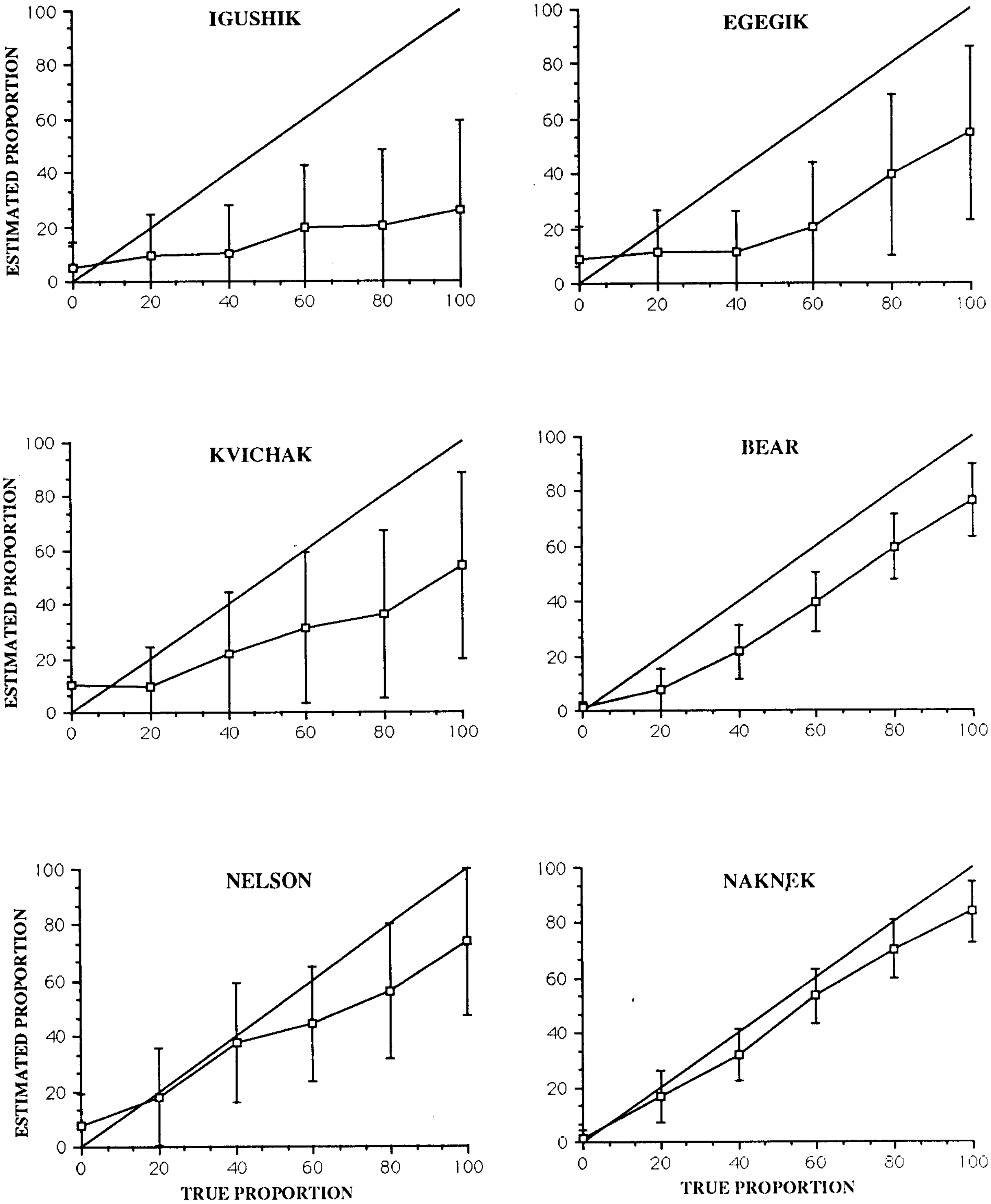

Figure 4.- Graphs of GSI-estimated stock proportions in simulated mixed stocks of Bristol Bay sockeye salmon. Point estimates are the mean of 100 resamplings (accompanied with ±1 standard deviation). All mixtures contained 1100 fish.

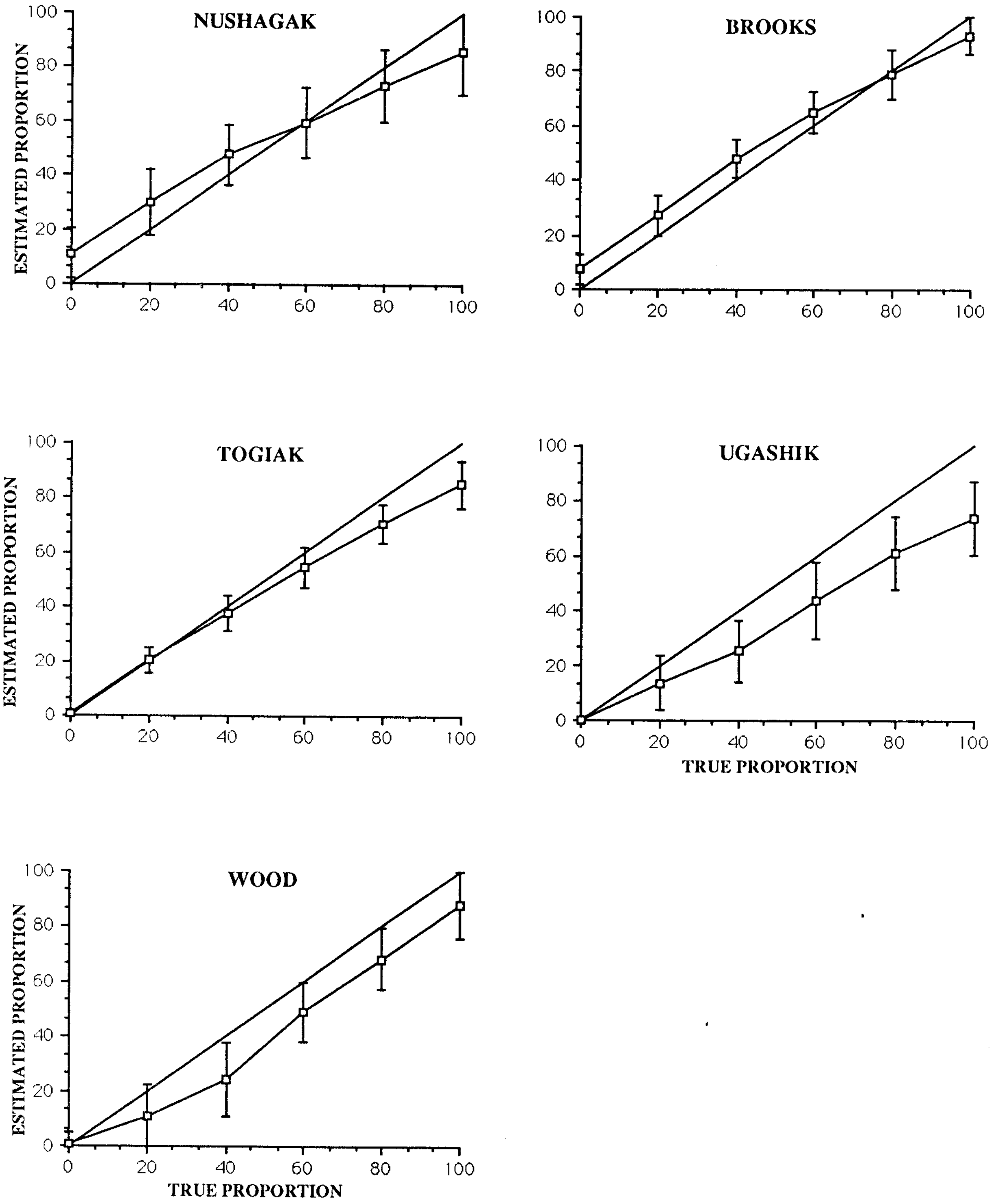

Figure 4.- Continued

were in expected proportions so the genotypic distribution at Idh3 may be a result of chance oversampling of the heterozygous genotype.

Allele frequency heterogeneity

Pairwise comparisons show that the allele frequencies of Alagnak, King Salmon, and Mother Goose chum salmon populations are not significantly heterogeneous (Table 8). Comparisons between all the other populations are statistically significant (G-test; $P<0.01$).

Genetic variation

The Idh3 locus has the highest measure of variability ($H_T = 0.614$) when averaged over all populations (Table 9). Peptidase loci (TaPep and Pep-LT) contribute the least to detectable gene variation found in

Table 8.- Pairwise comparisons for significant allele frequency heterogeneity between Bristol Bay chum salmon populations. G-values and degrees of freedom were summed over all variable loci that could be compared between populations.

1	King Salmon	-					
2	Nelson	*	-				
3	Togiak	*	*	-			
4	Alagnak	ns	*	*	-		
5	Mother Goose	ns	*	*	ns	-	
6	Herendeen	*	*	*	*	*	-
		1	2	3	4	5	6

* = P<.01
ns = not significant

Table 9.- Distribution of electrophoretically detectable gene diversity among six populations of Bristol Bay chum salmon. The absolute gene diversity averages are based on 42 loci (30 that are monomorphic).

	Absolute gene diversity		Relative gene diversity (%)		
Locus	Total (H_T)	Within populations (H_S)	Within populations	Between populations in areas	Between populations between areas
Aatl	0.286	0.277	96.8	0.2	3.0
Est-D	0.396	0.325	82.1	0.4	17.6
G3p2	0.225	0.222	98.7	0.2	1.1
Idhl	0.168	0.157	93.3	3.0	3.7
Idh3	0.639	0.612	95.8	2.1	2.1
Ldhl	0.175	0.160	91.6	0.9	7.5
TaPep	0.199	0.188	94.6	3.6	1.8
Pep-LT	0.037	0.036	97.5	0.1	2.4
6Pg	0.041	0.041	99.2	0.3	0.5
Mdh3	0.074	0.073	98.1	0.5	1.4
mMdhp2	0.320	0.309	96.8	0.5	2.7
Mpi	0.197	0.189	96.1	3.1	0.8
Average	0.066	0.062	93.9	1.4	4.7
S.E.	(0.137)	(0.128)			

Bristol Bay chum salmon. The overall population and subpopulation heterozygosities (H_T and H_S) are 0.066 and 0.062, respectively (Table 9). The normalized measure subpopulation divergence (G_{ST}) is 0.06, averaged over all loci.

Genetic similarity

The gene identity values between Bristol Bay chum salmon collections range from 0.966 to 0.997. The greatest amount of divergence (low value of I) is between the Herendeen and Togiak River populations (I = 0.966, Table 10). The identity values between Herendeen and Mother Goose; Herendeen and King Salmon; and Togiak and Nelson river populations have nearly the same similarity relationships (I = 0.969 - 0.970). Little divergence is found among the Alagnak, King Salmon, and Mother Goose collections.

The dendrogram of genetic relationships shows that Bristol Bay chum populations can be partitioned into two distinct groups (Figure 5): a northern group consisting of King Salmon, Mother Goose, Alagnak, and Togiak fish, and a southern group consisting of Herendeen Bay and Nelson Lagoon fish. Within the northern group, the Togiak fish are

Table 10.- Matrix of Nei's (1972) gene identity values between six populations of Bristol Bay chum salmon. Values were calculated using only polymorphic loci in the analysis.

1	King Salmon	-					
2	Nelson	.974	-				
3	Togiak	.990	.970	-			
4	Alagnak	.997	.978	.994	-		
5	Mother Goose	.997	.969	.992	.997	-	
6	Herendeen	.970	.986	.966	.976	.969	-
		1	2	3	4	5	6

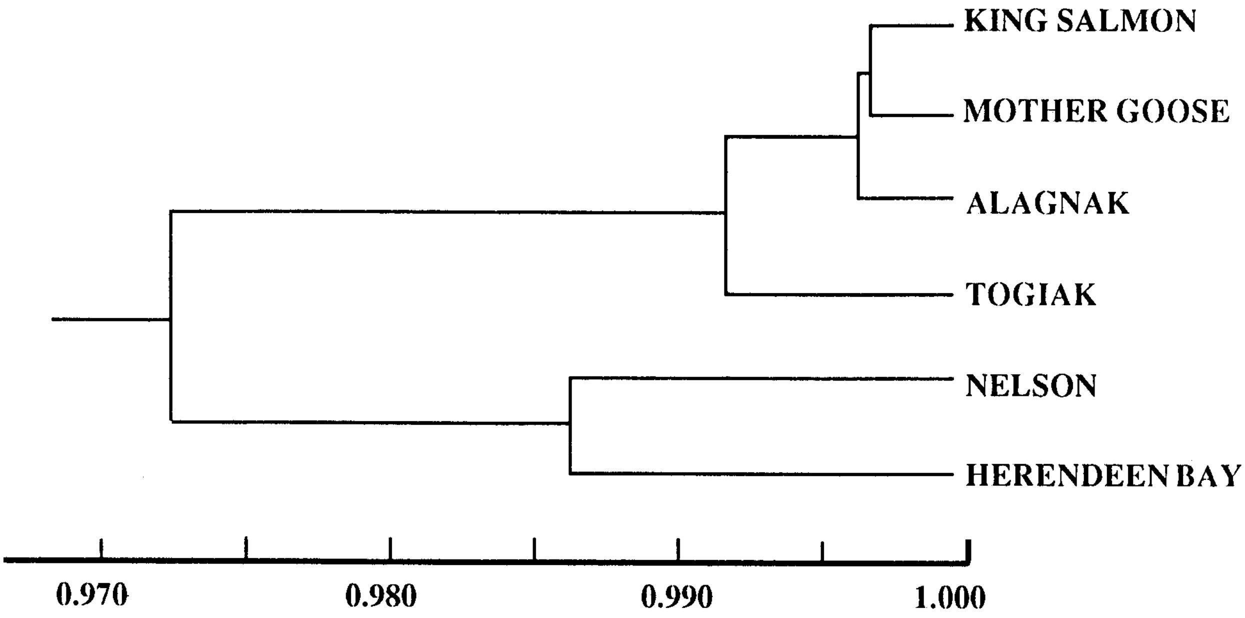

Figure 5.- Dendrogram depicting genetic relationships among six populations of Bristol Bay chum salmon. Clustering is based on unweighted averages of Nei's (1972) genetic identity values using 12 variable protein loci.

distinguishable from the other three populations. The southern group is not only different from the northern group, but also each population within the southern group is distinct.

Gene diversity

Ninety-four percent of the total gene diversity exists within populations of Bristol Bay chum salmon (Table 9). Of the remaining fraction, over 4% is due to differences between areas within Bristol Bay. Relatively little gene diversity (1.5%) is due to differences between populations of the same area of Bristol Bay.

Genetic stock identification

In the mixed fishery simulation (N = 598), each of the six chum salmon collections represented 16.7% (1/6) of the artificial mixture. Resulting stock contribution estimates for Nelson Lagoon, Togiak, Mother Goose, and Herendeen Bay collections are approximately 16% (Figure 6). Estimates for the contributions of the King Salmon and Alagnak stocks to the artificial mixture are biased (12.6 and 21.8%) towards each other.

The standard deviations of the stock contribution estimates are small for Nelson, Herendeen, and Togiak chum salmon stocks (2.3%, 2.5%, and 3.4%) while inner Bristol Bay stocks (Alagnak, King Salmon, and Mother Goose Rivers) have standard deviations that are twice as large.

For the incremental mixed-stock simulations, Herendeen, Nelson, and Togiak chum salmon stocks show consistently smaller standard deviations for each estimate when compared with the other three stocks (Figure 7). There are only three cases where the estimates are not within one standard deviation of the true values (King Salmon at 80%, and Mother Goose at 80% and 100%).

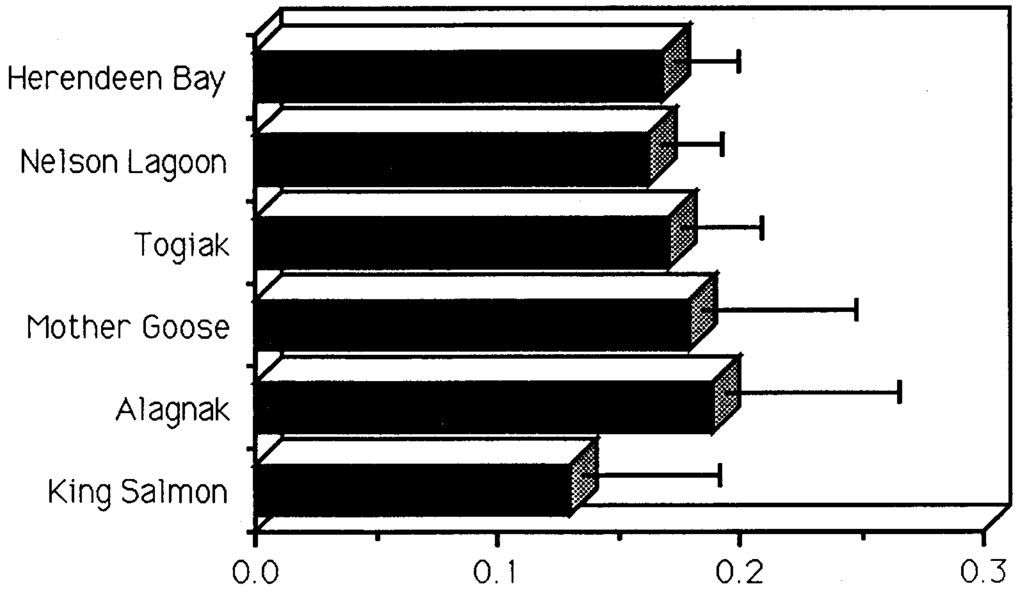

Figure 6.- Percent composition estimates for a single mixed fishery (N = 598) constructed from equal contributions of Bristol Bay chum salmon protein data. Each population comprised 16.7% of the artificial mixture. Standard deviations were calculated from 200 bootstrap resampling iterations.

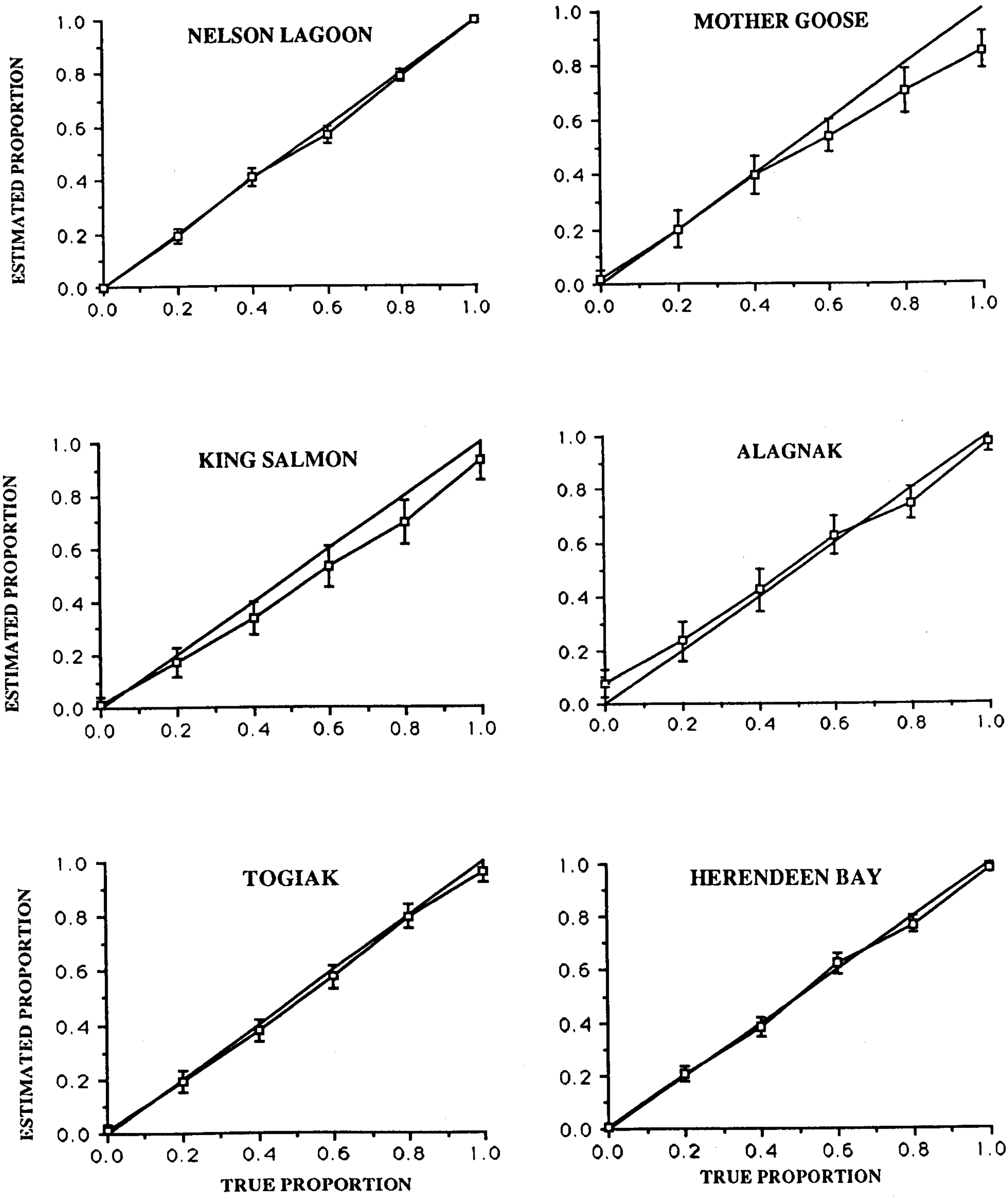

Figure 7.- Graphs of estimated stock proportions in simulated mixed stocks of Bristol Bay chum salmon. Point estimates are the mean of 100 resamplings (±1 standard deviation). Each mixture contained 500 fish.

DISCUSSION

The effectiveness of genetic stock identification analyses depends on the amount and distribution of detectable genetic variation within and between stocks of a region. Little detectable variation and/or similar patterns of variation between stocks will result in such large confidence limits on the estimates as to make them useless for management decisions. Other considerations include sampling error of both the baseline stocks and of the mixed fishery. The model assumes that all baseline stocks contributing substantially to the mixed fishery have been accurately sampled. If important stocks have not been sampled, or the sample of a stock is not truly representative, then estimates of contribution to the mixed fishery will be biased. Finally, we are assuming that the gene frequencies are stable from year to year and will not have to be validated every year.

Comparisons of our gene frequency results for sockeye salmon with studies in previous years (Grant 1980, Wilmot et al. 1985) showed that no significant differences exist between collections from different years. We therefore feel confident that our baseline data for sockeye salmon do not need to be validated yearly. No previous results for chum salmon of the Bristol Bay area are available for comparative purposes, but such comparisons will be made with samples taken in the 1988 field season.

Our work in Bristol Bay has shown that there is adequate genetic variation between stocks of chum salmon to allow accurate estimates of stock contribution in a mixed fishery. The stock contribution estimates made by the GSI program on the artificial mixed fishery (with every stock equally represented) are close to the true value (Figure 6). The results of the incremental mixed fishery (each stock added at 20% increments) are also very accurate, and with only three exceptions, the estimates are within one standard deviation of the true value (Figure 7). In general, the estimates are most accurate and the standard deviations the smallest when stock contributions are extreme (0 or 100%).

In contrast, composition estimates for sockeye salmon stocks are much less accurate. Only four variable enzymes could be reliably scored in Bristol Bay sockeye salmon. A fifth locus (Alat) is variable but could not be resolved on a consistent basis. The amount of genetic variation detected in stocks of Bristol Bay sockeye salmon is low compared to chum salmon stocks, but similar to estimates for sockeye salmon in other studies (Grant 1980, Grant et al. 1980, Wilmot et al. 1985, Utter et al. 1984, Wilmot and Burger 1985, Wishard 1980).

Estimated contributions of 11 sockeye salmon populations to an artificial mixed fishery (with every stock equally represented at 9%) show how these estimates are biased when attempting to discriminate between genetically similar stocks (Figure 3). Stock contribution estimates for Egegik, Wood, Igushik, and Kvichak fish are strongly underestimated. Only the estimated contribution for Togiak River fish was accurate. Ugashik, Naknek, Togiak, Brooks, Bear River sockeye salmon are close, and Nelson and Nushagak stocks are overestimated in the artificial mixture.

The results of the incremental mixed-fishery analysis (stocks added at 20% increments) again show the problems encountered with sockeye salmon composition estimates. Estimates for Naknek, Nushagak, Brooks, Togiak, and Wood River sockeye salmon are generally within one standard deviation of the true value. The estimated contributions for Ugashik, Nelson and Bear River fish are not within the confidence limits, but do increase linearly with their true contribution. The estimates for Igushik, Egegik, and Kvichak River salmon are poor, with large standard deviations throughout the range of their true contributions (Figure 4).

Our sample size from each system was adequate for accurate gene frequency estimates of the total population in chum salmon. Computer simulations by Wood et al. (1987) found that accuracy in stock composition estimates did not improve substantially by increasing the size of the baseline sample. The situation for sockeye salmon may be different. Part of the problem with the estimates of sockeye salmon stock contributions may be due to more complex breeding structures in certain river systems. The most accurate estimates are for the Naknek River Drainage where we had samples from many tributaries within the system. Only a single collection was taken from the other drainages and each single collection may not accurately reflect the genetic diversity of sockeye populations for these systems. We recommend that complex systems be sampled more thoroughly in the 1988 field season. This would involve determining the major spawning areas within these large drainages, and sampling from the spawning grounds.

There are two other methods that could greatly improve the contribution estimates. The first would be to intensify our efforts to resolve more enzyme loci so that we get more information from each fish sampled. Alat is a highly variable enzyme in sockeye salmon and successful resolution should improve our estimates substantially. The second method is to investigate the incidence in sockeye salmon of brain parasites. This method is currently useful in separating sockeye salmon stocks in southeast Alaska (Adam Moles, National Marine Fisheries Service, Juneau, personal communication) when used in conjunction with genetic stock identification techniques. The incidence of this parasite is treated as an additional character and incorporated into the GSI program, because it is present in some stocks but not in others.

Successful stock contribution estimates to an offshore mixture of chum salmon now requires only an adequate sample, and an assurance that we have sampled all the major contributors for our baseline. We are continuing our discussions with the fisheries managers in the Bristol Bay region to ensure our baseline is complete. For sockeye salmon, more work on the genetic baseline is necessary to resolve the problems outlined above, so that we can begin to determine stock origins with confidence.

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Appendix A.- Allele frequencies for variable loci in eleven populations of Bristol Bay sockeye salmon. Variation at duplicate loci [Mdh(1,2) and Mdh(3,4)] is attributed to a single locus of the pair for these calculations.

		Ldh4		Pgm2		Mdh1			Mdh3		
Population	N	100	117	100	135	100	147	58	100	122	60
Bear	100	.950	.050	.810	.190	.975	.025	-	1.000	-	-
Brooks	100	.945	.055	.870	.130	.980	-	.020	1.000	-	-
Egegik	100	.870	.130	.720	.280	.995	-	.005	1.000	-	-
Igushik	100	.910	.090	.740	.260	.990	.010	-	1.000	-	-
Kvichak	100	.880	.120	.710	.290	.995	.005	-	1.000	-	-
Naknek	100	.805	.195	.695	.305	.985	.005	.010	1.000	-	-
Nelson	100	.885	.115	.755	.245	1.000	-	-	1.000	-	-
Nushagak	100	.935	.065	.610	.390	.985	.015	-	1.000	-	-
Togiak	100	.855	.145	.745	.255	.985	.015	-	.960	.040	-
Ugashik	100	.905	.095	.725	.275	.990	-	.010	.990	.005	.005
Wood	100	.945	.055	.740	.260	1.000	-	-	1.000	-	-

Appendix B.- Allele frequencies for variable loci in six populations of Bristol Bay chum salmon. Variation at duplicate loci [Mdh(3,4) and Aat(1,2)] is attributed to a single locus of the pair for these calculations.

		Population[a]					
		KS	NN	TK	AK	MG	HN
Aat1	100	.845	.776	.918	.910	.888	.745
	118	.155	.208	.082	.090	.102	.220
	81	-	.016	-	-	.010	.035
	N	100	96	98	100	98	100
Est-D	100	.571	.899	.520	.625	.500	.929
	87	.429	.202	.480	.375	.500	.072
	N	98	99	98	100	100	98
G3p2	100	.935	.832	.852	.949	.910	.869
	90	.065	.168	.148	.051	.090	.131
	N	100	98	98	99	100	99
Idh1	100	.939	.925	.985	.955	.910	.785
	55	.061	.075	.015	.045	.090	.215
	N	99	100	98	100	100	100
Idh3	100	.505	.380	.495	.459	.430	.415
	88	.378	.200	.490	.465	.460	.445
	36	.056	.225	.015	.066	.075	.065
	25	.061	.195	-	.010	.035	.075
	N	98	100	98	99	100	100
Ldh1	-100	.715	.975	.954	.815	.760	.920
	-50	.285	.025	.046	.185	.240	.080
	N	100	100	98	100	100	100
Mdh3	100	.975	.930	.985	.995	.990	.945
	125	.025	.070	.005	-	.005	.030
	75	-	-	.010	.005	.005	.025
	N	100	100	98	100	100	100
mMdhp2	100	.783	.825	.699	.755	.810	.895
	127	.217	.175	.301	.245	.190	.105
	N	99	100	98	100	100	100
Mpi	100	.935	.960	.857	.939	.934	.805
	90	.065	.040	.143	.061	.066	.195
	N	100	100	98	99	99	100
Tapep	-100	.950	.930	.944	.920	.880	.765
	-185	.050	.065	.051	.070	.115	.230
	-150	-	.005	.005	.010	.005	.005
	N	100	100	98	100	100	100
Pep-LT	100	.975	1.00	.949	.970	.985	1.00
	82	.025	.000	.051	.030	.015	.000
	N	100	100	98	100	100	100
6Pgdh	100	.965	1.00	.969	.970	.970	.980
	85	.035	.000	.031	.030	.030	.020
	N	100	100	98	100	100	100

[a] KS=King Salmon; NN=Nelson; TK=Togiak; AK=Alagnak; MG=Mother Goose; HN=Herendeen.

Appendix C.- Estimated composition of artificial mixed stock made up of equal contributions of protein data from eleven populations of Bristol Bay sockeye salmon collected in 1987. Standard deviations were calculated from 200 bootstrap resampling iterations.

Population	Estimate	Standard deviation
Nelson River	0.333	0.140
Nushagak River	0.229	0.096
Brooks River	0.162	0.066
Togiak River	0.098	0.033
Naknek River	0.069	0.066
Ugashik River	0.061	0.063
Bear River	0.047	0.047
Egegik River	0.000	0.119
Kvichak River	0.000	0.157
Igushik River	0.000	0.134
Wood River	0.000	0.093

Appendix D.- Estimated composition of artificial mixed stock made up of equal contributions of protein data from six populations of Bristol Bay chum salmon collected in 1987. Standard deviations were calculated from 200 bootstrap resampling iterations.

Population	Estimate	Standard deviation
King Salmon	0.131	0.056
Alagnak	0.189	0.071
Mother Goose	0.179	0.063
Togiak	0.171	0.034
Nelson Lagoon	0.162	0.025
Herendeen Bay	0.168	0.027

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