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Status Review of Pacific Herring (*Clupea pallasii*) in Puget Sound, Washington

March 2001

**U.S. DEPARTMENT OF COMMERCE
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Status Review of Pacific Herring (*Clupea pallasii*) in Puget Sound, Washington

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EXECUTIVE SUMMARY

The Endangered Species Act (ESA) allows the listing of “distinct population segments”(DPSs) of vertebrate species or subspecies as threatened or endangered, if severe declines in abundance are indicated or substantial risks are facing the species. Thus, two key questions must be addressed in determining whether a listing under the ESA is warranted: 1) Is the entity in question a “species” as defined by the ESA? and 2) If so, is the “species” in danger of extinction (endangered) or likely to become so (threatened)? Guidance on what constitutes a “distinct population segment” is provided by the joint U.S. Fish and Wildlife Service (USFWS) and National Marine Fisheries Service (NMFS) interagency policy on vertebrate populations (USFWS-NMFS 1996). Once a DPS is identified, NMFS considers a variety of factors in determining whether a listing is warranted.

In response to a petition (Wright 1999) to list 18 species of marine fish in Puget Sound under the ESA, NMFS initiated status reviews of seven of these species: Pacific hake, *Merluccius productus* (Ayes, 1855); Pacific cod, *Gadus macrocephalus* (Tilesius, 1810); walleye pollock, *Theragra chalcogramma* (Pallas, 1814); Pacific herring, *Clupea pallasii* (Valenciennes, 1847); brown rockfish, *Sebastes auriculatus* (Girard, 1854); copper rockfish, *S. caurinus* (Richardson, 1845); and quillback rockfish, *S. maliger* (Jordan and Gilbert, 1880). The National Marine Fisheries Service formed three Biological Review Teams (BRTs): one for Pacific hake, Pacific cod, and walleye pollock; another for copper, quillback and brown rockfish; and the last for Pacific herring. These BRTs were composed of federal scientists with expertise in one or more of these species, to conduct these status reviews. This report summarizes the biological and environmental information gathered in that process and the scientific conclusions reached by the BRT for Pacific herring in Puget Sound.

Pacific Herring DPS Delineation

The BRT examined environmental, geologic, biogeographic, life-history, and genetic information in the process of identifying DPSs. Biogeography, ecological and habitat factors, and genetic population structure were found to be the most informative for this species. The four DPS options considered in this evaluation were:

- A. A separate DPS for each of the five basins of greater Puget Sound, which are: Hood Canal, Main Basin, Whidbey Basin, the Strait of Juan de Fuca/San Juan Islands, and South Sound.
- B. A DPS for two regions within the Georgia Basin, which are: Puget Sound proper (that portion of Puget Sound south of Admiralty Inlet and east of Deception Pass), and in north Puget Sound including the Strait of Juan de Fuca/San Juan Islands north to the mouth of the Fraser River and west to Cape Flattery.
- C. A DPS that encompasses Georgia Basin, extending from the southern end of Puget Sound proper to the northern end of the Strait of Georgia near Discovery Passage and westward to Cape Flattery.
- D. A single DPS that includes the populations in the area from Baja California to Southeast Alaska, with the northern boundary being the border of the zoogeographic zone near Dixon Entrance, or a line between Helm Bay and Lynn Canal, Alaska.

A majority of the BRT favored the Georgia Basin, which is option C, as the most likely DPS, with options B and D receiving considerably less support. No member of the BRT supported DPS option A. Members of the BRT utilized a variety of evidence to support their identification of a Georgia Basin DPS for Pacific herring. These included tagging studies in the Canadian portion of the Georgia Basin, vertebral counts, information on larval distribution and transport, as well as hydrographic studies conducted by the Department of Fisheries and Oceans Canada (DFO). Genetic studies by Grant and Utter (1984) were also utilized in concert with work by McQuinn (1997) on Atlantic herring that describes the hypothesized metapopulation stock structure in herring. Based on this examination, the BRT identified a DPS for the Georgia Basin, which includes Puget Sound, and it focused the risk analysis on this DPS.

Pacific Herring BRT Risk Conclusions

The ESA (Section 3) defines the term “endangered species” as “any species which is in danger of extinction throughout all or a significant portion of its range.” The term “threatened species” is defined as “any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.” According to the ESA, the determination of whether a species is threatened or endangered should be made on the basis of the best scientific information available regarding its current status, after taking into consideration conservation measures that are proposed or are in place. In this review, the BRT did not evaluate likely or possible effects of conservation measures, and therefore did not make recommendations as to whether identified DPSs should be listed as threatened or endangered species. Rather, the BRT drew scientific conclusions about the risk of extinction faced by identified DPSs under the assumption that present conditions will continue.

The BRT utilized Wainwright and Kope (1999), West (1997) and Musick et al. (2000) to assist in organizing the information presented regarding risk to the herring populations that comprise this DPS. The BRT concluded, by a large majority, that the Georgia Basin DPS of Pacific herring is neither at risk of extinction, nor likely to become so. The BRT also concluded that, at this time, the Georgia Basin DPS of Pacific herring does not meet the International Union for the Conservation of Nature (IUCN) criteria to be considered “vulnerable” (Musick et al. 2000). However, most members expressed concern that they could not entirely rule out the possibility that this Georgia Basin DPS at present is likely to become in danger of extinction, especially because some stocks within the Georgia Basin, such as Cherry Point and Discovery Bay, have declined to such an extent that they may meet the IUCN criteria to be considered “vulnerable” which is “(of special concern), not necessarily endangered or threatened severely, but at possible risk of falling into one of these categories in the near future” (Musick et al. 2000). Although, the BRT recognized that herring populations in north Puget Sound and Puget Sound proper may be vulnerable to extinction, these populations represent a relatively small portion of the overall DPS of herring in the Georgia Basin. Moreover, because of the moderate to high productivity of herring populations and the tendency of herring to stray among spawning sites, the BRT felt that there are reasonable possibilities at present for recolonization of depleted populations associated with specific spawning sites.

However, the BRT emphasized that while the DPS is defined at a larger scale than the stocks that are managed in Puget Sound by Washington Department of Fisheries and Wildlife (WDFW), and that the Georgia Basin DPS does not appear at risk of extinction at present, local populations are the appropriate scale for fisheries management activities, and, as McQuinn (1997) emphasizes, their “conservation is essential for the preservation of spawning potential and for the viability of coastal fisheries.”

Consideration of the Puget Sound Ecosystem

It is important to note that the BRT's considerations of the status and trends of Pacific herring in the Puget Sound area did not, and should not, occur in a vacuum. In addition to Pacific herring, several other fish species from this area have either been listed under the ESA, or have been petitioned for listing. These include at least 20 evolutionarily significant units (ESUs) of anadromous salmonids in the Pacific Northwest, copper, quillback and brown rockfish, Pacific cod, Pacific hake, and walleye pollock which are all in or close to the Puget Sound area. A significance emerges from consideration of these species collectively that is not apparent when any one is considered alone. Joint consideration of these species together suggests ecosystem-level implications that are difficult or impossible to evaluate under terms of the ESA. It is possible, hypothetically, that the reduced or declining trends of each of the individual species in this group could be considered as insufficient for affording that species legal protection under the ESA. But, taking no action under such circumstances might be a major mistake if this collective information is an indication that the Puget Sound area, as an ecosystem, is experiencing major change. Such changes could be of more far-ranging concern than could ever be recognized if any one species were considered individually. Environmental variation, and general ecosystem dynamics, could easily lead to at least some of the declines in abundance observed for any one of these species. However, we find the commonalities and synchronous nature of the information to be compelling. Scientifically, this raises the need to determine the degree to which these common changes are anthropogenic, both for individual species and within the Puget Sound ecosystem as a whole.

The complexity of factors responsible for population fluctuations emphasizes the need for better understanding of the unique features of Puget Sound compared to surrounding and similar environments, many of which are interconnected with the Sound via factors including the climate, currents, migrations, and dispersal of various species. It is important to understand the natural variation within such systems over various time scales from decades to thousands of years. The potential for stratigraphic sediment analysis is noted in this regard. So are studies of the dynamics of species compared across the observed diversity of life-history strategies. Measures of the ebb and flow, or the extinction, recolonization, and persistence of the populations of the various species in the Puget Sound ecosystem, are important for the following reasons: as a basis for judging how problematic the picture before us is, to what degree the changes are of anthropogenic origins, and how significant these changes are as a basis for taking management action. In the absence of such information, the BRT was restricted to a largely species-by-species consideration of the data. This leaves some members with the concern that, while action under the strict guidelines established under ESA may not be warranted, there is

evidence pointing to the potential for anthropogenic factors to be disrupting the Puget Sound Ecosystem. If we fail to close the gaps in our understanding necessary to determine what, if any, steps can be taken to address the adverse human effects on the ecosystem, permanent loss of marine and nearshore biodiversity may be the result in Puget Sound.

ACKNOWLEDGMENTS

The status review for Puget Sound Pacific herring was conducted by a team of scientists from the National Marine Fisheries Service (NMFS), Northwest Fisheries Science Center (NWFSC), and Alaska Fisheries Science Center (AKFSC). This biological review team (BRT; technical terms and abbreviations such as "BRT" are defined in the Glossary) relied on comments and informational reports submitted by the public and by state, tribal, and federal agencies. The Pacific herring extinction-risk assessments are the contribution of Dr. William H. Lenarz. The authors acknowledge the efforts of all who contributed to this record, especially the Washington Department of Fish and Wildlife (WDFW) and Department of Fisheries and Oceans Canada (DFO).

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The BRT for Puget Sound Pacific herring consisted of the following members: Tonya L. Builder, Dr. Bruce B. McCain, Dr. Richard Gustafson, Dr. Richard D. Methot, Dr. Peter W. Lawson, Heather A. Stout, Donald M. Van Doornik, and Dr. Robin S. Waples from the Northwest Fisheries Science Center; Dr. Charles Fowler and Mark Carls from the Alaska Fisheries Science Center; Dr. Alan Mearns from the National Ocean Survey; and, Curtis D. Tanner from U.S. Fish and Wildlife Service.

INTRODUCTION

The National Marine Fisheries Service received a petition on February 8, 1999, to list 18 species of marine fishes in Puget Sound under the U.S. Endangered Species Act (ESA 1973) (Wright 1999). The ESA allows the listing of "distinct population segments" of vertebrate species or subspecies as threatened or endangered, if severe declines in abundance indicate substantial risks are facing the species. NMFS evaluated the petition for each species to determine whether the petitioner provided "substantial information" as required by the ESA to list a species. The agency also reviewed other readily available information and consulted with state and tribal biologists to determine whether general agreement existed on the uniqueness, distribution, abundance and threats to the petitioned species/populations. Additionally, NMFS evaluated whether available information might support the identification of distinct population segments that might warrant listing under the ESA. NMFS (1999) concluded that the petitioner provided substantial information, or cited such information in other sources, to initiate a status review for Pacific hake, *Merluccius productus* (Ayres, 1855); Pacific cod, *Gadus macrocephalus* (Tilesius, 1810); walleye pollock, *Theragra chalcogramma* (Pallas, 1814); and Pacific herring, *Clupea pallasii* (Valenciennes, 1847). NMFS (1999) further concluded that the information provided in the petition on Puget Sound rockfish species was insubstantial for most of the species petitioned, but that compelling reasons existed to believe some Puget Sound rockfishes may warrant ESA protection. Information appeared to be sufficient to conduct a status review that could provide the basis for an ESA determination for three species: brown rockfish, *Sebastes auriculatus* (Girard, 1854); copper rockfish, *S. caurinus* (Richardson, 1845); and quillback rockfish, *S. maliger* (Jordan and Gilbert, 1880). NMFS (1999) decided, therefore, to also initiate status reviews for these three species of Puget Sound rockfish.

Scope and Intent of Present Document

This document reports the results of a comprehensive ESA status review of Pacific herring in Puget Sound. Biological, ecological and genetic information for populations throughout the species' distribution were also considered to provide a context for evaluating information for populations of these species in Puget Sound.

In order to meet the provision in the ESA that listing determinations be made with the best available scientific and commercial information, NMFS formed a team of scientists with diverse backgrounds in marine fish biology and marine habitats to conduct this review. This Biological Review Team (BRT)¹ reviewed and evaluated scientific information compiled by NMFS staff from published literature and unpublished data. Information presented at public meetings in 1999 in Seattle, Washington was also considered. The BRT also reviewed additional information submitted to the ESA Administrative Record.

¹ A list of the Biological Review Team members for Pacific herring is included in the Acknowledgments Section of this document.

Key Questions in ESA Evaluations

Two key questions must be addressed in determining whether a listing under the ESA is warranted: 1) Is the entity in question a “species” as defined by the ESA? and 2) If so, is the “species” in danger of extinction (endangered) or likely to become so (threatened)? These questions are addressed for Pacific herring in the following separate sections. If it is determined that a listing(s) is warranted, then NMFS is required by law (1973 ESA Sec. 4(a)(1)) to identify one or more of the following factors responsible for the species’ threatened or endangered status: 1) destruction or modification of habitat, 2) over-utilization by humans, 3) disease or predation, 4) inadequacy of existing regulatory mechanisms, or 5) other natural or human factors. This status review does not formally address factors for decline, except as they provide information about the degree of risk faced by the species in the future, if present conditions prevail.

The “Species” Question

The ESA, as originally enacted, defined “species” to include “any subspecies of fish or wildlife or plants and any other group of fish or wildlife of the same species or smaller taxa in common spatial arrangement that interbreed when mature.” As amended in 1978, the ESA defined “species” as “any subspecies of fish or wildlife or plants, and any distinct population segment of any species of vertebrate fish or wildlife which interbreeds when mature.” Thus, the ability to list distinct population segments (DPSs) is restricted to vertebrate animals, and specifically excludes plants and invertebrates. Furthermore, Congress has stated that the authority to list DPSs should be used “sparingly and only when the biological evidence indicates that such action is warranted” (Senate Report 151, 96th Congress, 1st Session, 1979). Listing of vertebrate DPSs has occurred relatively rarely, for example, USFWS-NMFS (1996) stated that “of over 300 native vertebrate species listed under the Act, only about 30 are given separate status as DPSs.” Wilcove et al. (1993) examined listings under the ESA between 1985 and 1991 and found that only 8.5% of the 94 vertebrate “species” listed or proposed for listing were classified as DPSs.

Guidance on what constitutes a “distinct population segment” is provided by the joint U.S. Fish and Wildlife Service (USFWS) and NMFS interagency policy on vertebrate populations (USFWS-NMFS 1996). To be considered “distinct,” a population, or group of populations, must be “discrete” from other populations and “significant” to the species as a whole. A population segment of a vertebrate species may be considered discrete if it is markedly separated from other populations of the same taxon as a consequence of physical, physiological, ecological, or behavioral factors. The policy states that quantitative measures of genetic or morphological discontinuity may provide evidence of this separation. If a population segment is considered discrete, considerations that can be used to determine its significance to the taxon as a whole include: 1) persistence of the discrete population segment in an ecological setting unusual or unique for the taxon, 2) evidence that loss of the discrete population segment would result in a significant gap in the range of the taxon, 3) evidence that the discrete population segment represents the only surviving natural occurrence of a taxon that may be more abundant elsewhere as an introduced population outside its historic range, and 4) evidence that the discrete

population segment differs markedly from other populations of the species in its genetic characteristics.

This joint policy applies to all vertebrate species, but does not elaborate on the information that can be used to assess distinctiveness in species of marine fishes. The types of evidence that can be considered to evaluate distinctiveness of populations in Pacific salmon species have been extensively reviewed (Waples 1991a, b, 1995), and similar kinds of evidence can be used to assess distinctiveness of populations or groups of populations of marine fishes. NMFS Pacific salmon framework advocates a holistic approach in which all available information is considered, as well as a consideration of the strengths and limitations of such information in delineating distinct population segments. Important information includes natural rates of migration and recolonization, evaluations of the efficacy of natural barriers to migration, phenotypic and life-history traits that reflect local adaptation, and measurements of genetic differences between populations. NMFS's Pacific salmon policy states that (Waples 1995):

A vertebrate population will be considered distinct (and hence a "species") for purposes of conservation under the Act if the population represents an evolutionarily significant unit (ESU) of the biological species. An ESU is a population (or group of populations) that (1) is substantially reproductively isolated from other conspecific population units, and (2) represents an important component in the evolutionary legacy of the species.

To date, NMFS has used the Pacific salmon policy to identify over 50 ESUs among seven biological species of anadromous Pacific salmonids (Busby et al. 1993, 1994, 1996; Gustafson et al. 1997; Hard et al. 1996; Johnson et al. 1994, 1997, 1999; Matthews and Waples 1991; Myers et al. 1998; Waknitz et al. 1995; Waples et al. 1991a, b; Weitkamp et al. 1995). Approximately half of these ESUs have been listed as threatened or endangered species. Although the joint DPS policy does not specifically identify evolutionary significance as a criterion for distinctness, "the first criterion (discreteness) is similar to the reproductive isolation criterion in the NMFS [Pacific] salmon policy, and the second (significance to the biological species) is roughly analogous to the contribution to ecological-genetic diversity criterion of the NMFS [Pacific] salmon policy" (Waples 1995).

The National Research Council (NRC), in a report entitled Science and the Endangered Species Act (NRC 1995), developed the concept of an evolutionary unit (EU) to assist in identifying DPSs. This report defined an EU as "a group of organisms that represents a segment of biological diversity that shares evolutionary lineage and contains the potential for a unique evolutionary future" (NRC 1995). The NRC (1995) stated that evidence of uniqueness of an EU can be found through analysis of morphology, behavior, physiology, and biochemistry, and that, in most cases, an EU will occupy a particular geographical area. The NRC (1995) suggested that a DPS can be thought of as "an evolutionarily distinct population segment that is geographically or otherwise isolated from other population segments." The DPS, in some cases, may be a group of populations (metapopulation, i.e., "a larger population made up of smaller, local breeding populations that have some genetic and ecological interactions among them") (NRC 1995). The

considerations identified by the NRC (1995) are very similar to those identified and used by the NMFS's ESU policy.

The "Extinction Risk" Question

The ESA (Section 3) defines the term "endangered species" as "any species which is in danger of extinction throughout all or a significant portion of its range." The term "threatened species" is defined as "any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range." NMFS considers a variety of information in evaluating the level of risk faced by a DPS. Important considerations include: 1) absolute numbers of fish and their spatial and temporal distribution, 2) current abundance in relation to historical abundance and carrying capacity of the habitat, 3) trends in abundance based on catch-per-unit effort (CPUE) or on estimates of spawner-recruit ratios, 4) possible threats to genetic integrity, and 5) recent events (e.g., climate variability or change in management) that have predictable short-term consequences for the abundance of the DPS. Additional risk factors, such as disease prevalence or changes in life-history traits, may also be considered in evaluating risk to populations.

The determination of whether a species is threatened or endangered should be made according to the ESA on the basis of the best scientific information available on its current status, after taking into consideration conservation measures that are proposed or are in place. We did not evaluate likely or possible effects of conservation measures in this review. Therefore, we did not recommend whether identified DPSs should be listed as threatened or endangered species, because that determination requires evaluation of additional factors not considered by the BRT. Instead, the BRT drew scientific conclusions about the risk of extinction faced by identified DPSs under the assumption that present conditions would continue and with the recognition that natural demographic and environmental variability is an inherent feature of present conditions. Conservation measures will be considered by NMFS Northwest Regional Office in making ESA listing recommendations.

Summary of Information Presented by the Petitioner

NMFS received on February 8, 1999, a petition from Sam Wright, a biologist retired from the Washington State Department of Fish and Wildlife, to list as threatened or endangered 18 species/populations of marine fishes in Puget Sound, Washington, and to designate critical habitat (Wright 1999). NMFS evaluated the petition to determine whether it presented substantial scientific or commercial information indicating that the petitioned action may be warranted. Section 424.14(b)(1) of NMFS ESA implementation regulations defines "substantial information" as the amount of information that would lead a reasonable person to believe that the measure proposed in the petition may be warranted. Section 424.14(b)(2) of these regulations lists factors to be considered in evaluating the petition, including whether the petition contains detailed narrative justification for the recommended measure, a description of past and present numbers of geographical distributions of the species, and of threats facing the species.

Stock Structure

The petitioner defined a stock as a “population of fish which is reproductively isolated, or partially isolated, from other such populations of the same species” (Wright 1999). Most of the petitioner’s arguments dealt with evidence for reproductive isolation between populations within Puget Sound, and between populations in Puget Sound and those along the outer coast of North America. Three kinds of information were presented to indicate that significant differences among populations may exist.

First, the petitioner argued that genetic differences between northern and southern regions of Puget Sound may be present, because reduced gene flow in some species may result from the physical isolation of north- and south-sound basins by a shallow sill in Admiralty Inlet and by the narrow passage through Deception Pass. The northern portion of Puget Sound is “exposed to storms, receives more oceanic water, and contains abundant, often contiguous, rocky reef habitat” (Wright 1999). The southern portion of Puget Sound is protected from the action of storms, is more influenced by freshwater, and contains fewer rocky reefs than the northern portion. Complex current patterns in both segments of the sound may also limit dispersal between localities by the entrainment of planktonic larvae in local gyres.

Second, the petitioner presented information on genetic population subdivision for some species. Allele-frequency differences between populations provide evidence for reproductive isolation between some populations.

Third, the petitioner noted the presence of life-history differences between populations or the occurrence of discrete spawning areas for some species. Life-history differences between areas may reflect genetic differences between populations or may be the result of environmental influences on development and growth in the absence of genetic differentiation. The occurrence of discrete spawning areas is a necessary, but not sufficient criterion, for the development of reproductive isolation between populations.

Risk of Extinction

Most of the petitioner’s assessment of abundances was based on fishery statistics and stock assessments by Washington State fishery management agencies. The petitioner reports that, as of the date of the petition, four herring stocks in Puget Sound and the Juan de Fuca Strait are rated as “depressed” (recent abundance well below the long-term mean, but not so low that permanent damage to the population is likely), or “critical” (abundance low enough that permanent damage to population is likely or has already occurred) by WDFW. In addition to these depressed populations, the petitioner points out that the natural mortality of herring has increased from 30% to 40% (as reported by WDFW prior to 1982) to 60% to 70% at the time of the petition.

He also reports that the number of age-classes in the bulk of herring stocks has decreased from five age-classes to two or three. The older age-classes have been predominantly lost.

According to the WDFW documents cited by the petitioner, fish are smaller, younger and carry fewer eggs per fish, thus reducing the fecundity rate. The petitioner also points out that herring survey biologists have reported increased sightings of harbor seals associated with the pre-spawning aggregations and that harbor seal predation may be an important contributor to the increase in natural mortality.

The petitioner then cites specific details of the at-risk stocks. These stocks are the Cherry Point, a particularly late spawning stock, and the Discovery Bay stock that was formerly one of the largest stocks in Washington, but had a run size of zero in 1998. The other two stocks are the Port Susan and the Port Orchard/Port Madison stocks. At the time of the petition, they were also exhibiting downward trends similar to the Cherry Point and Discovery Bay stocks.

The petitioner concludes by describing Pacific herring as a dominant species at the wasp-waist of the Puget Sound ecosystem, which is an ecosystem with relatively few species at the mid-level (Rice 1995). The petitioner suggests that with the decline of this crucial species, other forage fish populations do not appear to be replacing the reduction in biomass available to predators. This has serious implications to other trophic levels in Puget Sound and environs.

BACKGROUND

This section describes physical, oceanographic, and climatic features in the Georgia Basin, more particularly, Puget Sound and the Strait of Georgia, that may contribute to isolation of populations of Pacific herring considered in this review. The Georgia Basin is an international waterbody that encompasses the marine waters of Puget Sound, the Strait of Georgia, and the Strait of Juan de Fuca (Fig. 1). The coastal drainage of the Georgia Basin is bounded to the west and south by the Olympic and Vancouver Island mountains and to the north and east by the Cascade and Coast mountains. This section further provides a basis for identifying climatic and biological factors that may contribute to extinction risk for this species.

In addition, the general biology of the species is presented. These discussions are included here in order to provide the reader with the background used by the BRT in approaching the issues of distinct population segments and of risk to any DPSs defined. Specific information regarding DPS delineations and risk evaluation are found in their separate sections in this document and present more specific information regarding the species in and around Puget Sound.

Environmental History and Features of Puget Sound

Introduction

The following summary primarily considers the marine waters of Puget Sound that lie south of the boundary between Canada and the United States. However, because the Pacific herring populations are also found in the Strait of Georgia, a brief description of this system will also be presented. Puget Sound is a fjord-like estuary located in northwest Washington State and covers an area of about 2,330 km², including 3,700 km of coastline. It is subdivided into five basins or regions: 1) North Puget Sound, 2) Main Basin, 3) Whidbey Basin, 4) South Puget Sound, and 5) Hood Canal (Fig. 1). The latter four basins compose the Puget Sound proper. The average depth of Puget Sound is 62.5 m at mean low tide, the average surface water temperature is 12.8°C in summer and 7.2°C in winter (Staubitz et al. 1997). Estuarine circulation in Puget Sound is driven by tides, gravitational forces and freshwater inflows. For example, the average daily difference between high and low tide varies from 2.4 m at the northern end of Puget Sound to 4.6 m at its southern end. Mixing of oceanic and estuarine waters at the sill in Admiralty Inlet substantially reduces the flushing rate of nutrients and contaminants. Concentrations of nutrients (i.e., nitrates and phosphates) are consistently high throughout most of the Sound, largely due to the flux of oceanic water into the Main basin (Harrison et al. 1994). The freshwater inflow into Puget Sound is about 900 million gallons/day (gpd) (3.4 trillion liters /day). The major sources of freshwater are the Skagit and Snohomish Rivers located in Whidbey Basin (Table 1). However, the annual amount of freshwater entering Puget Sound is only 10% to 20% of the amount entering the Strait of Georgia, primarily through the Fraser River. The Fraser River has a drainage area of 234,000 km² (Bocking 1997). The rate of flow in the Fraser River ranges from an average of 750 m³/sec in the winter to an average of 11,500 m³/sec during the spring

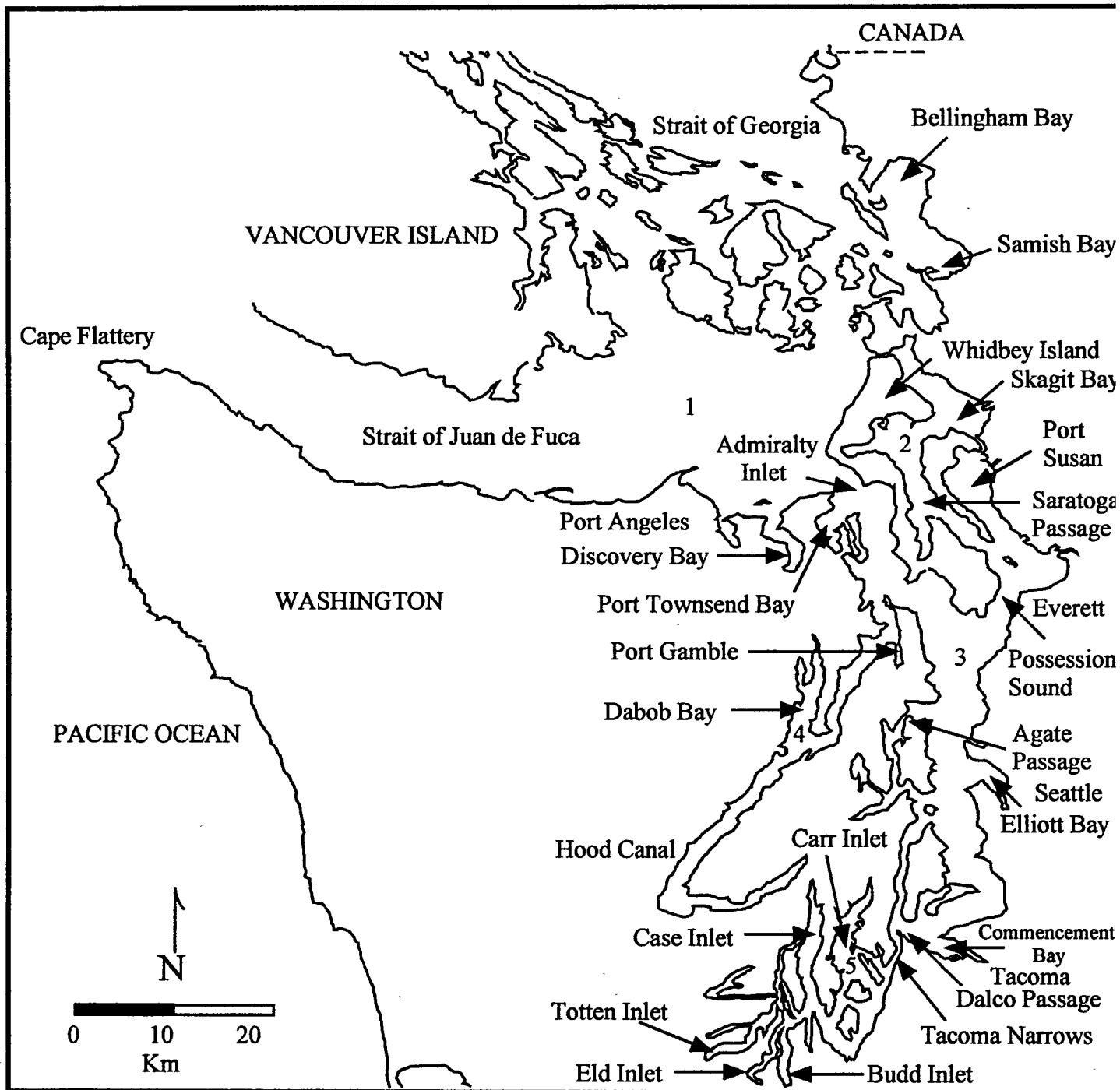


Figure 1. Regional water masses and subareas of Puget Sound: 1) Northern Puget Sound; 2) Whidbey Basin; 3) Main Basin; 4) Hood Canal, and 5) Southern Puget Sound; and geographical locations and important water bodies in Puget Sound mentioned in the text.

Table 1. Mean annual streamflow of major Puget Sound streams (Staubitz et al. 1997). Data converted from U.S. Customary to metric units.

Gaging Station Name	Drainage area (km ²)	Mean annual flow (m ³ /sec)	Mean annual runoff (cm)	Period of record (years)
Nooksack River at Ferndale	2,036	87.3	168	27
Samish River near Burlington	228	6.9	96	28
Skagit River near Mt. Vernon	8,011	469.9	185	53
N. F. Stillaguamish River at Arlington	679	53.5	249	65
Snohomish River near Monroe	3,981	270.1	214	30
Cedar River at Renton	477	18.9	125	48
Green River at Tukwila	1,140	42.2	117	27
Puyallup River at Puyallup	2,455	94.3	121	79
Nisqually River at McKenna	1,339	36.5	86	39
Deschutes River at Tumwater	420	9.3	70	6
Skokomish River near Potlatch	588	33.4	76	52
Dosewallips River near Brinnon	244	10.7	305	20
Dungeness River near Sequim	404	10.7	83	67
Elwha River near Port Angeles	697	42.5	192	83

freshet, although, flows of 20,000 m³/sec are not uncommon during the spring floods (Bocking 1997).

Eight major habitats occur in Puget Sound (Levings and Thom 1994). Kelp beds and eelgrass meadows cover the largest area (Figs. 2 and 3), at almost 1,000 km². Other major habitats include subaerial and intertidal wetlands (176 km²), and mudflats and sandflats (246 km²). The extent of some of these habitats have markedly declined over the last century. Hutchinson (1988) indicated that overall losses since European settlement, by area, of intertidal habitat were 58% for Puget Sound in general and 18% for the Strait of Georgia. Four river deltas (the Duwamish, Lummi, Puyallup, and Samish) have lost greater than 92% of their intertidal marshes (Simenstad et al. 1982, Schmitt et al. 1994). At least 76% of the wetlands around Puget Sound have been eliminated, especially in urbanized estuaries. Substantial declines of mudflats and sandflats have also occurred in the deltas of these estuaries (Levings and Thom 1994). The human population in the Puget Sound region is estimated to be about 3.6 million.

Geological and Climatic History

The Puget Sound Basin falls within the Puget Lowland, a portion of a low-lying area extending from the lower Fraser River Valley southward to the Willamette Lowland (Burns 1985). In the distant past, the Puget Lowland was drained by numerous small rivers that flowed northward from the Cascade and Olympic mountains and emptied into an earlier configuration of the Strait of Juan de Fuca. During the Pleistocene, massive Piedmont glaciers, as much as 1,100 m thick, moved southward from the Coast Mountains of British Columbia and carved out the Strait of Juan de Fuca and Puget Sound. The deepest basins were created in northern Puget Sound in and around the San Juan Islands. About 15,000 years ago, the southern tongue of the last glacier receded rapidly leaving the lowland covered with glacial deposits and glacial lakes, and revealing the Puget Sound Basin (Burns 1985). The large glacially-formed troughs of Puget Sound were initially occupied by large proglacial lakes that drained southward (Thorson 1980). Almost two dozen deltas were developed in these lakes as the result of streams flowing from the melting ice margins.

Considerable evidence indicates that climate in the Puget Sound region is cyclical, with maxima (warm, dry periods) and minima (cold, wet periods) occurring at decadal intervals. For example, according to the Pacific Northwest Index (PNI), since 1893 there have been about five minima and four maxima (Ebbesmeyer and Strickland 1995). Three minima occurred between 1893 and 1920, one between the mid-1940s and 1960, and one between the mid-1960s and mid-1970s. Two maxima occurred between the early-1920s and the early-1940s, and two more occurred between the late-1970s and 1997.

Mantua et al. (1997) and Hare and Mantua (2000) evaluated relationships between interdecadal climate variability and fluctuations in the abundance and distribution of marine biota. These authors used statistical methods to identify the Pacific Decadal Oscillation (PDO). The PDO shows predominantly positive epochs between 1925 and 1946 and following 1977, and

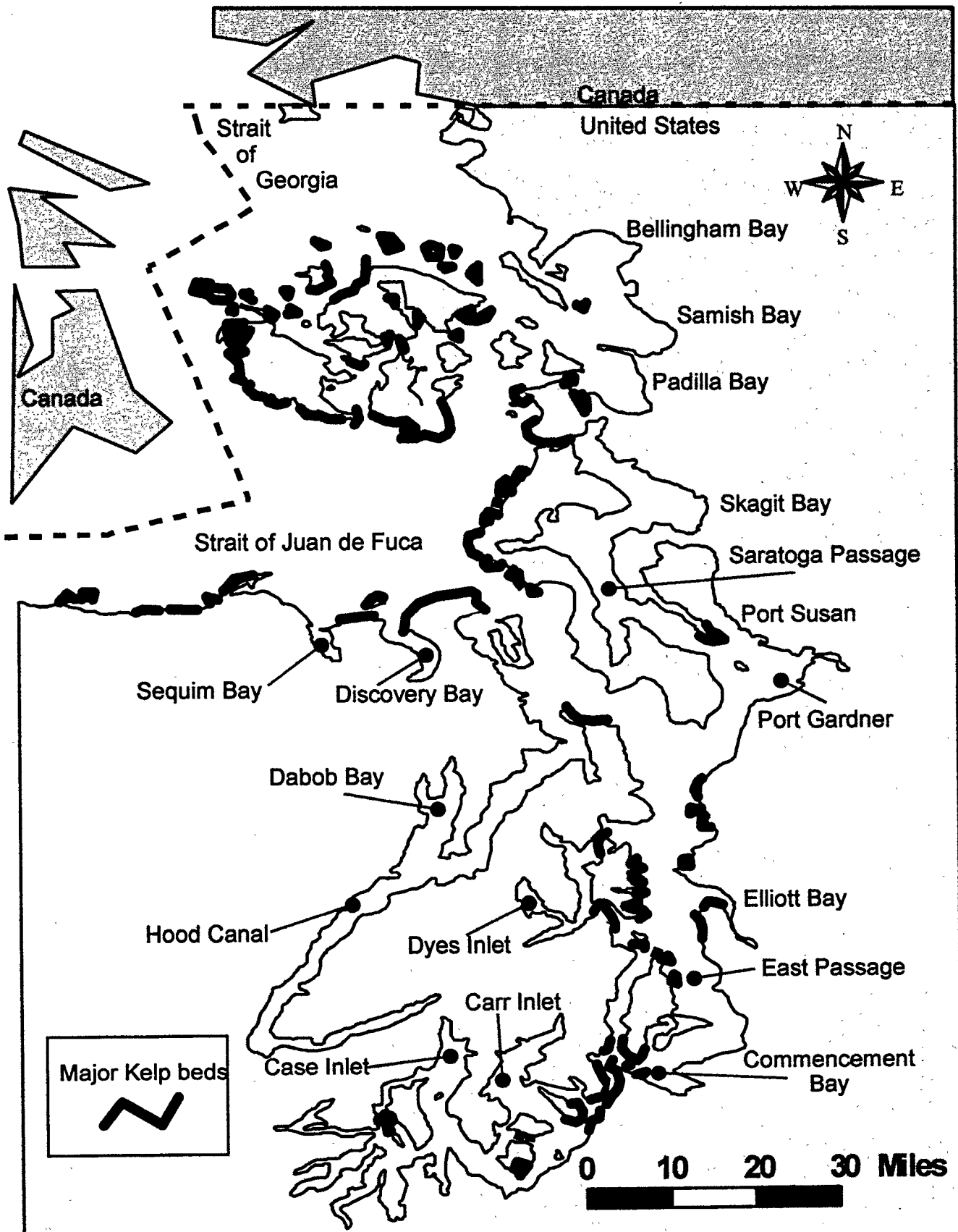


Figure 2. Locations of major kelp beds in Puget Sound (PSWQA 1987).

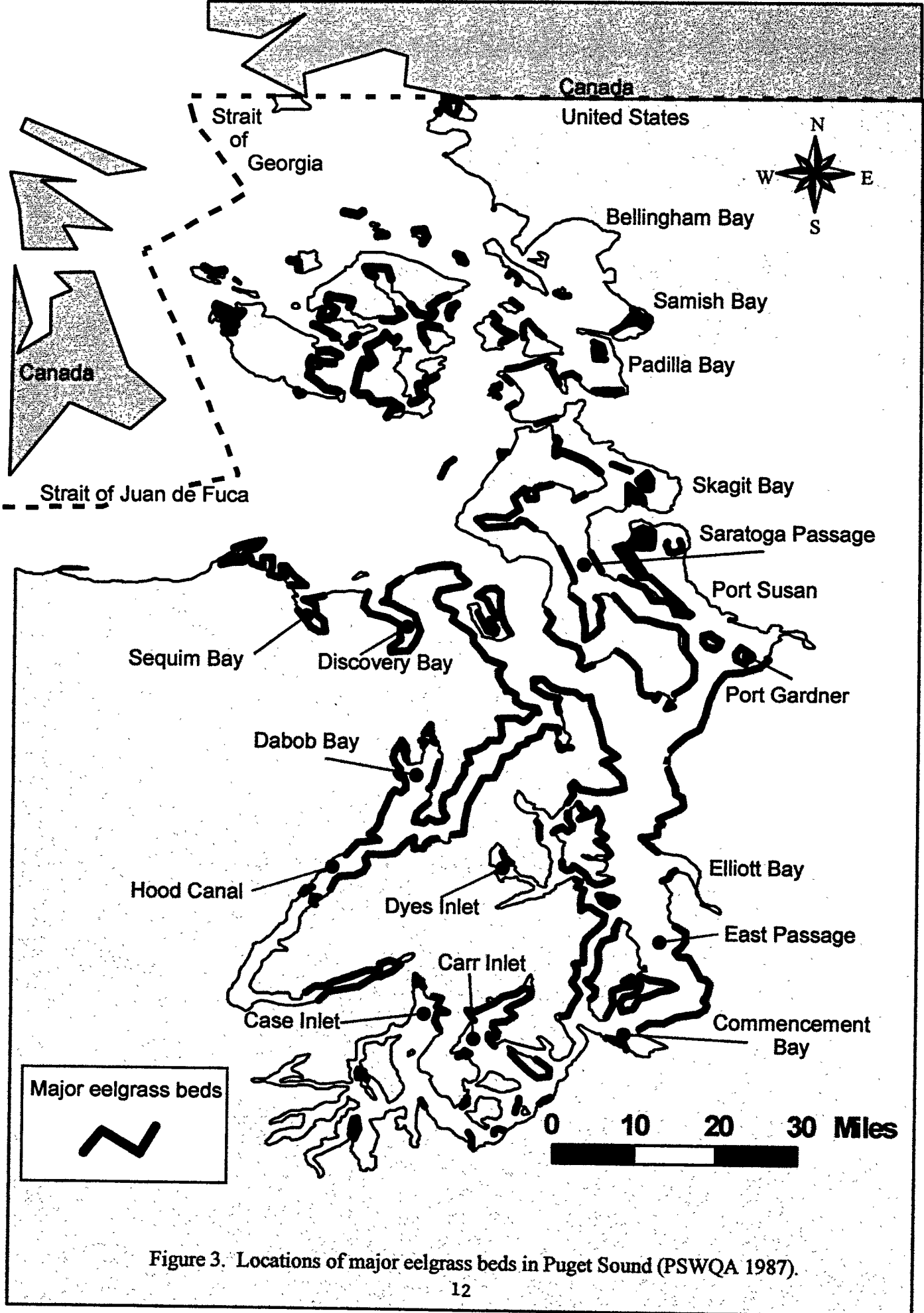


Figure 3. Locations of major eelgrass beds in Puget Sound (PSWQA 1987).

a negative epoch between 1947 and 1976. For Washington State, positive epochs are characterized by increased flow of relatively warm-humid air and less than normal precipitation, and the negative epochs correspond to a cool-wet climate. Mantua et al. (1997) reported connections between the PDO and indicators of populations of Alaskan sockeye and pink salmon and Washington-Oregon-California coho and chinook salmon, although the coho and chinook populations were highest during the negative epochs. Hare and Mantua (2000) found evidence for major ecological and climate changes for the decade following 1977 (a positive epoch). They also found less powerful evidence of a climate regime shift (a negative epoch) following 1989, demonstrated primarily by ecological changes. Examples of ecological parameters that were correlated with these decadal changes included annual catches of Alaskan coho and sockeye salmon, annual catches of Washington and Oregon coho and chinook salmon, biomass of zooplankton in the California Current, and the Oyster Condition Index (OAI) for oysters in Willapa Bay, Washington (Hare and Mantua 2000). This decadal and interannual scale climate variability is graphically represented in Pinnix's (1999) principal components analyses of climatic variables affecting Puget Sound as shown in Figure 4.

Few climatological records are available prior to the 1890s. Proxy measures of climatic variation have been used to reconstruct temperature fluctuations in the Pacific Northwest. Graumlich and Brubaker (1986) reported correlations between annual growth records for larch and hemlock trees located near Mt. Rainier and temperature and snow depth. A regression model was used to reconstruct temperatures from 1590 to 1913. Their major findings were that temperatures prior to 1900 were approximately 1°C lower than those of the 1900s, and that only the temperature pattern in the late-1600s resembled that of the 1900s.

Oceanographic and Geomorphological Features of Basins

Northern Puget Sound

Bathymetry and geomorphology—The North Puget Sound region is demarcated to the north by the U.S.-Canadian border, to the west by a line due north of the Sekiu River, to the south by the Olympic Peninsula, and to the east by a line between Point Wilson (near Port Townsend) and Partridge Point on Whidbey Island and the mainland between Anacortes and Blaine, Washington (Fig. 1). The predominant feature of the North Sound is the Strait of Juan de Fuca, which is 160 km long, and 22 km wide at its western end to over 40 km at its eastern end (Thomson 1994).

One of the deepest sections of this region is near the western mouth (about 200 m) (Holbrook et al. 1980), whereas the deepest sections of eastern portions are located northwest of the San Juan Islands (340-380 m) (Puget Sound Water Quality Action [PSWQA] 1987).

Subtidal depths range from 20 m to 60 m in most of the northwest part of the region. Deeper areas near the entrance to the Main Basin north of Admiralty Inlet range from 120 m to 180 m in depth (PSWQA 1987). Most of the rocky-reef habitat in Puget Sound is located in this region.

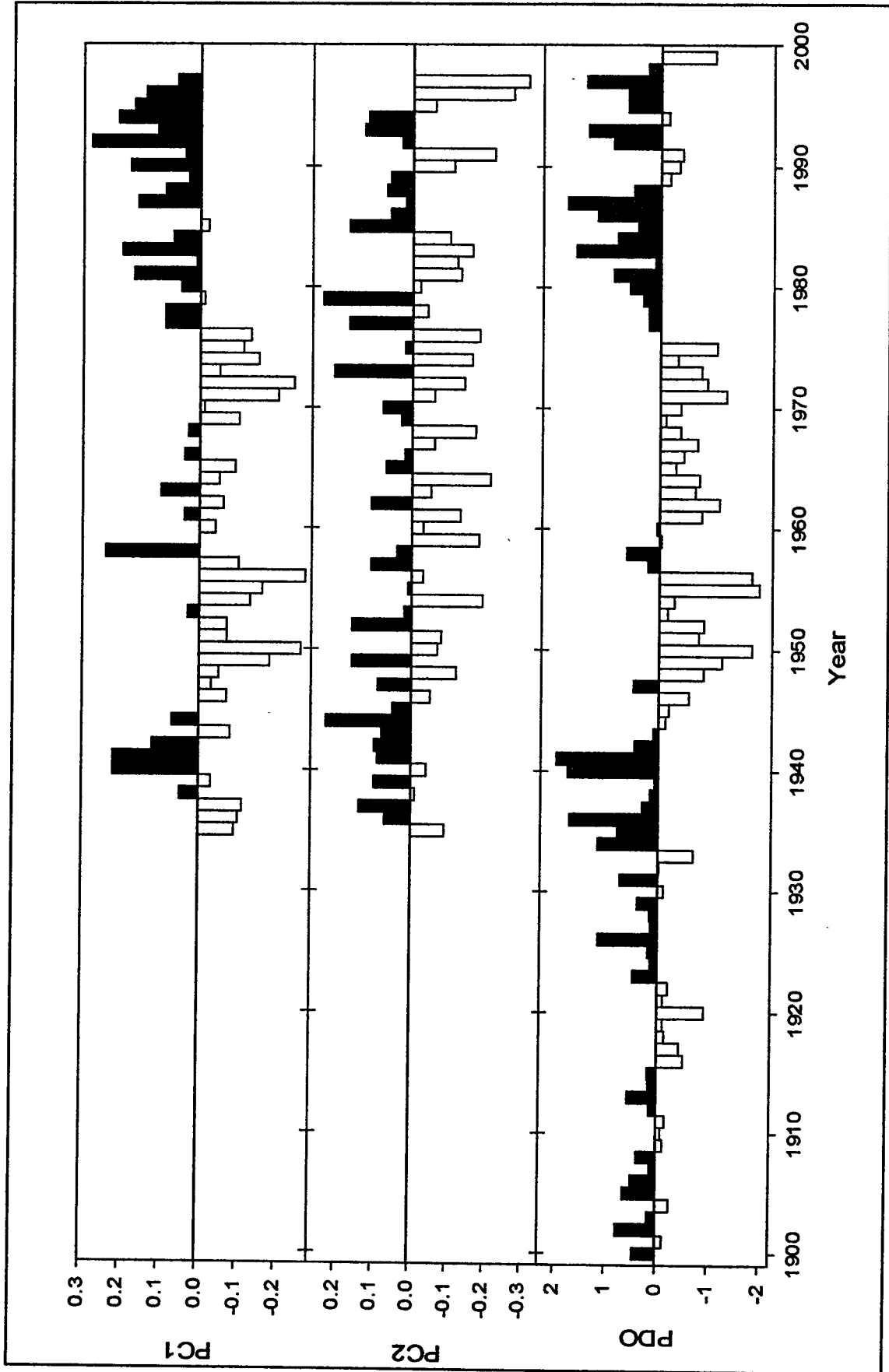


Figure 4. First (PC1) and second (PC2) principal components of climate variables affecting Puget Sound (Pinnix 1999) along with the Pacific Decadal Oscillation (PDO) (Mantua 1997). Puget Sound climate variables included: Race Rocks sea surface temperature (SST), Neah Bay SST, Skagit River stream flow, Paradise Meadows snowpack, and Climate Division 3 air temperature and precipitation. PC1 captures decadal scale variability and resembles the PDO. PC2 reflects interannual scale variability.

Sediment characteristics—The surface sediment of the Strait of Juan de Fuca is composed primarily of sand, which tends to be coarser and includes some gravel toward the eastern portion of North Sound and gradually becomes finer towards the mouth (Anderson 1968). Many of the bays and sounds in the eastern portion of the North Sound have subtidal surface sediments consisting of mud or mixtures of mud and sand (PSWQA 1987, Washington Department of Ecology [WDOE] 1998). The area just north of Admiralty Inlet is primarily gravel in its deeper portions, and a mixture of sand and gravel in its shallower portions, whereas the shallow areas north of the inlet on the western side of Whidbey Island and east of Protection Island consist of muddy-sand (Roberts 1979). The majority of the subtidal surface sediments among the San Juan Islands consist of mixtures of mud and sand. Within the intertidal zone, $61.2 \pm 49.7\%$ of the area also has mixed fine sediment and $22.6 \pm 27.5\%$ has sandy sediment (Bailey et al. 1998).

Currents and tidal activity—The Strait of Juan de Fuca is a weakly stratified, positive estuary with strong tidal currents (Thomson 1994). The western end of the Strait is strongly influenced by ocean processes, whereas the eastern end is influenced by intense tidal action occurring through and near the entrances to numerous narrow passages (Fig. 5). Seasonal variability in temperature and salinity is small because the waters are vertically well-mixed (Thomson 1994). On average, freshwater runoff makes up about 7% of the water by volume in the Strait and is derived primarily from the Fraser River. Generally, the circulation in the Strait consists of seaward surface flow of diluted seawater ($<30.0\text{‰}$) in the upper layer and an inshore flow of saline oceanic water ($>33.0\text{‰}$) at depth (Thomson 1994, Collias et al. 1974). Exceptions include an easterly flow of surface waters near the shoreline between Port Angeles and Dungeness Spit, landward flows of surface waters in many of the embayments and passages, and flows of surface water southward toward the Main Basin near Admiralty Inlet (PSWQA 1987).

Water quality—Temperatures generally range between 7° and 11°C , although occasionally surface temperatures reach as high as 14°C (WDOE 1999). In the eastern portion of North Sound, temperature and salinity vary from north to south, with the waters in the Strait of Georgia being slightly warmer than the waters near Admiralty Inlet. Waters near Admiralty Inlet also tended to have a higher salinities than waters to the north (J. Newton²). Dissolved oxygen levels vary seasonally, with lowest levels of about 4 mg/L at depth during the summer months, and highest levels of about 8 mg/L near the surface during the winter.

Macro vegetation—Eelgrass is the primary vegetation in the intertidal areas of the Strait of Juan de Fuca, covering $42.2 \pm 27.2\%$ of the intertidal area (Fig. 3), and green algae is the second most common covering $4.4 \pm 3.7\%$ of the intertidal area (Bailey et al. 1998). About 45% of the shoreline of this region consists of kelp habitat, compared to only 11% of the shoreline of the other four Puget Sound Basins (Shaffer 1998). Nevertheless, both intertidal areas each have approximately 50% of the total kelp resource. Most species of kelp are associated with shoreline exposed to wave action, whereas eelgrass is found in protected areas, such as Samish and Padilla Bays (Fig. 2). Some of the densest kelp beds in Puget Sound are found in the Strait of Juan de

² J. Newton, Washington Department of Ecology, 300 Desmond Drive, Lacey WA 98503. Pers. Commun., September 10, 1999.

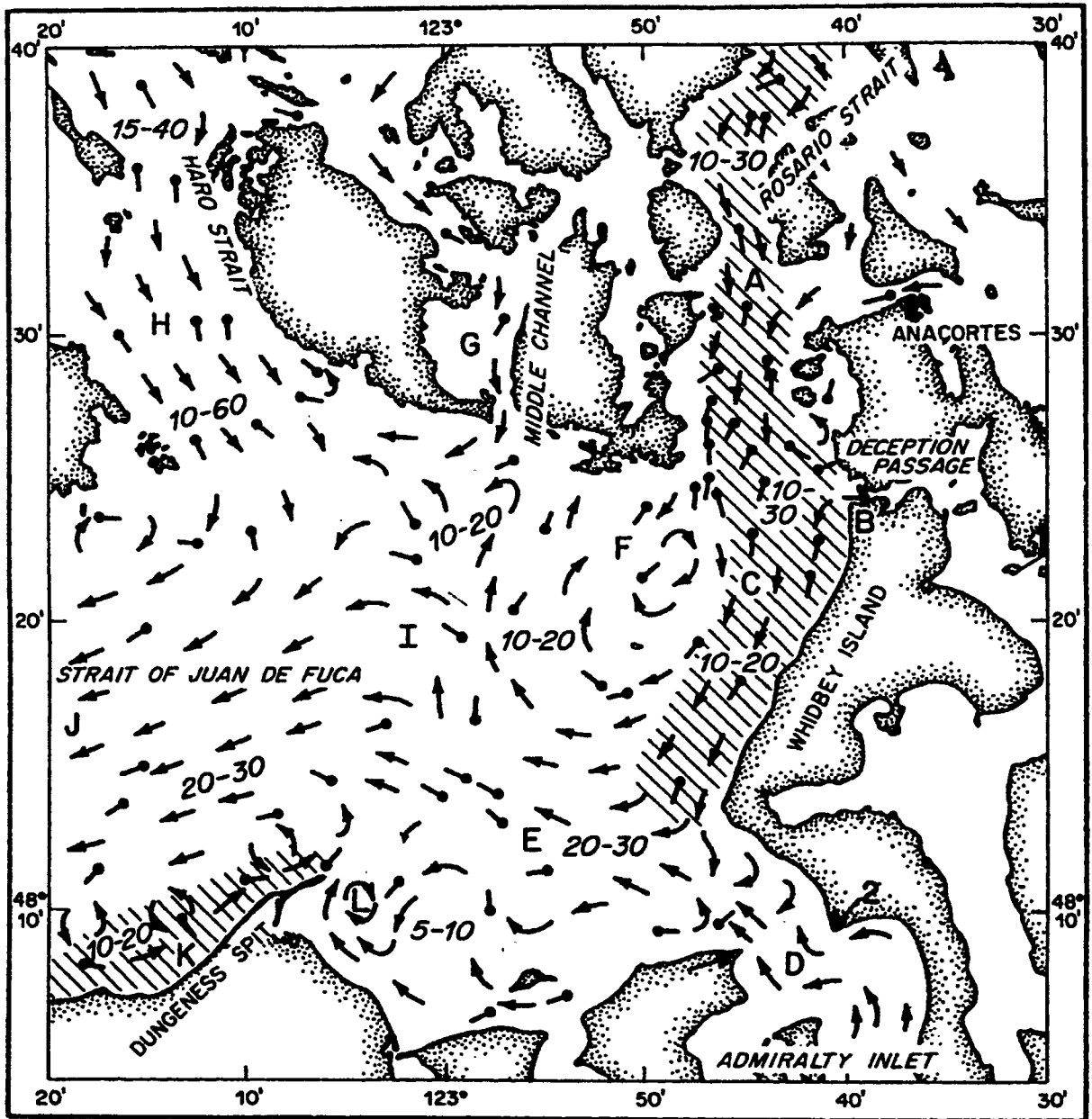


Figure 5. Plan view of net circulation in the upper layer (30 m) of the eastern end of the Strait of Juan de Fuca. Dots with sticks denote sties of measure currents and current direction. Numbers. denote approximate current speed ($\text{CM}^{\text{S}^{-1}}$) near the water surface. The arrows represent the flow patterns, and the hatched areas denote single layer flow. Figure from Ebbesmeyer et al. (1984).

Fuca. Kelp beds at the north end of Protection Island declined drastically between 1989 and 1997, decreasing from about 181 acres to “nothing” (Sewell 1999). The cause of this decline is currently unknown.

Urban, industrial, and agricultural development—The North Puget Sound Basin is bordered primarily by rural areas with a few localized industrial developments (PSWQA 1988). About 71% of the area draining into North Sound is forested, 6% is urbanized, and 15% is used for agriculture. Among the five Puget Sound basins, this basin is used most heavily for agriculture. The main human population in this area centers around Port Angeles (17,710), Port Townsend (7,000), Anacortes (11,500), and Bellingham (52,174) (Rand McNally 1998). About 10% of the total amount of wastes discharged from point-sources into Puget Sound comes from urban and industrial sources in this basin (PSWQA 1988). About 17% of the nutrients (in the form of inorganic nitrogen) entering Puget Sound originate from rivers carrying runoff from areas of agricultural and forest production (Embrey and Inkpen 1998). The Washington State Department of Natural Resources (WDNR 1998) estimated that 21% of the shoreline in this area has been modified by human activities.

Main Basin

Bathymetry and geomorphology—The 75 km-long Main Basin is delimited to the north by a line between Point Wilson (near Port Townsend) and Partridge Point on Whidbey Island, to the south by Tacoma Narrows, and to the east by a line between Possession Point on Whidbey Island and Meadow Point (near Everett) (Fig. 1). The western portion of the Main Basin includes such water bodies as Sinclair and Dyes inlets, and Colvos and Dalco passages. Large embayments on the east side include Elliott and Commencement bays.

Among of the most important bathymetric features of the Main Basin are the sills at its northern and southern ends. The sill at the north end of Admiralty Inlet is 30 km wide and is 65 m deep at its shallowest point. The sill at Tacoma Narrows is 45 m deep (Burns 1985). South of Admiralty Inlet, depths generally range from 100 m to 140 m in the central part of the basin, and 10 m to 100 m in the waterways west of Bainbridge and Vashon islands. The central basin consists of five sub-basins: 1) one near the southern end of Admiralty Inlet, west of Marrowstone Island, with depths to 190 m, 2) one near the southern tip of Whidbey Island with depths to 250 m, 3) one west of Port Madison, north of Seattle with depths to 400 m, 4) one northeast of West Point in Seattle with depths to 350m, 5) one south of Seattle, near Point Pulley, with depths to about 250 m (Burns 1985). Elliott and Commencement bays, associated with Seattle and Tacoma, respectively, are relatively deep, with depths in excess of 150 m. Freshwater flows into Elliott Bay through the Duwamish-Green River System, and into Commencement Bay through the Puyallup River.

Sediment characteristics—Subtidal surface sediments in Admiralty Inlet tend to consist largely of sand and gravel, whereas sediments just south of the inlet and southwest of Whidbey Island are primarily sand (PSWQA 1987). Sediments in the deeper areas of the central portion of the Main Basin generally consist of mud or sandy mud (PSWQA 1987, Washington Department [WDOE] 1998). Sediments in the shallower and intertidal areas of the Main Basin are mixed mud, sand,

and gravel. Bailey et al. (1998) reported that 92% of the intertidal area of the Main Basin consisted of mixed sand and gravel. A similar pattern is also found in the bays and inlets bordering this basin.

Currents and tidal activity—About 30% of the freshwater flow into the Main Basin is derived from the Skagit River. The Main Basin is generally stratified in the summer, due to river discharge and solar heating, and is often well-mixed in the winter due to winter cooling and increased mixing by wind. Circulation in the central and northern sections of the Main Basin consists largely of outflow through Admiralty Inlet in the upper layer and inflow of marine waters at depth (below approximately 50 m) (Fig. 6) (Strickland 1983, Thomson 1994). Oceanic waters from the Strait of Juan de Fuca flow over the northern sill at Admiralty Inlet into the Main Basin at about two-week intervals (Cannon 1983). In the southern section, currents generally flow northward along the west side of Vashon Island and southward on the east side through Colvos Passage. The sill at Tacoma Narrows also causes an upwelling process that reduces the seawater/freshwater stratification in this basin (Figs. 7a and 7b). With freshwater inflow, comes sediment deposits at an estimated rate of 0.18 to 1.2 grams/cm²/year (Staubitz et al. 1997).

Major circulation patterns in the Main Basin are greatly influenced by decadal climate regimes (Ebbesmeyer et al. 1998). During cool periods with strong oceanic upwellings and heavy precipitation, the strongest oceanic currents entering from the Strait of Juan de Fuca flow near mid-depth when the basin is cooler than 9.7°C. However, the strongest oceanic currents move toward the bottom of the basin, during warmer, dryer periods when waters are warmer than 9.7°C.

Water quality—Water temperature, salinity, and concentration of dissolved oxygen in waters of the Main Basin are routinely measured by the WDOE at six sites (WDOE 1999). Subsurface temperatures are usually between 8°C and 12°C. However, surface temperatures can reach 15°C to 18°C in summer, and temperatures at depth can get as low as 7.5°C in winter. Salinities in the deeper portions of the Main Basin are generally about 30‰ in summer and fall, but decrease to about 29‰ during the rainier months. Surface waters are also usually about 29‰, but occasionally have salinities as low as 25-27‰ during the rainy season (WDOE 1999).

The mid-basin site had consistently higher temperatures and lower salinity values compared to the water quality parameters at the site near the northern entrance to Admiralty Inlet (WDOE 1999). To demonstrate this trend, values from near mid-basin at West Point in Seattle, considered to be representative of this basin, were compared to values from the northern end of Admiralty Inlet. Values measured on the same dates (a summer month and a winter month) and depths at each site for two different years (1993 and 1996) were compared. For the summer month, the mean temperature at mid-basin site was 12.25°C vs. 9.19°C for the entrance site. The mean salinities for this same month were 29.65‰ and 31.43‰, respectively. For the winter month, the mean temperature at mid-basin site was 9.71°C and 8.11°C for the entrance site. The mean salinity values for this same month were 30.24‰ and 30.84‰, respectively.

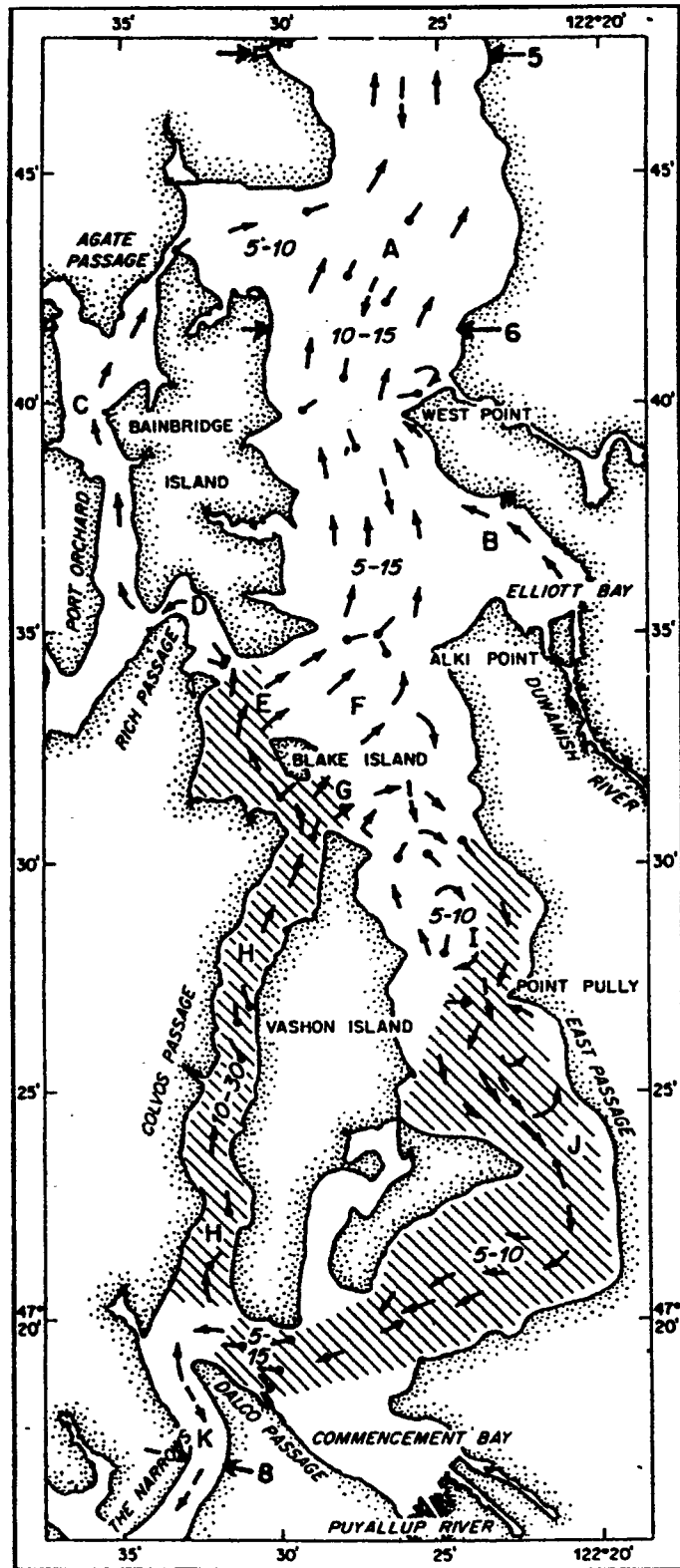


Figure 6. Plan view of net circulation in the upper layer (30 m) of Main Basin of Puget Sound proper. Dots with sticks denote sites of measure currents and current direction. Numbers denote approximate current speed ($\text{CM}^{\text{S}^{-1}}$) near the water surface. The arrows represent the flow patterns, and the hatched areas denote single layer flow. Figure from Ebbsmeyer et al. (1984).

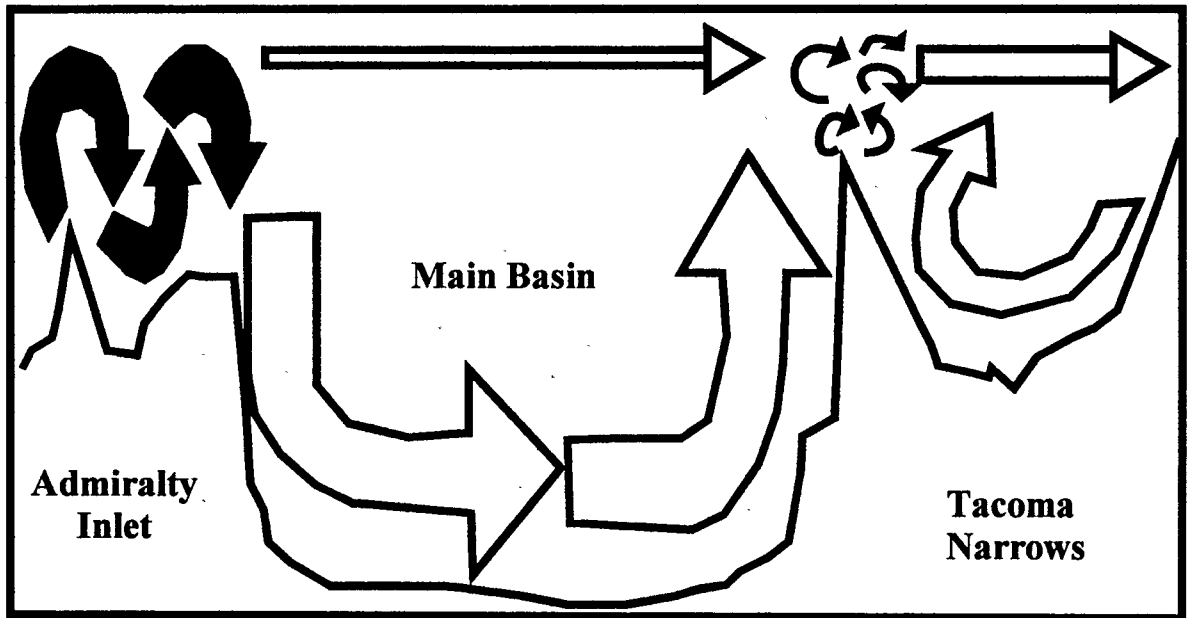


Figure 7A. Schematic of Puget Sound circulation during flood tide. Gray arrows represent strong vertical mixing. Light arrows represent horizontal currents. Modified after Strickland (1983).

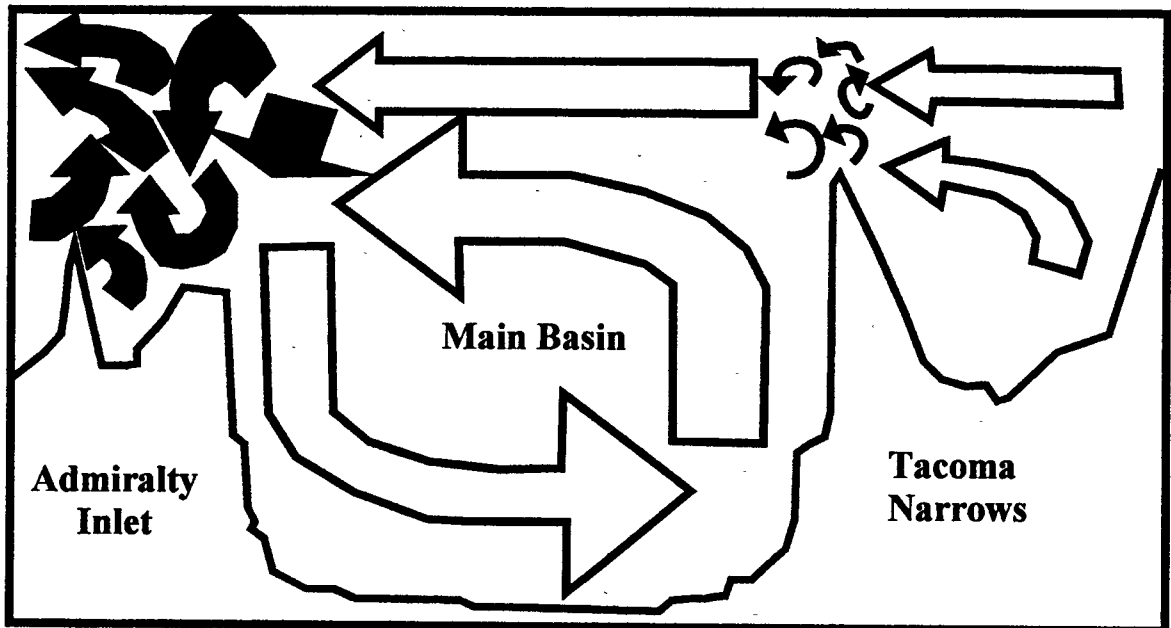


Figure 7B. Schematic of Puget Sound circulation during ebb tide. Gray arrows represent strong vertical mixing. Light arrows represent horizontal currents. Modified after Strickland (1983).

Dissolved oxygen varies seasonally, with lowest levels of about 5.5 mg/L occurring at depth in summer months, and highest levels of about 7.5 mg/L near the surface. Occasionally summer-time highs reach 13-14 mg/L at the surface.

Macro vegetation—The Main Basin has a relatively small amount of intertidal vegetation, with $28.3 \pm 10.4\%$ of the intertidal area containing vegetation (Bailey et al. 1998). The predominant types are green algae ($12.0 \pm 4.4\%$) and eelgrass ($11.4 \pm 6.6\%$). Most eelgrass is located on the western shores of Whidbey Island and the eastern shores of the Kitsap Peninsula (Fig. 3) (PSWQA 1987). Although Figure 3 suggests a continuous distribution of eelgrass on the eastern shores of the Main Basin, a recent report by the Puget Sound Water Quality Action Team (PSWQAT 2000) indicates that only 8% of the shoreline has a continuous distribution of eelgrass beds and 40% of the shoreline has a patchy distribution.

Urban, industrial and agricultural development—Areas bordering the Main Basin include the major urban and industrial areas of Puget Sound: Seattle, Tacoma, and Bremerton. Human population sizes for these cities are about 522,500, 182,900, and 38,142, respectively (Rand McNally 1998). Approximately 70% of the drainage area in this basin is forested, 23% is urbanized, and 4% is used for agriculture (Staubitz et al. 1997). About 80% of the total amount of waste discharged from point-sources into Puget Sound comes from urban and industrial sources in this region (PSWQA 1988). Moreover, about 16% of the waste entering Puget Sound, overall, enters this basin through its major river systems, in the form of inorganic nitrogen (Embrey and Inkpen 1998). The Washington State DNR (1998) estimates that 52% of the shoreline in this area has been modified by human activities.

Whidbey Basin

Bathymetry and geomorphology—The Whidbey Basin includes the marine waters east of Whidbey Island and is delimited to the south by a line between Possession Point on Whidbey Island and Meadowdale, west of Everett. The northern boundary is Deception Pass at the northern tip of Whidbey Island (Fig. 1). The Skagit River (the largest single source of freshwater in Puget Sound) enters the northeastern corner of the Basin, forming a delta and the shallow waters (<20 m) of Skagit Bay. Saratoga Passage, just south of Skagit Bay, separates Whidbey Island from Camano Island. This passage is 100 to 200 m deep, with the deepest section (200 m) located near Camano Head (Burns 1985). Port Susan is located east of Camano Island and receives freshwater from the Stillaguamish River at the northern end and from the Snohomish River (the second largest of Puget Sound's rivers) at southeastern corner. Port Susan also contains a deep area (120 m) near Camano Head. The deepest section of the basin is located near its southern boundary in Possession Sound (220 m).

Sediment characteristics—The most common sediment type in the intertidal zone of the Whidbey Basin is sand, representing $61.4 \pm 65.5\%$ of the intertidal area. Mixed fine sediments is the next most common sediment type covering $25.6 \pm 18.9\%$ of the intertidal area (Bailey et al. 1998). Similarly, subtidal areas near the mouths of the three major river systems are largely sand. However, the deeper areas of Port Susan, Port Gardner and Saratoga Passage

have surface sediments composed of mixtures of mud and sand (PSWQA 1987, WDOE 1998). Deception Pass sediments consist largely of gravel.

Currents and tidal activity—Although only a few water circulation studies have been performed in the Whidbey Basin, some general observations are possible. Current profiles in the northern portion of this basin are typical of a close-ended fjord (Fig. 8). For example, currents during the summer tend to occur in the top 40 m, moving at low velocities in a northerly direction (Cannon 1983). Currents through Saratoga Passage tend to move at moderate rates in a southerly direction. Due to the influences of the Stillaguamish and Snohomish River systems, surface currents in Port Susan and Port Gardner tend to flow toward the Main Basin, although there is some evidence of a recirculating pattern in Port Susan (PSWQA 1987).

Water quality—The waters in this basin are generally stratified, with surface waters being warmer in summer (generally 10-13°C) and cooler in winter (generally 7-10°C) (Collias et al. 1974, WDOE 1999). Salinities in the southern section of the Whidbey Basin in Possession Sound are similar to those of the Main Basin. In Port Susan and Saratoga Passage, salinities of surface waters (27.0-29.5‰) are generally lower than in the Main Basin, due to runoff from the two major rivers; moreover, after heavy rain these salinities range from 10-15‰. However, salinities in deeper areas often parallel those of the Main Basin (WDOE 1999).

Concentrations of dissolved oxygen in the waters of the Whidbey Basin are routinely measured by the WDOE in Saratoga Passage and in Port Gardner (WDOE 1999). Concentrations were highest in surface waters (up to 15 mg/L) and tended to be inversely proportional to salinity. Samples collected during spring run-off had the highest concentrations of dissolved oxygen. The lowest values (3.5 to 4.0 mg/L) were generally found at the greatest depths in fall.

Macro vegetation—Vegetation covers $23.6 \pm 8.8\%$ of the intertidal area of the Whidbey Basin (Bailey et al. 1998). The three predominant types of cover include green algae ($6.8 \pm 6.2\%$), eelgrass ($6.5 \pm 5.8\%$), and salt marsh ($9.0 \pm 9.4\%$). Eelgrass beds are most abundant in Skagit Bay and in the northern portion of Port Susan (Fig. 3) (PSWQA 1987).

Urban, industrial, agricultural, and development—Most of the Whidbey Basin is surrounded by rural areas with low, human population densities. About 85% of the drainage area of this Basin is forested, 3% is urbanized, and 4% is in agricultural production. The primary urban and industrial center is Everett, with a population of 70,000 (Rand McNally 1998). Most waste includes discharges from municipal and agricultural activities and from a paper mill. About 60% of the nutrients (as inorganic nitrogen) entering Puget Sound, enter through the Whidbey Basin by way of its three major river systems (Embrey and Inkpen 1998). The WDNR (1998) estimated that 36% of the shoreline in this area has been modified by human activities.

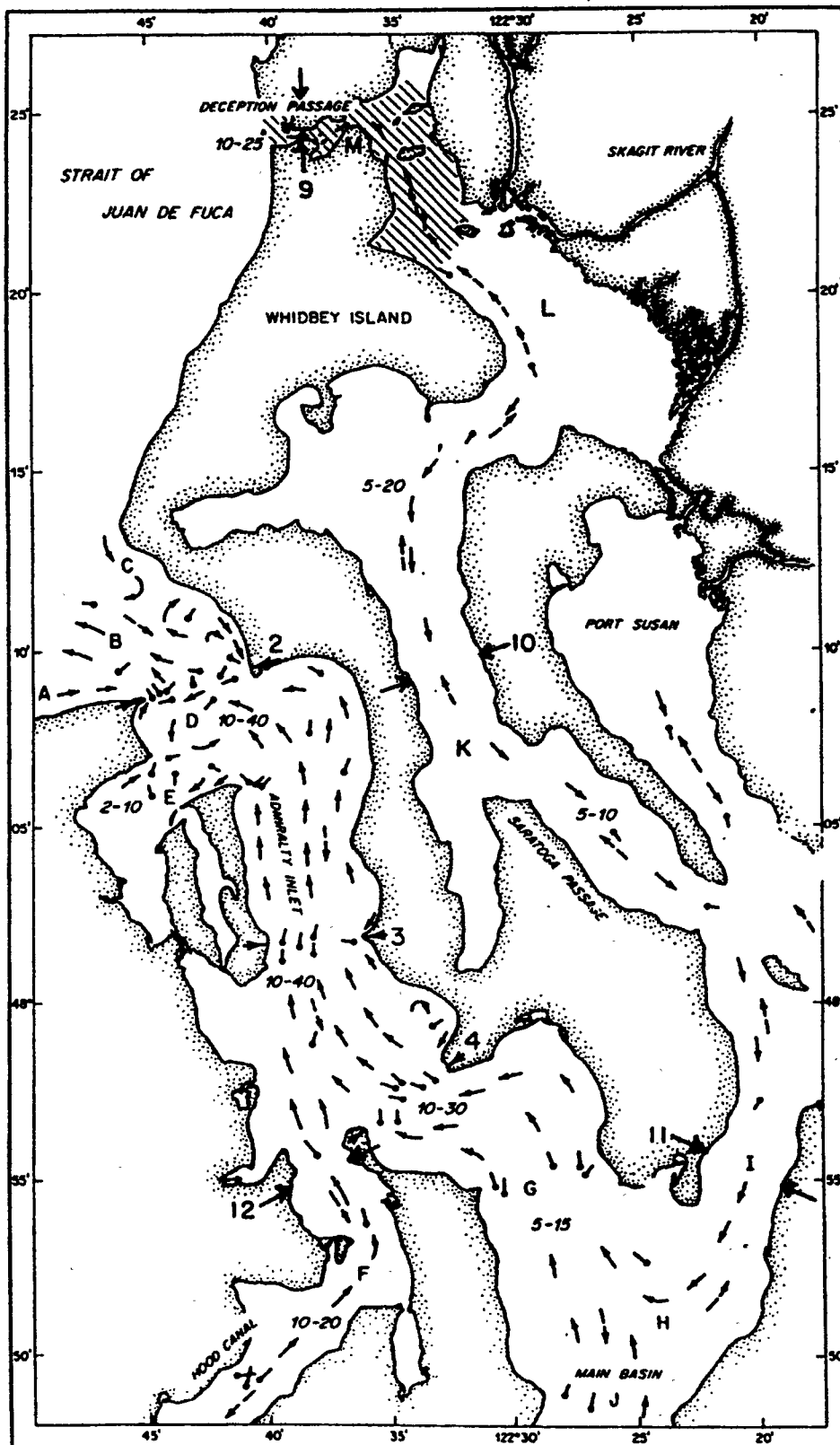


Figure 8. Plan view of net circulation in the upper layer (30 m) of Admiralty Inlet and Whidbey Basin. Dots with sticks denote sties of measure currents and current direction. Numbers. denote approximate current speed ($\text{CM}^{\text{S}^{-1}}$) near the water surface. The arrows represent the flow patterns, and the hatched areas denote single layer flow. Figure from Ebbesmeyer et al. (1984).

Southern Puget Sound

Bathymetry and geomorphology—The Southern Basin includes all waterways south of Tacoma Narrows (Fig. 1). This basin is characterized by numerous islands and shallow (generally <20 m) inlets with extensive shoreline areas. The mean depth of this basin is 37 m, and the deepest area (190 m) is located east of McNeil Island, just south of the sill (45 m) at Tacoma Narrows (Burns 1985). The largest river entering the basin is the Nisqually River which enters just south of Anderson Island.

Sediment characteristics—A wide assortment of sediments are found in the intertidal areas of this basin (Bailey et al. 1998). The most common sediment and the percent of the intertidal area they cover are as follows: mud, $38.3 \pm 29.3\%$; sand, $21.7 \pm 23.9\%$; mixed fine, $22.9 \pm 16.1\%$; and gravel, $11.1 \pm 4.9\%$. Subtidal areas have a similar diversity of surface sediments, with shallower areas consisting of mixtures of mud and sand, and deeper areas consisting of mud (PSWQA 1987). Sediments in Tacoma Narrows and Dana Passage consists primarily of gravel and sand.

Currents and tidal activity—Currents in the Southern Basin are strongly influenced by tides, due largely to the shallowness of this area. Currents tend to be strongest in narrow channels (Burns 1985). In general, surface waters flow north and deeper waters flow south. Among the five most western inlets, Case, Budd, Eld, Totten, and Hammersley, the circulation patterns of Budd and Eld inlets are largely independent of those in Totten and Hammersley inlets due largely to the shallowness of Squaxin Passage (Ebbesmeyer et al. 1998). These current patterns are characterized by flows of high-salinity waters from Budd and Eld inlets into the south end of Case Inlet, and from Totten and Hammersley inlets into the north end of Case Inlet. Flows of freshwater into the north and sound ends of Case Inlet originate from surface water runoff and the Nisqually River, respectively.

Water quality—The major channels of the Southern Basin are moderately stratified compared to most other Puget Sound basins, because no major river systems flow into this basin. Salinities generally range from 27-29‰, and, although surface temperatures reach 14-15°C in summer, the temperatures of subsurface waters generally range from 10-13°C in summer and 8-10°C in winter (WDOE 1999). Dissolved oxygen levels generally range from 6.5 to 9.5 mg/L. Whereas salinities in the inlets tend to be similar to those of the major channels, temperatures and dissolved oxygen levels in the inlets are frequently much higher in summer. Two of the principal inlets, Carr and Case inlets, have surface salinities ranging from 28-30‰ in the inlet mouths and main bodies, but lower salinities ranging from 27-28‰ at the heads of the inlets (Collias et al. 1974). Summertime surface waters in Budd, Carr and Case Inlets commonly have temperatures that range from 15-19°C and dissolved oxygen values of 10-15 mg/L. Temperature of subsurface water tends to be elevated in the summer (14-15°C); however, temperatures are similar to those of the main channels in other seasons of the year (WDOE 1999).

Macro vegetation—Among the five basins of Puget Sound, the Southern Basin has the least amount of vegetation in its intertidal area ($12.7 \pm 15.5\%$ coverage), with salt marsh ($9.7 \pm 14.7\%$ coverage) and green algae ($2.1 \pm 1.9\%$ coverage) being the most common types (Bailey et al. 1998).

Urban, industrial, and agricultural development—About 85% of the area draining into this basin is forested, 4% is urbanized, and 7% is in agricultural production. The major urban areas around the South Sound Basin are found in the western portions of Pierce County. These communities include west Tacoma, University Place, Steilacoom, and Fircrest, with a combined population of about 100,000 (Puget Sound Regional Council [PSRC] 1998). Other urban centers in the South Sound Basin include Olympia with a population of 33,729 and Shelton with a population of 7,200 (Rand McNally 1998). Important point sources of wastes include sewage treatment facilities in these cities and a paper mill in Steilacoom. Furthermore, about 5% of the nutrients (as inorganic nitrogen) entering Puget Sound, enter into this basin through non-point sources (Embrey and Inkpen 1998). The WDNR (1998) estimated that 34% of the shoreline in this area has been modified by human activities.

Hood Canal

Bathymetry and geomorphology—Hood Canal branches off the northwest part of the Main Basin near Admiralty Inlet and is the smallest of the Puget Sound basins, being 90 km long and 1-2 km wide (Fig. 1). Like many of the other basins, it is partially isolated by a sill (50 m deep) near its entrance that limits the transport of deep marine waters in and out of Hood Canal (Burns 1985). The major components of this basin consist of its Entrance, Dabob Bay, the central region, and The Great Bend at the southern end. Dabob Bay and the central region are the deepest sub-basins (200 and 180 m, respectively), whereas other areas are relatively shallow, <40 m for The Great Bend and 50-100 m at the entrance (Collias et al. 1974).

Sediment characteristics—Sediment in the intertidal zone consists mostly of mud ($53.4 \pm 89.3\%$ of the intertidal area), with similar amounts of mixed fine sediment and sand ($18.0 \pm 18.5\%$ and $16.7 \pm 13.7\%$, respectively) (Bailey et al. 1998). Surface sediments in the subtidal areas also consist primarily of mud, with the exception of the entrance, which consists of mixed sand and mud, and The Great Bend and Lynch Cove, which have patchy distributions of sand, gravelly sand, and mud (PSWQA 1987, WDOE 1998).

Currents and tidal activity—Aside from tidal currents, currents in Hood Canal are slow, perhaps because the basin is a closed-ended fjord without large-volume rivers. The strongest currents tend to occur near the entrance and generally involve a northerly flow of surface waters.

Water quality—Water temperature, salinity, and concentration of dissolved oxygen in Hood Canal are routinely measured by the WDOE at two sites, which are near The Great Bend and the Entrance (WDOE 1999). Salinities generally range from 29-31‰ and tend to be similar at both sites. In contrast, temperature and dissolved oxygen values are often markedly different between the two sites. Values measured on the same dates (a summer month and a winter month) and at the same depths at each site for 1993 and 1996 demonstrate these differences. Mean temperature

in the summer month at The Great Bend site was 9.9°C, but 12.1°C at the Entrance site. Mean dissolved oxygen values for this same month were 3.24 mg/L and 6.67 mg/L at The Great Bend and Entrance sites, respectively. For the winter month, the mean temperature at The Great Bend site was 10.6°C, but 9.1°C for the Entrance site. Mean dissolved oxygen values for this same month were 4.22 mg/L and 6.78 mg/L at the Great Bend and Entrance sites, respectively.

Macro vegetation—Vegetation covers $27.8 \pm 22.3\%$ of the intertidal areas of the Hood Canal Basin. Salt marsh ($18.0 \pm 8.8\%$) and eelgrass ($5.4 \pm 6.3\%$) are the two most abundant plants (Bailey et al. 1998). Eelgrass is found in most of Hood Canal, especially in the Great Bend and Dabob Bay (Fig. 3).

Urban, industrial, and agricultural development—The Hood Canal Basin is one of the least developed areas in Puget Sound and lacks large centers of urban and industrial development. About 90% of the drainage area in this basin is forested (the highest percentage of forested areas of the five Puget Sound basins), 2% is urbanized, and 1% is in agricultural production (Staubitz et al. 1997). However, the shoreline is well developed with summer homes and year-around residences (PSWQA 1988). A small amount of waste is generated by forestry practices and agriculture. Nutrients (as inorganic nitrogen) from non-point sources in this basin represent only 3% of the total flowing into Puget Sound annually (Embrey and Inkpen 1998). The WDNR (1998) estimated that 33% of the shoreline in this area has been modified by human activities.

Marine Species in Puget Sound

Algal productivity in the open waters of the central basin of Puget Sound is dominated by intense blooms of microalgae beginning in late April or May and recurring through the summer. Annual primary productivity in the central basin of the Sound is about 465 g C/m². This high productivity is due to intensive upward transport of nitrate by the estuarine mechanism and tidal mixing. Chlorophyll concentrations rarely exceed 15 µg/L. Frequently, there is more chlorophyll below the photic zone than within it. Winter et al. (1975) concluded that phytoplankton growth was limited by a combination of factors, including vertical advection and turbulence, light, sinking and occasional rapid horizontal advection of the phytoplankton from the area by sustained winds. Summer winds from the northwest would be expected to transport phytoplankton to the south end of the Sound which could exacerbate the anthropogenic effects that are already evident in some of these inlets and bays (Harrison et al. 1994).

The abundance and distribution of zooplankton in Puget Sound is not well understood. A few field surveys have been conducted in selected inlets and waterways, but reports on Sound-wide surveys are lacking. In general, the most numerically abundant zooplankton throughout the Puget Sound region are the calanoid copepods, especially *Pseudocalanus* spp. (Giles and Cordell 1998, Dumbauld 1985, Chester et al. 1980, Ohman 1990). Giles and Cordell (1998) reported that crustaceans (primarily calanoid copepods) were most abundant in Budd Inlet in South Puget Sound, although larvae of larvaceans, cnidarians, and polychaetes in varying numbers were also abundant during the year. A similar study conducted by Dumbauld (1985) at two locations in the Main Basin (a site near downtown Seattle and a cluster of sites in the East Passage near Seattle covering a variety of depths from 12 to 220 m), found that calanoid

copepods and cyclopoid copepods, and two species of larvaceans were numerically dominant. Dominant copepods at deeper sites were *Pseudocalanus* spp. and *Corycaeus anglicus*. The larvacean, *Oikopleura dioica*, was also relatively common at the shallow sites. Similarly, the most abundant zooplankton in the Strait of Juan de Fuca were reported by Chester et al. (1980) to be calanoid copepods, including *Pseudocalanus* spp. and *Acartia longiremis*, and the cyclopoid copepod, *Oithona similis*.

It is likely that zooplankton assemblages vary both seasonally and annually. Evidence of depth-specific differences was reported by Ohman (1990). In studies conducted in Dabob Bay near Hood Canal, Ohman (1990) compared the abundance of certain zooplankton species at a shallow and deep site. Ohman found one species of copepod (*Pseudocalanus newmani*) that was common at both sites, whereas species (e.g., *Euchaeta elongata* and *Euphausia pacifica*) that prey upon *P. newmani* were abundant at the deep site, but virtually absent from the shallow site. An example of seasonal variability was reported by Bollens et al. (1992). In Dabob Bay, *E. pacifica* larvae were abundant in the spring and absent in the winter, and juveniles and adults were most abundant in the summer and early fall, with their numbers declining in the winter (Bollens et al. 1992).

A few Sound-wide surveys of abundance and distribution of benthic invertebrates have been performed (Lie 1974, Llansó et al. 1998). A common finding among these surveys is that certain species prefer specific sediment types. For example, in areas with predominantly sandy sediments, among the most common species are *Axinopsida serricata* (a bivalve) and *Prionospio jubata* (a polychaete). In muddy, clayey areas of mean to average depth, *Amphiodia urtica-periercta* (a echinoderm) and *Eudorella pacifica* (a cumacean) are among the most common species. In areas with mixed mud and sand, *Axinopsida serricata* and *Aphelochaeta* sp. (a polychaete) are commonly found. And lastly, in deep muddy, clayey areas, the predominant species tend to be *Macoma carlottensis* (a bivalve) and *Pectinaria californiensis* (a polychaete). In general, areas with sandy sediments tend to have the most species (Llansó et al. 1998), but the lowest biomass (Lie 1974). Areas with mixed sediments tend to have the highest biomass (Lie 1974).

As with zooplankton, assemblages of benthic invertebrates vary both seasonally and annually. Lie (1968) reported seasonal variations in the abundance of species, with the maxima taking place during July-August, and the minima occurring in January to February. However, there were no significant variations in the number of species during different seasons. Annual variation was examined by Nichols (1988) at three Puget Sound sites in the Main Basin: two deep sites (200-250 m) and one shallow site (35 m). For one of the deep sites, he reported that *M. carlottensis* generally dominated the benthic community from 1963 through the mid-1970s. Subsequently, these species were largely replaced by *A. serricata*, *E. pacifica*, *P. californensis*, *Ampharete acutifrons* (a polychaete), and *Euphiomedes producta* (an ostracod). A similar dominance by *P. californensis* and *A. acutifrons* was reported for the other deep site over approximately the same time period.

Several macroinvertebrate species are widely distributed in Puget Sound. Among the crustacean species, Dungeness crab (*Cancer magister*) and several species of shrimp

(e.g., sidestripe [*Pandalopsis dispar*] and pink [*Pandalus borealis*]) are the most commonly harvested species (Bourne and Chew 1994). The non-indigenous Pacific oyster (*Crassostrea gigas*) accounts for approximately 90% of the landings of bivalves. Other abundant bivalves are the Pacific littleneck clam (*Protothaca staminea*), Pacific geoduck (*Panopea abrupta*), Pacific gaper (*Tresus nuttallii*), and the non-indigenous Japanese littleneck clam (*Tapes philippinarum*) and softshell clam (*Mya arenaria*) (Kozloff 1987, Turgeon et al. 1988).

The most common Pacific salmon species utilizing Puget Sound during some portion of their life cycle include chinook (*Oncorhynchus tshawytscha*), coho (*O. kisutch*), chum (*O. keta*), pink (*O. gorbuscha*), and sockeye salmon (*O. nerka*). Anadromous steelhead (*O. mykiss*) and cutthroat trout (*O. clarki clarki*) also utilize Puget Sound habitats.

Palsson et al. (1997) identified about 221 species of fish in Puget Sound. The marine species are generally categorized as bottomfish, forage fish, non-game fishes, and other groundfish species. In addition to Pacific hake, Pacific cod, and walleye pollock, other important commercial marine fish species in Puget Sound are Pacific herring, spiny dogfish (*Squalus acanthias*), lingcod (*Ophiodon elongatus*), various rockfish species (*Sebastes* spp.), and English sole (*Pleuronectes vetulus*). English sole are thought to be relatively healthy in the central portions of Puget Sound; however, significant declines have been recorded in localized embayments, such as Bellingham Bay and Discovery Bay. Other species of bottomfish species found throughout Puget Sound include skates (*Raja rhina* and *R. binoculata*), spotted ratfish (*Hydrolagus cooliei*), sablefish (*Anoplopoma fimbria*), greenlings (*Hexagrammos decagrammus* and *H. stelleri*), sculpins (e.g., cabezon [*Scorpaenichthys marmoratus*], Pacific staghorn sculpin [*Leptocottus armatus*], and roughback sculpin [*Chitonotus pugetensis*]), surfperches (e.g., pile perch [*Rhacochilus vacca*] and striped seaperch [*Embiotoca lateralis*]), wolf-eel (*Anarrhichthys ocellatus*), Pacific sanddab (*Citharichthys sordidus*), butter sole (*Pleuronectes isolepis*), rock sole (*Pleuronectes bilineatus*), Dover sole (*Microstomus pacificus*), starry flounder (*Platichthys stellatus*), sand sole (*Psettichthys melanostictus*), and over one dozen rockfish species (e.g., brown rockfish [*Sebastes auriculatus*], copper rockfish [*S. caurinus*], greenstriped rockfish [*S. elongatus*] yellowtail rockfish [*S. flavidus*], quillback rockfish [*S. maliger*], black rockfish, [*S. melanops*] and yelloweye rockfish [*S. ruberrimus*]) (DeLacy et al. 1972, Robins et al. 1991). Additional fish species that are less known, but widely distributed in Puget Sound, include surf smelt (*Hypomesus pretiosus*), plainfin midshipman (*Porichthys notatus*), eelpouts (e.g., blackbelly eelpout [*Lycodopsis pacifica*]), pricklebacks (e.g., snake prickleback, [*Lumpenus sagitta*]), gunnels (e.g., penpoint gunnel [*Apodichthys flavidus*]), Pacific sand lance (*Ammodytes hexapterus*), bay goby (*Lepidogobius lepidus*), and poachers (e.g., sturgeon poacher [*Podothecus acipenserinus*]) (DeLacy et al. 1972, Robins et al. 1991).

About 66,000 marine birds breed in or near Puget Sound (Mahaffy et al. 1994). About 70% of them breed on Protection Island, located just outside of the northern entrance to the Sound. The most abundant species are rhinoceros auklet (*Cerorhinca monocerata*), glaucous-winged gull (*Larus glaucescens*), pigeon guillemot (*Cephus columba*), cormorants (*Phalacrocorax* spp.), marbled murrelet (*Brachyramphus marmoratus*), and the Canada goose (*Branta canadensis*). Examples of less abundant species include common murre (*Uria aalge*)

and tufted puffins (*Fratercula cirrhata*). A number of additional bird species use Puget Sound during the winter months. Dabbling ducks, including American wigeon (*Anas americana*), mallard ducks (*A. platyrhynchos*) and northern pintail (*A. acuta*), are the most common, followed by geese and swans, such as trumpeter swans (*Cygnus columbianus*), tundra swans (*C. columbianus*), and Canada geese (*Branta canadensis*) (Mahaffy et al. 1994).

Populations of rhinoceros auklet and pigeon guillemot appear to be stable, whereas populations of glaucous-winged gull have increased slightly in recent years, especially in urban areas (Mahaffy et al. 1994). Accurate estimates of current populations of marbled murrelet and the Canada goose are not available, but the population of marbled murrelet has been greatly reduced and this species has been listed as threatened. Thirty years ago, year-around resident Canada geese were rare, but current anecdotal evidence from observations in waterfront parks suggests that their population is growing rapidly. The common murre and tufted puffin populations have declined drastically during the last two decades.

Nine primary marine mammal species occur in Puget Sound including (listed in order of abundance): harbor seal (*Phoca vitulina*), California sea lion (*Zalophus californianus*), Steller sea lion (*Eumetopias jubatus*), Northern elephant seal (*Mirounga angustirostris*), harbor porpoise (*Phocoena phocoena*), Dall's porpoise (*Phocoenoides dalli*), killer whale (*Orcinus orca*), gray whale (*Eschrichtius robustus*), and minke whale (*Balaenoptera acutorostrata*). Harbor seals are year-round residents, and their abundance has been increasing in Puget Sound by 5% to 15% annually at most sites (Calambokidis and Baird 1994).

California sea lions, primarily males, reside in Puget Sound between late summer and late spring, and spend the remainder of the year at their breeding grounds in southern California and Baja California. Sea lion populations are growing at approximately 5% annually. Populations of the remaining species are quite low in Puget Sound. Steller sea lions and elephant seals are transitory residents, whereas the Steller sea lion is currently listed as threatened in the U.S., the elephant seal is abundant in the eastern North Pacific but has few haul-out areas in Puget Sound. Although harbor porpoises are also abundant in the eastern North Pacific and were common in Puget Sound 50 or more years ago, they are now rarely seen in the Sound (Calambokidis and Baird 1994). Low numbers of Dall's porpoise are observed in Puget Sound throughout the year, but little is known about their population size—they are also abundant in the North Pacific.

A pod of resident fish-feeding killer whales, numbering about 100, resides just north of the entrance to Puget Sound, and the size of this group had reached about 100 by the mid-1990s and was increasing at about 2% per year. However, by 1999, the size of this population had decreased to about 83 whales, a decline of more than 15% (M. Dahlheim³). The causes of this decline are unknown, but could include exposure to chemical contaminants, reduced availability of prey items and increased human activities.

³ M. Dahlheim, NOAA Fisheries, 7600 Sand Point Way, N.E., Seattle, WA 98115. Pers. commun., November, 2000.

Minke whales are also primarily observed in this same northern area, but their population size is unknown. Gray whales migrate past the Georgia Basin en route to or from their feeding or breeding grounds; a few of them enter Puget Sound during the spring through fall to feed.

Environmental Features of the Strait of Georgia

The Strait of Georgia covers an area of approximately 6,800 km² (Thomson 1994) (Fig. 9) and is approximately 220 km long and varies from 18.5 to 55 km in width (Tully and Dodimead 1957, Waldichuck 1957). Both southern and northern approaches to the Strait of Georgia are through a maze of islands and channels from the San Juan and Gulf islands to the south and a series of islands to the north that extend for 240 km to Queen Charlotte Strait (Tully and Dodimead 1957). Both northern channels (Johnstone Strait and Cordero Channel) are from 1.5 to 3 km wide and are effectively two-way tidal falls, in which currents of 12-15 knots occur at peak flood (Tully and Dodimead 1957). However, both lateral and vertical constriction of water flow at the narrowest points in these northern channels are even more severe. Constrictions occur at Arran Rapids, Yuculta Rapids, Okisollo Channel, and to a lesser degree at Seymour Narrows (0.74 km wide, minimum depth of 90 m) in Discovery Passage (Waldichuck 1957). Overall, these narrow northern channels have only about 7% of the cross-sectional area as do the combined southern entrances into the Strait of Georgia (Waldichuck 1957).

The Strait of Georgia (Fig. 9) has a mild maritime climate and is dryer than other parts of the coast due to the rain shadow of the Olympic and Vancouver Island mountains. At sea level, air temperatures range from 0° to 5°C in January and 12° to 22°C in July, and winds are typically channeled by the local topography and blow along longitudinal axes of the straits and sounds. Winds are predominantly from the southeast in winter and the northwest in summer. It has a mean depth of 156 m (420 m maximum) and is bounded by narrow passages (Johnstone Strait and Cordero Channel to the north and Haro and Rosario straits to the south) and shallow submerged sills (minimum depth of 68 m to the north and 90 m to the south).

Freshwater inflows are dominated by the Fraser River, which accounts for roughly 80% of the freshwater entering the Strait of Georgia. Fraser River run-off and that of other large rivers on the mainland side of the Strait are driven by snow and glacier melt and their peak discharge period is generally in June and July. Rivers that drain into the Strait of Georgia off Vancouver Island (such as the Chemainus, Cowichan, Campbell, and Puntledge rivers) peak during periods of intense precipitation, generally in November (Waldichuck 1957).

Circulation in the Strait of Georgia occurs in a general counter-clockwise direction (Waldichuck 1957). Tides, winds, and freshwater run-off are the primary forces for mixing, water exchange, and circulation. Tidal flow enters the Strait of Georgia predominantly from the south creating vigorous mixing in the narrow, shallow straits and passes of the Strait of Georgia. The upper, brackish water layer in the Strait of Georgia is influenced by large freshwater run-off and salinity in this layer varies from 5 to 25‰. Deep, high-salinity (33.5 to 34‰), oceanic water enters the Strait of Georgia from the Strait of Juan de Fuca. The surface outflowing and deep inflowing water layers mix in the vicinity of the sills, creating the deep bottom layer in the Strait

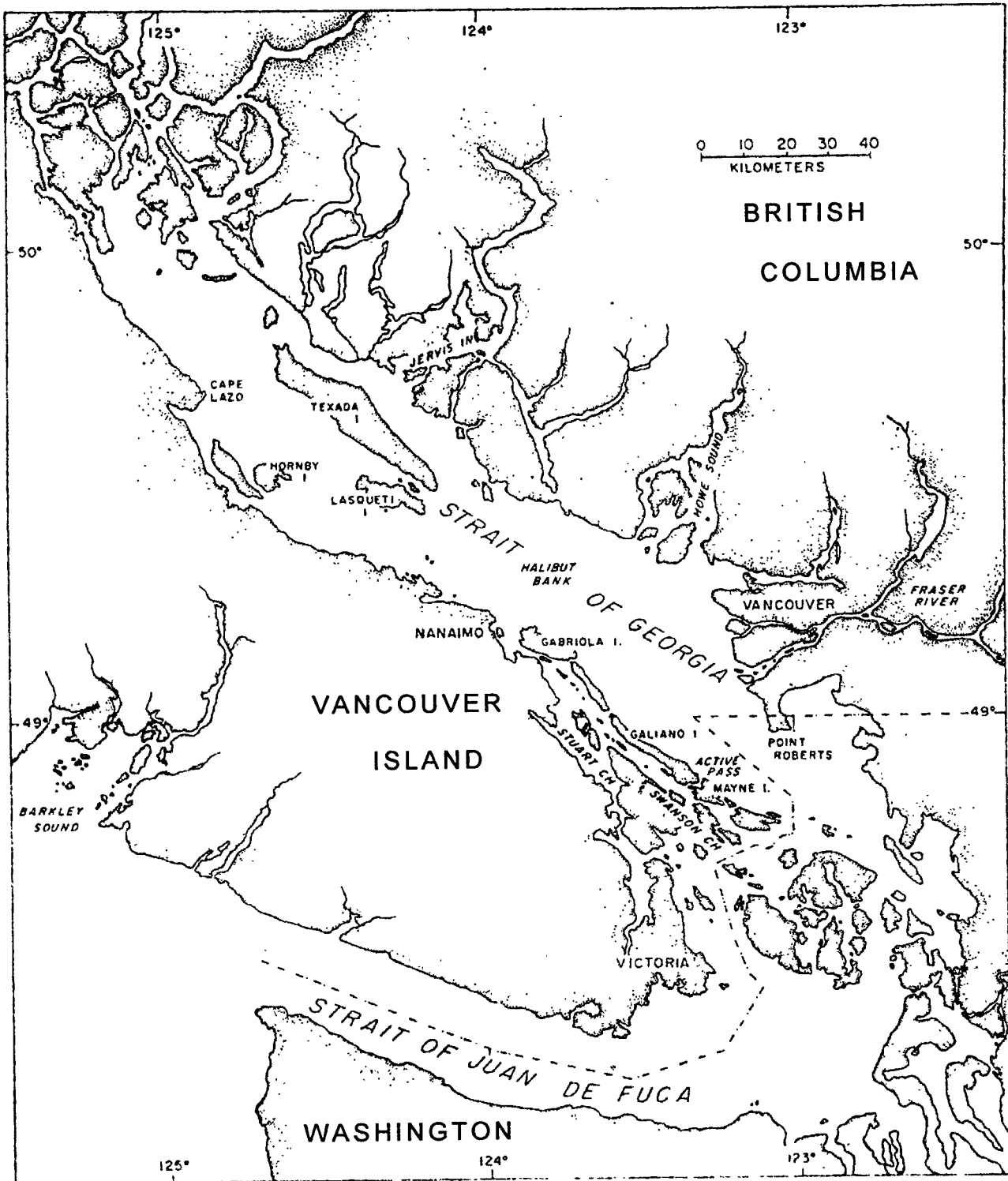


Figure 9. Geographical locations in the Strait of Georgia and on the southern coast of British Columbia considered in this manuscript.

of Georgia, where salinity is maintained at about 31‰ (Waldichuck 1957). The basic circulation pattern in the summer is the southerly outflow of relatively warm, low-salinity surface, with the northerly inflow of high salinity oceanic water from the Strait of Juan de Fuca at the lowest depths. In the winter, cool, low-salinity near surface water mixes with the intermediate depth high salinity waters; however, oceanic inflow is generally confined to the intermediate depths. Crean et al. (1988) reported that “the freshwater discharge finds primary egress through the southern boundary openings into the Strait of Juan de Fuca” and that subsurface waters (5 to 20 m below the region of the Fraser River discharge) also have “a predominantly southerly flow” (Fig. 10). Since surface water run-off peaks near the time of peak salinity of inflowing source water, the salinity of the deepwater in the Strait of Georgia undergoes only a small seasonal change in salinity (Waldichuck 1957).

Pacific Herring

General Biology

Geographical distribution and migrations

Pacific herring, *Clupea pallasii* (Valenciennes, 1847), in the Eastern Pacific, range from northern Baja California to St. Michael Island and Cape Bathurst in the Beaufort Sea (Hart 1973, Lassuy 1989). It is also found in Arctic waters from Coronation Gulf, Canada, to the Chuckchi Sea and the Russian arctic. In the Western Pacific, it is found from Toyama Bay, Japan, west to Korea, and the Yellow Sea (Haegele and Schweigert 1985, Wang 1986). In the Eastern Pacific, the effective commercial use is between San Francisco, California, and Central Alaska.

The general distribution and major spawning sites of Pacific herring along the Pacific Coast are shown in Figure 11 (Lassuy 1989). In the state of Washington, there are 19 well-defined spawning locations including three coastal locations (Willapa Bay, Grays Harbor and Columbia River Estuary) and 18 locations within Puget Sound (Fig. 12) (Bargman 1998, Lemberg et al. 1997, Pederson and Di Donato 1982). The location and timing of spawning at each location are very consistent and predictable from year-to-year (Hay and Outram 1981, O’Toole et al. 2000).

Although Pacific herring are not considered to be a migratory species, they exhibit onshore-offshore movements associated with spawning and feeding (Morrow 1980). Adults move onshore during winter and early spring, residing in “holding” areas before moving to adjacent spawning grounds (Emmett et. al 1991, Hay and McCarter 1997b). Their populations consist of many discrete stocks (Grosse and Hay 1989); however, offshore distributions of adults for many Pacific coast stocks are unknown (Barnhart 1988). Not all stocks of Pacific herring make extensive offshore migrations, however, many small resident populations remain in coastal inlets and bays (Stevenson 1962). For instance, following metamorphosis, Puget Sound stocks of herring spend their first year in Puget Sound. Some stocks of Puget Sound herring spend their entire lives within Puget Sound while other stocks summer in the coastal areas of Washington and southern British Columbia (Trumble 1983a).

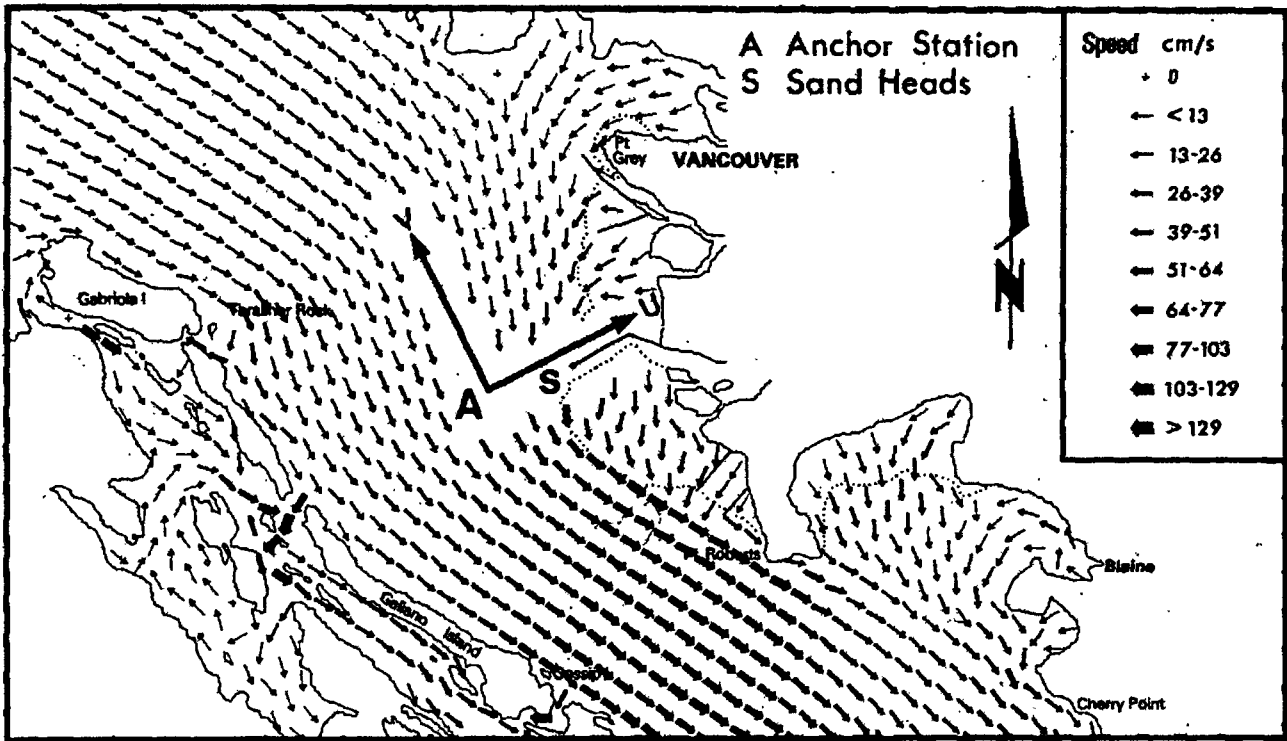


Figure 10. Representative ebb velocity vectors in the general vicinity of the Fraser River mouth in the Strait of Georgia and the location (A) of an anchor station. The axes denote directions into which the observed velocity components were resolved. (From Crean et al. 1988)

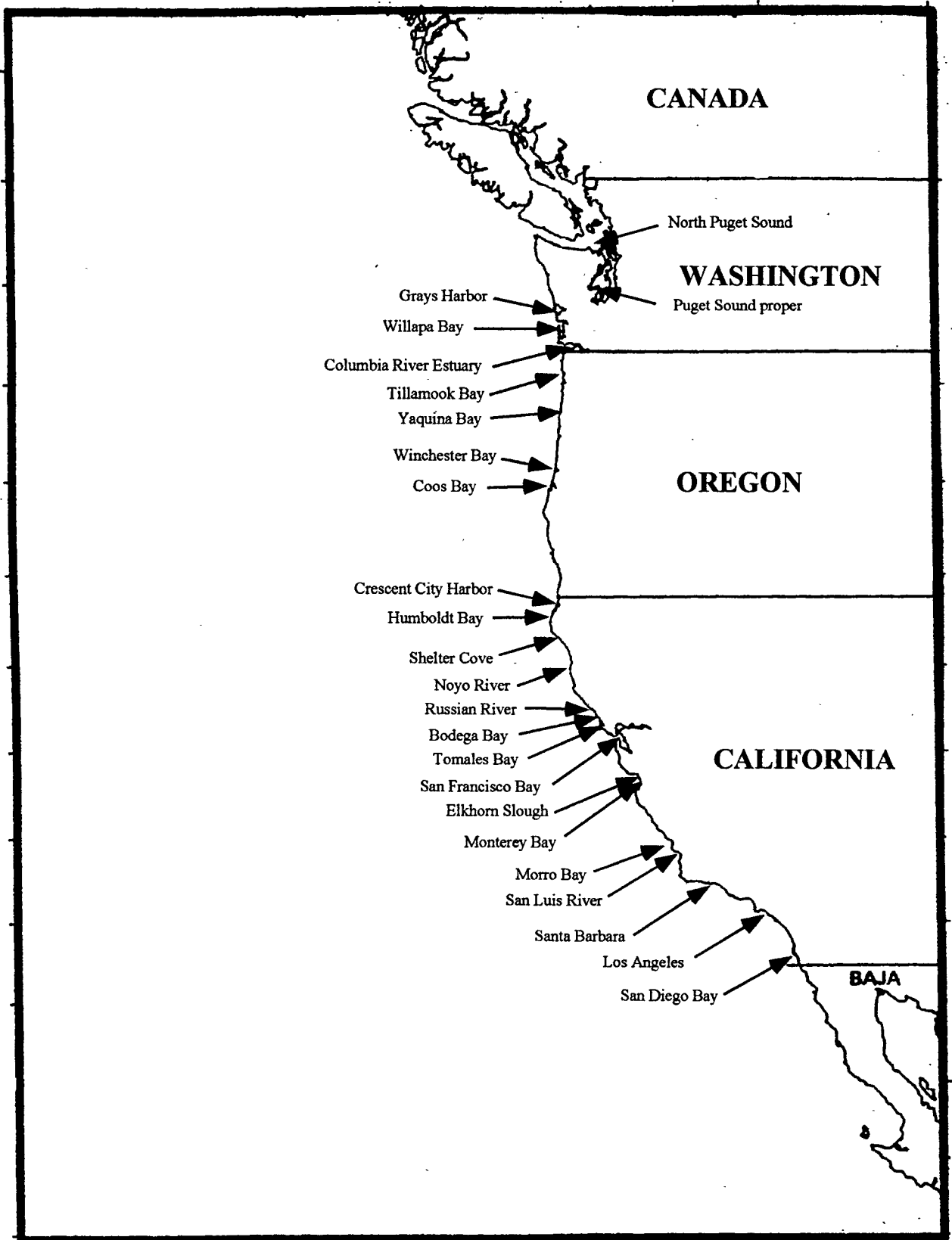


Figure 11. Known Pacific herring spawning locations on the U. S. west from Cape Flattery, Washington to southern California. Also, the distribution of Pacific herring spawning in the Washington State inland waters. Data from Scattergood et al. (1959), Miller and Schmidtke (1956), Alderdice and Velsen (1971), Spratt (1981), and Lassuy (1989).

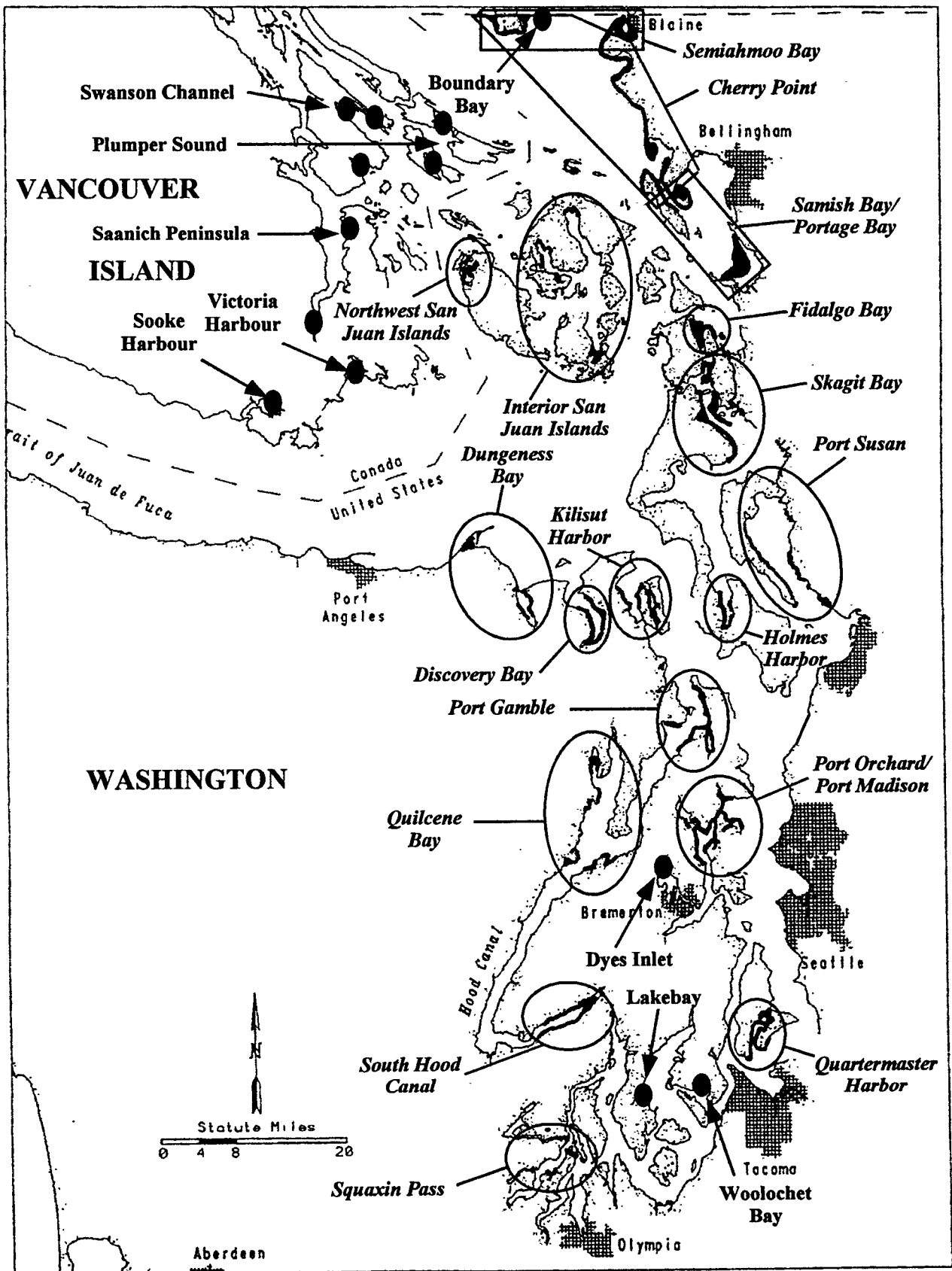


Figure 12. Geographic distribution of Pacific herring spawning grounds in Puget Sound and southern Strait of Georgia and extent of WDFW Pacific herring stocks (*italics*). Map modified from Lemberg et al. (1997) and <http://www.wa.gov:80/wdfw/fish/forage/herring.htm> (WDFW 2000).

Tagging studies in British Columbia have shown that herring exhibit homing to the geographical regions near where they were spawned, however, their straying rates are relatively high, about 20 percent on average (Hourston 1982). See further discussion in the "Tagging and distribution" section, specifically under the British Columbia tagging section. Pacific herring larvae may be transported by currents but their behavior and local currents often retain them in specific areas (Emmett et al. 1991). Some juveniles stay in nearshore shallow-water areas until fall when they disperse to deeper offshore waters. However, others may reside year-round in some estuaries (San Francisco Bay) (Wang 1986). Adult Pacific herring are found between 100-150 m, with vertical distribution influenced by temperature (Grosse and Hay 1989). It has also been observed that larvae, juveniles, and adult herring move toward the surface to feed at dawn and dusk.

Reproduction and development

Pacific herring are gonochoristic, oviparous, and iteroparous with external fertilization (Emmett et al. 1991). Fecundity increases with female size, producing on average 19,000 eggs annually at 19 cm standard length and 29,500 at 22 cm (Hart 1973). On a large geographic scale, there appears to be a decline in fecundity for a given length when moving from south (Puget Sound) to north (Prince William Sound) and northwest (Peter the Great Bay) (Garrison and Miller 1982). Unfertilized Pacific herring eggs are about 1.0 mm in diameter (Outram 1955) and the fertilized egg is 1.2-1.5 mm in diameter (Hart 1973, Hourston and Haegele 1980). Salinity effects on egg development are relatively unimportant (Hart 1973).

Within the range of the species, there is a latitudinal cline in spawning time (Figs. 13a-d). Spawning begins in November in the southern part of the range to August in the far north (Emmett et al. 1991, Lassuy 1989). Spawning peaks in December and January in California (Spratt 1981) and February and March in Puget Sound (Trumble 1983b). Peak spawning in Puget Sound starts the last week of February or the first week of March, except for the Cherry Point spawners (Fig. 13b) (O'Toole et al. 2000). Spawning at Cherry Point begins in early April and ends in early June with peak spawning activity around May 10th.

Pacific herring usually spawn at night in the shallow subtidal zone (Bargman 1998, Emmett et al. 1991). They spawn in water temperatures between 3.0 to 12.3°C. Most egg deposition occurs from 0-10 feet in tidal elevation. Pacific herring spawn by depositing eggs on vegetation or other shallow water substrate such as seagrass (*Zostera*), brown and red algae (*Macrocystis*, *Fucus*, and *Gracilaria*) (Haegele and Schweigert 1985). The eggs hatch in 11-12 days at 10.7°C, 14-14 days at 8.5°C, and 28-40 days at 4.4°C (Outram 1955).

Spawning grounds of Pacific herring are typically in sheltered inlets, sounds, bays, and estuaries rather than along open coastlines (Haegele and Schweigert 1985). The Pacific herring is particularly susceptible to influences of shoreline development because spawning grounds are limited to these rather specific intertidal and shallow subtidal locations. Substrates that herring spawn on may vary from eelgrass and kelp to gravel depending on location, however, eelgrass is the most often utilized spawning substrate. When shoreline development, and particularly shoreline armoring occurs, the dynamics of current and wave action are altered and may result in

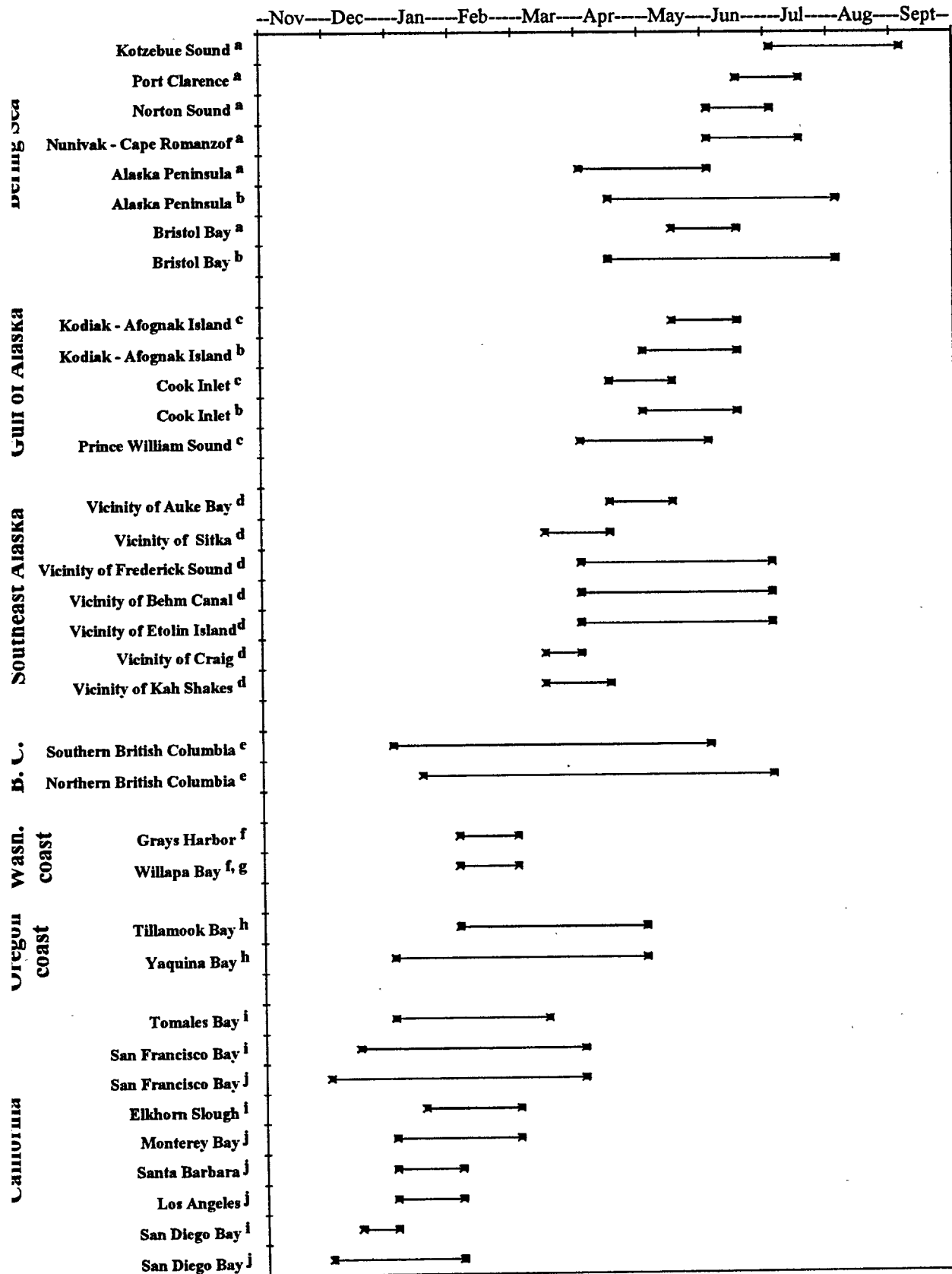


Figure 13a. Range of spawn timing of Pacific herring aggregations on the west coast of North America. Additional detail is presented in Figs. 13b-d for spawning locations in Puget Sound and British Columbia. (a, Barton and Wespestad (1980); b, ADFG (1985); c, Rounsefell (1930) and Hay (1985); d, Skud (1960); e, Hourston (1980) and Hay (1985); f, Chapman et al. (1941); g, Lemberg et al. (1997); h, Scattergood et al. (1959); i, Miller and Schmidtke (1956); j, Alderdice and Velsen (1971)).

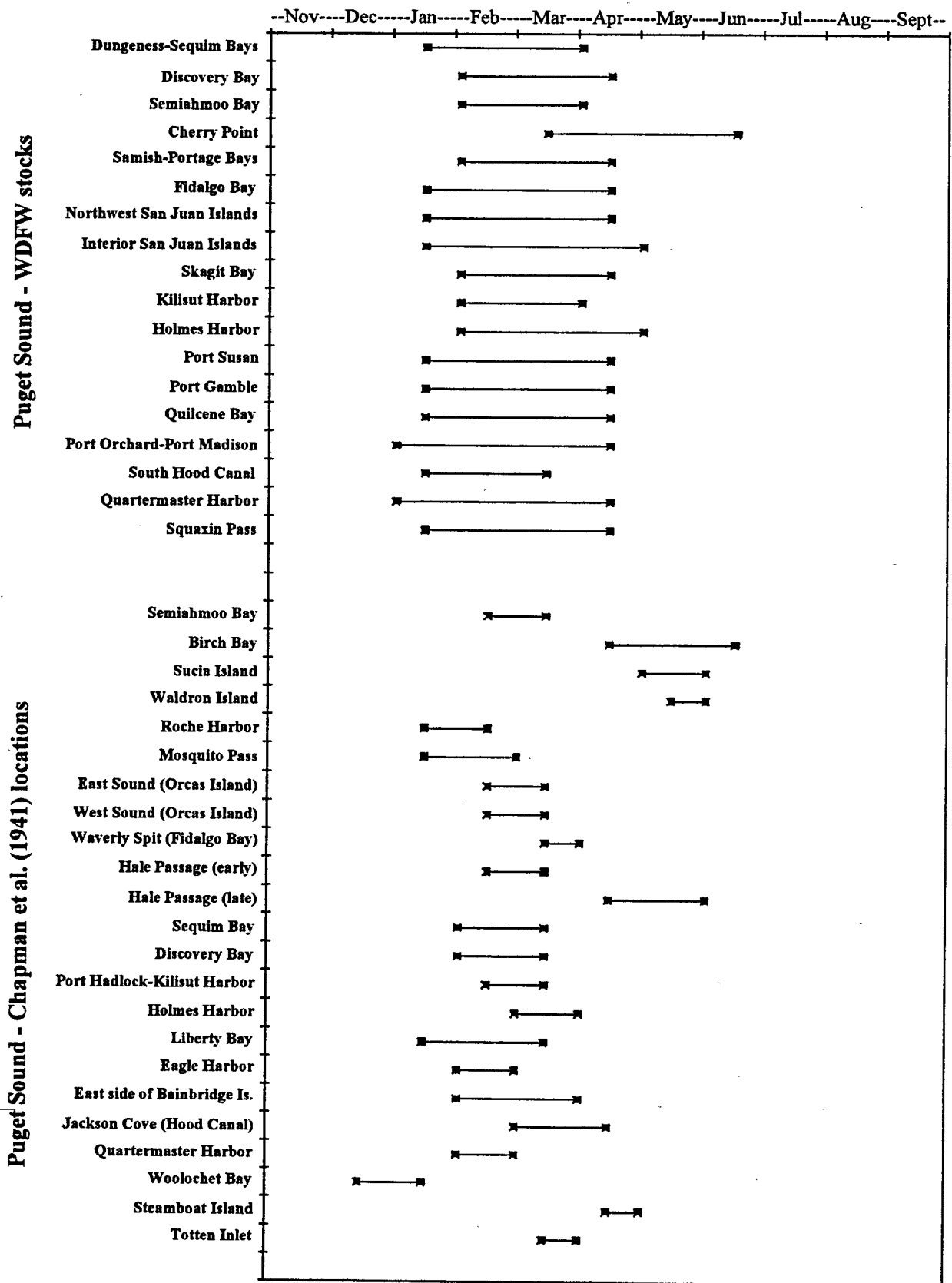


Figure 13b. Range of spawn timing of Pacific herring aggregations in Puget Sound as presented by Lemberg et al. (1997) and O'Toole et al. (2000) for WDFW stocks, and by Chapman et al. (1941) for Puget Sound in general.

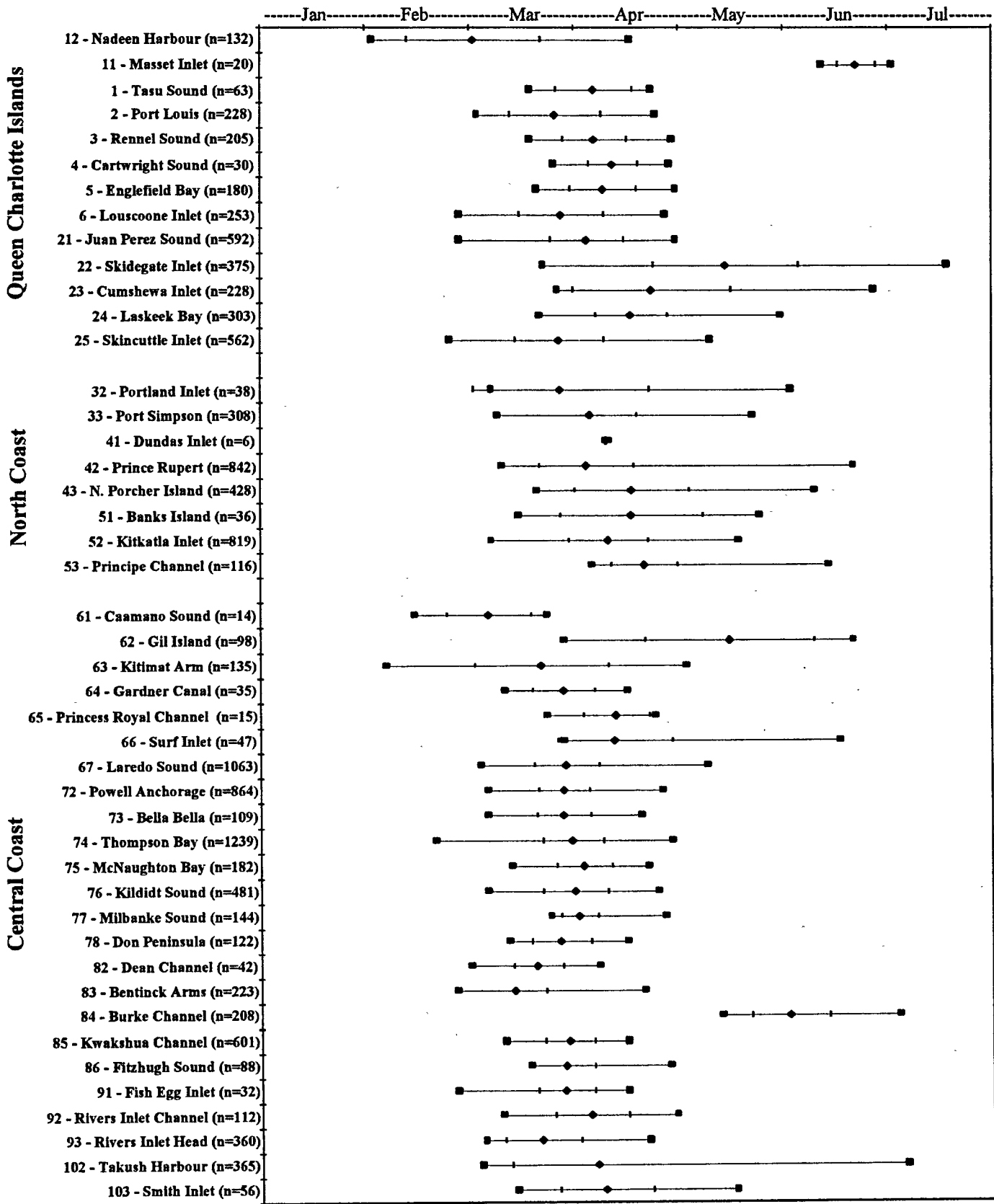


Figure 13c. Pacific herring spawn timing--mean day (◆), 1 standard deviation (|), and range (■)--by DFO Pacific herring Sections in Queen Charlotte Islands, North Coast (Prince Rupert District), and Central Coast regions from 1940-99. (n, number of spawn observations). Data from <http://www-sci.pac.dfo-mpo.gc.ca/herspawn/default.htm> (DFO 2000a).

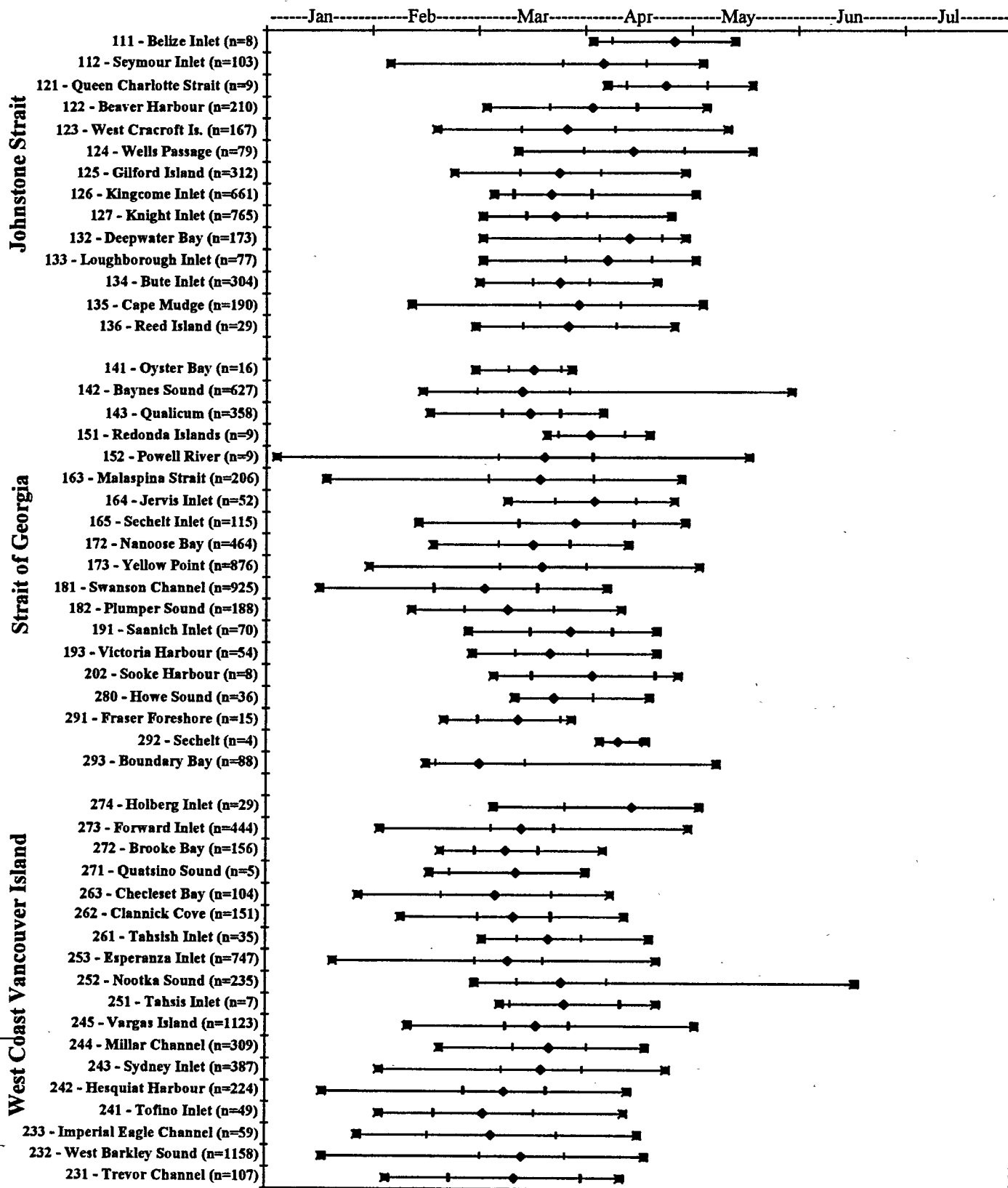


Figure 13d. Pacific herring spawn timing--mean day (◆), 1 standard deviation (—), and range (■)--by DFO Pacific herring Sections in Johnstone Strait, Strait of Georgia, and West Coast Vancouver Island regions from 1940-99. (n, number of spawn observations). Data from <http://www-sci.pac.dfo-mpo.gc.ca/herspawn/default.htm> (DFO 2000a).

the loss of eelgrass or change in the physical substrate of the intertidal area (Thom and Hallum 1990).

Pacific herring larvae range from 5 to 26 mm total length (TL) (Emmett et al. 1991). Following hatching, the larvae drift in the ocean currents. Acuity of the larval eye is low until they are 10-12 mm long at which time they are able to detect prey at short distances (Blaxter and Jones 1967). Survival in these early stages therefore depends on stable current patterns that promote larval retention in areas favorable to feeding and growth (Stevenson 1962). They begin to metamorphose at 26 mm TL and complete this process by 35 mm TL (Hourston and Haegele 1980, Hay 1985). Metamorphosis is complete in about two to three months.

Juveniles are 35 to 150 mm TL, depending upon region (Emmett et al. 1991). During their first summer, juveniles gather in large schools and remain primarily in inshore waters. Juveniles may gather after their first summer and move offshore until maturation (Stocker and Kronlund 1998) or they may remain inshore until their first spawn (Hay 1985). First-year juvenile fish that move offshore live mainly in waters with depth of 150-200 m. Two- and three-year-old herring are found at depths between 100-150 m (Hourston and Haegele 1980). Age at first maturity is generally 2-5 years but increases with increasing latitude (Hay 1985) and decreases with increasing exploitation (Ware 1985). For example, in Alaska waters, age at first maturity is 3-4 years and 2-6 years in the Bering Sea (Garrison and Miller 1982). In California, herring spawn at age-2 and all are mature by age-3 (Spratt 1981). Pacific herring mature at lengths from 13-26 cm TL, again depending upon region, with fish getting larger as latitude increases (Emmett et al. 1991, Garrison and Miller 1982).

Trophic interactions

Larvae, juveniles, and adults are selective pelagic plankton feeders, although filter feeding has been observed (Emmett et al. 1991). More specifically, larval Pacific herring start feeding on copepods, invertebrate eggs, and diatoms at a length of 9.5-11.0 mm (Hart 1973, Lasker 1985). Juvenile Pacific herring in sublittoral habitats eat calanoid copepods, decapod crab larvae, and chaetognaths (Fresh et al. 1981). Juveniles in pelagic habitats eat calanoid copepods, harpacticoid copepods, and euphausiids. After Pacific herring mature, copepods remain an important food source but are partly superseded by euphausiids (Hart 1973). As spawning season approaches, herring migrate toward shore and feeding ceases. A characteristic cycle of fattening in the summer and fasting in the winter appears to also coincide with spawning. Adult herring eat planktonic crustaceans (copepods, euphausiids, and amphipods) and small fishes, such as eulachon, herring, starry flounder, ronquil, sand lance, hake, marbled sculpin, and rockfish (Hart 1973).

Herring are an important food source within the trophic web. Eggs and larvae of Pacific herring are eaten by walleye pollock, herring, juvenile salmon, invertebrates, and most notably, birds (Bayer 1980, Hart 1973, Hourston and Haegele 1980). Bayer (1980) directly observed feeding of gulls at low tide and diving ducks obtained eggs by diving, by piracy, or by picking up eggs by swimming at high tide in Yaquina Bay, Oregon. Adult herring are most susceptible to predation while holding inshore before and during the spawning season (Lassus 1989).

Among the predators that prey on herring at these times are salmon, seals, sea lions, killer whales, dogfish, and birds (Hourston and Haegele 1980). In the inshore waters of the northern coast of Washington, it was observed that adult herring were preyed upon by the northern fur seal (*Callorhinus ursinus*) (Perez and Bigg 1986). When herring are feeding offshore they are preyed upon by hake, sablefish, dogfish, Pacific cod, and salmon (Lassuy 1989).

Growth and age distributions

Coastwide there appears to be an increase in size, with an increase in latitude. Adult herring lengths range from 13-26 cm TL, depending upon region, with fish obtaining a larger length as latitude increases (Garrison and Miller 1982). For example, Pacific herring in San Francisco Bay, California, had an average length-at-age of 200 mm for a 5-year-old fish (Spratt 1981); whereas, herring in the Togiak District, Alaska, had an average length-at-age of 254 mm for a 5-year-old fish (Fried et al. 1983). Herring live up to 19 years and grow to a maximum length of 38 cm TL (Hart 1973).

According to Bargmann (1998), after maturity at ages of two to four years for Puget Sound, they migrate back to their natal spawning grounds. In Puget Sound, herring may reach sexual maturity at age-2 and lengths of 14-16 cm (Katz 1942), but some may not reach sexual maturity until age-4, as in the Strait of Georgia populations (Trumble 1979). Lemberg et al. (1997) presented information about the length-at-age distributions of Pacific herring populations in Puget Sound. Table 2 shows that the average length-at-age for herring collected at Cherry Point are among the largest in the state. For example, the average length-at-age for a 5-year-old herring from Port Gamble was 199 mm but the Cherry Point population had an average length-at-age of 224 mm. The large size seen at Cherry Point suggests that the population may migrate to rich summer feeding grounds on the continental shelf (Lemberg et al. 1997). In Puget Sound, herring formerly lived to ages in excess of 10 years, however, fish older than 6 are now rare.

Marine Zoogeographic Provinces

Ekman (1953), Hedgpeth (1957), and Briggs (1974) summarized the distribution patterns of coastal marine fishes and invertebrates and defined major worldwide marine zoogeographic zones or provinces. Along the coastline of the boreal Eastern Pacific, which extends roughly from Point Conception, California to the Eastern Bering Sea, numerous schemes have been proposed for grouping the faunas into zones or provinces. A number of authors (Ekman 1953, Hedgpeth 1957, Briggs 1974, Allen and Smith 1988) have recognized a zoogeographic zone within the lower boreal Eastern Pacific that has been termed the Oregonian Province. Another zone in the upper boreal Eastern Pacific has been termed the Aleutian Province (Briggs 1974). However, exact boundaries of zoogeographic provinces in the Eastern boreal Pacific are in dispute (Allen and Smith 1988). Briggs (1974) and Allen and Smith (1988) reviewed previous literature from a variety of taxa and from fishes, respectively, and found the coastal region from Puget Sound to Sitka, Alaska to be a "gray zone" or transition zone that could be classified as

Table 2. Average length-at-age for Washington State Herring stocks measured in 1996. Data from Lemberg et al. 1997.

Average Length-at-Age (mm)

Stock	2 Years	3 Years	4 Years	5 Years
Squaxin Pass				
Quartermaster Harbor	150	165	180	~
Port Orchard/Madison	151	167	187	~
Port Gamble	150	167	184	212
Kilisut Harbor	154	171	189	199
Port Susan	158	184	208	~
Holmes Harbor	161	177	196	~
Skagit Bay	148	174	192	~
Fidalgo Bay	145	173	~	~
Samish/Portage Bay	143	165	171	216
Interior San Juan Islands	157	171	190	~
Semiahmoo Bay	147	160	174	199
Cherry Point	153	176	201	205
Discovery Bay	158	182	201	224
Dungeness Bay	161	179	200	197
	158	179	194	~

Source: Lemberg et al. (1997)

Note: Length-at-age not reported for South Hood Canal, Quilcene Bay, and Northwest San Juan Islands stocks.

~ = no data available

part of either of two provinces: Aleutian or Oregonian (Fig. 14). The southern boundary of the Oregonian Province is generally recognized as Point Conception, California and the northern boundary of the Aleutian Province is similarly recognized as Nunivak in the Bering Sea or the Aleutian Islands (Allen and Smith 1988).

Briggs (1974) placed the boundary between the Oregonian and Aleutian Provinces at Dixon Entrance, based on the well-studied distribution of mollusks, but indicated that distributions of fishes, echinoderms, and marine algae gave evidence for placement of this boundary in the vicinity of Sitka, Alaska. Briggs (1974) placed strong emphasis on the distribution of littoral mollusks (due to the more thorough treatment this group has received) in placing a major faunal break at Dixon Entrance. The authoritative work by Valentine (1966) on distribution of marine mollusks of the northeastern Pacific shelf showed that the Oregonian molluscan assemblage extended to Dixon Entrance with the Aleutian fauna extending northward from that area. Valentine (1966) erected the term Columbian Sub-Province to define the zone from Puget Sound to Dixon Entrance.

Several lines of evidence suggest that an important zoogeographic break for marine fishes occurs in the vicinity of Southeast Alaska. Peden and Wilson (1976) investigated the distributions of inshore fishes in British Columbia, and found Dixon Entrance to be of minor importance as a barrier to fish distribution. A more likely boundary between these fish faunas was variously suggested to occur near Sitka, Alaska, off northern Vancouver Island, or off Cape Flattery, Washington (Peden and Wilson 1976, Allen and Smith 1988). Briggs (1974) reported that of the more than 50 or more rockfish species belonging to the genus *Sebastes* occurring in northern California, more than two-thirds do not extend north of British Columbia or Southeast Alaska. Briggs (1974) further stated that "about 50 percent of the entire shore fish fauna of western Canada does not extend north of the Alaskan Panhandle." In addition, many marine fish species common to the Bering Sea, extend southward into the Gulf of Alaska but apparently occur no further south (Briggs 1974). Allen and Smith (1988) stated that "the relative abundance of some geographically-displacing [marine fish] species suggest that the boundary between these provinces [Aleutian and Oregonian] occurs off northern Vancouver Island."

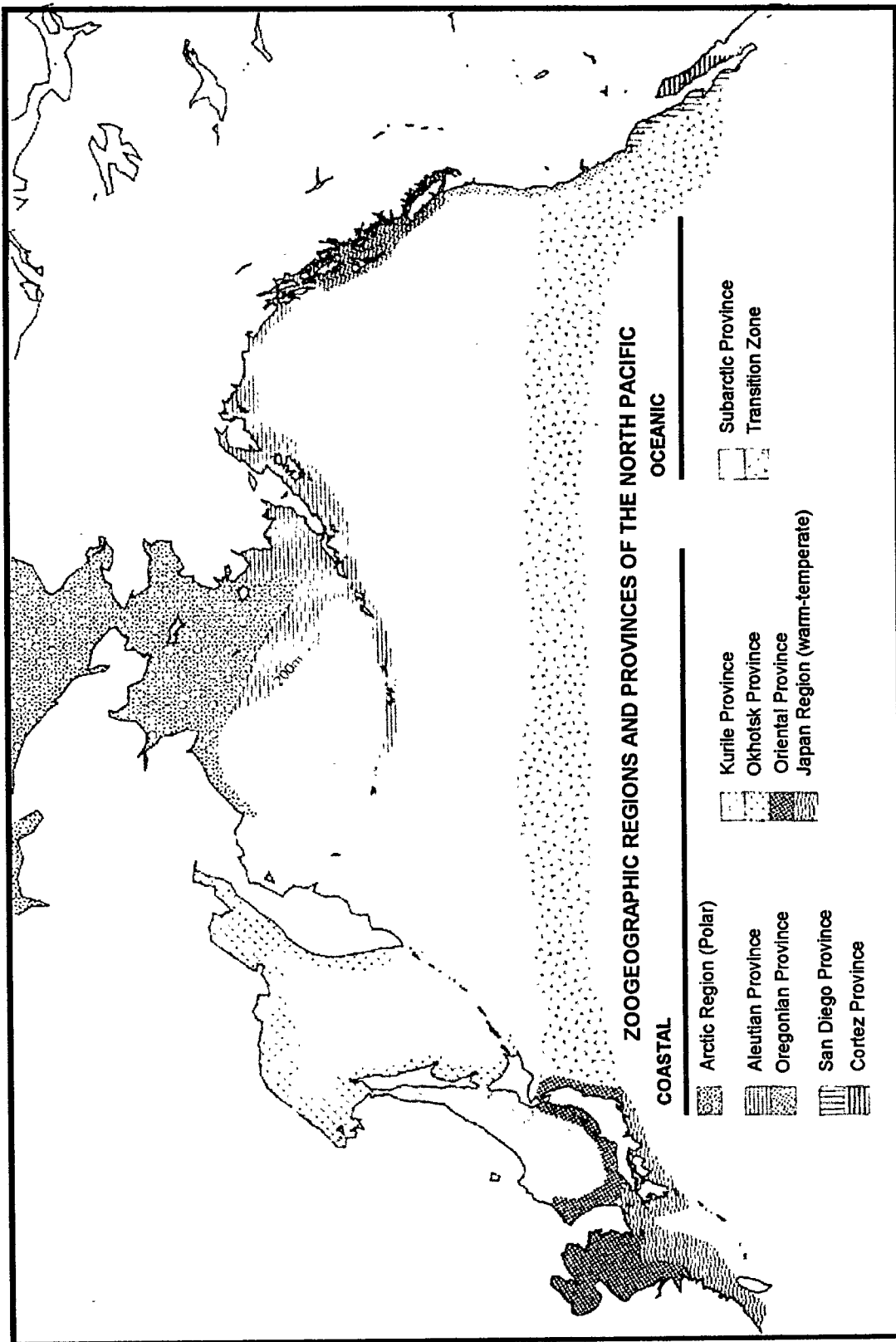


Figure 14. Marine zoogeographic provinces of the North Pacific Ocean. Modified after Allen and Smith (1988).

APPROACHES TO THE SPECIES QUESTION

The “Species” Question

The joint policy of the U.S. Fish and Wildlife Service and the National Marine Fisheries Service provides guidelines for defining distinct population segments below the taxonomic level of species (USFWS-NMFS 1996). The first of two elements to be considered is the discreteness of a population segment with respect to the rest of the populations within the species. Discreteness may result from physical factors that isolate the population segment and may be reflected as life-history differences in physiology, ecology, or behavior between the DPS and other populations. Genetic or morphological differences between the population segment being considered and other populations may also be used to evaluate discreteness. The policy also states that international boundaries within the geographical range of the species may be used to delimit a distinct population segment in the United States. This criterion is applicable if differences in the control of exploitation of the species, the management of the species' habitat, the conservation status of the species, or regulatory mechanisms differ between countries that would influence the conservation status of the population segment in the United States. In past assessments of evolutionarily significant units (ESUs) in Pacific salmon, however, NMFS has placed the emphasis on biological information in defining DPSs and has considered political boundaries only at the implementation of ESA listings.

A second element in defining distinct population segments is that the segment must be biologically or ecologically significant. Significance is evaluated in terms of the importance of the population segment to the overall welfare of the species and may be considered in the light of, but not limited to, the following factors. The population segment may be considered significant if it persists in an unusual or unique ecological setting for the species. A population segment may also be considered significant, if its loss would result in a significant gap in the geographical range of the species. Such a gap may disrupt the normal connectivity between populations. A segment also meets the significance guideline, if it represents the only surviving natural occurrence of the species that may be more abundant elsewhere as an introduced population outside its historical range. Another guideline is that the population segment differs markedly in its genetic characteristics from other populations of the species. Genetic differences may be detected by molecular genetic methods or may be reflected in unique adaptations to habitats not found in other parts of the species' geographical range. Other classes of information may also bear on the biological or ecological importance of a discrete population segment.

We considered several kinds of information in this status review to attempt to delineate DPSs of Pacific herring, particularly the geographic limits of the DPS which contains herring from Puget Sound. The first kind of information was to consider geographical variability in life-history characteristics and morphology. Such traits usually have an underlying genetic basis, but are often strongly influenced by environmental factors from one locality to another. The second kind of information consisted of tag and recapture studies, which give insight into the physical movement of individuals between areas. The third kind of information consisted of traits that are inherited in a predictable way and remain unchanged throughout the life of an

individual. Differences among populations in the frequencies of markers at these traits may reflect isolation between the populations. The analyses of these kinds of information are discussed briefly in the following sections.

Habitat Characteristics

The analysis of habitat characteristics may indicate that a population segment occupies an unusual or distinctive habitat, relative to the biological species as a whole. The persistence of a discrete population segment in an ecological setting unusual or unique for the taxon is one factor identified in the joint DPS policy (USFWS-NMFS 1996) that may provide evidence of the population's significance. However, Waples (1991a) cautioned against "drawing inferences based on physical characteristics of the habitat without supporting biological information linking the habitat differences to adaptations."

Conversely, the continuous distribution of a population segment within a region possessing similar habitat and ecological characteristics makes it less likely that unique adaptations have arisen in local populations. Without associated compelling phenetic or genetic evidence for a finer population structure, marine fish continuously distributed throughout similar habitat and lacking physical or behavioral barriers to migration are not likely to be composed of multiple DPSs.

Phenotypic and Life-History Traits

Isolation between populations may be reflected in several life-history variables, including differences in behavior (e.g., spawning timing, migration) and demography (e.g., growth rate, fecundity, age structure), among others. Although some of these traits may have a broad genetic basis and may reflect local adaptations of evolutionary importance, they are usually strongly influenced by environmental factors over the lifetime of an individual or over a few generations. Differences can arise among populations in response to environmental variability among areas and they can sometimes be used to infer the degree of independence among populations. However, differences in phenotypic and life-history traits among populations do not provide definitive information on reproductive isolation between populations, because the genetic basis of many phenotypic and life-history traits is weak or unknown. Likewise, elemental profiles present in otoliths, and other structures, reflect local environmental conditions or diets and although they may indicate that different areas or environments are occupied, they also provide little definitive information on the degree of reproductive isolation between populations.

Variation in reproductive behavior within a species of marine fish is an important factor to consider because it may provide the isolating mechanism required for differentiation. The presence of geographically-discrete and temporally-persistent spawning aggregations in a species indicates that reproductive isolation may be occurring. However, it is necessary to evaluate the degree of reproductive isolation by addressing the questions of migration rate, gene flow, and re-colonization rate. These later considerations are dependent on the degree of homing ability and natal-site fidelity of adults.

Studies of parasite incidence can provide important information about the degree of intermingling of marine fish stocks, particularly when a parasite is present in one area and totally absent in an adjoining area. However, parasite studies have some inherent interpretation problems: 1) in most cases parasite incidences exhibit clinal trends with latitude, and the degree to which parasite occurrence is due to environmental differences, acting on the parasite, or to a lack of host stock intermingling, is unknown, 2) the lack of a parasite in an area may be due to a regional absence of an alternate host organism, independent of host distribution, and 3) parasites may not be permanent natural tags in that parasites may be lost during the lifetime of the host.

Mark/Recapture Studies

The analysis of applied or acquired tags can indicate the degree of migration between localities. These tags consist of physical tags that are attached to a fish and later recovered. These tags provide evidence of movement of individuals from one place to another, but not necessarily of population connectivity through gene flow. Since these kinds of population markers largely lack a genetic basis and are not inherited, they must be applied each generation or must arise naturally anew each generation.

The application and recovery of physical tags on adult marine fish on spawning grounds can answer the question of whether fish return to the same locality to spawn in subsequent years, but these studies lack the direct evidence of parent-offspring linkage. In other words, these studies do not provide direct evidence that fish return to their natal area for spawning; however, they may provide evidence of straying and thus, the potential for gene flow between spawning aggregations.

Morphological Differentiation

Two problems inherent in the use of morphometric and meristic characteristics to separate marine fish populations are: 1) the characteristics are often under strong environmental influence and are not inherited in a simple Mendelian fashion, and 2) the characteristics are continuously variable and exhibit clinal trends and a high variance about the mean. A further drawback of using morphometric and meristic characteristics to detect population structure in fish is that few of these characteristics have been examined from a genetic standpoint. As shown by studies on several species, environmental parameters such as temperature, salinity, pH, and oxygen concentration can modify the expression of genes responsible for meristic characters (Ihssen et al. 1981).

Genetic Differentiation

Molecular genetic evidence can be used to define reproductively-isolated populations or groups of populations of Pacific herring in Puget Sound, as well as throughout the range. Molecular genetic markers appear to be largely unaffected by natural selection, so that geographical differences in gene frequencies can be interpreted in terms of genetic flow and genetic drift. The analysis of the geographical distributions of these markers may reveal

historical dispersals, equilibrium levels of migration (gene flow), and past isolation. Evidence for genetic population structure is based on the analysis of protein variants (allozymes), microsatellite loci (variable numbers of short tandem DNA repeats), and mitochondrial DNA (mtDNA).

Evidence of substantial genetic divergence between populations, as shown through analysis of these neutral molecular markers, is an important aspect of distinctiveness because even a small amount of interbreeding between populations will reduce the genetic differentiation between them. Although these molecular genetic methods “provide valuable insight into the process of genetic differentiation among populations” they offer “little direct information regarding the extent of adaptive genetic differences” (Waples 1995).

One widely used method of population analysis is sequence or RFLP (restriction fragment length polymorphism) analysis of mtDNA, which codes for several genes that are not found in the cell nucleus. Mitochondrial DNA differs from nuclear DNA (nDNA) in two important ways. One way is that recombination is lacking in mtDNA, so that gene combinations (haplotypes) are passed unaltered from one generation to the next, except for new mutations. A second way is that mtDNA is inherited from only the maternal parent in most fishes, so that gene phylogenies correspond to female lineages. A greater amount of random genetic drift among populations is expected for mtDNA genes, because the effective population size for mtDNA is about one-fourth of that for nuclear genes. These characteristics permit phylogeographical analyses of mtDNA haplotypes, which can potentially indicate dispersal pathways for females and the extent of gene flow between populations (Avice 1994).

Microsatellite DNA markers can potentially detect stock structure on finer spatial and temporal scales than can other DNA or protein markers, because of higher levels of polymorphism found in microsatellite DNA (reflecting a high mutation rate). When populations are at least partially isolated, genetic markers at loci with high mutation rates may accumulate more rapidly in some areas than in others.

Several standard statistical methods have been used to analyze molecular genetic data to detect reproductive isolation between populations. Comparisons of genotypic frequencies in a sample with frequencies expected under random mating (Hardy-Weinberg proportions) may be used to infer the breeding structure of a population or to detect population mixing (Wahlund's effect). Contingency-table comparisons of allozyme or microsatellite allele frequencies among population samples with chi-square or G (log-likelihood ratio) test statistics, or with randomization tests, can be used to detect significant differences between populations, which may be evidence of reproductive isolation.

A complementary way of assessing genetic isolation between populations is to analyze genetic distances based on allele-frequency estimates. Several genetic distance measures (Cavalli-Sforza and Edwards 1967, Nei 1972, 1978) have been used to study the population genetic structure of anadromous salmonids. It is unclear, however, which measure is most appropriate in a particular case or whether there is one measure that is always most appropriate. Discussions of the features of genetic distances appear in Nei (1978), Rogers (1991), and

Hillis et al. (1996). Most of this discussion has focused on the merits of the various measures for phylogenetic reconstruction among species or higher taxa.

Sample sizes and heterozygosity may also influence the power of the genetic-distance approach to resolving genetic population structure. When sample sizes used to estimate allelic frequencies are 50 individuals or more, the difference between Nei's genetic distance, D , (Nei 1972) and Nei's unbiased genetic distance (Nei 1978) is small in absolute terms, but still might be a substantial proportion of D , if D is small. When genetic distances between populations are also small, as they often are between populations of marine fishes, low but significant levels of genetic differentiation may not be detected by an unbiased distance measure because sample-size corrections may reduce estimates of genetic distance to zero. These measures range from 0.0 (identity) to infinity (complete dissimilarity). In most cases, the different genetic-distance measures yield highly-correlated results.

The degree of reproductive isolation between populations can be inferred from an analysis of the pattern of genetic distances between populations. Clustering methods, such as the unweighted pair group method with averages (UPGMA, Sneath and Sokal 1973) and the neighbor-joining method (Saitou and Nei 1987), find hierarchical groupings of genetically similar populations. Multivariate methods, such as multidimensional scaling (MDS, Kruskal 1964) or principal components analysis (PCA), find groupings of genetically-similar populations in several dimensions, which are depicted here in two or three dimensions.

Various studies have estimated levels of genetic variability within populations, because the level of within-population variability may reflect evolutionary or historical differences in population size and in migration patterns between populations. Within-population gene diversity was measured by the expected proportion of heterozygous genotypes in a population of randomly mating individuals averaged over the number of loci examined (H). Estimates of H based on a small number of individuals are usually accurate, as long as a large number of loci (>30) are surveyed for variability (Nei 1978).

Genetic differentiation between populations at various hierarchical levels has been estimated in many studies with a gene diversity analysis (Nei 1973, Chakraborty 1980), which apportions allele-frequency variability among populations into its geographical or ecological components. For example, the proportion of the total genetic variability in a set of samples that is due to differences among populations may be estimated with F_{ST} or the multiallelic equivalent statistics, G_{ST} . These variables range from 0.0 (no difference among populations) to 1.0 (fixed allele-frequency differences). The range 0.05-0.15 for F_{ST} indicates moderate differentiation, and the range 0.15-0.25 indicates strong genetic differentiation among populations (Wright 1978). These statistics facilitate comparisons among groups of populations that may reveal regional differences in gene flow between populations.

Relationship of DPS and Stock Concepts

The term “stock” has been used rather loosely in fisheries management and no single definition has been accepted by all fisheries biologists. Stock may be used to refer to groups of fish being harvested in a particular area, whether these fish are genetically related or not. However, in most cases, identification of a group of fish as a stock implies that these fish are in some way different or distinct from those in another stock, and generally implies some genetic relatedness among its members (Ihssen et al. 1981). Evidence of stock structure may be shown through differences in demographic population statistics (age composition, growth rate, fecundity, etc.), morphology (morphometrics and meristics), or genetics (differentiation at allozyme or DNA loci).

Ricker (1972) defined a salmon stock as “the fish spawning in a particular lake or stream (or portion of it) at a particular season, which fish to a substantial degree do not interbreed with any group spawning in a different place, or in the same place at a different season.” Larkin (1972) defined a stock as “a population of organisms, which, sharing a common environment and participating in a common gene pool, is sufficiently discrete to warrant consideration as a self-perpetuating system which can be managed.” Booke (1981) provided a general definition of a stock as “a species group, or population, of fish that maintains and sustains itself over time in a definable area.” Ihssen et al. (1981) defined a stock as “an intraspecific group of randomly mating individuals with temporal or spatial integrity.” In none of these definitions is it implied that a fish stock is ecologically or biologically significant in relation to the biological species as a whole.

By contrast, not only must a marine fish DPS be “markedly separated from other populations of the same taxon,” it must also exhibit ecological or biological significance in comparison to other population segments of the biological species. Thus, following the guidance supplied by the joint policy statement (USFWS-NMFS 1996), a distinct population segment of marine fish may be viewed as a group of related stocks (or in some cases, if the evidence warrants, a single stock) that form(s) a discrete population and are (is) significant to the biological species as a whole. As stated previously, considerations that can be used to determine a discrete population’s significance to the taxon as a whole include: 1) persistence of the population segment in an ecological setting unusual or unique for the taxon, 2) evidence that loss of the population segment would result in a significant gap in the range of the taxon, 3) evidence that the population segment represents the only surviving natural occurrence of a taxon that may be more abundant elsewhere as an introduced population outside its historic range, and 4) evidence that the population segment differs markedly from other populations of the species in its genetic characteristics.

Pacific Herring DPS Information

Phenetic and Genetic Information Relating to the Species Question

Phenetic and genetic information examined for evidence for DPS delineations of Pacific herring included presence of geographically-discrete and temporally-persistent spawning aggregations, and variation in seasonal migration patterns, parasite incidence, growth rate and body size, length and age at maturity, fecundity, and meristics and morphometrics.

Genetic information

Genetic studies searching for population structure in Pacific herring have followed a course similar to many other fishes. Early studies concentrated on finding protein electrophoretic variation using starch-gel electrophoresis. This search in Pacific herring was begun by Utter (1972) who identified two polymorphic allozyme loci from four Pacific herring samples from Washington State (three from Puget Sound, one from the Washington coast). No significant differences in allele frequencies were found among the samples. This research was expanded further to include six polymorphic loci collected from samples ranging from Oregon to Kodiak Island, Alaska (Utter et al. 1974). Again, there was no evidence of significant genetic differentiation among these populations either. It should be pointed out that the Washington coast sample in the Utter et al. (1974) and Utter (1972) studies was composed of immature fish. The other samples, as well as all of the samples in the studies described below, were composed of adult fish collected from known herring spawning grounds.

Grant expanded upon Utter's initial work, and surveyed 40 allozyme loci in Pacific herring (Grant 1979, 1981; Grant and Utter 1984). Grant and Utter (1984) found 26 polymorphic loci in 21 samples collected from five areas throughout the range of Pacific herring -- Asia, the northeastern Bering Sea, the southeastern Bering Sea, the Gulf of Alaska, and the eastern North Pacific Ocean (including samples from the Strait of Georgia and Hale Passage in Puget Sound) (Fig. 15). Their analyses revealed two main genetic stocks: Asian-Bering Sea herring and eastern North Pacific herring, separated by a Nei's genetic distance (D) (Nei 1972) of 0.039 (Fig. 16). The authors postulated that these two distinct stocks arose because of restricted gene flow between them, due to repeated Pleistocene glaciation on the southern coast of Alaska. Genetic differentiation was also detected among all five areas. However, only the Bering Sea and the Gulf of Alaska showed any significant genetic differentiation within an area. The samples from the eastern North Pacific Ocean, which include the two Puget Sound samples, were not genetically distinct from each other, even though the collection sites ranged from California to southeast Alaska. The average D value between pairs of samples within the eastern North Pacific Ocean was not significantly different from zero. A gene diversity analysis revealed that only 0.5% of the observed variation was due to differences among populations within an area. The authors also reported a north to south cline in allele frequencies of the locus *GAPDH-1** for eastern North Pacific Ocean samples. The reason for this is uncertain, but because no other loci showed a similar cline, one possible explanation is that selection is occurring at this locus.

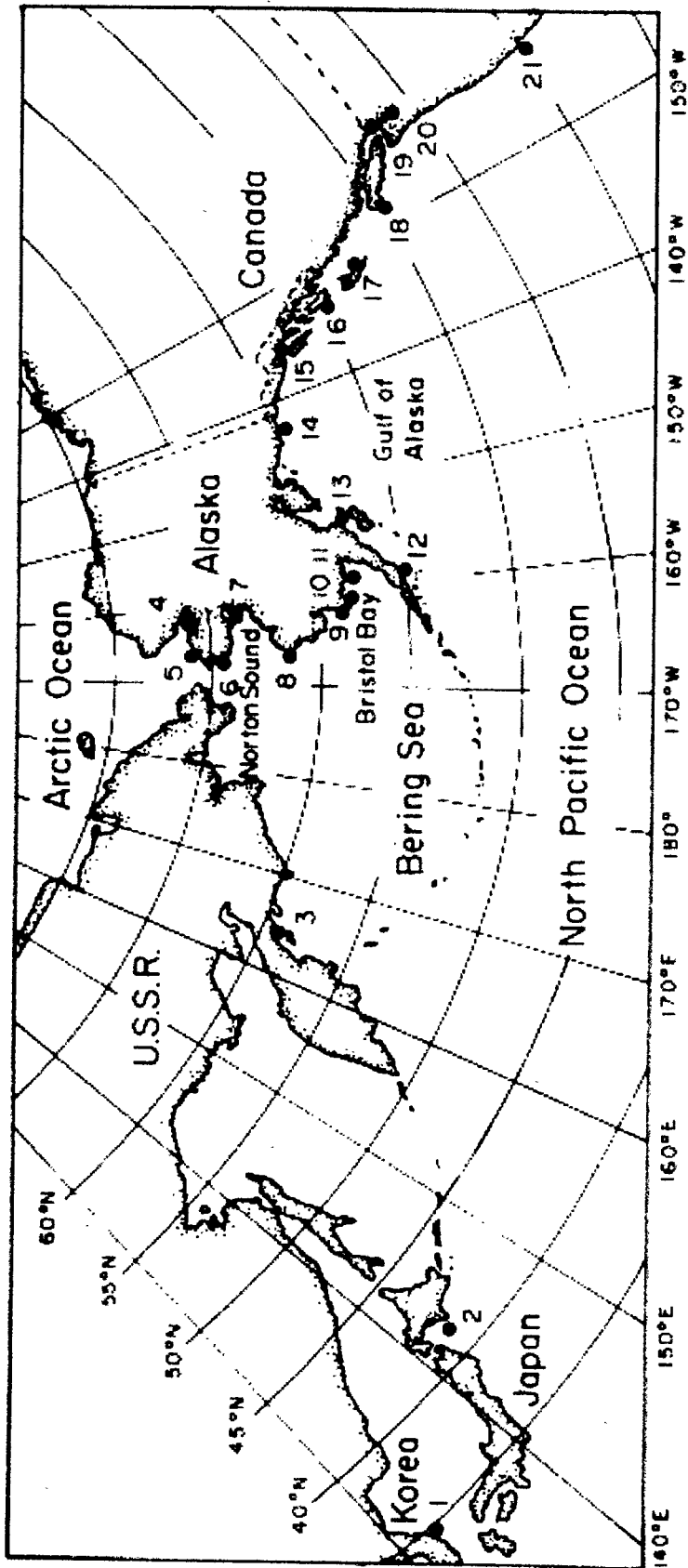


Figure 15. Locations sampled for a Pacific herring allozyme study (from Grant and Utter 1984, fig. 1). Sample locations are as follows: 1. Eastern Korean Peninsula; 2. Hokkaido, Japan; 3. Gulf of Kori; 4. Shismaref Inlet; 5. Hotham Inlet; 6. Port Clarence; 7. Cape Denbigh; 8. Cape Romanzof; 9. Security Cove; 10. Hagemeister Strait; 11. Kulukak Bay; 12. Ramsey Bay; 13. West of Kodiak Island; 14. Yakutat Bay; 15. Lynn Canal; 16. Helm Bay; 17. Queen Charlotte Island; 18. Vancouver Island; 19. Strait of Georgia; 20. Hale Passage; 21. San Francisco Bay.

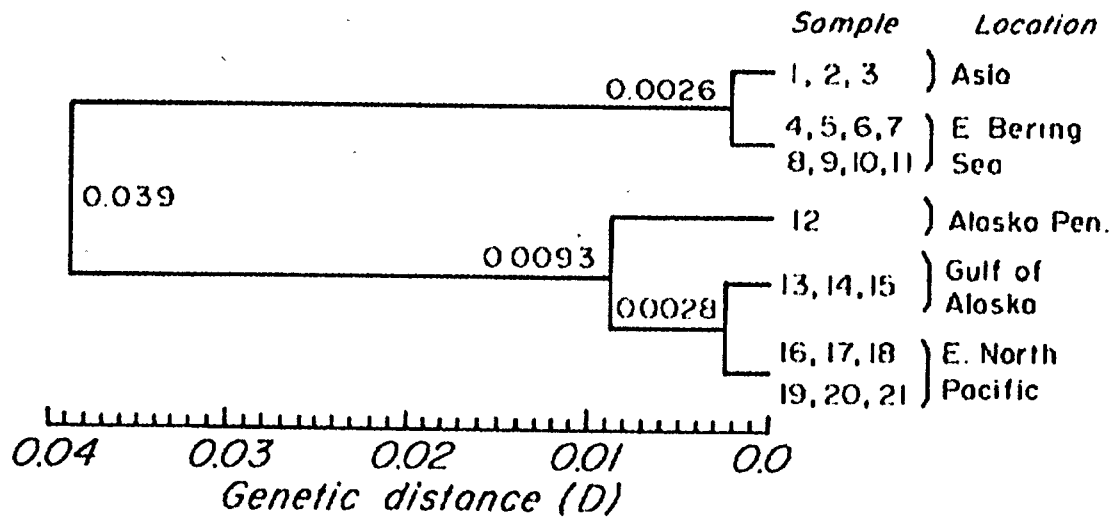


Figure 16. Dendrogram showing the results of a UPGMA cluster analysis of Nei's genetic distance (Nei 1972) for 21 Pacific herring samples (from Grant and Utter 1984, fig. 3). The average D between pairs of samples within the eastern North Pacific was not significantly different than zero. Sample numbers refer to those identified in Figure 15.

Similar to Grant and Utter's study, Kobayashi (1993) used allozyme analyses to conduct a genetic study of Pacific herring throughout their range. The majority of the samples were from Asia ($N = 18$), however the study also included one sample from San Francisco Bay, one sample from Puget Sound, and three samples from Alaska. Analogous to the findings of Grant and Utter (1984), Kobayashi found significant genetic differentiation between Asia-Bering Sea samples and eastern North Pacific samples, separated by a Nei's distance value of 0.054 (Fig. 17). Very little differentiation was evident among the southeastern samples. Nei's distance values between the Puget Sound sample and the sample from Vancouver Island (data was obtained from Grant 1981) and San Francisco Bay, were both less than 0.001.

Unfortunately, the Kobayashi study is the last to include any Pacific herring samples from Puget Sound. Currently, microsatellite data is being collected from Puget Sound herring by the Washington Department of Fish and Wildlife (J. Shaklee⁴) and mtDNA data from the same samples by the University of Washington School of Aquatic and Fishery Sciences (P. Bentzen⁵), but the results from these studies is not yet available. However, other genetic studies of Pacific herring have been done, some of which include samples from areas geographically close to Puget Sound.

Schweigert and Withler (1990) examined 12 samples of Pacific herring using seven polymorphic allozyme loci, and a restriction endonuclease analysis of mitochondrial DNA (mtDNA). The majority of their samples ($N = 10$) were collected from southern British Columbia, while two temporally-spaced samples came from one location in northern British Columbia. One of the southern samples was collected from Yellow Point which lies about 50 km from the northern boundary of Puget Sound. Neither the allozyme nor mtDNA data provided any evidence of significant genetic differentiation among the locations. Their cluster analysis of Nei's (1978) D resulted in D values ranging from 0.000 - 0.004. A gene diversity analysis showed that 99.6% of the variation observed was due to differences within samples, whereas the amount attributed to variation among samples within years was less than 0.3%. Similar to Grant and Utter (1984), a north to south decline in the *GAPDH-1*50* frequency was observed. They also found that samples taken from the same location in two consecutive years showed considerable temporal variation. The gene diversity analyses revealed almost as much variation among years within areas then variation among samples within years.

Sequence variation in ribosomal DNA of Pacific herring, as well as Atlantic herring was investigated by Domanico, Phillips, and Schweigert (1996). Their sampling sites spanned the entire coast of British Columbia, including Tumbo Channel in the Strait of Georgia, which is only 4 km from the northern boundary of Puget Sound. The restriction site they examined was polymorphic, but based upon the percent difference between fragment patterns

⁴ J. Shaklee, Washington Department of Fish and Wildlife, 600 Capital Way N., Olympia, WA 98501. Pers. commun., July 2000.

⁵ P. Bentzen, Marine Molecular Biotechnology Laboratory, University of Washington, 3707 Brooklyn Ave. NE, Suite 175, Seattle, WA 98105. Pers. commun., July 2000.

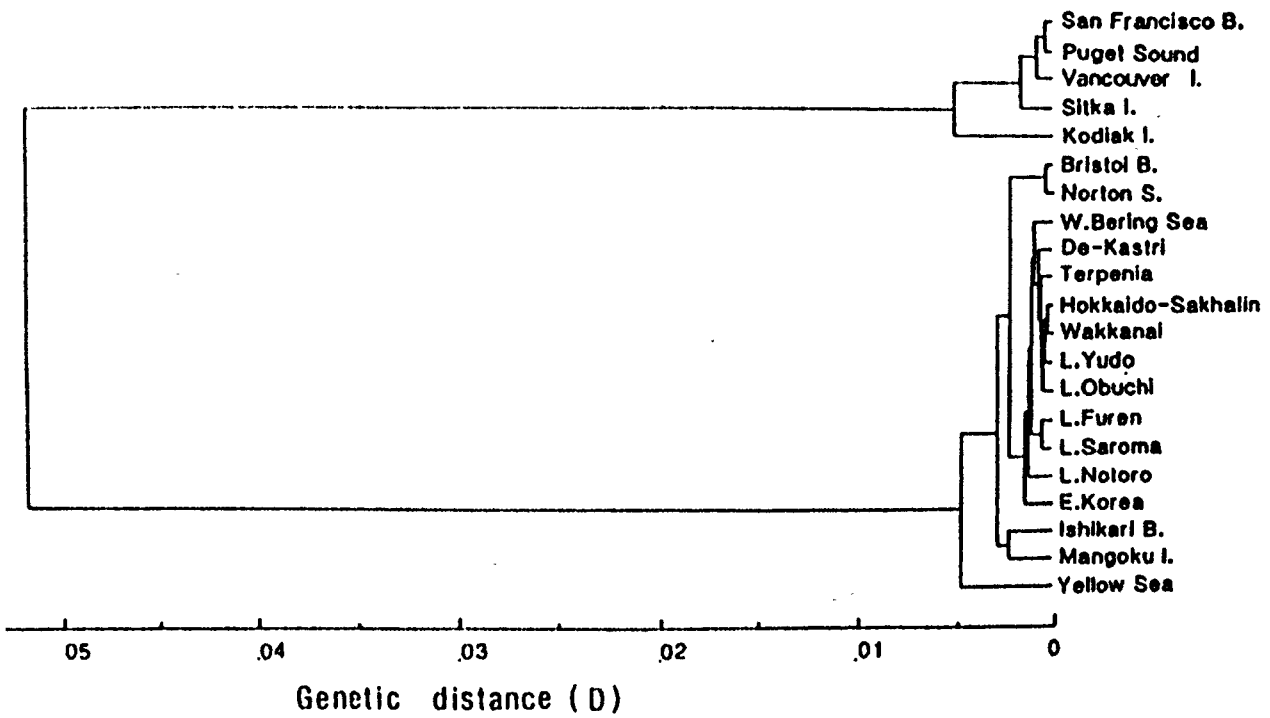


Figure 17. UPGMA cluster analysis of Nei's genetic distance (Nei 1972) for 21 Pacific herring populations (from Kobayashi 1993, fig. 29). Data for the Vancouver Island sample was obtained from Grant (1981).

(Wayne et al. 1991) there was no stock-specific patterns of differentiation for the six British Columbia locations they sampled.

Several genetic studies of Alaska Pacific herring have also been conducted. Burkey (1986) analyzed 16 samples collected from seven locations by commercial herring fisheries within Prince William Sound, Alaska. He analyzed 14 polymorphic allozyme loci but did not find any significant differences among samples, among locations, or between years within a location. A gene diversity analysis showed that over 99% of the total variability was due to variability within samples.

Seven populations of Alaskan Pacific herring were sampled in two different years and examined for microsatellite variation (Wright et al. 1996, Wright and Dillon 1997, O'Connell et al. 1998a, 1998b) and mtDNA variation (Bentzen et al. 1998). The results of these studies were summarized by Seeb et al. (1999). Differences in microsatellite allele frequencies were significant among all samples, whereas the mtDNA haplotype frequency variation was not significant among samples collected in 1995, but were significant among 1996 Prince William Sound samples. Similar to previous studies, the greatest amount of genetic divergence was between samples from the Bering Sea and the Gulf of Alaska. Analogous to what was found by Schweigert and Withler (1990), samples collected from the same location in different years showed a high degree of genetic differentiation. The authors state that "the magnitude of genetic variation among sampling years within locations was equal to or greater than the magnitude of variation among locations within sea basins." They concluded "the DNA data provide no evidence of stable differentiation among populations within sea basins on spatial scales of up to ~700 km. Rather, the DNA data suggest that temporal variation among spawning aggregations dominates genetic variability on these spatial scales."

Two main conclusions about genetic differentiation among Pacific herring populations can be drawn from these studies. First, Pacific herring show considerable temporal variation in allele frequencies. Bentzen et al. (1998), Wright and Dillon (1997) and Schweigert and Withler (1990) all found significant temporal variation in the samples they analyzed. A high degree of temporal variation has the potential to confound genetic population studies. Ideally, all samples for a study should be sampled in the same year. Such was the case for the majority of the studies reviewed here. Additionally, sampling all locations in multiple years as Wright and Dillon (1997) and Bentzen et al. (1998) did, will provide valuable information regarding the nature of any observed genetic variation.

Second, Pacific herring have comparatively low levels of genetic differentiation among populations. According to Hartl (1980), gene diversity values of 0.05 - 0.15 indicate moderate differentiation among populations. Reported gene diversity values for Pacific herring of 0.005 (Grant and Utter 1984), 0.004 (Burkey 1986), 0.003 (Schweigert and Withler 1990), 0.013 (mtDNA) and 0.030 (microsatellites) (Seeb 1999) for comparisons among samples within a predefined area, are all below this range. While some genetic differentiation was evident in Alaskan samples, neither Utter et al. (1974), Grant and Utter (1984), or Kobayashi (1993) found any evidence of significant genetic differentiation between Puget Sound herring populations and California, Oregon, British Columbia, or southeast Alaska herring populations. Grant and Utter

(1984) determined that “very little migration is required to maintain genetic homogeneity at the very large population sizes that are characteristic of herring.” Significant migration among Pacific herring populations would result in a high degree of gene flow, and thus little to no genetic differentiation among populations.

Life-history information

Pre-historical and historical persistence in Puget Sound—Tunncliffe et al. (in press) examined fish remains in a complete Holocene sediment core sequence from Saanich Inlet, Vancouver Island, British Columbia. Pacific herring were one of the first fish species to occur in Saanich Inlet following glacial retreat from the region, after approximately 12,000 years before present (BP) (Tunncliffe et al. in press). Fish abundance and species diversity peaked in Saanich Inlet between 7,500 and 6,000 BP, and the last 1,000 years have seen some of the lowest abundances of fishes in Saanich Inlet’s marine history (Tunncliffe et al. in press). The close proximity of Saanich Inlet to Puget Sound would suggest that Pacific herring were also likely established in Puget Sound by about 12,000 BP. Pacific herring were identified in prehistoric fish skeletal remains from the Duwamish No. 1 archeological site (45-KI-23), located 3.8 km upstream from Elliott Bay on the Duwamish River, utilized by aboriginal humans between A.D. 15 and A.D. 1654 (Butler 1987). However, Pacific herring remains were infrequently found at this site and the family Clupeidae ranked 19th out of the 25 fish groups, in order of abundance (Butler 1987). In historic times, Pacific herring were reported as “exceedingly abundant” in Puget Sound by Jordan and Starks (1895).

Spawning location and spawn timing

The overall distribution and spawn timing of Pacific herring stocks in North America were reviewed by Scattergood et al. (1959), Hay (1985), and Haegele and Schweigert (1985). Pacific herring spawning has been reported in sheltered inlets, sounds, bays and estuaries from San Diego, California in the southern extreme of the range, north along the West Coast of North America to Cape Bathurst in the Beaufort Sea (Hay 1985, Haegele and Schweigert 1985). In general, Pacific herring spawn timing varies with latitude, and over their entire range spawning occurs for nearly 10 months of the year (Hay 1985). The earliest spawning reportedly occurs in southern California in early fall and the latest occurs in August in Bristol Bay, Alaska (Hay 1985). However, it is also apparent that in some regions, the earliest and latest spawnings can be up to six months apart. Figures 13a-d summarize selected information on spawn timing of Pacific herring.

In some locations, Pacific herring are known to spawn in several discrete waves that are separated by several days to weeks, although individual female herring deposit all their eggs in one to two days. It has also been noted that the older and larger fish tend to spawn in the earliest wave, with subsequent waves being made up of smaller fish (Hay 1985, Ware and Tanasichuk 1989, Hay 1990). Pacific herring in some aggregations, such as in Barkley Sound on the west coast of Vancouver Island, can hold in a state of full maturity for several days to weeks, whereas herring in more protected inshore spawning locations usually spawn as soon as full maturity is achieved (Ware and Tanasichuk 1989). Ware and Tanasichuk (1989) examined maturation rates in selected

groups of male and female Pacific herring in British Columbia during the month prior to spawning for 1982-87. These latter authors found that the influence of water temperature and body size on the maturation rate (as measured by the gonosomatic index (GSI)) could explain: 1) why Pacific herring spawn in waves, 2) much of the variation in spawn timing between regions, and 3) much of the year-to-year variation in spawn timing at a given location.

Hay (1990) suggested that differences in spawn timing of Pacific herring stocks could possibly be explained by herring having “spawning times that match local zooplankton production schedules, particularly the time of egg production by copepods because copepod eggs are, overwhelmingly, the dominant food organism of larval herring.”

California—According to Miller and Schmidtke (1956) and Spratt (1981), Pacific herring have been known to spawn in California in the following estuaries: 1) Crescent City Harbor, 2) Humboldt Bay, 3) Shelter Cove, 4) Noyo River, 5) Russian River, 6) Bodega Bay, 7) Tomales Bay, 8) San Francisco Bay, 9) Elkhorn Slough, 10) Monterey Bay 11) Morro Bay, 12) San Luis River, and 13) San Diego Bay (Fig. 11). Miller and Schmidtke (1956) stated that spawning is also believed to occur in Los Angeles Harbor, Santa Ynez Lagoon, Drakes Bay, and at Fort Bragg; however, the spawning grounds have not been documented in these areas. Within California, the Tomales Bay and San Francisco Bay populations have the largest populations (Barnhart 1988).

Since larval herring have been found in San Francisco Bay as early as October (Eldridge and Kaill 1973), Hay (1985) stated that “earliest spawnings probably occur in the early fall in California.” Barnhart (1988) stated that herring spawn from November to June in California, although most spawning occurs from December to February. Figure 13a summarizes known spawn timing for Pacific herring in California.

Oregon—Because herring are of minor economic importance in Oregon, only limited information is available on the species (Scattergood et al. 1959). Scattergood et al. (1959) stated that principal spawning grounds for Pacific herring in Oregon included Yaquina, Tillamook, and Coos bays (Fig. 11). Lassuy (1989) indicated that spawning also occurs in the vicinity of Reedsport, Oregon (Winchester Bay) and in the Columbia River estuary (Fig. 13a). Spawning was reported to occur in Yaquina Bay from January to April and in Tillamook Bay from February to April (Scattergood et al. 1959) (Fig. 13a).

Washington—Currently, WDFW recognizes eighteen spawning stocks of Pacific herring in Puget Sound: 1) Squaxin Pass, 2) Quartermaster Harbor, 3) Port Orchard-Port Madison, 4) South Hood Canal, 5) Quilcene Bay, 6) Port Gamble, 7) Kilisut Harbor, 8) Port Susan, 9) Holmes Harbor, 10) Skagit Bay, 11) Fidalgo Bay, 12) Samish Bay-Portage Bay, 13) Interior San Juan Islands, 14) Northwest San Juan Islands, 15) Semiahmoo Bay, 16) Cherry Point, 17) Discovery Bay, and 18) Dungeness Bay (Lemberg et al. 1997, O’Toole et al. 2000). Geographic distribution of the spawning sites for these stocks are illustrated in Figure 12. Detailed descriptions of these spawning stocks can be found in Lemberg et al. (1997) and O’Toole (2000). Most Puget Sound Pacific herring stocks, as recognized by WDFW(1998), spawn on multiple shoreline locations within a restricted geographic location. For example, the

Squaxin Island stock in South Puget Sound spawns in the mouth of Hammersley Inlet, in Totten Inlet at Gallagher Cove, and in Squaxin Passage. Similarly, the Interior San Juan Islands herring stock is a combination of spawners from East Sound and West Sound on Orcas Island; Mud, Hunter, and Swifts bays on Lopez Island; and Blind Bay on Shaw Island.

O'Toole (2000) provided an historical overview of spawning ground locations for Pacific herring in Puget Sound as gathered from the existing literature, which commences with observations by Chapman et al. (1941), and contrasts these with locations currently supporting spawning aggregations. According to O'Toole (2000), most of the Pacific herring spawning grounds that Chapman et al. (1941) reported as existing in their 1936-37 surveys are included in the grounds or stocks that WDFW currently assesses for abundance. These include Cherry Point, Portage Bay, Semiahmoo Bay, Northwest San Juan Islands, Interior San Juan Islands, Fidalgo Bay, Discovery Bay, Sequim Bay (designated Washington Harbor in Chapman et al. 1941), Kilisut Harbor, Holmes Harbor, Port Orchard-Port Madison, Quartermaster Harbor, and certain spawning grounds in central Hood Canal and in southern Puget Sound south of the Tacoma Narrows.

According to O'Toole (2000), Pacific herring spawning locations that were observed in 1936-37 by Chapman et al. (1941) that no longer support spawning aggregations include Port Blakely and Rolling Bay on the east side of Bainbridge Island and Wollochet Bay in southern Puget Sound. Chapman et al. (1941) and Katz (1942) also identified Echo Bay and Shallow Bay on Sucia Island and a small bay on the President Channel side of Waldron Island in the San Juan Islands as herring spawning locations. Updated information in Koenings (unpubl. data) shows that Wollochet Bay was used as a spawning ground by Pacific herring in the year 2000. Koenings (unpubl. data) also noted that "there has been a relative lack of exploratory herring spawn deposition survey efforts" over the years, and that no recent-era WDFW spawn surveys have been conducted in Port Blakely, Eagle Harbor, Rolling Bay, Shallow Bay, Echo Bay, or near Waldron Island. Thus, it is uncertain whether or not every herring spawn site reported in Chapman et al. (1941) is currently utilized by Pacific herring.

Pacific herring do not apparently utilize these areas for spawning at the present time. In addition, O'Toole (2000) identified a number of spawning grounds for Pacific herring that were not included in the list published by Chapman et al. (1941), but have since been documented: 1) Port Gamble, 2) Quilcene Bay, 3) Dungeness Bay, 4) Port Susan, 5) Samish Bay, 6) South Hood Canal, 7) Skagit Bay, and 8) the Point Whitehorn to Lummi Bay and Point Roberts portions of the Cherry Point stock.

Chapman et al. (1941) referred to an unpublished report of observations of Pacific herring spawning grounds in Puget Sound made in 1927 by Arthur S. Einarsen of the Washington Department of Fisheries. According to Chapman et al. (1941), the Einarsen report listed the spawn timing of the Birch Bay (Cherry Point) population as occurring from May 1st to June 10th in 1927. These dates are within the range of spawn dates of late-March to mid-June reported for recent years at Cherry Point by O'Toole (2000). According to Chapman et al. (1941), the Einarsen report listed Eagle Harbor, on the east side of Bainbridge Island, as supporting a spawning aggregation of Pacific

herring during the first three weeks of February. Apparently, no Pacific herring spawning has been reported in Eagle Harbor since the Einarsen report (Chapman et al. 1941, O'Toole 2000).

Within Puget Sound, major Pacific herring stocks spawn from late-January through early-April (Trumble 1983b, Lemberg et al. 1997, O'Toole 2000). An exception to this is the Cherry Point stock, which spawns from early April through early June (Lemberg et al. 1997, O'Toole 2000) (Figs. 12 and 13b). According to Lemberg et al. (1997) each stock generally spawns over approximately a two-month period. In summary, O'Toole et al. (2000) stated that:

Although some changes in Puget Sound herring spawning behavior have been observed, the consistency of timing and specific spawning locations, comparing historical and current descriptions, is remarkable. Descriptions of peak spawning timing to date typically vary by two weeks or less and most spawning locations have shifted very little, if at all.

On the outer coast of Washington, Pacific herring spawning has been reported to occur in Willapa Bay during February (Chapman et al. 1941, Katz 1942, Lemberg et al. 1997). Chapman et al. (1941) reported that a small number of Pacific herring spawn in Grays Harbor on an irregular basis. Although Lemberg et al. (1997) stated that a survey of Grays Harbor in 1988 "failed to yield any evidence of spawning activity," Koenings (unpubl. data) revealed that herring spawn activity has been documented by WDFW in the South Bay/Elk River estuary of Grays Harbor, annually from 1998-2000. Lassuy (1989) indicated that Pacific herring spawn in the Columbia River estuary (Fig. 11). Lemberg et al. (1997) also stated that spawning activity has been reported from the Ilwaco, Washington and Hammond, Oregon areas of the Columbia River estuary; however, this reported activity has not been documented. Lemberg et al. (1997) stated that currently "the only documented Washington coastal herring spawning stock is the Willapa Bay stock."

British Columbia—Records of Pacific herring spawning activities have been collected in British Columbia since 1928, originally by the Fisheries Research Board of Canada, and in recent times by the Department of Fisheries and Oceans Canada (DFO) (Hay and Kronlund 1987, Hay et al. 1989a-f, Hay and McCarter 1999a). These records generally include data on spawn timing, the location of spawning, the shoreline width and length of spawning, and spawning intensity for each location (Hay and Kronlund 1987). Pacific herring spawn data up to 1986 were described in a detailed six-volume publication (Hay et al. 1989a-f) and data through the 1999 season are available at the DFO operated Herring Spawn Home Page at <http://www-sci.pac.dfo-mpo.gc.ca/herspawn/default.htm>. Approximately 1,300 locations have been identified in British Columbia as having had at least one or more Pacific herring spawnings since 1928 (Hay and Kronlund 1987, Hay and McCarter 1999a, 2000). Generalized locations of major Pacific herring spawning grounds in British Columbia are illustrated in Figures 18 and 19. Detailed spawning site information can be found at the above mentioned website.

Currently, for management purposes, DFO recognizes six Pacific herring management regions in British Columbia: 1) Queen Charlotte Islands, 2) the North Coast British Columbia (Prince Rupert District), 3) the Central Coast, 4) Johnstone Strait, 5) the Strait of Georgia, and

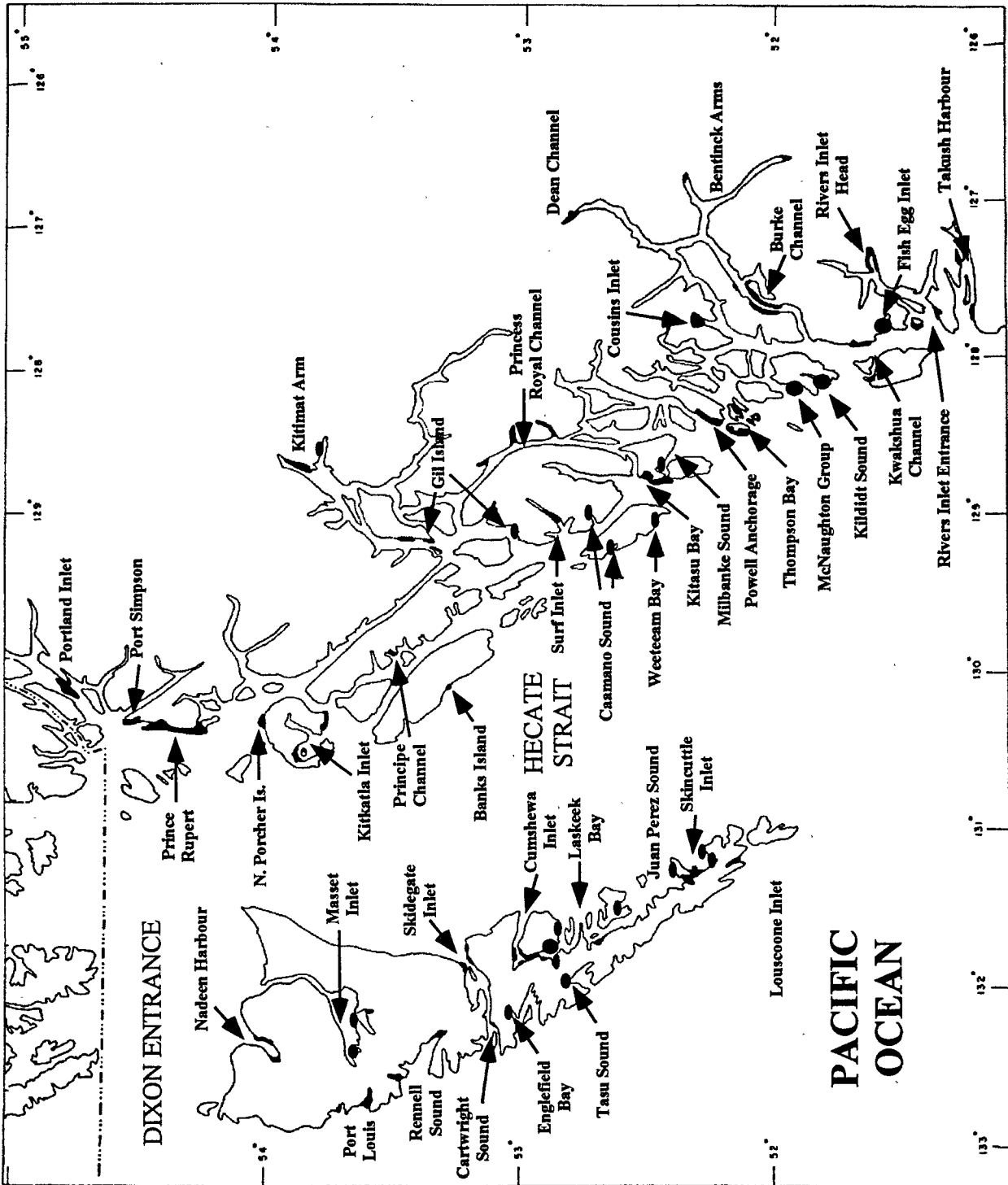


Figure 18. Geographic distribution of major Pacific herring spawning locations in herring Sections on the northern and north-central coast of British Columbia. Map modified from Hourston (1980, figure 1a), with additional information from <http://www.sci.pac.dfoempo.gc.ca/herspaw/default.htm> (DFO 2000a). Named locations refer to DFO herring Section designations and not necessarily to geographical locations.

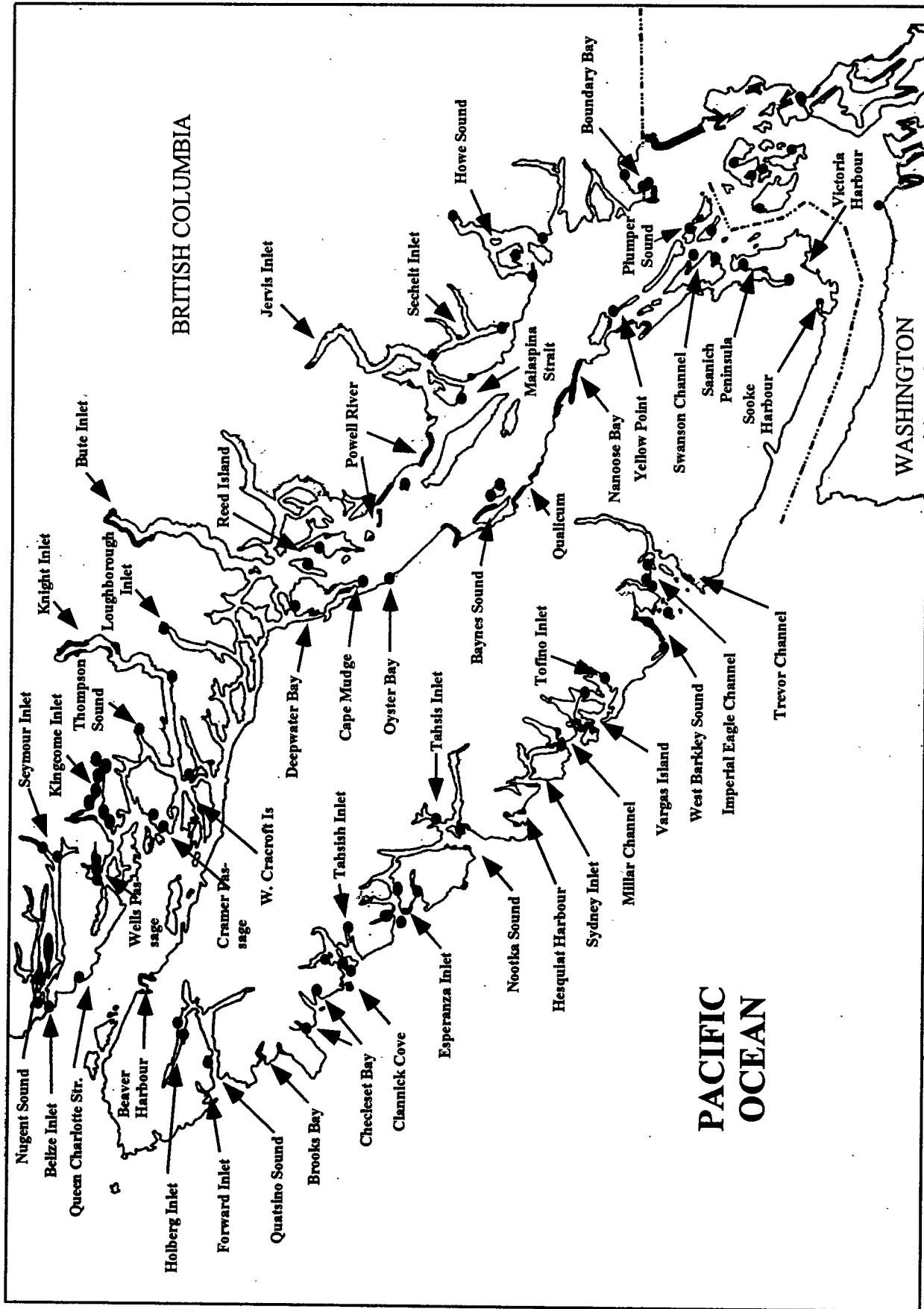


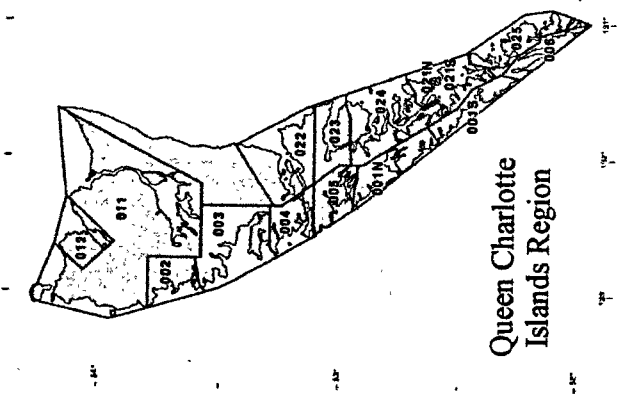
Figure 19. Geographical distribution of major Pacific herring spawning locations in herring Sections in southern British Columbia. Map modified from Hourston (1980, figure 1a), with additional information from <http://www-sci.pac.dfo-mpo.gc.ca/herspawm/default.htm> (DFO 2000a). Named locations refer to DFO Pacific herring Section designations and not necessarily to geographical locations. Pacific herring spawning locations in northern Puget Sound and the U.S. portion of the Strait of Georgia are named in Figure 12.

6) the west coast of Vancouver Island. Each of these Regions is further divided into Statistical Areas, which are further divided into Sections (= Subareas), each of which is named and numbered (Hay and McCarter 2000). The boundaries of each of the 108 Pacific herring Sections are illustrated by Region in Figure 20. Schweigert (unpubl. data) stated that a "location" within a Section is an "artificial construct, usually a local geographic name used to identify a section of shoreline" and that within a Section, "locations are often contiguous and often differ markedly in size." Figures 13c and 13d provide mean spawning day of the year (\pm one standard deviation) and earliest and latest spawning day of the year for most of the Pacific herring Sections in British Columbia.

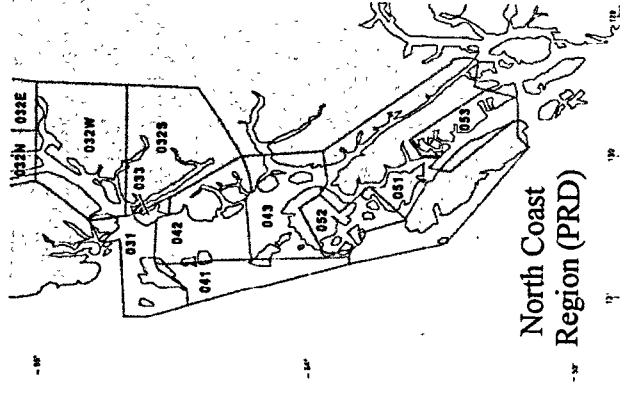
In general, Pacific herring spawn from January to May in southern British Columbia and from mid-January to June in northern British Columbia (Taylor 1964, Hourston 1980) (Figs. 13a, c, d). Outram and Haegele (1969) found a difference of six weeks in the mean spawn timing (from March 8-9 to April 20-21) that occurred between spawning areas in extreme southern and northern British Columbia. However, several exceptions to these generalities occur. For instance, Pacific herring in two geographically adjacent spawning sections in the northern Queen Charlotte Islands, Masset Inlet (Section 011) and Naden Harbour (Section 012), possess some of the extreme latest and earliest spawn timings on the British Columbia coast, respectively (Hay 1985) (Figs. 13c, 20 and 21). Masset Inlet spawnings have been documented in late-June to July (Hay 1985, 1990, Hay and McCarter 1999a) with a mean spawn date of June 20 (DFO 2000b), while Naden Harbour spawnings may occur in late-January or in early-February (Hay 1985, 1990, Hay and McCarter 1999a) with a mean spawn date of March 2 (DFO 2000b) (Fig. 13c, and 21). Pacific herring in other nearby spawning sections in the Queen Charlotte Islands Region spawn mainly in April (Hay 1985). Pacific herring from Skidegate Inlet (Section 022, mean spawn date of May 14) and Burke Channel (Section 084, mean spawn date of June 1) also possess consistently later spawn timings than other Sections in their respective regions (Hay 1985, DFO 2000b) (Figs. 13c, 20 and 21).

Barraclough (1967) reported on the occurrence of larval Pacific herring in surface trawls on July 5-8, 1966 in the southern Strait of Georgia, between the Fraser River delta and Vancouver Island. Based on the size of these larval herring, Barraclough (1967) calculated that they were the result of spawning that had occurred between May 22 and June 4, which was considerably later than any previously reported Pacific herring spawn timing in the British Columbia portion of the Strait of Georgia (Barraclough 1967). Based on the counterclockwise flow of currents in the Strait of Georgia, Barraclough (1967) postulated that these larvae had hatched from spawn deposition in the vicinity of Boundary Bay. The estimated timing of this spawn deposition suggests the larvae encountered by Barraclough (1967) were progeny of the WDFW Cherry Point Pacific herring stock.

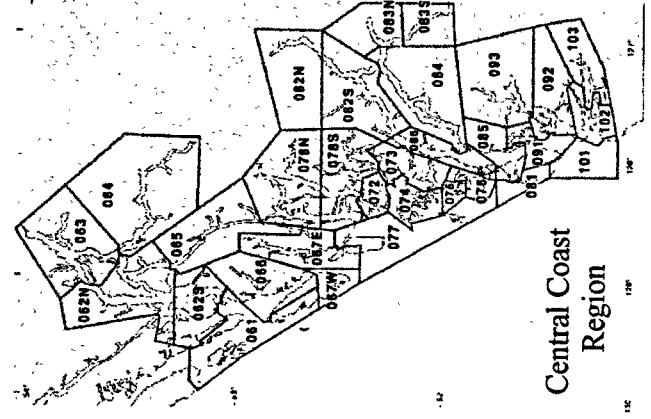
Hay and McCarter (1999a) examined long-term trends (1928-99) in the minimum, mean, and maximum day of spawning for each of the Pacific herring management regions in British Columbia and found that: 1) the range of spawn timing and the mean spawning day of the year have steadily declined in both the Queen Charlotte Islands and North Coast British Columbia (Prince Rupert District) regions, 2) both the long-term mean and range of spawn timing in the Central Coast and Johnstone Strait regions have remained steady, 3) the Strait of Georgia Region has experienced "a striking contraction of the range of spawning times, mainly from the loss of early spawning fish.", and 4) the west coast of Vancouver Island Region has also experienced a loss of early spawning herring, but the mean spawn day of the year has remained steady. Overall, Hay and McCarter



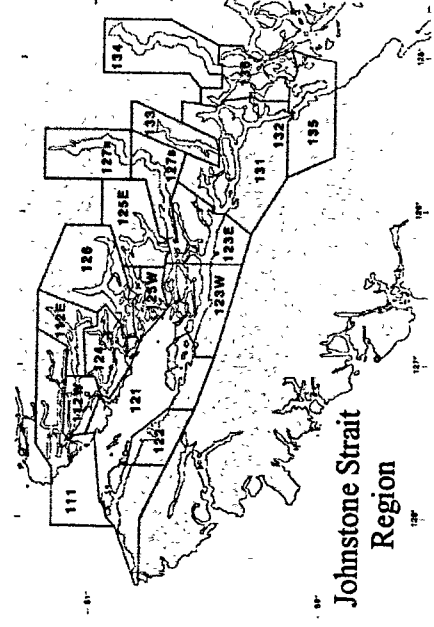
Queen Charlotte Islands Region



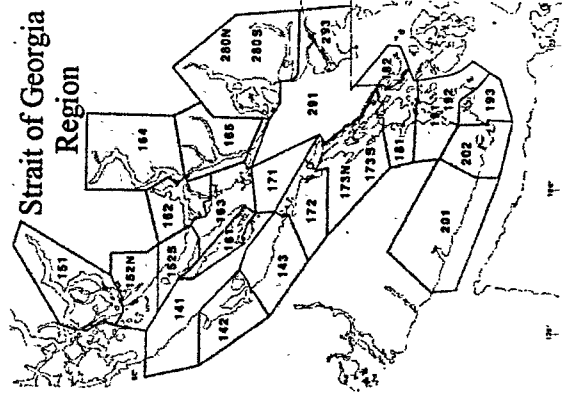
North Coast Region (PRD)



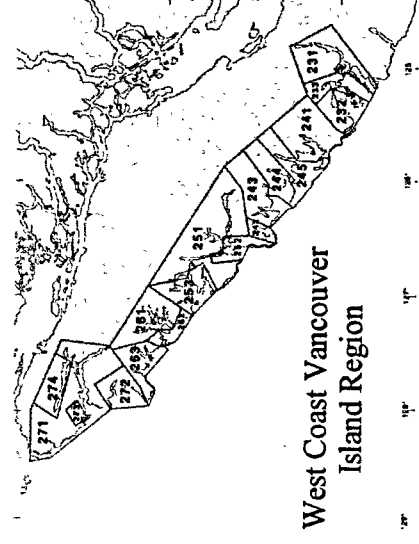
Central Coast Region



Johnstone Strait Region



Strait of Georgia Region



West Coast Vancouver Island Region

Figure 20. DFO Pacific herring Sections in the six Regions of British Columbia. Maps modified from those available at <http://www-sci.pac.dfo-mpo.gc.ca/herspawnt/default.htm> (DFO 2000a).

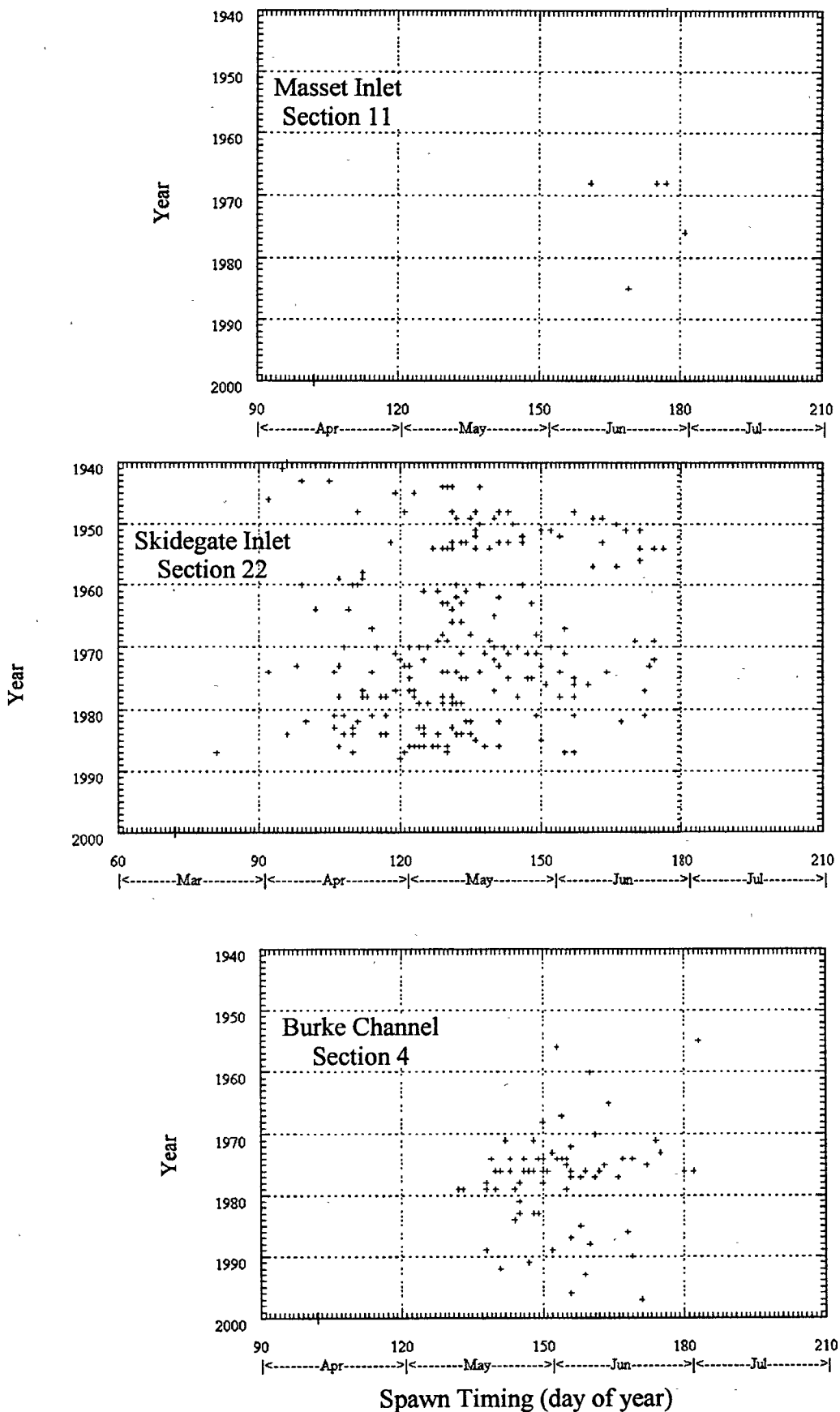


Figure 21. Timing of Pacific herring spawn observations at Masset and Skidegate Inlets in the Queen Charlotte Islands Region, and at Burke Channel in the Central Coast Region of British Columbia. See Fig. 20 for geographical locations. Spawn timing diagrams modified from those available at <http://www-sci.pac.dfo-mpo.gc.ca/herspawn/default.htm> (DFO 2000a).

(1999a) noted that the duration of Pacific herring spawn timing in British Columbia is becoming shorter and, in most areas Pacific herring are starting to spawn later and completing spawning earlier than in the past. Hay and McCarter (1999a) postulated that factors such as fisheries or climate change may account for some of the observed temporal changes in spawn timing; however, declining survey efforts, particularly in the non-assessment Sections, could also be a factor in the observed changes (Hay and McCarter 1999a).

Hay (1985) found a statistically significant inverse correlation between the mean temperatures for March and the mean spawning date (as Julian calendar day of the year) for Pacific herring in the Strait of Georgia between 1951 and 1982. Thus, within the limited geographical area of the Strait of Georgia, these analyses indicated that spawning occurs earlier in high temperature years and later in low temperature years (Hay 1985).

Alaska—In Southeast Alaska, six major Pacific herring stocks are recognized on the basis of their particular wintering grounds: 1) Ketchikan, 2) Dear Island-Etolin Island (near Wrangell, Alaska, 3) Craig-Hydaburg, 4) Auke Bay, 5) Sitka (Carlson 1980), and 6) Tenakee Inlet (east side of Chichagoff Island) (Carlile, unpubl. data). Carlile (unpubl. data) indicated that the Tenakee Inlet stock has recently been recognized as a major herring stock in Southeast Alaska. In the year 2000, the Tenakee Inlet stock had the second largest spawn abundance, behind the Sitka stock (Carlile, unpubl. data). Rounsefell (1930), Skud (1960), Blankenbeckler (1978), and Blankenbeckler and Larson (1982, 1985) provided information on the Pacific herring spawning localities and timing in Southeast Alaska (Table 3). Spawning localities identified by Rounsefell (1930) and Skud (1960) are listed in Figure 13a and their general locations are illustrated in Figure 22. Skud (1960) stated that although many Pacific herring spawning localities are utilized year after year, “in others there is a definite change in location of spawning beaches from year to year.” Skud (1960) failed to detect spawning at 37 of the 57 localities listed by Rounsefell (1930) as Pacific herring spawning locales (Fig. 13a). Skud (1960) suggested three possible explanations for this discrepancy: 1) spawning locales may have changed between 1930 and the mid-1950s, 2) surveys may have missed spawning events, or 3) information supplied to Rounsefell (1930) may have been incorrect.

Between Southeast Alaska and Prince William Sound, few suitable Pacific herring spawning grounds are available and the continental shelf is of limited extent (Burkey 1986). Pacific herring spawn in south-central Alaska in Yakutat, Kenai Peninsula (Burkey 1986), Prince William Sound, Cook Inlet, and in the Kodiak-Afognak islands vicinity (Rounsefell 1930, Kruse 2000) (Fig. 23).

Pacific herring spawn on the western coast of Alaska in the eastern Bering Sea on the north side of the Alaska Peninsula, in Bristol Bay in the Togiak District, near Nunivak and Nelson islands, at Cape Romanzof, in Norton Sound, in Port Clarence and in Kotzebue Sound (Rounsefell 1930, Barton and Wespestad 1980, Haegle and Schweigert 1985, Kruse 2000) (Fig. 23).

Pacific herring spawning in the Bering Sea and northward is associated with climatological conditions, particularly ice-break-up (Barton and Wespestad 1980). Thus spawning in the eastern Bering Sea commences along the northern coast of the Alaska Peninsula in April-May and occurs progressively later to the north (Barton and Wespestad 1980, Kruse 2000), not occurring until early August in some years at Kotzebue (Figs. 13a and 23). Pacific herring spawning does not begin until after break-up, in June to July, in the Beaufort Sea (Tanasichuk et al. 1993).

Table 3. Localities in Southeast Alaska with reported Pacific herring spawning activity prior to 1930 and in the 1950s. Letter pre-fixes indicate the general vicinity of the sites as defined by Skud (1960): K, vicinity of Ketchikan; C, vicinity of Craig; F, vicinity of Frederick Sound; A, vicinity of Auke Bay; S, vicinity of Sitka. (X, spawning observed; O, no spawning observed; dashes indicate data were unavailable).

Site number	Locality	Spawn activity prior to 1930 (Rounesfell 1930)	Spawn activity 1953-55 (Skud 1960)
K-1	Foggy Bay	-	X
K-2	Kirk Point	-	X
K-3	Kah Shakes Cove	-	X
K-4	Kah Shakes Point	-	X
K-5	Annette Point	-	X
K-6	Ham Island	-	X
K-7	Mountain Point	-	X
K-8	George Inlet	-	X
K-9	Clover Pass	-	X
K-10	Loring	X	O
K-11	Indian Point	-	X
K-12	Spacious Bay	X	O
K-13	Port Steward	X	O
K-14	Morgan's Cove	X	-
K-15	Point Francis	-	X
K-16	Raymond Cove	-	X
K-17	Wadding Cove	-	X
K-18	Trunk Island	X	X
K-19	Helm Bay	-	X
K-20	Smuggler's Cove	-	X
K-21	Bond Bay	-	X
K-22	Caamano Point	X	X
K-23	Kasaan Village	-	X
K-24	Sandy Point	-	X
K-25	Karta Bay	-	X
K-26	Tolstoi Bay	-	X
K-27	N. E. of Ship Island	-	X
K-28	Meyer's Chuck	X	O
K-29	Lemesurier Point	-	X
K-30	Union Bay	X	O
K-31	Vixen Inlet	X	O
K-32	Stones Island	-	X
K-33	Etolin Island	-	X
K-34	Kelp Point	-	X
K-35	Stanhope Island	-	X
K-36	Marble Point	-	X
K-37	Burnett Inlet	-	X

Table 3. (Continued-2).

Site number	Locality	Spawn activity prior to 1930 (Rounesfell 1930)	Spawn activity 1953-55 (Skud 1960)
C-1	Rose Inlet	X	O
C-2	Goat Island	-	X
C-3	Trocadero Bay	X	O
C-4	Suemez Island	-	X
C-5	Baker Island	-	X
C-6	Coronado Islands	-	X
C-7	Port Bagial	-	X
C-8	Cape Suspiro	-	X
C-9	Bellana Islands	-	X
C-10	Craig (small boat harbor)	-	X
C-11	Crab Bay	-	X
C-12	Craig	X	O
C-13	Fish Egg Island	X	X
C-14	Klawock Reef	-	X
C-15	Clam Island	X	X
C-16	Wadleigh Island	-	X
C-17	Klawock Inlet	-	X
C-18	Alberto Islands	-	X
C-19	Abness Island	-	X
C-20	Shinaku Inlet	-	X
C-21	Warmchuck Inlet	X	O
C-22	Tonowek Narrows	X	O
C-23	Tuxekan Passage	X	O
C-24	Sierra Sound	X	O
C-25	Shakan (El Capitan) Pass	X	O
F-1	Ideal Cove	-	X
F-2	Hicks Point	-	X
F-3	Little Duncan Bay	-	X
F-4	Duncan Canal	X	O
F-5	Point Baker	-	X
F-6	No Name Bay	-	X
F-7	Elena Bay	-	X
F-8	Rocky Pass Inlet	X	O
F-9	Port Camden	-	X
F-10	Saginaw Bay	-	X
F-11	Hamilton Bay	X	O
F-12	Kake	X	O
F-13	Cape Bendel	-	X
F-14	Farragut Bay	-	X
F-15	Port Houghton	X	O
F-16	Pybus Bay	X	X

Table 3. (Continued-3).

Site number	Locality	Spawn activity prior to 1930 (Rounesfell 1930)	Spawn activity 1953-55 (Skud 1960)
F-17	Pleasant Bay	X	O
F-18	Mole Harbor	X	O
F-19	Flaw Point	-	X
F-20	west shore Glass Peninsula	-	X
A-1	Idaho Inlet	X	O
A-2	Mud Bay	X	O
A-3	Flynn Cove	X	O
A-4	Port Frederick	X	O
A-5	Douglas Island	X	X
A-6	Spuhn Island	-	X
A-7	Coghlan Island	X	X
A-8	Auke Bay	X	X
A-9	Auke Cape	-	X
A-10	Point Louisa	X	X
A-11	Point Lena	X	X
A-12	Lena Cove	X	X
A-13	Point Stephens	X	X
A-14	Tee Harbor	X	X
A-15	Pearl Harbor	-	X
A-16	Eagle Harbor	-	X
A-17	Eagle River	-	X
A-18	east of Benjamin Island	-	X
A-19	Bridget Cove	-	X
A-20	Berners Bay (Echo Cove)	-	X
A-21	Flat Bay	-	X
A-22	Nudik Point	-	X
A-23	Tanani Point	-	X
S-1	Port Alexander	X	-
S-2	Redfish Bay	X	O
S-3	Biorka Island	X	O
S-4	Redoubt Bay	-	X
S-5	Kidney Cove	-	X
S-6	Iput Island	-	X
S-7	Taigud Island	-	X
S-8	Korga Island	-	X
S-9	Kizhuchia Creek	-	X
S-10	Caution Island	-	X
S-11	Povorotni Point	-	X
S-12	Meilkoi Cove	-	X
S-13	Three Entrance Bay	-	X
S-14	Cape Buronof	-	X

Table 3. (Continued-4).

Site number	Locality	Spawn activity prior to 1930 (Rounesfell 1930)	Spawn activity 1953-55 (Skud 1960)
S-15	Pirate Cove	-	X
S-16	Samsing Cove	-	X
S-17	Sandy Cove	-	X
S-18	Deep Inlet	-	X
S-19	Aleutkina Bay	-	X
S-20	Leesoffskaia Bay	-	X
S-21	Silver Bay	X	O
S-22	Jamestown Bay	X	X
S-23	Whale Island	X	X
S-24	Apple Island	X	X
S-25	Kasiana Island	X	X
S-26	Middle Island	X	X
S-27	Starrigavan Bay	X	X
S-28	Whitestown Narrows	X	O
S-29	Kakul Narrows	-	X
S-30	Kelp Bay	-	X
S-31	Hood Bay	X	O
S-32	Killisnoo Lagoon	X	O
S-33	Kootznahoo Inlet	X	O

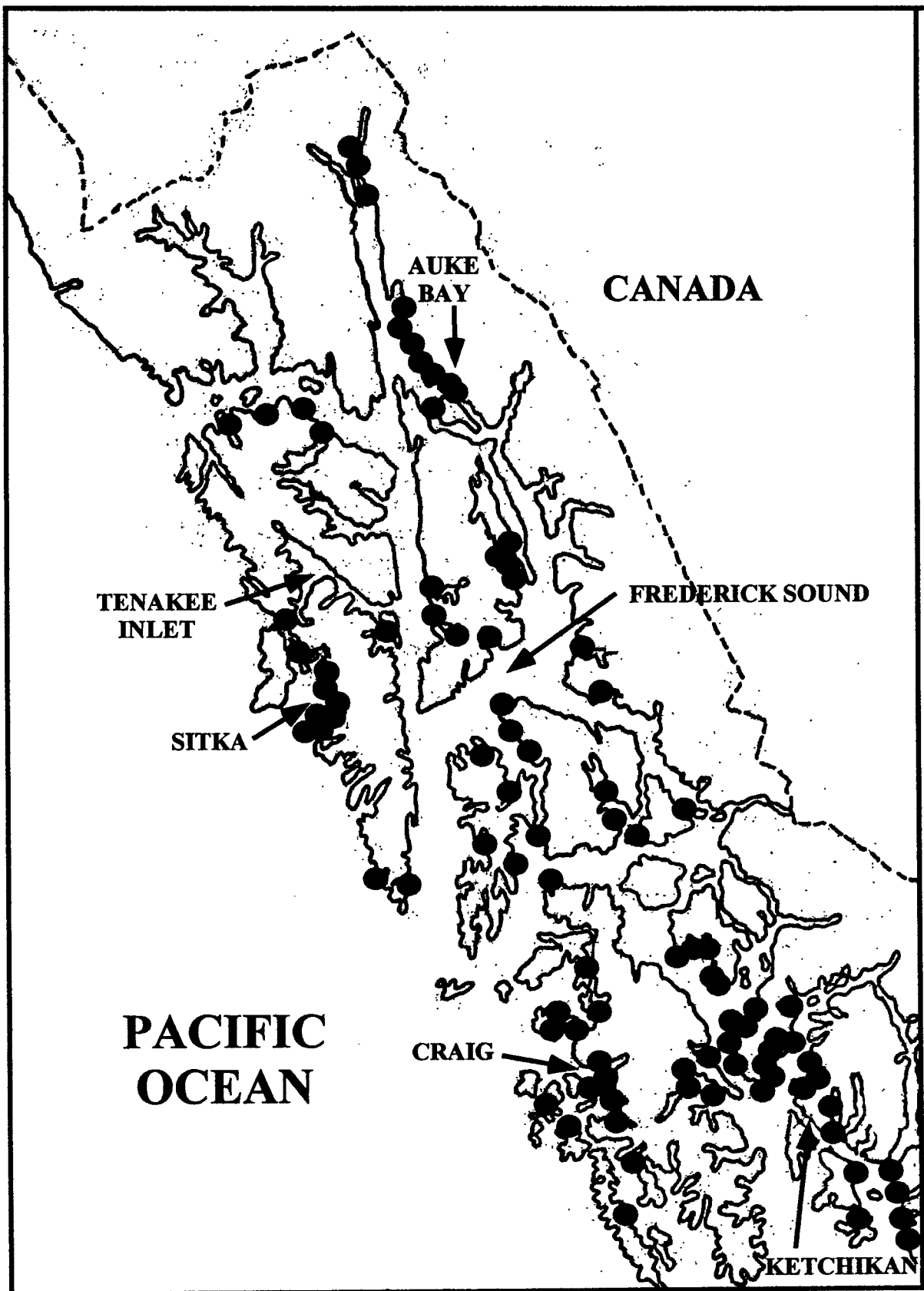


Figure 22. Geographical distribution of major Pacific herring spawning locations in Southeast Alaska. Solid circles (●) represent approximate locations of named Pacific herring spawning localities listed in Rounsefell (1930) and Skud (1960) (see Table 3).

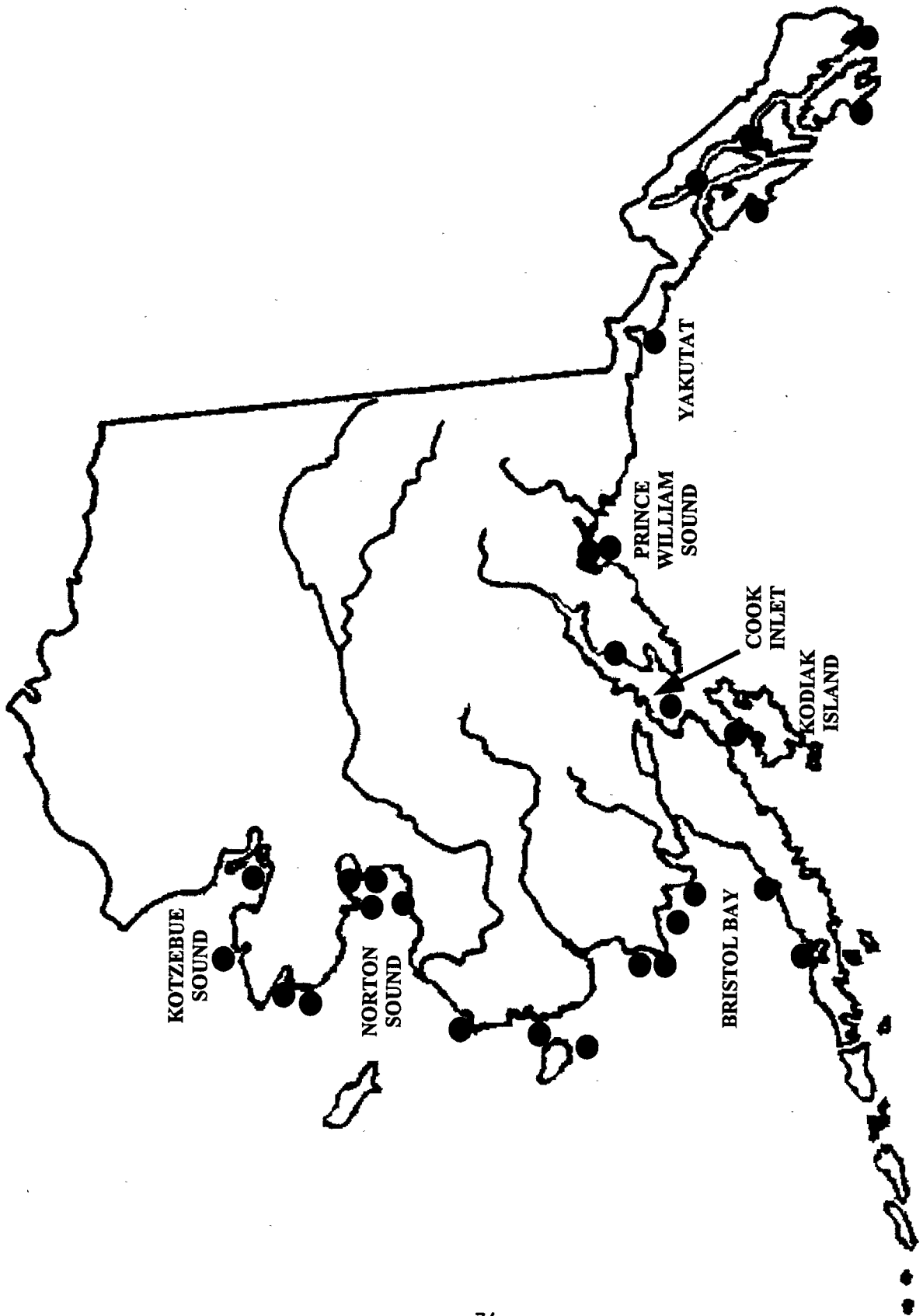


Figure 23. Geographical distribution of major Pacific herring spawning locations in south-central and western Alaska. Solid circles (●) represent approximate locations of Pacific herring spawning localities listed in Rounsefell (1930), Westestad (1978), Barton and Westestad (1980), Hay (1985), ADFG (1985), and Burkey (1986).

Tagging and distribution

In the context of delineation of Pacific herring population structure, key questions that tagging studies address are: 1) To what degree do the same fish return to spawn on the same grounds year after year? and 2) How much interchange (gene flow) occurs between spawning populations? Unfortunately, adult tagging studies cannot help answer another important question: do adult Pacific herring return to the same spawning grounds where they were hatched?

Puget Sound—Taylor (1973) reviewed the results of tagging of over 70,000 Pacific herring in Puget Sound from 1953-59. Tagging apparently occurred both during summer fisheries in the San Juan Islands, Holmes Harbor, and Hood Canal, and during winter fisheries (presumably on pre-spawning populations) in Holmes Harbor, Hood Canal, Bellingham Bay, and Boundary Bay (Taylor 1973). Taylor (1973) addressed only the 52 tag recoveries that occurred in British Columbia, which were mainly from fisheries off the lower east coast of Vancouver Island. Other recoveries included one Holmes Harbor and four Hood Canal herring, tagged in summer fisheries, recovered at Swiftsure Bank off the southwestern tip of Vancouver Island, and one Bellingham Bay and five Boundary Bay herring, tagged in winter fisheries, recovered off the west coast of Vancouver Island (Taylor 1973). Taylor stated that:

These recoveries suggest that movement of herring from the Puget Sound, the San Juan Islands, and the Boundary Bay-Bellingham Bay regions into British Columbia is mostly from the adjacent areas and is probably no greater than between adjacent stocks of similar size in B.C. The recoveries on Swiftsure Bank and on the west coast of Vancouver Island suggest that the American stocks tagged perhaps move to offshore summer feeding grounds in the same way as the Canadian Strait of Georgia stocks.

O'Toole (2000) also reviewed results of the same Puget Sound tagging experiments conducted in the 1950s on Pacific herring from the Holmes Harbor, Port Orchard-Port Madison, and Quilcene Bay WDFW stocks. O'Toole (2000) emphasized that since none of the tag recoveries occurred during the spawning season, they provide little evidence toward resolving the question of spawning site fidelity for Pacific herring. Two Holmes Harbor tags were recovered in December from southern Johnstone Strait, and another Holmes Harbor herring was recovered in Holmes Harbor five years after tagging (O'Toole 2000). O'Toole (2000) reported on the recovery of four tagged Quilcene Bay herring: one was recovered in December from southern Johnstone Strait, two others were recovered at Swiftsure Bank in July, and one was recovered off Victoria, B.C. in September. Two tagged herring of the Port Orchard-Port Madison stock were recovered in Puget Sound: one in the Tacoma Narrows, three months after tagging, and another four-and-a-half years after tagging in the Waldron Island fishery (O'Toole 2000). O'Toole (2000) reported that both Williams (1959) and Buchanan (1986) felt that these tagging results indicate that Quilcene Bay (Hood Canal) herring migrate out of Puget Sound to summer feeding areas off southwest Vancouver Island.

British Columbia—Hay et al. (1999) stated that over 1.5 million tagged Pacific herring were released and over 42,000 of these were recovered in British Columbia between 1936 and 1991. Pacific herring tagging programs in British Columbia utilized small (19 mm long, 4 mm wide, 1.6 mm thick) metallic "belly tags" inserted into the herring body cavity from 1936-67, and plastic "anchor tags" inserted into the dorsal musculature from 1979-91 (Daniel et al. 1999, Hay et al. 1999).

Both Daniel et al. (1999) and Hay et al. (1999) provided extensive bibliographies of technical publications that document these Pacific herring tagging programs. Recovery of belly tags occurred mainly in fish plants processing herring from the reduction fishery. According to Hay et al. (1999), belly tags were detected using magnetic detectors for the most part, and since these tags weren't retrieved until the end of the fishing season, the date of recovery is known only to the nearest year. According to Daniel et al. (1999) and Hay et al. (1999), locations of many belly tag recoveries were also not exact and were often reported as being recovered from within a large geographic area at the level of one of the DFO Pacific herring Regions. Since anchor tags are readily visible on the external surface of the fish, the recent anchor tag recovery data, on the other hand, was usually reported by the day, year, and precise location of recovery that corresponds to a roe fishery location (Daniel et al. 1999, Hay et al. 1999). Figures 24, 25, and 26 (modified from figures available at the DFO Herring Tag Home Page at <http://www-sci.pac.dfo-mpo.gc.ca/herspaw/hertags/default.htm>) (DFO 2000a) illustrate the geographic origin and recovery locations (within the six major Regions) of all Pacific herring tagged in one location and recovered in another location in British Columbia after at least one year at large.

As previously stated, DFO recognizes six Pacific herring management Regions in British Columbia: 1) Queen Charlotte Islands, 2) the North Coast British Columbia (Prince Rupert District), 3) the Central Coast, 4) Johnstone Strait, 5) the Strait of Georgia, and 6) the west coast of Vancouver Island. Each of these Regions is further divided into Statistical Areas, which are further divided into Sections (= Subareas), each of which is named and numbered (Hay and McCarter 2000). The numbered Statistical Areas can be identified by the first two digits of the Section number. The boundaries of each of the 108 Pacific herring Sections are illustrated by Region in Figure 20. In general, each Section contains several spawning beaches or "locations."

Hourston (1982) analyzed Pacific herring belly tag recovery data for British Columbia for the period 1937-67, at the level of the six management Regions and the then current herring-roe fishery "management units," and determined that 77-94% and 54-84% of recovered herring had "homed" to the Region and to the "management unit," respectively, in which they were tagged. Many authors (Schweigert 1991, O'Connell et al. 1998b, O'Toole 2000) have cited Hourston (1982) as evidence that Pacific herring return at high rates to spawning grounds that they spawned on in previous years. However, Hay et al. (1999) have reanalyzed these belly-tag data and included new analyses of the anchor tag data that show that estimations of spawning site fidelity in Pacific herring in British Columbia at large for more than one year are highly dependant on geographical scale. Although, these analyses corroborate Hourston's (1982) conclusion that Pacific herring have high homing or fidelity rates (80-100%) at the large geographic scale of the herring management Regions (Hay et al. 1999), at the smaller geographic scales of Statistical Area, Section, and spawning location the mean fidelity rates are much lower; 50-60% for Statistical Areas, 17-24% for Sections, and 1-2% for specific spawning locations (Fig. 27).

Hay et al. (1999) determined that the best fidelity or homing rates would be obtained by restricting the herring tag recovery database to only those herring released during the spawning months of February to April and to those recovered one or more years later during the same three months. Hay et al. (1999) stated that these restrictions essentially eliminate all of the belly tag data from the analyses since exact recovery dates are unknown for the belly tags. When this was done, the total number of informative tag returns dropped to 395 (321 were recovered after one year, 60

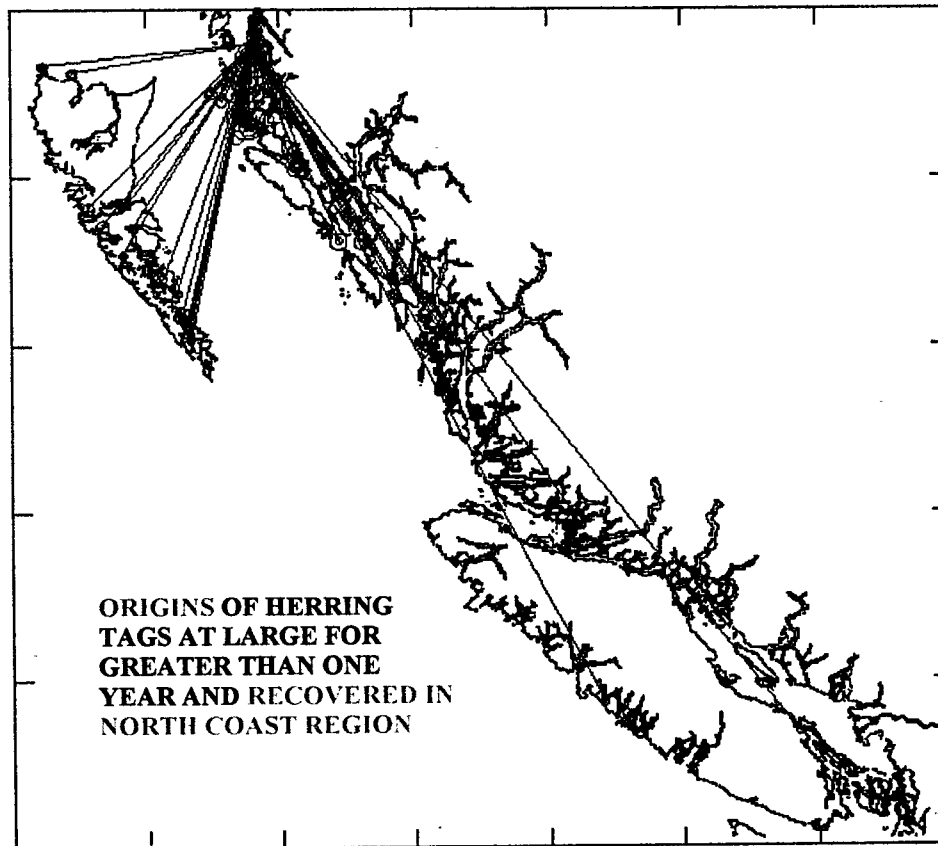
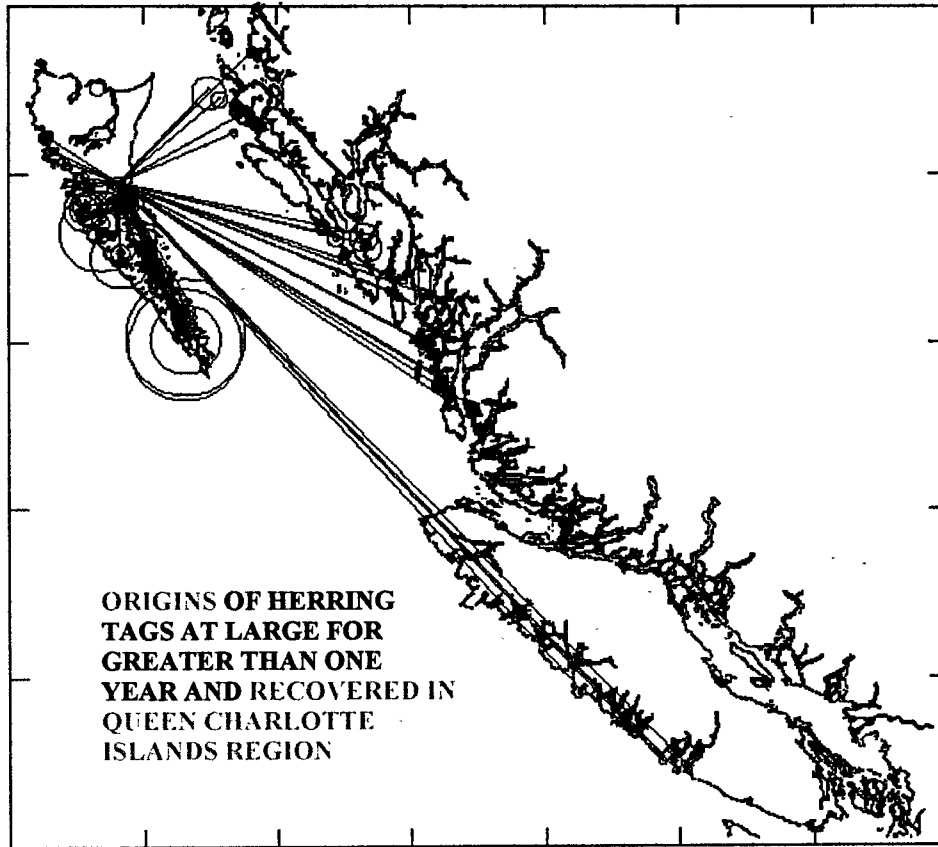


Figure 24. Geographic origins of tagged Pacific herring at liberty for greater than one year and recovered in Queen Charlotte Islands and North Coast Regions of British Columbia. Maps obtained and modified from the DFO Herring Tagging Home Page at <http://www-sci.pac.dfo-mpo.gc.ca/herspaw/hertags/default.htm> (DFO 2000a).

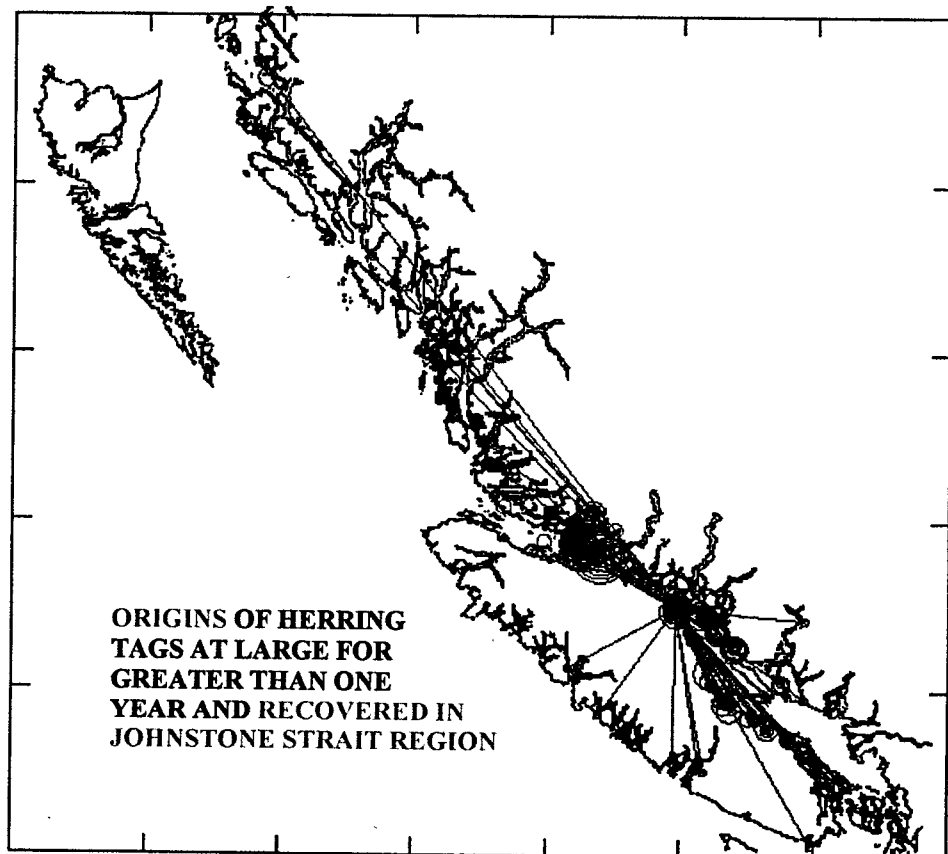
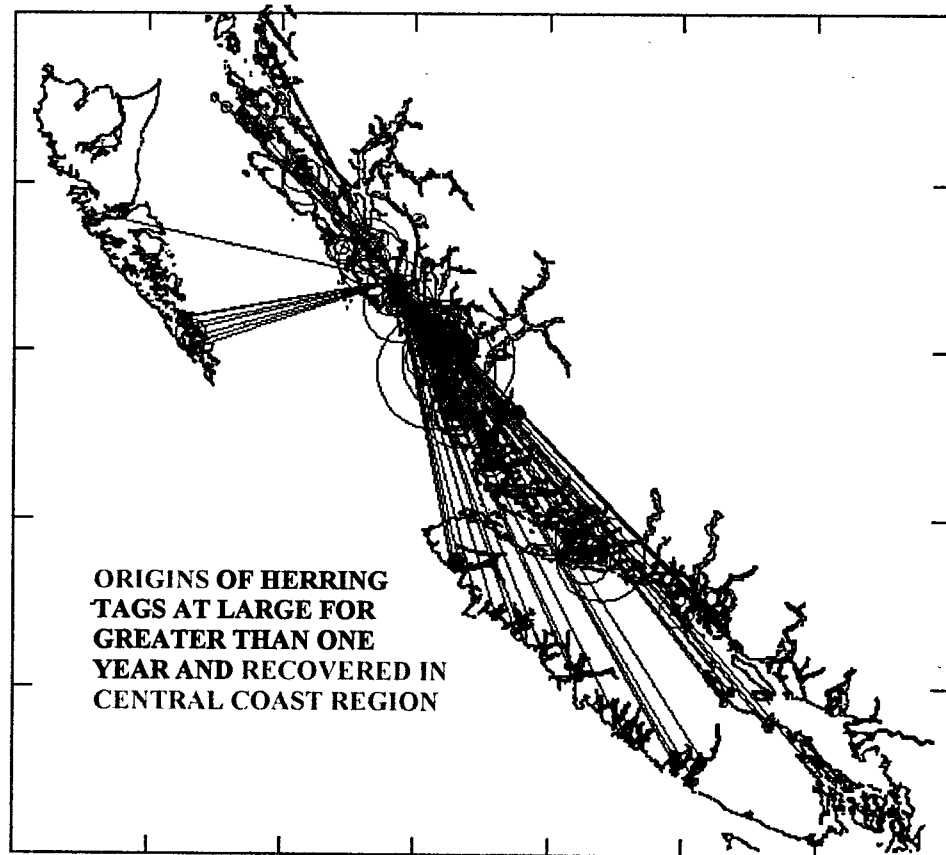


Figure 25. Geographic origins of tagged Pacific herring at liberty for greater than one year and recovered in Central Coast and Johnstone Strait Regions of British Columbia. Maps obtained and modified from the DFO Herring Tagging Home Page at <http://www-sci.pac.dfo-mpo.gc.ca/herspawn/hertags/default.htm> (DFO 2000a).

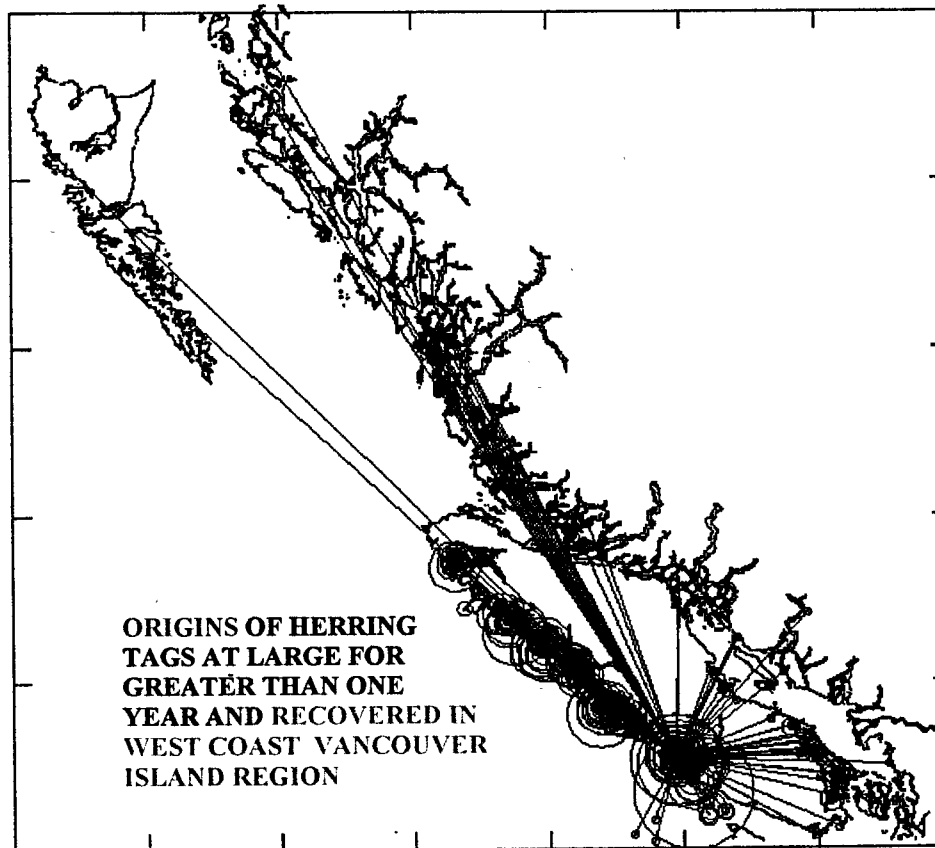
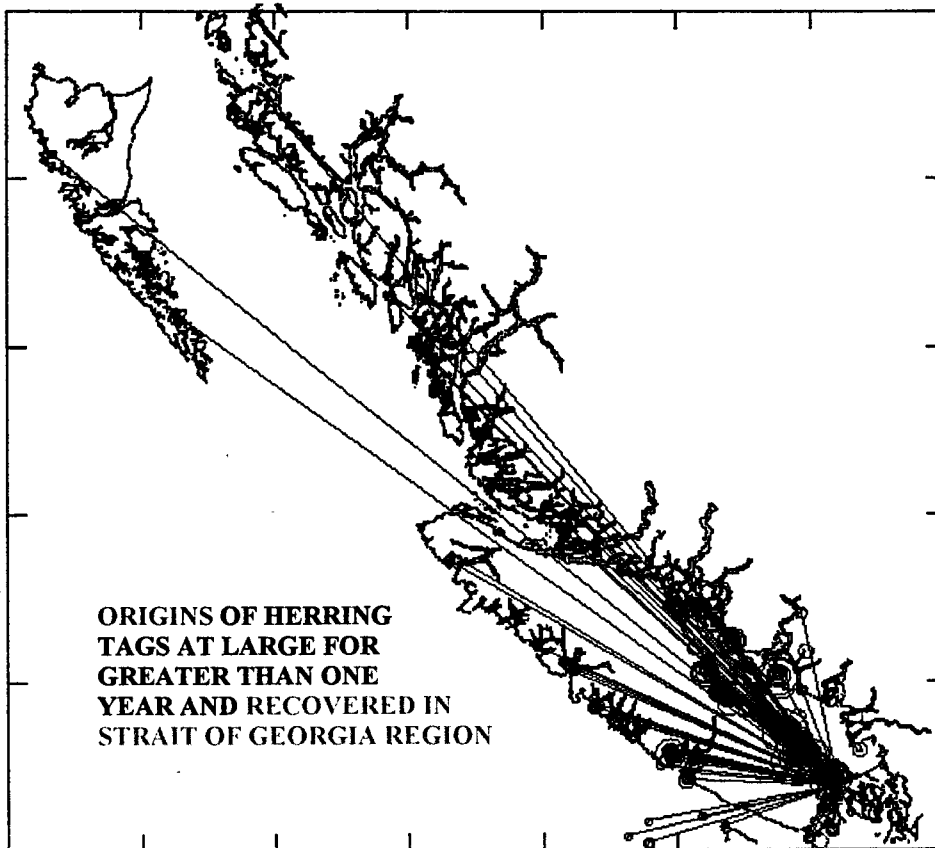


Figure 26. Geographic origins of tagged Pacific herring at liberty for greater than one year and recovered in Strait of Georgia and West Coast Vancouver Island Regions of British Columbia. Maps obtained and modified from the DFO Herring Tagging Home Page at <http://www-sci.pac.dfo-mpo.gc.ca/herspaw/hertags/default.htm> (DFO 2000a).

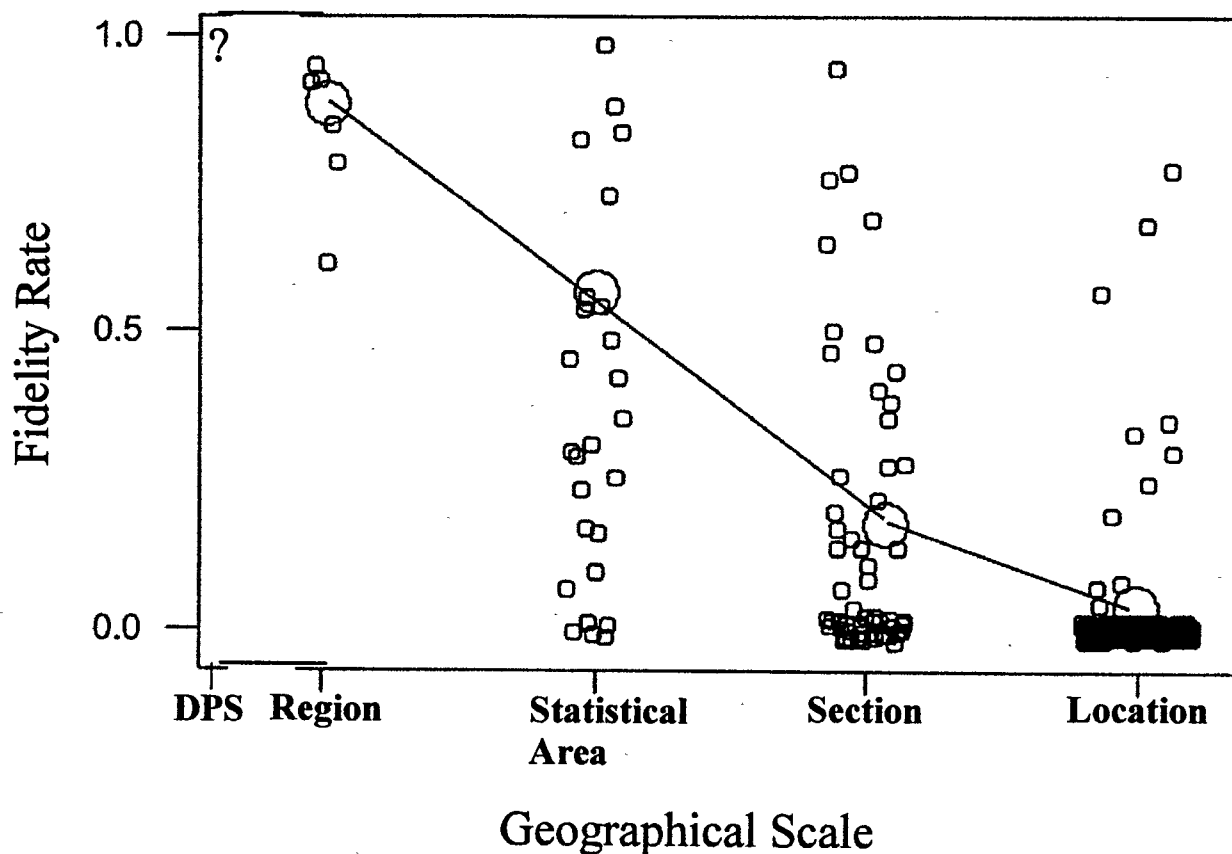


Figure 27. Comparison of fidelity rates of Pacific herring by DFO Regions, Statistical Areas, Sections, and Locations in British Columbia compared to the geographical scale of the Georgia Basin DPS. Large circles represent the mean fidelity rate for each geographic level and small circles represent the mean fidelity rate of individual geographic units within each category. Figure based on data presented in Hay et al. (1999) and modified from Hay et al. (1999; their fig. 2).

after two years, 8 after three years, 5 after four years, and 1 after five years) (Hay et al. 1999). At the level of the six management Regions, the mean fidelity rate after one year at large was 78%, and 82% after two years at large (Hay et al. 1999). Mean estimates of fidelity rate after one year at large at the level of Statistical Area were 56.8% (Hay et al. 1999) and 24.2% at the Section level (Hay et al. 1999). Among the highest fidelity rate estimates identified for Statistical Areas (SA) by Hay et al. (1999) were SA 02 in southeast Queen Charlotte Islands (72% after one year), SA 05 in the North Coast British Columbia Region (72% after one year), SA 07 in the Central Coast Region (82% after one year), and SA 23 in Barkley Sound (84% after one year). Hay et al. (1999) stated that, in general, fidelity rate estimates by Section were lower; however, fidelity rates after one year at large were 60% (n=1) for Section 042 (Chatham Sound), 72% (n=12) for Section 052 (Kitkatla Inlet), 69% (n=13) for Section 072 (Spiller Channel), 67% (n=12) for Section 142 (Lambert Channel), and 75% (n=38) for Section 232 (Macoah Passage) (Fig. 28). Hay et al. (1999) pointed out that because these tagging and recovery data span a three month period, "it is possible that many of these tag return data that show high fidelity to specific Sections, represent fish that were tagged and released before they reached their exact spawning destination or recovered after they had previously spawned elsewhere, perhaps in a different Section." Hay et al. (1999) suggested that fidelity rate of Pacific herring in British Columbia to a "Location" is only slightly higher than 0%. Hay et al. (1999) defined the approximate size of a "Location" as representing about 15 km of coastline per location.

Hay et al. (1999) also suggested that there is potential for episodic changes in rates of fidelity for Pacific herring, and present tagging data that indicates herring may tend to move more in some years than in others. Although Hay et al. (1999) stated that "tags released in each of the 6 Regions have been recovered in each of the other Regions," most British Columbia herring, except those in the Strait of Georgia and in mid-Hecate Strait, may not have a regular migration out of the Region. Conversely, most British Columbia Pacific herring seem to move extensively within their Region (Hay et al. 1999). Hay et al. (1999) postulated that:

'Migratory' herring, regardless of whether they move among Regions, may not show the same 'fidelity' to spawning areas as is shown by non-migratory herring. In the case of non-migratory herring, the return to the same spawning areas may not reflect active 'homing' as much as seeking the best spawning area, within their home range.

It should be noted that the above discussion concerns tagging studies on adult Pacific herring and as such provides little information in regards to homing of Pacific herring to their natal spawning grounds. Hourston (1959) described the results of tagging experiments on juvenile Pacific herring from Barkley Sound on the west coast of Vancouver Island. Hourston (1959) stated that, based on 50 tag returns, 52% of juvenile herring homed to the same sub-district (lower west coast of Vancouver Island) after two years at large and 64% homed after three years at large. This compared to homing rates of adult Pacific herring in the same sub-district after two and three years at large of 82% and 81%, respectively. Hourston (1959) postulated that:

As the young herring mature, they join adult schools on their spawning migration. Presumably, once the newly-maturing fish have joined an adult school, they stay with it. The adult schools, although intermixed, would have had the experience of at least one spawning migration and may thus be better equipped to find their way back to a certain beach.

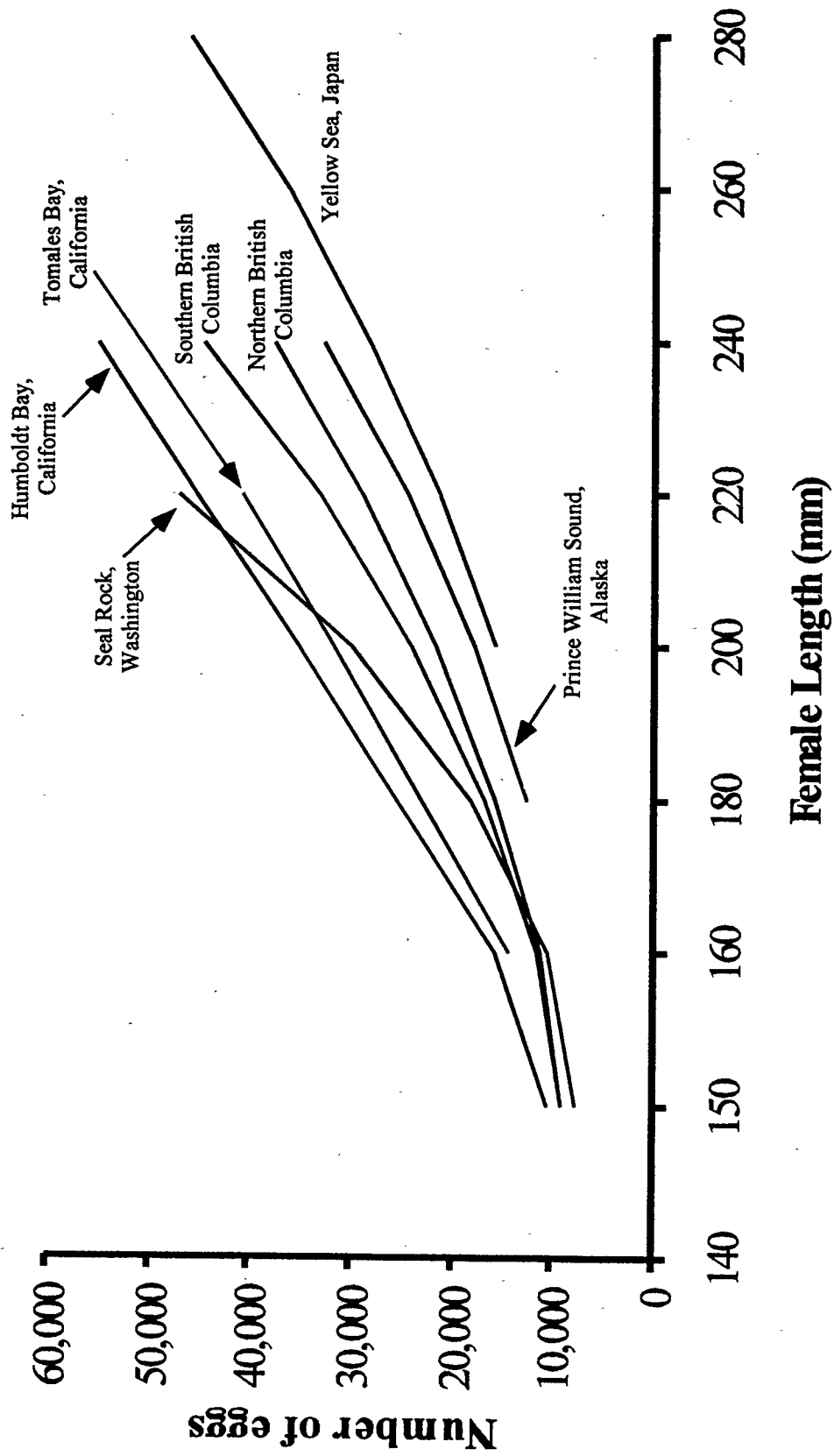


Figure 28. Comparison of Pacific herring length-fecundity relationships at different geographical locations. Data sources and linear regression equations describing these length-fecundity relationships are presented in Table 4.

Schweigert and Schwarz (1993) and Schwarz et al. (1993) modeled Pacific herring migration rates using tag-recovery data and concluded that “although rates of migration between stocks [on the Region level] are quite small and probably insignificant for all practical fishery management purposes,” they are sufficient to homogenize genetic differentiation between “geographically distinct stocks of herring.” In particular, Schweigert and Schwarz (1993) stated that their results suggested Pacific herring stocks in the North Coast British Columbia (Prince Rupert District) and Central Coast regions “are effectively discrete [based on tagging data] and should be managed as separate production units.”

Southeast Alaska—The goal of tagging experiments of Pacific herring on spawning grounds in Southeast Alaska has been, for the most part, to determine the degree of intermingling of stocks in the fishery and thus provides little new information relevant to the question of spawning site fidelity (Rounsefell and Dahlgren 1933, Dahlgren 1936, Skud 1963, Carlson 1977).

Seasonal migrations

Taylor (1964) recognized two types of Pacific herring in British Columbia, based on their migration patterns: 1) large migratory populations that migrate to the open ocean to feed, and 2) minor local populations that are found towards the heads of inlets or as resident populations that remain in inshore regions throughout the year. According to Taylor (1964), separation of these two types of Pacific herring is based on: 1) population abundance (migratory populations greatly exceed the local populations in abundance), 2) seasonal migration (minor local stocks stay inshore throughout the year, while the large migratory stocks feed offshore during the summer and return to inshore waters in the fall and winter), 3) growth and age composition (minor local populations have a slower growth rate), 4) location of spawning grounds (small local stocks tend to spawn at the heads of inlets and large migratory stocks spawn in more exposed regions such as near the mouths of inlets), and 5) homogeneity of individual stocks (minor stocks are complex assemblages of small individual runs, whereas various runs of the large migratory stocks are similar to one another). Similarly, Hay (1985) stated that in British Columbia, particularly in the Strait of Georgia, there appear to be a group of non-migratory herring that do not go to offshore summer feeding grounds, but remain in inside waters throughout the summer.

Penttila (1986) also postulated that some proportion of adult herring remain in Puget Sound throughout the summer while others migrate to offshore feeding grounds. A similar situation obtains in Southeast Alaska. Carlson (1980) reported that the major Sitka and Craig stocks of Pacific herring in Southeast Alaska make extensive summer feeding migrations, whereas the Pacific herring that spawn in the vicinity of Auke Bay and Ketchikan do not migrate to intermingle with the larger stocks.

Trumble (1983b) stated that many juvenile herring in Puget Sound overwinter in southern and central Puget Sound and migrate to Pacific Ocean feeding grounds in March to July, not returning until their first year of maturity. Adult herring were thought to migrate, on an annual, basis between summer feeding grounds (primarily off the Washington and British Columbia coasts) and Puget Sound spawning grounds (Trumble 1983b).

Larval retention areas

Hay and McCarter (1997b) surveyed Pacific herring larval distributions in several Sections in the Queen Charlotte Islands, North Coast British Columbia (Prince Rupert District), and Strait of Georgia regions in British Columbia and determined that “each major stock [Region] had a discrete larval distribution with continuous larval distributions within stock boundaries.” In other words, extensive mixing of larvae occurred within the Regions investigated, but larval mixture was not detected between Regions (Hay and McCarter 1997b). According to Hay and McCarter (1997b), herring stock structure in British Columbia may be established at relatively early life-history stages independent of the exact spawning location, which can vary between years. Iles and Sinclair (1982) also identified larval distributions and larval retention areas as being of prime importance in defining Atlantic herring stock structure.

Parasite incidence

Mackenzie (1987) provided a recent review of the relationship of Pacific and Atlantic herring to their parasites, including the use of parasites as biological tags in stock structure analyses. According to Mackenzie (1987), this use of “biological tags” has been used for herring (mostly in the case of Atlantic herring) more than for any other marine fish.

Katz (1942) stated that Pacific herring collected in Willapa Bay in 1937 were heavily infested with nematodes, but that similar infestations were not present in Pacific herring collected in Puget Sound in 1936-37. Conversely, Trumbull (1980) stated that “Infestation of the roundworm parasite *Anisakis* [sic] occurs much more heavily for the sac-roë herring [Cherry Point stock] than for herring elsewhere in Puget Sound.” Similarly, O’Toole (2000) stated that “nonquantitative observations indicate that body cavities of Cherry Point herring are normally full of the roundworm *Anisakis* [sic], which is uncommonly noted in adult herring from other areas in Puget Sound.” According to Mackenzie (1987), the definitive host for adult *Anisakis simplex* are cetaceans such as whales and porpoises, and the first intermediate host(s) are euphausiids. Pacific herring become infected with *Anisakis* larvae when they ingest infected euphausiids.

Bishop and Margolis (1955) studied the level of infestation of Pacific herring with larvae of the nematode parasite *Anisakis* sp. in British Columbia. The mean level of infestation with *Anisakis* was found to increase with the age of the herring host; age-1 Pacific herring were free of the parasite. These differences are likely due to accumulation of the parasite in the diet from year to year (Bishop and Margolis 1955). The incidence of infection with *Anisakis* sp. was found to be between 90% and 100% in Pacific herring populations from the Queen Charlotte Islands and the west coast of Vancouver Island, and between 80% and 90% in herring from the Strait of Georgia (Bishop and Margolis 1955).

Arthur and Arai (1980) examined parasites of Pacific herring from seven spawning locations as an indicator of geographical origin: 1) Lisianski Strait in Southeast Alaska, 2) Skincuttle Inlet in the Queen Charlotte Islands, 3) Lockhart Bay on the central British Columbia coast, 4) Barkley Sound on the west coast of Vancouver Island, 5) Nanoose Bay, 6) Northwest Bay in the Strait of Georgia, and 7) Port Gamble in Puget Sound. Although Arthur and Arai (1980) stated that “reliable separation of adjacent stocks of spawning herring could not be accomplished,” they identified three

parasites that served to separate the Port Gamble population from the others: 1) *Thynnascaris adunca* (= *Hysterothylacium aduncum*) larvae (Nematoda), 2) bucephalid metacercariae, and 3) *Anisakis simplex* larvae. Arthur and Arai (1980) stated that “separation of Port Gamble herring from other stocks was due primarily to high counts of *Thynnascaris adunca* [= *Hysterothylacium aduncum*] larvae in this collection.”

Moser (1991) and Moser and Hsieh (1992) determined that differences in the degree of infestation with *Lacistorhynchus dollfusi* (Cestoda) and the nematodes *Anisakis simplex*, *Contracaecum* sp., and *Hysterothylacium* indicated that Pacific herring that spawn in Tomales Bay and San Francisco Bay were separate stocks, and that they remain separate when at sea. Moser and Hsieh (1992) suggested that given the distribution of various definitive hosts of these parasites, Tomales Bay herring appear to spend more time offshore where they are infected with *A. simplex*, whereas San Francisco Bay herring spend more time inshore where they are more likely to be infected with *L. dollfusi* and *Contracaecum* sp. In all the above studies, differences between Pacific herring populations were determined on the basis of statistically significant differences in mean parasite prevalence or mean intensity of infection.

Growth rate, body size-at-age, and age structure

Differences in size-at-age and age structure, which should be reflections of differing growth and mortality rates, of herring populations may result from: 1) differences in migration patterns and consequent differences in food production and availability, 2) temperature differences, 3) density-dependant factors, 4) differences in the physical environment, and/or 5) differences in genetically determined growth characteristics. Since the degree to which growth rate is under genetic control in Pacific herring is unknown, it is difficult to determine whether differences in growth between populations are due to genetic or environmental differences.

California—Spratt (1981) found significant differences in the rate of growth of Pacific herring sampled in Tomales and San Francisco Bays, and suggested that “This difference may be evidence that the herring populations in Tomales bays and San Francisco Bay are distinct.”

Puget Sound—Trumble (1980), Gonyea and Trumble (1983), and O’Toole (2000) described statistically significant differences in mean growth rate and length-at-age data for three populations of Pacific herring sampled in the mid-1970s in Puget Sound: 1) Case Inlet/Squaxin Pass, 2) Hale Passage-Carr Inlet, and 3) southern Strait of Georgia purse seine catch (Cherry Point stock). Trumbull (1980) found that the Strait of Georgia (Cherry Point) herring were consistently longer at age than the other populations and continued to grow later in life. Herring from Case Inlet/Squaxin Pass grew rapidly to age-3 and then growth slowed, culminating in a smaller size-at-age than was apparent for herring from the Strait of Georgia (Cherry Point) and Hale Passage-Carr Inlet stocks (Trumbull 1980). Herring from Hale Passage-Carr Inlet showed intermediate growth rate and size-at-age, and continued to grow as the fish aged (Trumbull 1980). Lassuy (1989) suggested these differences “may result because the Strait of Georgia stocks are migratory while the Case Inlet stocks are resident.”

Buchanan (1985a) reported on the identification of a minor group of Pacific herring spawning in Fidalgo Bay-Padilla Bay that were differentiated from other stocks on the basis of their small size-at-age, scale pattern, and advanced maturity stage.

British Columbia—Tester (1937b) surveyed length-at-age and age composition of Pacific herring in selected commercial fisheries throughout British Columbia in the late-1920s to early-1930s and concluded that:

Due to the tendency for the Pacific herring to form local populations, a considerable diversity in age composition is present among the various runs. In localities separated by but a few miles different year classes may form predominating groups.

Ware (1985) compared growth rates and size-at-age for Pacific herring in five of the six DFO management Regions in British Columbia and determined that herring from the Queen Charlotte Islands and the North Coast British Columbia appear to grow at higher rates after age-4 than do the Central Coast and Johnstone Strait groups. Pacific herring from the west coast of Vancouver Island appeared to grow at intermediate rates (Ware 1985).

Schweigert (1991) applied multivariate statistical analyses to three years of size and age structure data for 26 spawning populations of Pacific herring in British Columbia. Schweigert (1991) stated that these analyzes “indicated stock separation on a smaller spatial scale” than is currently recognized. Schweigert (1991) found evidence that: 1) three distinct stocks occur in the Queen Charlotte Islands, 2) the North Coast British Columbia Region (Prince Rupert District) consists of a single stock, 3) Johnstone Strait and Strait of Georgia stocks are distinct, 4) Jervis Inlet is a distinct stock from the rest of the Strait of Georgia, 5) four spawning areas (Lambert Channel, Powell River, Nanoose Bay, and Deepwater Bay) in the Strait of Georgia represent a single stock, and 6) three separate stocks exist on the west coast of Vancouver Island (Barkley-Clayoquot sounds, Esperanza Inlet-Nootka Sound, and Quatsino Sound). Ware (1985) postulated that some of the resident stocks grow more slowly than migratory stocks due to the poorer production of food in the nearshore environment.

Alaska—Leon (1993) detected statistically significant differences in length-at-age and/or growth rates between three stocks of Pacific herring in Southeast Alaska, separated from one another by a minimum of 160 miles: 1) Sitka Sound, 2) Seymour Canal, and 3) Kah Shakes-Boca de Quadra. Comparison between two spawning sites separated by only 15-20 miles, Annette Island and Boca de Quadra, also indicated area-specific differences in growth characteristics (Leon 1993). Burkey (1986) compared the mean length-at-age of fishery caught samples of Pacific herring from Afognak Island, southern Alaska Peninsula, Cook Inlet, and Prince William Sound and found Prince William Sound herring were consistently smaller at age than any of the other three populations. Similarly, Burkey (1986) found the age composition of Pacific herring from Prince William Sound to be significantly different from the other three areas. However, similar comparisons of length-at-age and age composition between Pacific herring from Prince William Sound and Southeast Alaska did not show significant differences (Burkey 1986). Rowell (1980) stated that three distinct stocks of Pacific herring could be distinguished in the eastern Bering Sea on the basis of differences in scale growth patterns: 1) Togiak, 2) Port Clarence A, and 3) Port Clarence B-Cape Denbigh-Cape Romanzof (McBride and Whitmore 1981).

Age at maturity

In general, age at maturity varies with latitude; beginning at age-2 in California and at age-4 or age-5 in the eastern Bering Sea (Hay 1985). Rabin and Barnhart (1986) reported that Pacific herring in Humboldt Bay, California recruit into this spawning population at age-2. Similarly, Spratt (1981) found that Pacific herring recruit into the spawning populations in Tomales and San Francisco bays beginning at age-2 and are fully recruited by age-3. Hay and McCarter (1999b) stated that sexual maturity occurs at age-3 in all major Pacific herring assessment areas in British Columbia, based on ovarian histology and the gonosomatic index. Barton and Weststad (1980) stated that maturation begins at age-4 or age-5 in Alaskan stocks in the eastern Bering Sea.

Fecundity

The relationship of fecundity to length of Pacific herring has been studied from Peter the Great Bay off the Asian mainland (Ambroz 1931), Seal Rock (in Hood Canal), Washington (Katz 1942, 1948), British Columbia (Hart and Tester 1934, Nagasaki 1958, Hourston et al. 1981, Hay 1985), Tomales Bay, California (Hardwick 1973), Humboldt Bay, California (Rabin and Barnhart 1977), Prince William Sound, Alaska (Paulson and Smith 1977), and the Yellow Sea (Qisheng 1980) (Table 3 and Fig. 28). Over large geographic distances, fecundity of Pacific herring at a particular length has been found to decrease with an increase in latitude (Paulson and Smith 1977, Hay 1985, Lassuy 1989). Paulson and Smith (1977) suggested that the apparent decline in fecundity with increasing latitude is "offset by an increase in mean length of reproductively active females" with increasing latitude. Hay (1985) expanded on the data set of Paulson and Smith (1977), through inclusion of additional data from California and British Columbia herring populations, and observed a similar decreasing trend in fecundity with an increase in latitude (Table 4 and Fig. 28).

On the other hand, Nagasaki (1958) studied fecundity of Pacific herring in British Columbia and found the opposite relationship to latitude than that observed by Paulson and Smith (1977) and Hay (1985). Nagasaki (1958) stated that "the fecundity of herring of the same body length decreases from north to south and in the northern part of the province from west to east." In addition, Nagasaki (1958) found statistically significant differences in mean fecundity of Pacific herring of the same age and length between northern and southern population groups in British Columbia. Nagasaki (1958) stated that fecundity was significantly higher in northern than in southern British Columbia. Hourston et al. (1981) listed several possible reasons why the fecundity estimates of Nagasaki (1958) may be questionable, including: 1) three of the ten localities sampled by Nagasaki (1958) contain few herring, 2) only three or four of the ten runs sampled by Nagasaki (1958) were large enough to support fisheries, 3) most of the major herring management units in British Columbia were not sampled by Nagasaki (1958), and 4) all of Nagasaki's (1958) samples came from a single spawning year.

Katz (1948) studied fecundity of Pacific herring from Seal Rock in Hood Canal, Washington and stated that "the Seal Rock herring produce more eggs than the British Columbia herring of the same length, and that the Siberian herring from Peter the Great Bay are less efficient egg producers than the British Columbia herring of the same size." However, Katz (1948) also noted that the Pacific herring in British Columbia studied by Hart and Tester (1934) and in Peter the Great Bay

Table 4. Length-fecundity relationship and total eggs/gram body weight for female Pacific herring from selected regions.
 L, length; SL, standard length; A, age (years).

Region	F, fecundity	n	Fecundity at 180 mm	Fecundity at 200 mm	Fecundity at 220 mm	Eggs/g body weight	Source
Northeast Pacific							
Alaska							
Prince William Sound	$F=0.00042L^{3.316}$	156	12,640	17,925	24,588	--	Paulson and Smith (1977)
British Columbia							
Northern B.C.							
	$\text{Log } F=3.25 \log SL + 0.08 \log A - 3.17$	--	--	--	--	--	Nagasaki (1958)
Southern B.C.							
	$F=0.00233L^{3.028}$	921	15,715	21,621	28,854	200	Hay (1985)
	$\text{Log } F=2.16 \log SL + 0.32 \log A - 0.90$	--	--	--	--	--	Nagasaki (1958)
	$F=0.000419L^{3.372}$	290	16,865	24,060	33,179	200	Hay (1985)
Washington							
Seal Rock	$F=0.000000436L^{4.71}$	55	18,273	30,015	47,022	--	Katz (1942)
California							
Humboldt Bay	$F= -63920.9 + 496.6SL$	37	25,467	35,399	45,331	220	Rabin and Barnhart (1977)
Tomales Bay	$F= -56788.4 + 443.4SL$	--	23,024	31,892	40,760	227	Hardwick (1973), Lassuy (1989)
Northwest Pacific							
Japan							
Yellow Sea	$F=0.000798L^{3.171}$	--	--	15,797	21,371	--	Qisheng (1980)

studied by Ambroz (1931) “ultimately grow much larger and produce far more ova” than Pacific herring from Seal Rock.

Ware (1985) found Pacific herring fecundity to be directly proportional to female body weight in the six DFO management Regions in British Columbia. Tanasichuk and Ware (1987) examined Pacific herring fecundity at a grand mean weight of 126 g for seven British Columbian populations in five different years and found significant differences in fecundity between years, but not between locations. Fecundity in 1983, an El Niño year, were 12.7% higher than in the other four years (Tanasichuk and Ware 1987). Tanasichuk and Ware (1987) also determined that sea-temperature 60-90 days prior to spawning “best accounted for variations in weight-specific fecundity.” In comparisons between Pacific herring in the Strait of Georgia and the Beaufort Sea, Tanasichuk et al. (1993) found weight-specific fecundities to be 1.5 times greater in the Strait of Georgia fish.

Hay (1985) emphasized the utility of using the number of eggs per gram of adult female body weight as measure of relative fecundity in comparing populations (Table 4). Hay (1985) stated that this relative measure of fecundity “is more similar among size groups than is total fecundity,” since the total number of eggs increases exponentially with female length and egg size also increases with adult female body size. Within British Columbia, the mean number of eggs per gram of female body weight for ripe Pacific herring, as presented in (Hay 1985, his Table 2), varied from a low of 184 on the North Coast British Columbia to a high of 224 in the Strait of Georgia. Hay (1985) suggested that a good estimate for British Columbia in general is 200 eggs/g of female body weight. Tanasichuk and Ware (1987) found the number eggs per gram of female body weight to range between 166 and 233 for seven sampling locations in five different years in British Columbia. The mean number of eggs/g of female body weight for Pacific herring in Humboldt Bay, California was estimated by Rabin and Barnhart (1977) at 220 ± 35 . In Tomales Bay, California, Hardwick (1973) estimated relative fecundity of Pacific herring to be 227 ± 50 eggs/g female body weight.

Morphological differentiation

Numerous researchers have attempted to separate “races” or stocks of Pacific herring on the basis of differences in body proportions or meristic characters. These differences may be due either to environmental (phenotypic) or hereditary (genotypic) factors, and it is extremely difficult to determine the underlying causes of these differences. In addition, morphometric and meristic differences between groups of fish are not normally apparent in individual fish but only in the mean value of a large number of individuals.

Thompson (1917) compared the head length; distance from the snout to insertion of the dorsal, anal, and ventral fins; and the mean number of vertebrae, gill-rakers, anal fin rays, and dorsal fin rays in Pacific herring from various locations in British Columbia and from San Francisco Bay, California. Thompson (1917) found differences between British Columbia and California populations of Pacific herring in mean vertebral and gill raker counts, but not between populations within British Columbia. Results from analyses of other meristic and morphometric characters were inconclusive (Thompson 1917). Hubbs (1925) extended the work of Thompson (1917) and studied differences in the number of dorsal fin rays, anal fin rays, and vertebrae in Pacific herring from California and British Columbia and found that the mean number of vertebrae increased from south to north. Subsequently, Rounsefell (1929, 1930) examined differences in mean counts of vertebrae,

dorsal fin rays, and anal fin rays, and head length measurements between 32 samples of Pacific herring from San Diego, California to the Bering Sea. Evidence from head length and anal and dorsal rays were inconclusive, but Rounsefell (1929, 1930) found marked differences between locations in mean vertebral counts. Rounsefell (1929, 1930) also verified that the mean number of vertebrae in Pacific herring populations increases to the north and westward. Rounsefell (1929, 1930) found that between San Diego and the Shumagin Islands in the Bering Sea the mean vertebral count differed by nearly four vertebrae. When comparing adjacent localities, Rounsefell (1929, 1930) found significant differences in the mean vertebral count in some instances. On the other hand, Rounsefell (1929, 1930) also found significant differences in mean vertebral counts between samples collected in the same location but in different years. These differences most likely reflected variation between year-classes (Ahlstrom 1957). Rounsefell (1929, 1930) identified the following groupings that he considered distinct populations based on variation in vertebral counts: 1) California, 2) southern British Columbia, 3) Stephens Passage in Southeast Alaska, 4) Chatham Strait in Southeast Alaska, 5) Craig in Southeast Alaska, 6) Prince William Sound, 7) Cook Inlet-Shuyak Strait, 8) Shearwater Bay-Old Harbor in south-central Alaska, 9) Chignik in western Alaska, 10) Shumagin Islands, 11) Unalaska, and 12) Golovin Bay.

Rounsefell and Dahlgren (1935) examined herring stock structure in Southeast Alaska, mainly through comparison of the mean number of vertebrae in different year-classes between 32 localities. Individual year-classes were studied, since a high negative correlation was found between temperature during development and the mean vertebral number in different year-classes. Rounsefell and Dahlgren (1935) identified six populations in Southeast Alaska that they considered independent of one another, based on a combination of differences in vertebral counts, growth rates, and year-class strength: 1) Juneau-Icy Strait area, 2) Sitka-Cape Ommaney-Chatham Strait area, 3) Noyes Island-west coast of Prince of Wales Island, 4) inner areas of Southeast Alaska, 5) vicinity of Petersburg, and 6) Todd-Peril Strait.

Similarly, Tester (1937a) examined meristic and morphometric variation (vertebrae count, head length, length to dorsal fin insertion) in Pacific herring from 19 localities in British Columbia, and, as in earlier studies, found differences in mean vertebral counts to be most informative for stock discrimination. Tester (1937a) also confirmed that the mean vertebral count in Pacific herring populations increases with latitude. Tester (1937a) concluded that meristic characters could be used to separate British Columbia herring into the following discrete units or populations: 1) Point Grey, 2) Granite Bay, 3) Saltspring Island-Departure Bay-Nanose Bay, 4) Barkley Sound-Sydney Inlet, 5) Nootka Sound-Kyuquot Sound, 6) Quatsino Sound, 7) Bella Bella, and 8) Butler Cove-Pearl Harbour and the area currently designated as N. Porcher Island. In a later paper, Tester (1938) stated that "variation in the number of vertebrae and certain other meristic characters in fishes is caused in part at least by variation in environmental conditions, notably water temperature." This statement was based in part on evidence that the mean count of vertebrae in successive year-classes of Pacific herring from Barkley Sound on the west coast of Vancouver Island, varies inversely with water temperature at the time of spawning and early development (Tester 1938). In a later paper, Tester (1949) found this relationship to hold in general for Pacific herring from the entire west coast of Vancouver Island. McHugh (1942) also found significant differences in vertebral counts of juvenile herring from the same year-class sampled at a number of localities within the Strait of Georgia.

Both Tester (1937a) and McHugh (1942) reported that within certain samples, the largest fish tended to have the highest vertebral counts. However, Tester (1949) later stated that analysis of data from the west coast of Vancouver Island between the years 1929-1941 revealed "no significant tendency for older fish of a year-class to have a higher mean [vertebral] count, as had been indicated by results previously published."

Tester (1949) concluded, on the basis of mean number of vertebrae in Pacific herring samples from the west coast of Vancouver Island, that Pacific herring represented "essentially discrete populations, between which mixing was generally limited, but with the reservation that mixing more extensive than "limited" might take place occasionally." However, when Pacific herring tag recovery data were taken into account for west coast of Vancouver Island, Tester (1949) stated that "the latter method demonstrated that mixture did take place and that it was considerably more extensive than would be anticipated by the term "limited"—so much so that for practical purposes the series of intergrading "units" [of Pacific herring determined to exist on west coast of Vancouver Island on the basis of mean vertebral counts] were considered to constitute one major population." In addition, Royce (1957) determined that Tester's (1949) vertebral count data for west coast of Vancouver Island Pacific herring indicates that mixture between northernmost and southernmost areas "could be as high as 93 percent."

McHugh (1954) reviewed meristic and morphometric studies on Pacific herring and stated that "the number of vertebrae is capable of modification by temperature during early development, so that in any one locality the mean vertebral number may vary from year to year. This finding, however, has not invalidated the general conclusion that the number of vertebrae decreases from north to south."

Schweigert (1981) reanalyzed morphometric and meristic data published by Thompson (1917) for Pacific herring from San Francisco and Point Grey and Departure Bay in British Columbia using pattern recognition, a form of multivariate analysis. Morphometric characters included standard length; length from the snout to the insertion of the dorsal, pelvic and anal fins; head length; and occiput length. Meristic characters included numbers of vertebrae, gillrakers and anal and fin rays. Schweigert (1981) stated that the morphometric characters were more useful in separating the three groups of Pacific herring from one another than were meristic characters. Although these three groups of Pacific herring are known to be dissimilar, Schweigert (1981) stated that "the separation obtained between the two British Columbia stocks in this study based solely on morphometric considerations is sufficient to warrant examination of morphometric differences among British Columbia herring stocks on a larger scale."

Meng and Stocker (1984) applied discriminant function analysis to a set of twenty-seven morphometric and eight meristic characters taken from Pacific herring sampled in commercial fisheries at five localities in British Columbia. Pacific herring from the Strait of Georgia were detectably different from those in northern British Columbia, although exchange between these two geographical regions was indicated (Meng and Stocker 1984). Meng and Stocker (1984) recommended the use of meristic characters to separate Pacific herring populations on a broad geographic scale and the use of 12 identified "best" morphometric characters for finer scale separation of spawning populations.

Schweigert (1990) used univariate and multivariate statistical analyses to compare the ability of traditional morphometric and meristic data sets and the new method of truss measurements to differentiate Pacific herring stock structure in British Columbia. Schweigert (1990) found “no substantial differences in the ability of truss networks and traditional morphometric and meristic data to differentiate among groups of” Pacific herring. Analyses of the morphometric and meristic data did not reveal significant differences between Pacific herring from North Coast British Columbia, Central Coast, and the Strait of Georgia; however, each of these areas was significantly different from the west coast of Vancouver Island (Schweigert 1990). Analyses of the truss network data revealed a significant difference only between Pacific herring from North Coast British Columbia and the west coast of Vancouver Island.

Within Washington, Chapman et al. (1941) and Katz (1942) compared mean vertebral counts between Pacific herring collected at eleven locations in 1936 and 1937. These locations are: 1) Woollochot Bay (in south Puget Sound), 2) Poulsbo (Port Orchard-Port Madison stock), 3) Holmes Harbor, 4) Hales Pass (Samish Bay-Portage Bay stock), 5) Seal Rock (Quilcene Bay stock), 6) Birch Bay (Cherry Point stock), 7) Pt. Migley, 8) Willapa Bay, 9) East Sound (Interior San Juan Islands stock), 10) Gig Harbor, and 11) Steamboat Island (Squaxin Pass stock). Comparison of Pacific herring samples from Willapa Bay, Woollochot Bay, and Birch Bay revealed “good separation of the mean vertebral counts in the two- and three-year-old age classes, but in the four-, five-, and six-year-olds, the differences of the mean vertebral counts were slight” (Katz 1942). Katz (1942) stated that,

... the older age classes of the herring of Washington fail to show a significant difference in their mean vertebral counts and cannot, therefore, be designated as races if vertebral differences are to be used as a racial criterion. Whether this lack of racial distinctiveness in the older age classes is due to intermingling or to other causes cannot be determined with the scanty data on hand.

Katz (1942) also observed that annual variation in mean vertebral counts of Pacific herring was greater for the Woollochot Bay aggregation in southern Puget Sound than in the Birch Bay aggregation, whose spawning location was closer to the open ocean. Katz (1942) postulated that the greater variation in the Woollochot Bay vertebral counts “might be due to a greater temperature fluctuation of the southern waters of the Sound.”

Herring Stock Discreteness and the Metapopulation Concept

Several hypotheses, pertinent to the question of distinct population segments for Pacific herring, have been proposed in Europe and eastern North America to explain the apparent stock structure pattern of Atlantic herring. Iles and Sinclair (1982) and Smith and Jamieson (1986) proposed diverging hypotheses to explain phenetic and genetic data on Atlantic herring stock structure. McQuinn (1997) articulated the differences between these hypotheses and termed the Iles and Sinclair (1982) hypothesis “the discrete population concept” and the Smith and Jamieson (1986) hypothesis “the dynamic balance population concept.” McQuinn (1997) then attempted to unify these opposing hypotheses under the metapopulation concept.

The discrete population concept of Iles and Sinclair (1982) states that “the number of herring stocks and the geographic location of their respective spawning sites are determined by the number, location, and extent of geographically stable larval retention areas.” This concept depends upon the maintenance of reproductive isolation of spawning populations through both homing to natal spawning sites and natural selection against less fit hybrids that result from straying of individuals from other spawning populations (Iles and Sinclair 1982, McQuinn 1997). Smith and Jamieson (1986) and McQuinn (1997) suggest that the discrete population concept is inconsistent with several lines of evidence, including: 1) observed rates of straying of adult and juvenile tagged Pacific and Atlantic herring, 2) observations of Atlantic herring hatched in autumn (as indicated by their otolith pattern) spawning as adults in the spring, and vice versa, and 3) the lack of consistent genetic differentiation among regional herring populations.

In contrast, the dynamic balance population concept of Smith and Jamieson (1986) contends that herring populations expand and contract their range in response to external pressures and that local population structure is transient on evolutionary time scales (McQuinn 1997, Corten 1999). McQuinn (1997) suggested that the major weakness in this latter concept was “the lack of an explanation for the temporal persistence of populations in geographic space on an ecological time scale.”

McQuinn (1997) stated that neither of the above concepts is consistent with all the data on herring stock structure, and that “contradictory evidence supporting both discreteness and mixing has prevented a clear definition of population structure.” However, McQuinn (1997) proposed that “Atlantic herring population structure and dynamics are well described within the metapopulation concept” (McQuinn 1997). A metapopulation has been defined by Levins (1968) as:

a population of populations which were established by colonists, survive for a while, send out migrants, and eventually disappear. The persistence of a species in a region depends on the rate of colonization successfully balancing the local extinction rate.

Under this metapopulation concept of herring stock structure, McQuinn (1997) suggested that local herring populations may be perpetuated through a process he termed the “adopted-migrant hypothesis,” where juvenile herring that associate with and synchronize their maturation with schools of adult herring will adopt the migration and homing patterns of the adults. Thus, local spawning populations are maintained by “repeat rather than natal homing to spawning areas, while local population persistence is ensured through the social transmission of migration patterns and spawning areas from adults to recruiting individuals” (McQuinn 1997). In McQuinn’s (1997) “adopted-migrant hypothesis,” hydrographic forces on larvae and the effects of schooling of juveniles leads to the majority of individuals spawning in their native population. Thus, differences in the mean values of meristic and morphometric measurements that reflect environmental differences during development are maintained, although strays from other populations are adopted by local populations and gene flow is significant (McQuinn 1997). McQuinn (1997) stated that the “adopted-migrant hypothesis” is consistent with genetic studies on herring that have not observed temporally-persistent differences, since no genetic differences

would be expected between sympatric herring populations with the hypothesized level of gene flow.

McQuinn (1997) emphasized that local populations should be considered the basic fisheries management unit and that their “conservation is essential for the preservation of spawning potential and for the viability of coastal fisheries,” although when fisheries occur on a mixture of local populations, the metapopulation becomes the practical management unit. Although McQuinn’s (1997) metapopulation concept and “adopted-migrant hypothesis” were first formulated for Atlantic herring, the similar ecological characteristics of Pacific herring suggests these concepts are pertinent to stock structure questions for this species as well.

Pacific Herring DPS Delineation

The BRT examined environmental, geologic, biogeographic, life-history, and genetic information in the process of identifying DPSs of Pacific herring. In particular, biogeography, ecological and habitat factors, and genetic population structure were found to be most informative for these species. The DPSs considered in this evaluation were:

A. A separate DPS for each of the five basins of Puget Sound which are: Hood Canal, Main Basin, Whidbey Basin, the Strait of Juan de Fuca/San Juan Islands, and South Sound. The BRT constructed this scenario based on such factors as differences in spawning distributions, behavior and timing, and possible larval transport restrictions brought about by basin physiography in these basins. This might lead to sufficient differentiation of spawning aggregations to meet the “distinct” criteria for definition of a DPS. The WDFW is presently conducting a herring genetics study that may shed some light on whether these basins define DPSs, or simply multiple stocks. DPS of this size would compare with the DFO section or subarea management unit.

B. A DPS for two regions within the Georgia Basin, which are: Puget Sound proper (that portion of Puget Sound south of Admiralty Inlet and east of Deception Pass), and in north Puget Sound including the Strait of Juan de Fuca/San Juan Islands up to the mouth of the Fraser River. In order to construct this DPS scenario, the BRT used evidence for processes that would lead to distinct populations at this scale. These include the limitation of larval transport through the natural barrier at Admiralty Island and Deception Pass, evidence that the Puget Sound proper spawning aggregations are resident fish and that straying rates inferred from Canadian tagging studies do not apply to these Puget Sound resident populations. Fidelity to spawning aggregations could be increased due to the resident nature of the populations. This could result in less mixing and straying of herring populations than is seen in the Canadian populations that were the subject of the tagging studies. The DFO defines this scale as a District or Regional scale management unit.

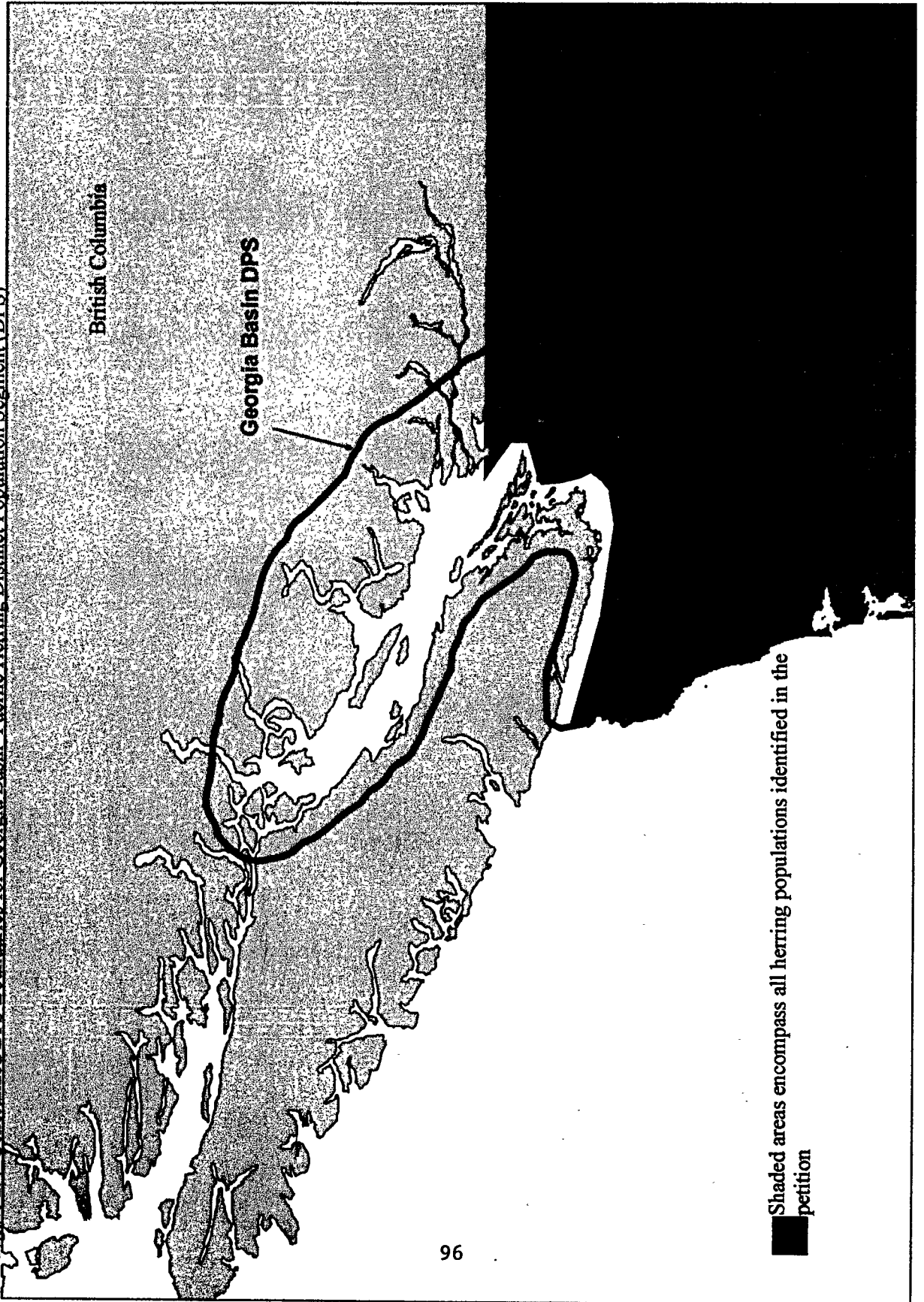
C. A DPS that encompasses Georgia Basin, extending from the southern end of Puget Sound to the northern end of the Strait of Georgia near Discovery Passage. This DPS extends from the north end of Vancouver Island to the south end of Puget Sound and includes the Strait of Juan de Fuca. This DPS would define the populations in Puget Sound at the DFO District-level

management unit. District-level criteria used by DFO are derived by evidence from tagging studies, vertebral counts, assessment of larval distribution and transport, and hydrographical studies of the adjacent area. This type of information, however, is generally not available for the Puget Sound populations.

D. A single DPS that includes the populations in the area from Baja California to Southeast Alaska, with the northern boundary being the border of the zoogeographic zone near Dixon Entrance, or a line between Helm Bay and Lynn Canal, Alaska. At this scale, the DPS is defined by the genetics investigations of Grant and Utter (1984), and by the zoogeographic boundary of Ekman (1953), Hedgpeth (1957), and Briggs (1974). This DPS exceeds any management area defined by DFO for Canadian populations.

A majority of the BRT favored the Georgia Basin, which is option C, (Fig. 29) as the most likely DPS, with options B and D receiving considerably less support. No member of the BRT supported DPS option A. Members of the BRT utilized a variety of evidence to support their identification of a Georgia Basin DPS for Pacific herring. These included tagging studies in the Canadian portion of the Georgia Basin, vertebral counts, information on larval distribution and transport, as well as hydrographic studies conducted by the Department of Fisheries and Oceans Canada (DFO). Genetic studies by Grant and Utter (1984) were also utilized in concert with work by McQuinn (1997) that describes the metapopulation stock structure in herring. Based on this examination, the BRT identified a DPS for the Georgia Basin, which includes Puget Sound, and focused the risk analysis on this DPS.

Figure 29. Generalized DPS Boundaries for Georgia Basin Pacific Herring Distinct Population Segment (DPS)



APPROACHES TO EVALUATING RISK OF EXTINCTION

The “Extinction Risk” Question

The ESA (Section 3) defines “endangered species” as “any species which is in danger of extinction throughout all or a significant portion of its range.” “Threatened species” is defined as “any species which is likely to become an endangered species within the foreseeable future throughout all or a significant portion of its range.” NMFS considers a variety of information in evaluating the level of risk faced by a DPS, including: 1) absolute numbers of fish and their spatial and temporal distributions, 2) current abundance in relation to historical abundance and carrying capacity of the habitat, 3) trends in abundance, based on indices such catch statistics, CPUE, and spawner-recruit ratios, 4) natural and human-influenced factors that cause variability in survival and abundance, 5) possible threats to genetic integrity (e.g., selective fisheries and interactions between cultured and natural populations), and 6) recent events (e.g., climate change and changes in management) that have predictable short-term consequences for the abundance of a DPS. Additional risk factors, such as disease prevalence or changes in life-history traits, also may be considered in the evaluation of risk to a population. We briefly describe these six considerations as follows, then proceed to a detailed examination of available information for herring in the Georgia Basin DPS.

The determination of whether a species is threatened or endangered, according to the ESA, should be based on the best scientific information available, after taking into consideration conservation measures that are proposed or in place. The BRT did not evaluate likely or possible effects of conservation measures. Therefore, they did not make recommendations on whether DPSs should be listed as threatened or endangered species, because that determination requires evaluation of factors not considered by the BRT. However, the BRT did draw scientific conclusions about the risk of extinction faced by DPSs under the assumption that present conditions will continue, recognizing that natural demographical and environmental variability is an inherent feature of present conditions. Conservation measures will be taken into account by the NMFS Northwest Regional Offices in making listing recommendations. The following sections summarize the kinds of information the BRT considered in evaluating the potential effects of risk factors on the each of the DPSs identified by the BRT.

Absolute Numbers

The absolute number of individuals in a population is important in assessing two aspects of extinction risk. First, a small population, even one that appears stable or increasing, may not be able to sustain itself in the face of environmental fluctuations and small-population stochasticity. This conclusion follows from the theory of minimum viable populations (MVP) (see Gilpin and Soulé 1986, Thompson 1991). Second, present abundance in a declining population is an indicator of the time expected until the population reaches critically low numbers. This follows from the idea of “driven extinction” (Caughley 1994). In addition to absolute numbers, the spatial and temporal distributions of adults are important in assessing risk to a DPS. Spatial distribution is important, both at the scale of the spawning population and the metapopulation.

Assessments of marine fish populations have focused on the biomass or numbers of adults harvested by commercial and sports fishing. Catch records, catch-per-unit effort (CPUE), and biomass estimates from research cruises constitute most of the data available to estimate abundance trends. However, the numbers of reproductive adults is the most important measure of abundance in assess the status of a population. Data on other life-history stages can be used as a supplemental indicator of abundance.

Historical Abundances and Carrying Capacity

The relationship of present abundance to present carrying capacity is important for evaluating the health of a population, but a population with abundance near the carrying capacity of the habitat it occupies does not necessarily indicate that the population is healthy. Population abundances near carrying capacity imply that the effectiveness of short-term management actions is limited in increasing population abundance. The relationship between current abundance and habitat capacity to the historical relationship between these variables is an important consideration in evaluating risk. An understanding of historical conditions provides a perspective of the conditions under which present populations evolved. Estimates of historical abundances also provide the basis for establishing long-term abundance trends. Comparisons of past and present habitat capacity can also indicate long-term population trends and potential problems stemming from population fragmentation.

Trends in Abundance

Short- and long-term trends in abundance are primary indicators of risk in natural populations. Trends may be calculated with a variety of quantitative data, including catch, CPUE, and survey data. Spawning-biomass estimates are available for Puget Sound populations of herring, but uninterrupted time-series of adequate length for trend analysis are only available for the six most important populations. The influence of environmental variability on population abundances also limits the interpretation of short-term trends, because the climate changes in the late-1970s and 1980s coincided with apparent declines in population abundances for the species being considered in this review.

Factors Influencing Abundance

Several natural and anthropogenic factors influence the degrees of risk facing populations of marine fish in Puget Sound. Recent changes in these factors may influence the degree of risk of a population without apparent changes in abundance, because of time lags between the events and the effects on the population. Thus, a consideration of these effects extends beyond the examination of recent trends in abundance. The BRT considered documented physical and climatic changes, but did not consider possible effects of recent or proposed conservation measures. Population variability in itself may not be an indication of risk. Habitat degradation and harvest have most likely weakened the resilience of populations in Puget Sound to climate variability. However, these effects are not easily quantified. Manmade contaminants and

predation by marine mammals are additional factors that may influence herring mortality and lead to changes in abundance.

Threats to Genetic Integrity

Artificial propagation of herring populations does not occur in Puget Sound so is not a risk factor for the species considered here. However, mariculture of some species is under development, and the effects of hatchery releases on natural populations may be important in the future. The interbreeding of cultured and natural fish can potentially lead to a loss in fitness of naturally-spawning populations. The genetic effects of artificially-propagated releases of species with high fecundities, as is common for many marine fishes, could be substantial. Ryman and Lairkre (1991), Waples and Do (1994), and Ryman et al. (1995) discussed possible risks associated with enhancement of marine populations, but these risks are difficult to quantify and to incorporate into risk analysis. The chief concern is that the release of propagated fish, which may be inadvertently modified by breeding practices and novel rearing environments, may lead to the erosion of genetic diversity and fitness in natural populations.

Human activities, other than population enhancement, can also influence the genetic characteristics of natural populations. These include size-selective harvest methods (Nelson and Soulé 1987); introductions of non-native species; and alterations of marine habitats by shoreline development, increased siltation in river runoff, and pollution. At the present time, empirical information documenting the genetic effects of these kinds of changes is largely lacking.

Climate Variability

Coupled changes in climate and ocean conditions have occurred on several different time scales and have influenced the geographical distributions, and hence local abundance, of marine fishes. On time scales of hundreds of millennia, periodic cooling produced several glaciations in the Pleistocene Epoch (Imbrie et al. 1984, Bond et al. 1993). The central part of Puget Sound was covered with ice about 1 km thick during the last glacial maximum about 14,000 years ago (Thorson 1980). Since the end of this major period of cooling, several population oscillations of pelagic fishes, such as anchovies and sardines, have been noted on the west coast of North America (Baumgartner et al. 1992). These oscillations, with periods of about 100 years, have presumably occurred in response to climatic variability. On decadal time scales, climatic variability in the North Pacific and North Atlantic Oceans has influenced the abundances and distributions of widespread species, including several species of Pacific salmon (Francis et al. 1998, Mantua et al. 1997) in the North Pacific, and Atlantic herring (Alheit and Hagen 1997) and Atlantic cod (Swain 1999) in the North Atlantic. Recent declines in marine fish populations in Puget Sound may reflect recent climatic shifts (Fig. 4). However, we do not know whether these climatic shifts represent long-term changes or short-term fluctuations that may reverse in the near future. Although recent climatic conditions appear to be within the range of historical conditions, the risks associated with climatic changes may be exacerbated by human activities (Lawson 1993).

Risk-Assessment Methods

One of the greatest difficulties in the status review process is organizing the large amount of information regarding the biology of the species, genetics, and population trends over time. Often, the ability to measure or document risk factors is limited, and information is not quantitative and is very often lacking altogether. In assessing risk, it is often important to include both qualitative and quantitative information, and the method by which a BRT can do so takes several forms. In the next section, information to assist in assessing risk is presented in the format of the types of methods used in the BRT deliberations. The first is a presentation of risk factors discussed in West (1997). This is a qualitative discussion that presents and references important pieces of information, but does not attempt to make a quantitative assessment of these factors. The second method for assessing risk is that of Wainwright and Kope (1999). This method was used in the Pacific salmon BRT process and provides a method to organize and summarize the professional judgement of a panel of knowledgeable scientists. It is a risk matrix approach and includes information on abundance, population trends, productivity and variability, genetic integrity and habitat condition/capacity. Another approach recently presented by Musick et al. (2000), provides criteria by which to define risk. These criteria are based on productivity measures such as intrinsic rates of increase, age at maturity and maximum age. These criteria are similar to those examined in Wainwright and Kope, however, they are organized somewhat differently. The criteria are rarity, small range and endemics, specialized habitat requirements and population decline. Decline thresholds are based on population resilience of the species. This method provides another method to examine and organize available information for the evaluation of risk and an opportunity to compare the results of the methods

Risk Factors

Major risks to the survival of Pacific herring include overharvesting, predation by pinnipeds, birds and fish, adverse climatic conditions, loss or degradation of habitat, and pollution-related effects as identified in West (1997). Each of these risk factors will be described in the following sections.

Overharvesting

Most human harvest of Pacific herring since about 1970 has been for the lucrative roe market. Policies on human harvest of herring for roe are similar for California, Washington, British Columbia, and Alaska. No harvest is allowed below specified thresholds. When mature biomass is above a threshold, allowed exploitation rates are gradually increased to a maximum of 20%. The level of exploitation is thought to be sufficiently low to protect the resource. Minor bait and subsistence harvests are also allowed, and Washington does not control tribal fisheries which have been very minor in recent years. The tribes cooperate with WDFW in management of their harvest. Much larger harvests were allowed prior to 1970. In recent years, however, Washington has not allowed a sac roe fishery because of low biomass in the Cherry Point population. Harvests in recent years appear to be much lower than the amount consumed by natural predators.

Predation

The WDFW fishing regulations have reduced human exploitation rates to low levels, however, pinniped exploitation of herring may have increased. Herring-survey biologists have observed increased nocturnal occurrences of harbor seals near schools of herring and concurrent changes in herring schooling behavior (West 1997).

Two species of pinnipeds, California sea lion (*Zalophus californianus*) and Pacific harbor seal (*Phoca vitulina*), that are common in Puget Sound and British Columbia exploit herring. Schmitt et al. (1995) estimated that herring comprised 6% of the diet of California sea lions in Puget Sound during the 1986-1994 period. Total fish consumption by California sea lions in Puget Sound was estimated to be 830 mt per year (NMFS 1997). Thus about 50 mt (0.06×830) of herring were consumed by California sea lions per year in Puget Sound during the 1986-1994 period. Large aggregations of California sea lions were not reported in Puget Sound until 1979 (Schmitt et al. 1995), numbers increased through 1986, and then fluctuated without trend (Schmitt et al. 1995, and J. Laake⁶). California sea lions also occur in British Columbia waters but estimates of their consumption of herring were not available.

More data are available on Pacific harbor seals in British Columbia waters than for Puget Sound. Olesiuk et al. (1990) estimated that harbor seals consumed 3,206 mt of herring in the Canadian Strait of Georgia (CSG) during 1988, which represented 9.6% of the herring spawning biomass (Table 5). They estimated that herring comprised 32.4% of harbor seal diet in 1988. NMFS (1997) estimated that harbor seals consumed 14,997 mt of prey in Washington inland waters during 1993. If herring comprised 32.4% of the diet of Washington harbor seals, they would have consumed 4,859 mt (5,356 tons) of herring in Washington's inland waters in 1993, which represented 34.9% of estimates of spawning biomass of herring for 1993 (Table 6). While herring biomass was not estimated for all areas and harbor seals consume immature as well as mature herring, it appears that harbor seals could be a significant source of mortality for Washington populations of herring and could account for some of the increases estimated for non-fishing mortality (Bargmann 1998). NMFS (1997) estimated that harbor seals in Washington waters increased at 7.7% annually between 1978 and 1993. They did not provide rate of increase for inland waters alone. Herring are also reported to be an important prey item for harbor porpoises in the Strait of Juan de Fuca (Gearin et al. 1994).

Forage fish, including herring, are prey for some birds. Fish-eating species documented for inland waters of Washington and/or British Columbia included red-throated loon, Pacific loon, common loon, horned grebe, eared grebe, pied-billed grebe, red-necked grebe, western grebe,

⁶ J. Laake, NOAA Fisheries, 7600 Sand Point Way, N.E., Seattle, WA 98115. Pers. commun, March, 2000.

Table 5. British Columbia herring biomass and landing estimates (metric tons 2205 lbs).

W. C. Vancouver I. = West Coast Vancouver Island. Schweigert and Fort (1999)

Year	Queen Charlotte		Prince Rupert		Central Coast		Strait of Georgia		W.C. Vancouver I.	
	Biomass	Landings	Biomass	Landings	Biomass	Landings	Biomass	Landings	Biomass	Landings
1973	15226	7520	12867	1607	22270	7799	25906	7649	34522	18303
1974	16221	6318	12712	3819	19511	8887	68622	4004	41108	16334
1975	16675	7724	12811	1702	17903	8739	82871	6179	70703	26109
1976	29258	14116	18520	4307	28545	12411	69372	12238	102160	38825
1977	25151	12635	17877	8142	29587	11106	75512	17509	87441	30043
1978	23177	11726	13325	8588	24143	14046	121084	24002	62676	22745
1979	16610	7953	11871	4317	6555	5	79380	20338	82357	18694
1980	24520	3316	13661	3425	16517	538	80666	5818	66601	3982
1981	24654	5631	13622	3090	19522	2573	60282	12052	66608	8090
1982	22788	3778	14616	1984	24782	6370	103072	12833	34911	5486
1983	24679	5597	19653	0	22258	5640	64641	17218	23904	8575
1984	25084	4647	26633	3706	21368	7171	38632	11045	28719	6577
1985	20501	6109	42605	6747	13689	5209	33659	7030	29310	178
1986	9140	3503	41205	8679	18920	3386	61690	594	38551	204
1987	15193	2061	37693	6271	16607	3615	48390	9353	45849	15934
1988	14488	32	41647	7968	31544	4527	33566	8215	49013	9724
1989	25448	1461	21257	8474	41776	9442	62447	8369	56620	13289
1990	32812	7801	24903	5505	39853	8805	67031	8119	48458	10121
1991	19750	5530	25869	4326	29512	9357	54524	11103	34813	8906
1992	13112	3612	40984	4992	54792	8756	93541	13419	40797	3986
1993	9356	3951	29157	7717	50773	11060	98702	13741	35122	5884
1994	6282	1387	18852	5413	42113	12332	78509	17647	26075	6310
1995	4946	0	18738	2877	29227	10308	72897	13190	27625	2586
1996	5827	0	26282	4178	23150	5209	90404	14113	33445	1516
1997	11686	0	27559	6815	30011	4806	73251	19809	46497	7383
1998	20906	2100	20952	4218	39351	9965	82303	13604	44261	7363
1999	13506	3792	28813	3114	37662	8738	83450	13285	23926	5097

Table 6. Puget Sound herring biomass estimates (tons). Shaded cell indicates estimate is from acoustic trawl survey. Unshaded cell indicates estimate is from spawn deposition survey. Empty cell indicates no survey was done. SQUA = Squaxin Pass, QM = Quartermaster Harbor, PO-PM = Port Orchard/Port Madison, SHOOD = South Hood Canal, QUIL = Quilcene Bay, PG = Port Gamble, KILI = Killisut Harbor, DISCO = Discovery Bay, DUNG = Dungeness Bay, PT SUS = Port Susan, HOLM = Holmes Harbor, SKAGIT = Skagit Bay, FIDAL = Fidalgo Bay, SEMI = Samish-Portage Bay, INT.SJ = Interior San Juan Islands, NWSJ = Northwest San Juan Islands, SEMI = Semiahmoo Bay, and CHPT = Cherry Point. (M. O'Toole, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000).

YEAR	SQUA	QM	PO-PM	SHOOD	QUIL	PG	KILI	DISCO	DUNG	PT SUS	HOLM	SKAGIT	FIDAL	SAMP	INT.SJ	NWSJ	SEMI	CHPT
1973																		14998
1974																		13963
1975	298		887				279							109			772	10337
1976	2138	1357	447	492	279	1142	495	697			126	478		77	10	157	321	11844
1977	20	1413	1348	444	232	2525		1488			135	227		32	18	29	634	11097
1978	58	1860			14	1984	254	1305										10973
1979	137	1941	1255			1790		882						333				9957
1980	683	1930	2133			2309	477	3220	43		78	453	276	1008				9329
1981	772	1777	891			1753	324	3070				456					1008	6219
1982		1778	1214	177		1463		2356		1391	78		182	310			1389	5342
1983		909	1651			2407		2578	197	1398			640	159			874	8063
1984		1386	1293			2685		3144		1555			742	160			772	5901
1985		667	1415			2387		1447		1321	914		761	78			2325	5760
1986		1181	1926			2050		1566	234	934			731	79			1464	5671
1987		924	2538			68	2046	1593		1216			887			400		3108
1988		750	1705			1390		853		570			1340				1965	4428
1989		898	1739			2395		1225		345	693			58	541		1701	4003
1990	566	681	1795			2969	364	855		291	380				391	218	1930	4998
1991	943	580	722	357	204	2259	613	925		245			1079		60	298	2061	4624
1992	771	518	314	144	97	2270		727		545			1399	262	17		1501	4009
1993	596	1075	304			1521	538	737		1693			1417	198	472		1902	4894
1994	225	1412	424			2857	292	375		365			1207	455			1389	6324
1995	157	2001	863			817	3158	261	287	363			891	1173			1245	4105
1996	374	805	806	239	328	2058	380	747	180	118	336	736	590	616	277	53	1215	3095
1997	149	1402	360	226	465	1419	307	199	158	828	530	893	929	509	30	79	621	1574
1998	68	947	489	101	1152	971	311	0	112	3084	464	309	844	643		107	919	1322
1999	174	1257	3006	516	2464	1664	307	307	352	545	175	905	1005	555	197		868	1266
2000	371	743	1756	140	2426	2459	107	159	138	785	281	649	737	196	128	90	926	808

POPULATION

double-crested cormorant, Brandt's cormorant, pelagic cormorant, great-blue heron, common merganser, red-breasted merganser, Caspian tern, common murre, pigeon guillemot, rhinoceros auklet, and tufted puffin (Mahaffy et al. 1994). Estimates of herring consumption by these birds were not available. Palsson (1984) studied the consumption of herring eggs by birds in Puget Sound. He found 14 species of ducks and gulls feeding over spawning beds. The most important egg-predators were surf scoters, white-winged scoters, glaucous-winged gulls, and Bonaparte's gulls. The birds were mainly attracted to areas with high egg densities and bird densities dropped soon after consumption reduced the abundance of eggs in an area. It is difficult to estimate the impact of birds on egg mortality because there are other sources of high egg mortality, such as suffocation when there are multiple layers of eggs and predation by snails and amphipods that can occur if the eggs are not first consumed by birds (Palsson 1984).

Herring are estimated to comprise 71% of lingcod, 62% of chinook salmon, 58% of coho salmon, 53% of Pacific halibut, 42% of Pacific cod, 32% of Pacific hake, 18% of sablefish, and 12% of dogfish diets off the west coast of Vancouver Island (Environment Canada 1998). Pacific hake and cod abundance in Puget Sound decreased in recent years (Gustafson et al. 2000), but West (1997) expressed the concern that increased abundance of hake in offshore waters may be affecting herring. The proportion of offshore hake that feeds off British Columbia during summer months is directly related to ocean temperatures, which tended to be higher than normal between 1976 and 1998. West (1997) also noted that spiny dogfish apparently increased in Puget Sound since 1985, and that WDFW increased releases of yearling chinook salmon from low levels in the early-1970s to more than 3,000,000 fish in most years since 1975 (WDF 1993). Chinook salmon released as yearlings tend to remain in Puget Sound and could account for some of the increased non-fishing mortality estimated for Puget Sound herring, but much of the increase in mortality occurred after yearling releases had increased to present levels.

In summary, herring are important diet components for many predators. However, time series of estimates of total herring consumption by predators have not been made. While it seems safe to conclude that predation is a major source of mortality for herring, it is not possible to determine what portion of the apparent increase in non-fishing mortality of herring is due to changes in predation intensity.

Climate

The decline in some of the Puget Sound herring populations coincided with warm/dry conditions in the Pacific Northwest (Fig. 4). Similar conditions occurred during the 1930s when Chapman et al. (1941) reported that the Discovery Bay and Cherry Point herring populations were at low levels. Conditions changed to cold/wet or average during the 1940s and 1950s (Fig. 4), and by 1959 Williams (1959) reported that the Cherry Point and Discovery Bay populations had "regained their productive levels after many years without exploitation". The Cherry Point and Discovery Bay populations experienced the steepest declines observed in the Washington populations since 1986 (see Table 11 on page 130 of this document). EVS (EVS Environment Consultants 1999) found significant negative correlations between biomass of the Cherry Point population and annual sea surface temperatures at British Columbia light houses at Active Pass (in Gulf Islands near Cherry Point), Race Rocks (Strait of Juan de Fuca), and Amphitrite Point

(west coast of Vancouver Island). The correlations ranged from -0.64, Race Rocks, to -0.75, Amphitrite Point, which is the farthest from Cherry Point.

The Cherry Point population is thought to migrate to off the coasts of Washington and southern British Columbia during summer months (Lemberg et al. 1988). Discovery Bay is on the Strait of Juan de Fuca and thus closer to the outer coast than populations in Puget Sound. Herring year-class strength of the west coast of Vancouver Island population averaged twice as large in cool years than in warm years (Canada Fisheries and Oceans 1998). Tanasichuk (1997) found that length-at-age of herring of the southwest coast of Vancouver Island was negatively related to sea temperature during the first growing season.

The observed correlations with temperature could be caused by increased predation and/or competition resulting from increased populations of hake and Pacific sardines off the west coast of Vancouver Island during warm years or adverse direct effects of high temperature at some life stage(s). EVS (1999) reviewed the literature on temperature tolerances of herring eggs and larvae and found that “the preponderance of data in the scientific literature suggest that the upper threshold for effects is between 13 and 14°C”. They collected temperature data at 12 stations in the Cherry Point area between May 14 and June 9, 1998. Station averages ranged from 11.1 and 11.9°C during the first half of the study and 11.5 and 12.1°C during the second half. The maximum observed temperature in June was 16.8°C. Environment Canada (1999) also summarized surface temperature data collected once per month by the Washington State Department of Ecology between 1978 and 1997 at a station in the Strait of Georgia (16 km west of the Cherry Point area) and a station in Bellingham Bay (13 km south of the Cherry Point area). May and June temperatures exceeded 13°C on several occasions. While data are limited, in recent years the observed temperatures at and near Cherry Point during the time of spawning and early larval stages are close to or above the upper tolerance reported in the literature suggesting that temperature related mortalities could have occurred in early life stages of Cherry Point herring. Because juvenile and adult herring are very mobile, it seems likely that they could avoid excessive temperatures.

Habitat

Because herring spawn at shallow depths in nearshore waters, their spawning grounds are particularly vulnerable to human disturbance. Chapman et al. (1941) reported that herring had spawned in Port Hadlock, but no longer spawned there by 1936. They quoted local inhabitants, who “claimed that no fish have spawned in that vicinity since the digging of the ship canal between Marrowstone Island and the mainland.” Herring no longer spawn in Nanaimo Harbor and the adjacent Newcastle Channel and Ladysmith Harbor, which have been heavily affected by human activities (Environment Canada 1998). Herring also have not returned since 1977 to spawn in Pender Harbor, which has had considerable waterfront residential growth (Environment Canada 1998). There are three industrial piers in the Cherry Point spawning area. The last one was completed in 1971 (EVS 1999). The piers have had modest impacts on the spawning habitat through light shading, current modifications, and wave shading (EVS 1999). There is evidence of some changes in vegetation in the area (EVS 1999).

Pacific herring almost always spawn on aquatic vegetation. Three species of plants (*Zostera marina*, *Desmarestia* spp., and *Odonthalia* spp.) appear to be preferred as herring spawning substrate over other plants at Cherry Point (Stick 1995 cited in EVS 1999). The percent frequency used for spawning was 58.0% for *Zostera marina*, 46.9% for *Desmarestia* spp., and 6.8% for *Odonthalia* spp., while their frequency of occurrence in samples was 53.6%, 30.4%, and 6.6% respectively. These data suggest that *Desmarestia* spp. was preferred over *Zostera marina* at this site. Pacific herring also sometimes spawn on gravel, rocks, and human-made structures. There is little aquatic vegetation in Squaxin Pass and the Port Susan areas and herring often spawn on rocks and gravel there (Lemberg 1997). The introduced *Zostera japonica* was not listed, and it is not clear that the study distinguished between the two species of eelgrass. *Zostera japonica* does not function well as a spawning substrate for herring, because it is an annual plant and beds are not established until after the spawning season of winter spawners. Because of this there is concern about its spread in Puget Sound (West 1997). While the Cherry Point data suggest that *Desmarestia* spp. was preferred over *Zostera marina*, WDFW staff believe that *Zostera* generally is a preferred spawning substrate throughout Puget Sound and that subtidal beds of *Gracilaria* are also important (Koenings, unpubl. data). The Washington Departments of Natural Resources and Fish and Wildlife have a policy of no net loss of vegetated habitat, but "many Puget Sound researchers and managers think that significant anthropogenic loss of eelgrass continues" (West 1997). There is inadequate information to assess the cumulative loss of eelgrass or habitat in Puget Sound during historical times. Prior losses of intertidal habitats such as are documented in Hutchinson (1988) may be a factor in the declines of herring populations due to ecosystem effects. However, many of these losses are historic (prior to 1950) and predate the recent declines in some herring stocks within the Georgia Basin.

Effects of Pollution

Herring in Puget Sound, the Strait of Juan de Fuca, the southern Strait of Georgia, and elsewhere in British Columbia, have been potentially exposed to a variety of anthropogenic pollutants at various sites during the past century. Both the local and region-wide understanding of contaminant patterns, injuries, and trends are relevant because herring: 1) have local spawning sites in proximity to known pollution sources, 2) spawn at sites scattered across a wide range of urban, industrial and rural locations, and 3) are migratory, thus they may be exposed to potentially-contaminated water and food over large areas.

Contaminants of most concern include synthetic chlorinated organic chemicals, such as: 1,1,1-trichloro-2,2-bis-(p-chlorophenyl)ethane and related compounds (DDTs) and the polychlorinated biphenyls (PCBs); polycyclic aromatic hydrocarbons (PAHs) from petroleum and hydrocarbon combustion; dioxins and a host of other organic compounds; trace elements, such as mercury and lead; and organic matter and nutrients, such as nitrogen. Documented sources of contaminants have included: industrial discharges, pulp and paper mills, oil spills, sewage treatment plant discharges, runoff from urban and agriculture area, and coal mining and processing. Local and onshore sources also include creosoted pilings and seepage from hazardous waste sites. Poorly-documented sources of contaminant include: atmospheric deposition and advection of marine water from other locations. Major efforts to stem, control or re-direct pollution began in the 1940s, following World War II industrial activity. By the early-

1970s there were major reductions in pollutant loads discharged by the wood and paper industries (Dexter et al. 1985). By the late-1970s there were major improvements in municipal wastewater treatment, effective industrial pre-treatment or source control, and the onset of clean-up of hazardous waste sites. However, urban and suburban development, highway construction and increased traffic continue.

Herring can be exposed to contaminants through all stages in their life cycle. Developing eggs and larvae can be exposed to contaminants in water and in the surface micro-layer. Juveniles, sub-adults, and adults that migrate through urban waters, may accumulate persistent organic chemicals through feeding. These bio-accumulated contaminants may be passed to their gametes as well as their predators (larger fish, mammals and birds).

Pollution in Georgia Basin DPS spawning sites

The near-shore, shallow-water spawning habitat of herring makes them particularly vulnerable to exposure to contaminants from such sources as oil spills, urban and agriculture runoff and chronic air pollution. Herring eggs can be exposed to contaminants during embryonic development. Herring at Cherry Point, one of 18 spawning sites in the Puget Sound/Straits region, has been studied in detail for possible problems with contaminants. The ARCO refinery experienced three minor discharge permit violations (EVS 1999): fecal coliform bacteria, biochemical oxygen demand (BOD), and oil and grease. In the Ferndale refinery effluent, concentrations of mercury, copper, and lead have been problematic, but probably not of particular concern after dilution by mixing (EVS 1999). In the effluent from the Intalco refinery, concentrations of nickel, phenanthrene and fluoranthene have also exceeded standards but mixing would reduce concentrations below levels of concern (EVS 1999). Studies of the receiving waters indicate no evidence of contaminants above current standards (EVS 1999). However, standards for PAHs may not be appropriate and concentrations of PAHs may have been above 1 ppb, a concentration that caused problems in herring larvae hatched from eggs that were exposed to weathered Alaska North Slope crude oil (Carls et al. 1999, Brown et al. 1996, Kocan et al. 1996, Laur and Haldorson 1996).

Some scientists are becoming increasingly concerned about the effects of endocrine-disrupting chemicals, such as PCBs and PAHs on animals (Vos et al. 2000). Sediments near the ARCO refinery were found to be contaminated with chemicals similar to those found in coal tar epoxy, which was used to protect pier pilings (EVS 1999). The Intalco facility was ranked third highest of 49 sites in Puget Sound with sediment contamination (excluding Superfund sites) and was the highest ranking site not undergoing cleanup (EVS 1999). Two of four studies (conducted in 1990-1992, and 1998) found either lower-hatching success or a reduction in the percent of normal larvae for herring eggs collected from Cherry Point sites compared to controls (EVS 1999). The ARCO and Tosco Cherry Point facilities have reported 73 oil spills ranging from sheens reported on 12 occasions to 21,000 gallons spilled on 6/4/72 (EVS 1999).

Exposure to PAHs by adult male herring collected during spawning from five spawning sites in Puget Sound and the Strait of Georgia in 1995, 1999 and/or 2000 was evaluated by

West (J. E. West⁷). Fish are able to extensively biotransform PAHs to more polar metabolic products, most of which are readily excreted into the bile (Varanasi et al. 1989). Therefore, exposure of male herring to PAHs was estimated by measuring fluorescent aromatic compounds (FACs) in bile. Concentrations of biliary FACs were reported as benzo[a]pyrene (BaP) equivalents, representing the high molecular weight aromatic hydrocarbons (HAHs); or as naphthalene (NPH) and phenanthrene (PHN) equivalents, representing molecular low weight aromatic hydrocarbons (LAHs), on a mg biliary protein basis. Sources of LAHs include all fossil fuels, as well as crude oil. The HAHs are also present in crude oil and fossil fuels, and another important source is combustion residue (e.g., soot) from incomplete combustion processes with fossil fuels, including natural processes, such as forest fires. The spawning sites in North Puget Sound from which herring were collected and the years in which they were sampled included: Semiahmoo Bay (1999 and 2000), Cherry Point (1999), and Fidalgo Bay (1995, data not presented here). The Puget Sound proper spawning sites from which herring were collected and the years in which they were sampled included: Port Orchard (1999 and 2000) and Johnson Point (1999 and 2000). A spawning site near Nanaimo, B.C. was sampled in 1999.

In bile samples analyzed in 1999, the highest mean concentration of BaP equivalents was found in the bile of herring from Port Orchard (Fig. 30). This result is not unexpected because of this site's proximity to Elliott Bay. McCain et al. (2000) reported that concentrations of HAHs in sediment and BaP equivalents from the bile of English sole (*Pleuronectes vetulus*) from a site in Elliott Bay were among the highest found on the West Coast. Concentrations of NPH equivalents also tended to be higher in the bile of herring the Port Orchard site; however, the mean concentration was not significantly different from the Cherry Point site (Fig. 30). This higher concentration at the Cherry Point site may be the result of oil refinery-related activities at this site which could yield LAHs (EVS 1999). For samples collected in 2000, mean concentrations of BaP, NPH, and PHN equivalents tended to be higher in herring from the spawning sites in Puget Sound proper, but the differences from the Semiahmoo Bay site were not significant.

Puget Sound-wide contaminant investigations have been recently conducted at sites either with or without a history of pollution or near known point sources. Some studies have been done near a few of these herring spawning areas. For example, total PAH concentrations in Sound and Straits sediments in 1998 ranged from less than 100 ppb dry weight (dw) at sites in the Straits of Georgia, Discovery Bay, Dash Point and Port Townsend to 11,000 ppb dw in the Duwamish River (PSWQAT, 1998). In this survey, sediments at sites at Birch Point, north of Cherry Point, appeared to contain on the order of 300 ppb dw. Similar values (ca 300 ppb) were reported for a site in Port Madison and a value of over 3,000 ppb was reported for Dyes Inlet. This region (Dyes Inlet to Port Madison) hosts many kilometers of herring spawning beaches such that if PAH's are affecting herring, the Port Orchard area spawning populations should be affected.

⁷ J. E. West, Washington Dept. of Fish and Wildlife, P.O. Box 40900, Olympia, WA 98501-1091. Pers. Commun., October 6, 2000.

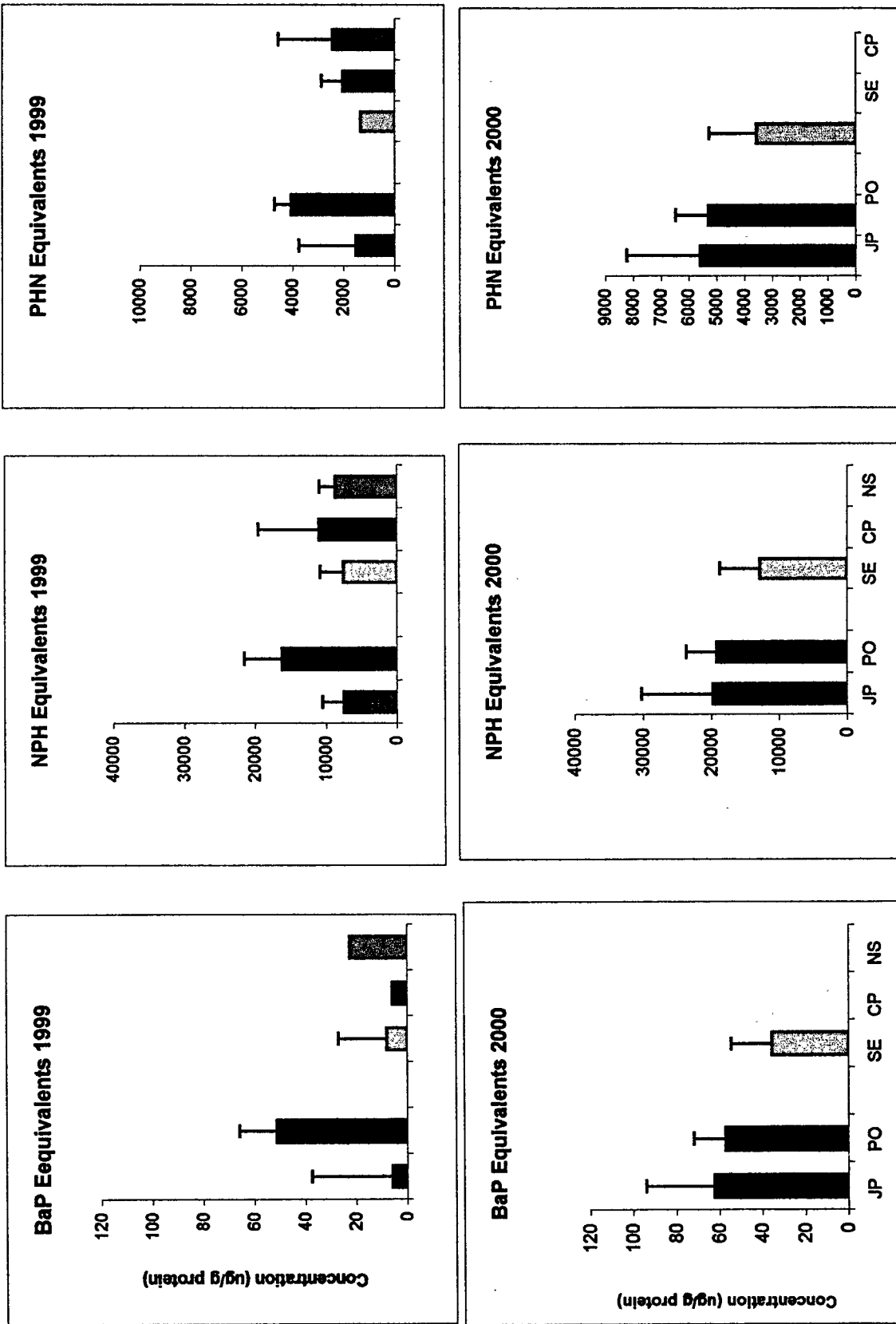


Figure 30. Concentrations of fluorescent aromatic hydrocarbons in the bile of Pacific herring from selected sites in Puget Sound and the Strait of Georgia in 1999 and 2000. JP, Johnson Point; PO, Port Orchard; SE, Semiahmoo Bay; CP, Cherry Point; NS, Nanaimo

Relatively high levels of PCBs were found in herring from spawning sites in Puget Sound proper. Whole bodies of male herring were used for analyses of PCBs. Data from analyses for PCBs are presently only available for herring collected in 1999. Concentrations of PCBs in composites of homogenized whole bodies (10 composites per site, 5 fish per composite) were consistently higher in herring from the Port Orchard and Johnson Point spawning sites compared to sites in North Puget Sound and the Strait of Georgia (Fig. 31). McCain et al. (2000) also reported concentrations of PCBs in the sediments and in the livers of English sole from Elliott Bay to be among the highest on the West Coast. The proximity of Port Orchard to Elliott Bay and Johnson Point to Olympia (another urban center in Puget Sound) may account for these higher levels of PCBs.

In the 1980s the upper layer (neuston layer) of Puget Sound waters contained concentrations of PCBs, PAHs, and metals exceeding EPA standards by orders of magnitude (Hardy and Antrim 1988). Herring eggs deposited in the inter-tidal zone are exposed to upper water surface and larvae feed on organisms that at least partially inhabit the neuston layer.

Herring populations in several areas could have been affected by contaminants in the past (prior to the 1970s), such as pulp mills discharged large volumes of primary treated effluent (including those in Port Susan, in Sinclair Inlet, near Port Townsend and in southern Puget Sound). There have been other identifiable and pollution events such as oil spills in Discovery Bay, LaConner, Port Susan, Manchester, Washington Narrows (Port Orchard), Winslow, and Budd Inlet (Dexter et al. 1985) and at Anacortes and other localities (A. J. Mearns⁸). Therefore, we cannot conclude that other populations are not, or have not been, at risk from chemical contaminants similar to those at Cherry Point.

Region-wide status and long-term trends in pollution

Herring migrate throughout the Puget Sound/Straits region and therefore can encounter pollutants at locations other than spawning sites. Region-wide contaminant monitoring has been spotty, both geographically and over time. However, recent and historical surveys generally support several regional patterns and trends of contamination. Concentrations of organic chemical contaminants in water, sediments, shellfish and fish have been high in sub-areas of the Main Basin surrounding Seattle and Tacoma and considerably lower in the Straits of Juan de Fuca and Georgia, north to the international boundary. In 1997 and 1998, concentrations of selected contaminants were measured in mussels from 18 marine sites in Washington as part of NOAA's Mussel Watch Program (Mearns et al. 1999) (Fig. 32). Mean concentrations of total PAHs (TPAHs) ranged from 174 ppb dw at Cape Flattery to nearly 33,000 ppb at Four Mile Rock in Seattle (Fig. 33). Mean concentrations of TPAHs in mussels from Puget Sound proper ranged from 681 to 33,000 ppm while those from sites near Bellingham and Point Roberts were about

⁸ A. J. Mearns, Hazardous Materials Response Division, National Oceanic and Atmospheric Administration, 7600 Sand Point Way NE, Seattle WA 98115. Pers. Commun., October 23, 2000

Figure 31. Concentrations of PCBs in whole body tissues of Pacific herring from selected sites in Puget Sound and the Strait of Georgia in 1999 and 2000. JP, Johnson Point; PO, Port Orchard; SE, Semiahmoo Bay; CP, Cherry Point; NS, Nanaimo.

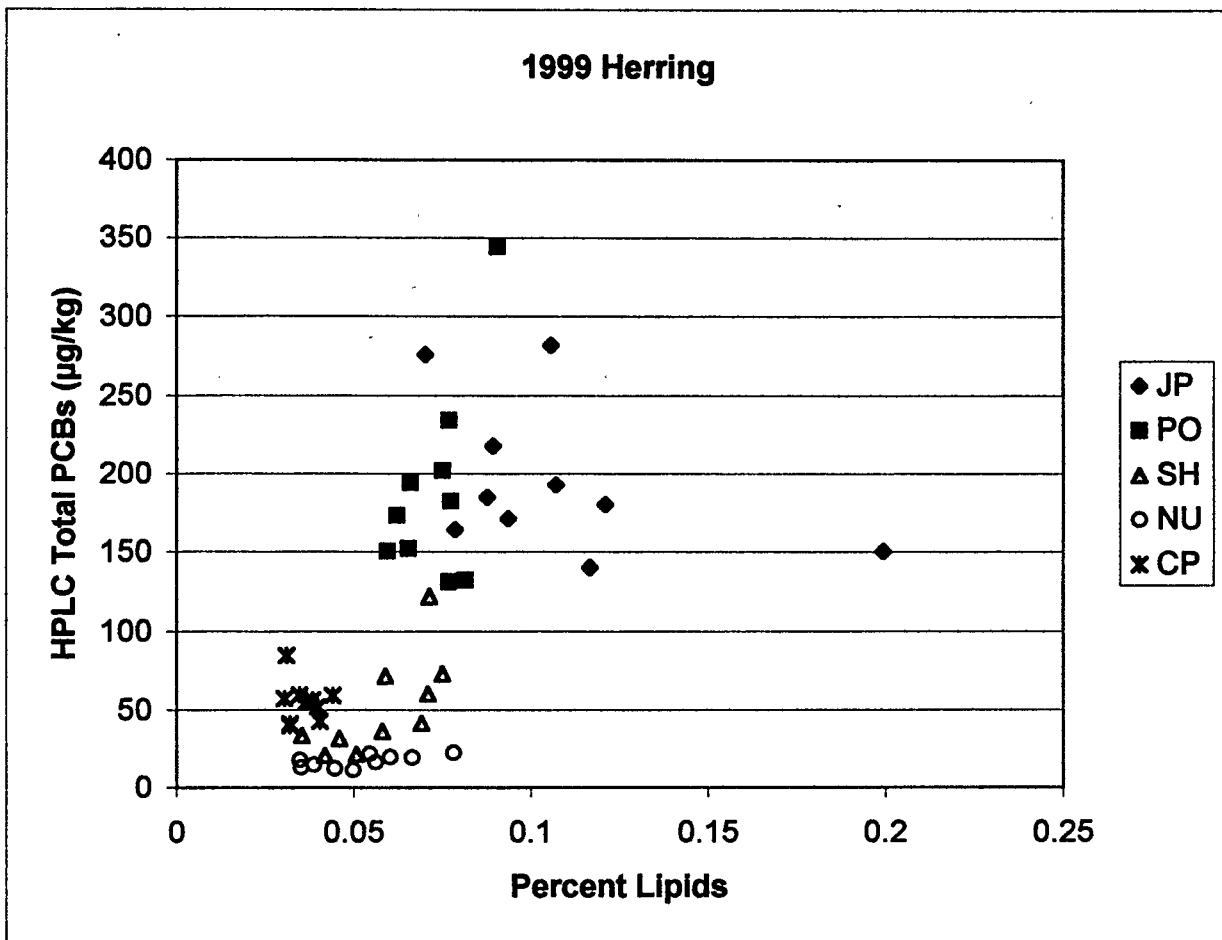


Figure 32. Locations of sites in Washington State from which mussels were collected for chemical analyses as part of NOAA's Mussel Watch Program.

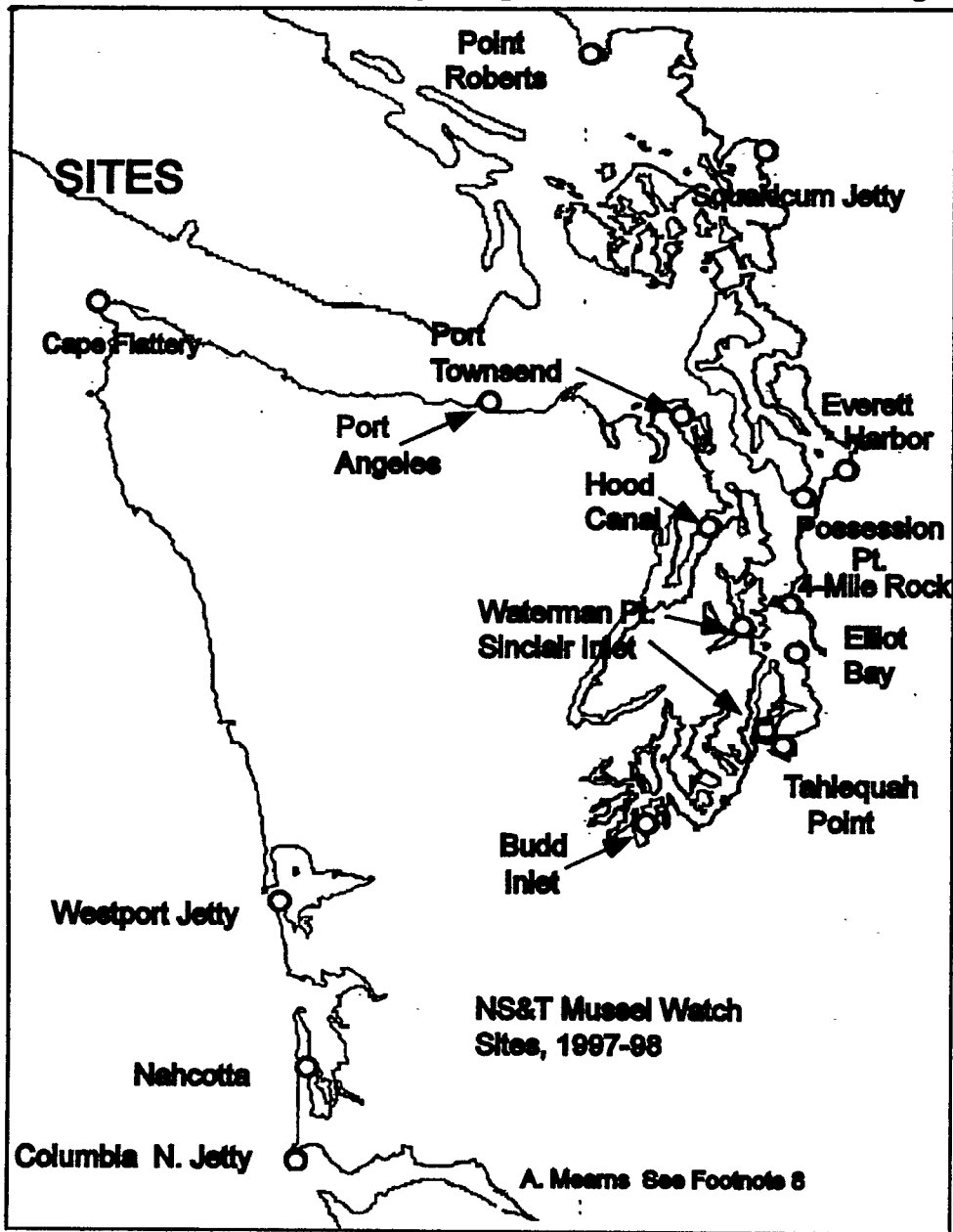
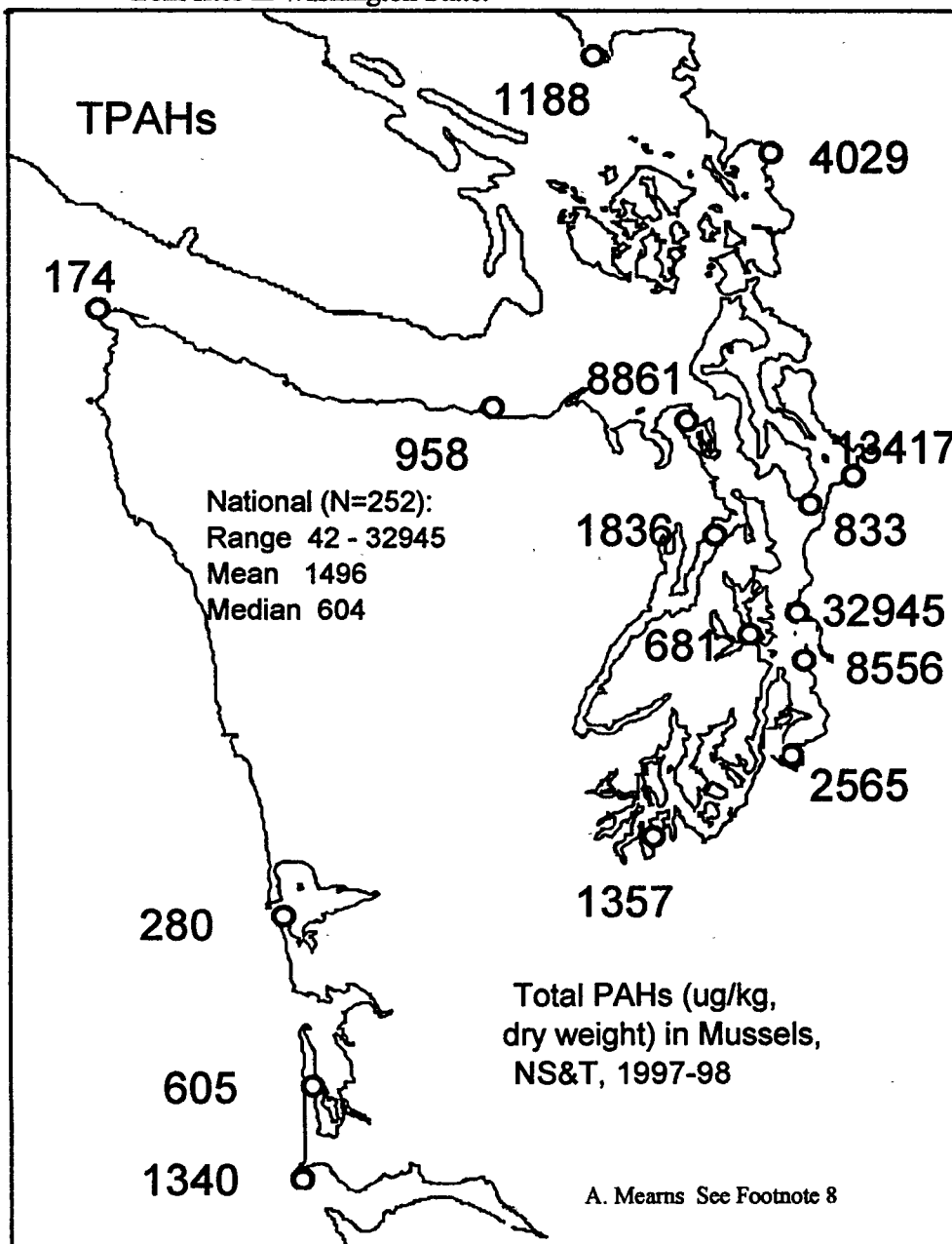


Figure 33. Mean concentrations (ppb, dry weight) of summed TPAHs in mussels from sites in Washington State.



4,000 and 1,200 ppb, respectively. Salazar (M. Salazar⁹) reported that composites of mussels from Cherry Point contained between 300 and 400 ppb TPAHs. This site is about halfway between Bellingham and Point Roberts and thus actually appears low compared to surrounding areas.

Mussel Watch sites near Port Townsend, in Hood Canal and at the south end of Vashon Island were located near known herring spawning sites. These sites are: Kulisut Harbor, Port Gamble, Quartermaster Harbor, respectively. Mussels from all three of these sites had TPAH concentrations comparable to or greater than the sites in the northern Strait (Fig. 33). The extremely high mean concentrations of TPAHs in mussels from Port Townsend (8,861 ppb) is of considerable interest because the site is located within a few meters of an active sand lance spawning beach and within 1-4 km of Kulisut Harbor. Mussels at the site in northern Hood Canal contained unusually high mean concentrations of TPAHs (1,836 ppb dw). This site is at the "old" ferry landing which is 3-4 km south of the Hood Canal Bridge and across the canal from the herring spawning sites in and outside Port Gamble. Although, it is possible Hood Canal Bridge traffic contributes PAH's to this region.

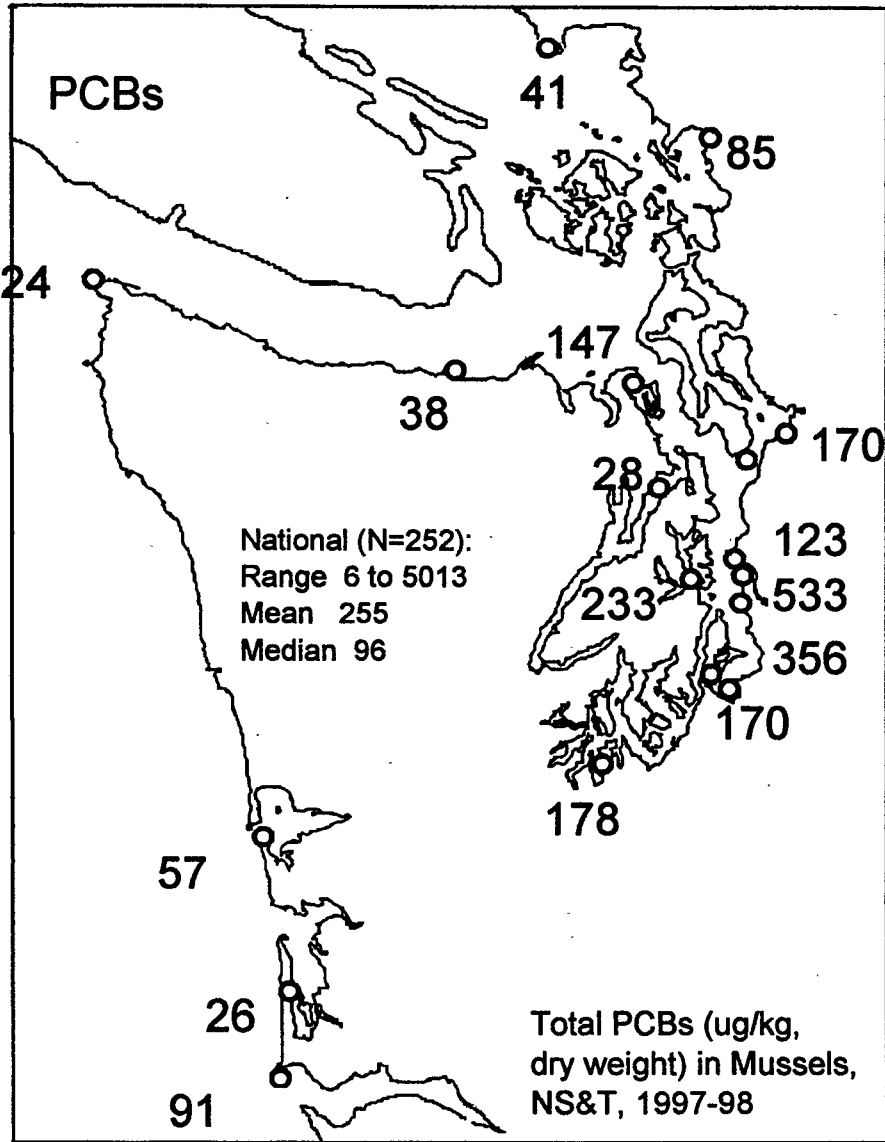
Similar patterns were observed for PCBs, with higher concentrations in mussels from the central Puget Sound area (123 to 533 ppb dw), Sinclair inlet (233 ppb) and Port Townsend (147 ppb), compared with the mean concentrations in mussels from the two sites in the northern Strait of Juan de Fuca (24 and 38 ppb dw) (Fig. 34).

About 38% of Puget Sound proper has been identified as contaminated above state standards, evidence for potential adverse effects on marine resources. Concentrations of number of heavy metals; chlorinated pesticides, such as DDTs, chlordanes, and dieldrin; dioxins and furans; PCBs; and PAHs in sediments are monitored regularly as part of the Puget Sound Ambient Monitoring Program (PSAMP), operated by the Puget Sound Water Quality Action Team, and have also been measured by Federal agencies such as NOAA and EPA. Currently, over 15,000 acres of intertidal and subtidal lands have been surveyed in urban embayments of Puget Sound as part of the PSAMP (PSWQAT 2000). Most contaminated sediments are located in industrialized areas of the Sound, such as Elliott Bay, Commencement Bay, Sinclair Inlet, and Everett Harbor. Some contaminants of concern (e.g., PCBs, DDTs) are no longer being released into the environment, and levels are gradually declining, but high-residual concentrations are still found in many industrialized areas. Others, such as PAHs, are still being released, especially through non-point sources, and do not appear to have declined greatly over the last 20 years.

Dated sediment cores taken from the middle of the Main Basin of Puget Sound in the late-1970s and again in 1990, clearly document a Main Basin-wide rise of contamination during the period 1920 to 1960 and then decreasing contamination to the present (Lefkovitz et al. 1997). For example, the cores reflect that inputs of PCBs, PAHs, DDTs, chemicals from mills, and several trace elements (mercury, arsenic, lead) increased through the 1950s and 1960s and then

⁹ M. Salazar, NOAA, Office of Ocean Conservation Resources and Assessment, 7600 Sand Point Way NE, Seattle, WA, Pers. commun. October 10, 2000.

Figure 34. Mean concentrations (ppb, dry weight) of summed PCBs in mussels from sites in Washington State.



A. Mearns See Footnote 8

progressively decreased through the 1980s. Older mass emission data, water column toxicity data and anecdotal information, confirm the past heavy input of contaminants into herring spawning regions such as the Port Susan complex (Dexter et al. 1985).

Fifteen years (1986-2000) of more recent data on contaminants in mussels, coupled with some 25-year-old data, show a variety of geographic scales, patterns, processes, and response times, some of which are rather surprising. For example, mussels within Puget Sound and the Straits are depleted in several metals (arsenic and cadmium) compared to those from open coastal sites of the Pacific Northwest (Mearns, see Footnote 8). For most metals, there are no "hot spots" or long-term trends, regardless of trends in inputs and discharges. Both cores and mussels from the Sound confirm that PCB concentrations and, presumably, inputs, have been declining over the past three to four decades. Compared to mussels from other Pacific and U.S. coastal areas, Puget Sound mussels contain comparable concentrations of PCBs, but incomparably high concentrations of PAHs.

These trends are reflected in fish and shellfish surveys and monitoring data from specific sites. For example, by 1975, PCB concentrations in flounder and sole in the Duwamish waterway were declining at rates comparable to those seen in deep-basin sediment cores. Recent (1997-2000) surveys indicate that sediments along the coast north of Admiralty Inlet, and in Ports Susan are largely uncontaminated and non-toxic and support robust benthic assemblages (Long et al. 1999).

Counter to these trends is continued chemical contamination and biological effects of chemicals, including diseased bottomfish populations, within and around historic contaminant hot spots. These include such inshore areas of Commencement Bay, the Duwamish Waterway in Seattle, and a creosote-contaminated site at Eagle Harbor on Bainbridge Island. Focused studies at "pollutant bottlenecks" show that juvenile chinook salmon migrating through still-polluted waterways are at risk of poor health due to exposure to organic chemicals such as PAHs and PCBs. Documented adverse health effects include increased susceptibility to infectious diseases and genetic aberrations (Arkoosh et al. 1991, Stein et al. 1995). There are no similar "pollutant bottleneck" local studies for Pacific herring, except at Cherry Point. Similar studies at sites such as in Port Madison and in Port Susan would help clarify the extent to which ambient levels of contamination may pose risk to herring. Further, it would also be instructive to understand how herring fared in past decades in areas where pollution inputs were much greater than they are today.

While there are useful data on contaminants in sediments, shellfish, and fish, we still have no comparable synthesis of contaminant inputs into Puget Sound or the Straits. Inputs may be coming from sources yet to be adequately assessed, such as urban and agriculture runoff channels and ferry terminal tarmacs. Inputs data, coupled with maintenance or enhancement of dated core and mussel watch monitoring, are needed to understand and derive benefit from contaminant management actions and spill responses and, ultimately, to determine clean safety levels.

In conclusion, it is clear that herring residing in Puget Sound proper are generally exposed to higher levels of a variety of chemical contaminants compared to herring in North Puget Sound

and nearby coastal areas. Many of these chemicals have known negative effects on aquatic life, and while their effects on Pacific herring stocks within Puget Sound is unknown, laboratory and field evidence suggests that negative effects are likely. The concentrations of specific contaminants vary over spatial and temporal scales. Concentrations of some contaminants, such as polychlorinated biphenyls (PCBs), are declining over time, whereas concentrations of others, such as polynuclear aromatic hydrocarbons (PAHs), are either remaining constant, or are increasing.

Summary of Risk Factors

West's (1997) presentation of risk factors for Pacific herring in Puget Sound points to climatic trends (high temperatures) and increased predation by pinnipeds, spiny dogfish, and Pacific salmon as the probable major factors contributing to the decline of these fish. Other factors that may be important are loss or degradation of nearshore nursery habitats; however, no recent, comprehensive Puget Sound-wide information on this exists. What information that remains comes from isolated reports of researchers reporting habitat loss. The increase in abundance in California sea lions and harbor seals may also play a role in the decline of the species, and new studies of diet for these species may shed additional light on this. Increased predation on larval and juvenile fish by delayed-release Pacific salmon may also be important. Loss of fitness due to exposure of larvae, juveniles and adults to contaminants cannot be ruled out. However, some of the contaminant loads in these fish seem to be lessening and there is no clear-cut evidence as to the effects of these contaminants on Pacific herring.

Pacific Herring Abundance and Productivity

This section assesses the risk of extinction of herring populations in the Georgia Basin DPS, including Puget Sound and the southern Strait of Georgia, and examines trends in California, other British Columbia regions, and Southeast Alaska. The primary considerations are abundance, trends and productivity of Pacific herring populations. Following the presentation of this information, we will use the methods of Wainwright and Kope (1999) and Musick et al. (2000) to evaluate the magnitude of the overall risk.

Abundance and Trends

Abundance

Puget Sound—The Forage Fish Management Plan (FFMP) (Bargmann 1998) is the most recent management publication by WDFW on Puget Sound herring. The FFMP recognized that forage fish populations tend to be unstable even in the absence of human impacts and that management will not produce stable populations of individual species (Table 7). It stated that “Once a forage fish stock reaches a low level of abundance, recovery may require a protracted period of time, even if fisheries are curtailed or stopped.” The FFMP considered herring that utilize specific spawning grounds as individual stocks and contrasted this approach with British Columbia.

Table 7. Commercial landings (tons) of herring in Washington: Years 1961-1996 (Data from Bargmann 1989) and years 1935-1960, 1997-1999 (Data from M. O'Toole, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000.). Landings were not available by fishery type before 1965.

Landings		Landings					
Year	Total	Total	Sport Bait	General Purpose	Sac Roe	Spawn on Kelp	
1935	69	1965	4173	312	3861	0	0
1936	454	1966	2257	307	1950	0	0
1937	438	1967	3224	327	2897	0	0
1938	508	1968	3224	484	2740	0	0
1939	142	1969	4148	479	3669	0	0
1940	462	1970	2209	530	1679	0	0
1941	147	1971	1893	429	1464	0	0
1942	36	1972	1771	559	1047	165	0
1943	394	1973	3450	629	794	2027	0
1944	303	1974	6070	622	998	4450	0
1945	269	1975	7171	1223	2104	3844	0
1946	227	1976	3045	730	60	2255	0
1947	597	1977	3115	711	108	2296	0
1948	242	1978	3030	625	270	2135	0
1949	420	1979	3592	979	698	1915	0
1950	194	1980	3513	846	1080	1587	0
1951	273	1981	1531	677	854	0	0
1952	359	1982	1314	576	300	438	0
1953	283	1983	872	664	208	0	0
1954	133	1984	576	426	150	0	0
1955	230	1985	466	466	0	0	0
1956	266	1986	602	602	0	0	0
1957	549	1987	628	499	0	98	31
1958	4152	1988	1027	901	0	5	121
1959	2768	1989	961	704	0	38	219
1960	2052	1990	1076	781	0	17	278
1961	1801	1991	1003	741	0	24	238
1962	3184	1992	968	778	0	13	177
1963	3486	1993	938	635	0	23	280
1964	1980	1994	799	460	0	22	317
		1995	793	460	0	26	307
		1996	590	458	0	6	126
		1997	399	399	0	0	0
		1998	361	361	0	0	0
		1999	385	385	0	0	0

“In Washington, we attempt to maintain viable populations utilizing each ground each year; in British Columbia loss of herring utilizing a specific ground is not a concern, the management goal is to maintain the overall abundance” (Bargmann 1998).

The WDFW classifies populations into five status categories: 1) Healthy – recent two year mean abundance above or within 10% of the 20 year mean; 2) Moderately Healthy – recent two year mean abundance within 30% of the 20 year mean; and/or with high dependence on recruitment; 3) Depressed – recent abundance well below the long term mean, but not so low that permanent damage to the population is likely (i.e., recruitment failure); 4) Critical – abundance low enough that permanent damage to population is likely or has already occurred; 4) Extinct – no longer can be found in a formerly consistently utilized spawning ground; and 5) Unknown – insufficient assessment data to identify stock status with confidence. The FFMP classified status of the 18 inland water populations as 8 in healthy condition, 1 in moderately healthy condition, 3 depressed, 1 critical, and 5 unknown based on data through 1996 (Table 8). The FFMP also reported that estimates of natural mortality rates increased from less than 0.4 from 1976 to 1980 to more than 0.6 from 1990 to 1995. During this time period the number of age groups comprising the bulk of the populations decreased from five to two or three. While herring formerly lived to ages exceeding 10 years, fish older than 6 years are now rare (Bargmann 1998). Washington Department of Fish and Wildlife (WDFW) (K. Stick and M. O’Toole¹⁰) has updated the classifications twice using data through 1998 and 2000 (Table 8). The updates resulted in many changes in the classifications. The latest update classified status of the populations as 10 in healthy condition, 2 in moderately healthy condition, 3 depressed, 2 critical, and 1 unknown.

An earlier study also expressed concern about the status of some of the Puget Sound populations (Chapman et al. 1941). The Cherry Point population was too low to attract fishermen, but fishermen said it had previously been “one of the most productive herring grounds in Puget Sound” (Chapman et al. 1941). The Discovery Bay population also did not attract fishing, but there had been a “fishery of considerable size here” (Chapman et al. 1941). But, in 1959, Williams (1959) found that the Cherry Point and Discovery Bay populations had “regained their productive levels after many years without exploitation”.

The petition submitted by Wright (1999) referred to 18 populations of herring in Puget Sound and provided detailed discussion about the “depressed” Cherry Point and “critical” Discovery Bay populations. The Cherry Point population has been the largest Puget Sound population (Table 5), and its late spawning time is unique for Puget Sound. The population is thought to migrate to productive coastal waters because members exhibit relatively rapid growth rates after age-1. Spawn deposition biomass estimates declined from 11,097 tons in 1977 to 1,530 tons in 1997. The extent of the area now used for spawning is only a small fraction of historical observations, and the current spawning area is centered in an area of industrial impacts.

¹⁰ K. Stick and M. O’Toole, Washington Department of Fish and Wildlife, P.O. Box 1100 La Conner, WA 98253. October, 2000.

Table 8. Comparison of WDFW classifications of status of inland water herring populations of Washington based on three stock assessments. Data from Bargmann (1998), and WDFW (K. Stick, Washington Department of Fish and Wildlife, P.O. Box 1100, La Conner, WA 98253, Pers. commun. October 2000), and (M. O'Toole, Washington Department of Fish and Wildlife, P.O. Box 1100, La Conner, WA 98253, Pers. commun. January 2000).

Number	Name	Stock Status		
		1996	1998	2000
1	Squaxin Pass	Mod. Healthy	Depressed	Healthy
2	Quartermaster Harbor	Healthy	Healthy	Healthy
3	Port Orchard/Port Madison	Depressed	Depressed	Healthy
4	South Hood Canal	Unknown	Mod. Healthy	Healthy
5	Quilcene Bay	Healthy	Healthy	Healthy
6	Port Gamble	Healthy	Depressed	Healthy
7	Kilisut Harbor	Unknown	Mod. Healthy	Healthy
8	Port Susan	Depressed	Healthy	Mod. Healthy
9	Holmes Harbor	Unknown	Healthy	Depressed
10	Skagit Bay	Healthy	Mod. Healthy	Mod. Healthy
11	Fidalgo Bay	Mod. Healthy	Healthy	Healthy
12	Samish-Portage Bay	Healthy	Healthy	Healthy
13	Interior San Juan Islands	Unknown	Unknown	Depressed
14	NW San Juan Islands	Unknown	Depressed	Unknown
15	Semiahmoo Bay	Healthy	Depressed	Depressed
16	Cherry Point	Depressed	Critical	Critical
17	Discovery Bay	Critical	Critical	Critical
18	Dungeness Bay	Healthy	Healthy	Healthy

The Discovery Bay population is the largest Strait of Juan de Fuca population in U.S. waters and was one of the largest in Washington waters. In 1979, surveyors estimated that the biomass was 3,220 tons. It has declined to low levels of abundance and surveyors were unable to detect herring eggs at this site in 1998. The Port Susan and Port Orchard/Port Madison populations are also called depressed by Bargmann (1998). The petition states they “show the same type of distinct downward trends exhibited by the Cherry Point and Discovery Bay herring populations.”

The petition cites evidence that marine ecosystems tend to have relatively few forage species and such species tend to have decadal-scale changes in abundance. An ecosystem with relatively few species at the mid-level is called a “wasp-waist ecosystem” (Rice 1995). The petition states, “A recurring theme in Bakun (1996) is the decadal-scale shifts in abundance that may occur in wasp-waist species; often, but not always, due to replacement by other forage fishes. Puget Sound herring appear to be one of the exceptions to this generalization.” However, Bargmann (1998) indicated that assessments of other forage species in Puget Sound may not be adequate to verify that other forage species have not replaced herring in Puget Sound. For example, Pacific sand lance spawning habitat was virtually unknown until discovery of spawn deposits in Port Gamble Bay in 1989. Systematic surveys were developed, but reduced by budget constraints in 1997 (Bargmann 1998). Bargmann (1998) stated “Judging from the reported biology of the species, the widespread nature of their spawning grounds, spawn densities on the spawning beaches, and numbers of spawnings per spawning season, it is possible that there are thousands of tons of sand lances residing in the Puget Sound basin on a year-round basis.”

The conclusions expressed in the FFMP and the petition are based upon a substantial time series of herring survey and fishery data in Puget Sound. The WDFW has estimated spawning biomass of important populations annually and minor populations tri-annually (Lemberg 1997). They usually conducted spawn deposition surveys. In some cases, both acoustic/trawl and spawn deposition surveys were made and in some cases only acoustic/trawl surveys were conducted. Spawn deposition results were used for analysis when available. Acoustic/trawl results were similar to egg deposition results when both types of surveys were made (Lemberg 1978, Lemberg et al. 1997). Acoustic/trawl methods were used for analysis when egg deposit surveys were not made. Catches up to survey dates were added to the survey estimates to obtain total run size. The California Department of Fish and Game (Spratt 1981), and Alaska Department of Fish and Wildlife (Rooper et al. 1998) adjust egg deposition estimates for post-spawn mortality. Although Palsson (1984) of WDFW stated “The management of herring stocks might be improved if egg loss rates were incorporated into the procedure of estimating spawning biomass”, the department has not done so. Palsson conducted more research “which indicated other biases (e.g., vegetation width variations) that may offset the negative bias of egg loss” (Koenings, unpubl. data). Acoustic/trawl biomass estimates assume that target strength is independent of length. Average length has decreased compared to earlier years. Thus acoustic/trawl surveys could overestimate biomass in recent years relative to earlier surveys. Biomass estimates are shown in Table 6. A quantitative analysis of these trend data will be presented in a later section of this document.

Commercial landings from Washington state inland waters since 1935 are shown in Table 7. Recreational landings are trivial and commercial fishing for herring is not allowed in coastal

waters. Only commercial fishing for sport bait has been allowed by the state in recent years. The state does not control treaty fishing and there has been a low-level treaty fishery for sac-roe in recent years. Treaty landings may be incompletely reported in Table 7 prior to 1973. Total landings were modest and did not exceed 1,000 tons until 1958 and then remained above 1,000 tons until 1983. Since then landings ranged from 1,076 tons in 1990 to 361 tons in 1998, which is well below peak landings of 7,171 tons in 1975.

The sport bait fishery occurs primarily in south and central Puget Sound and primarily exploits 1.5-year-old herring that are at the size preferred by recreational salmon fishermen. Sources of these immature herring are not known. Demand for bait has decreased in recent years because of restrictive salmon regulations (Bargmann 1998). The general purpose fishery occurred in northern Puget Sound and most of the catch was reduced to meal and oil, food for zoo animals, and bait (Bargmann 1998). Tagging studies (Buchanan 1985a) indicated that some fish exploited by this fishery migrated to and from Canadian waters and expansion of the fishery was encouraged in the 1960s because it was thought that it would primarily intercept fish bound for Canada. The general-purpose fishery exploited immature and mature herring, but did not exploit herring that were ready to spawn. The sac-roe and spawn-on-kelp fisheries mainly exploit fish thought to be from the Cherry Point population. The spawn-on-kelp fishery impounds herring caught by seine and releases them after spawning. Mortality of these fish was estimated to be no more than 10% (Bargmann 1998), but assumed to be harvested for management and abundance estimation purposes (Koenings, unpubl. data). The non-treaty sac-roe fishery was closed in 1980 because of low stock size (Bargmann 1998). The spawn-on-kelp fishery was closed in 1996 because of continued decreases in stock size (Bargmann 1998).

British Columbia—Schweigert and Fort (1999) conducted the most recent published assessment of Pacific herring in waters of British Columbia. The Department of Fisheries and Oceans Canada (DFO) uses five areas for assessing and managing herring (Fig. 20). The Prince Rupert area (PR) is adjacent to Alaskan waters and Williams (1999) found some evidence that herring from PR respond to environmental conditions similarly to herring from inshore waters of the Gulf of Alaska. The west coast of Vancouver Island (WCVI) and Strait of Georgia (SG) areas are adjacent to Washington and tagging results indicate some movement of herring between British Columbia and Washington waters (Buchanan 1985a). The SG is larger than Puget Sound and landings in the combined SG and WCVI areas were considerably higher than Washington landings (Table 5). While DFO manages herring on a larger geographical scale than WDFW, some data were available for smaller geographical regions denoted sections (Fig. 20).

The Department of Fisheries and Oceans Canada (DFO) made annual spawning biomass estimates using egg deposition surveys and added catches from the roe fishery to obtain total mature stock size. These data were used as input to an age-structured model to produce estimates adjusted for estimated efficiency of each survey. Both results were used to make annual management recommendations for catches from each area based on up to 20% of forecast stock size when the biomass was estimated to be above cutoff set at 25% of estimated unfished average biomass (Schweigert and Fort 1999). Only the survey-based estimates of total mature stock size were used in this review to be comparable to Washington estimates.

The southeast part of the SG is adjacent to the Cherry Point area. Herring spawn in May on Roberts Bank, British Columbia, which is just north of the May spawning area at Cherry Point (Levings 1983). Thus the "Cherry Point population" may extend into Canadian waters and WDFW biomass surveys may not include all of the areas used by this group of fish. The heaviest spawning in section 293 (see Fig. 20) was reported in the Boundary Bay area along the east shore of Point Roberts just north of the B.C.-Washington border (<http://www.sci.pac.dfo-mpo.gc.ca/herspaw/herspaw/293fig.htm>) (DFO 2000a). The DFO had permission to survey in Washington waters and their estimates for section 293 some spawning that occurred in Washington. The border did not appear to have an impact on the distribution of spawning. Most of the DFO spawning records for section 293 occurred during February and March (<http://www.sci.pac.dfo-mpo.gc.ca/herspaw/herspaw/293fig.htm>) (DFO 2000a). It appears that the herring population denoted Semiahmoo by WDFW is part of a larger spawning group shared with Canada. The WDFW was aware that during peak years of the Cherry Point population spawning occurred on the west side of Point Roberts to the Canadian border and probably extended past the border. The WDFW also was aware that spawning by the Semiahmoo population extended into Canadian waters (Koenings, unpubl. data). The WDFW has not had permission to survey in Canadian waters (Mark O'Toole¹¹).

Summaries for all herring spawn deposition surveys in SG since 1951 were obtained from <http://www.sci.pac.dfo-mpo.gc.ca/herspaw/herspaw> (DFO 2000a) Sections 201, 202, 280, 291, and 293 (Fig. 20), which comprise most of the SG sections that border Washington waters, were not included in the DFO assessments for the SG (Schweigert and Fort 1999) and were not regularly surveyed since 1978. The summaries were presented as spawn habitat indices (product of total length of spawn deposits, mean width of spawn deposits, and mean layers of eggs). Survey methodologies changed over the years. Prior to 1987, survey techniques varied but were similar to those used by WDFW.

Since 1987 most major spawning areas, excluding non-assessment areas, were surveyed using self-contained underwater breathing apparatus (SCUBA). Schweigert and Fort (1999) used procedures that varied as the survey methodologies changed to first estimate total number of eggs deposited and then used fecundities and sex ratios to estimate spawning biomass, but did not give details. A plot of the ratio of spawning biomass to spawn habitat index for the assessed portion of the SG indicated that the ratio was relatively constant from 1951 to 1975 (average 0.0090), 1976 to 1986 (average 0.0055), and 1987 to 1999 (average 0.0028). These averages were used to estimate spawning biomass from three portions of the SG: South, all sections adjacent to Washington waters; Northwest, sections 141, 142, 143, 161, 171, 172, and 173; and Northeast, sections 151, 152, 162, 163, 164, 165, and 280. Because SCUBA surveys were rarely used in the South portion, the 1976 to 1986 spawning biomass to spawning habitat ratio was used for the 1987 to 1999 period in the South portion. The Northwest portion dominated herring spawning biomass except for a short period in the 1960s (Fig. 35). Spawning biomass in the Boundary Bay area, Section 293, comprised a dominant proportion of biomass in the entire SG region during this

¹¹ Mark O'Toole Washington, Department of Fish and Wildlife, P.O. Box 1100 La Conner, WA 98253. Pers commun. December, 2000.

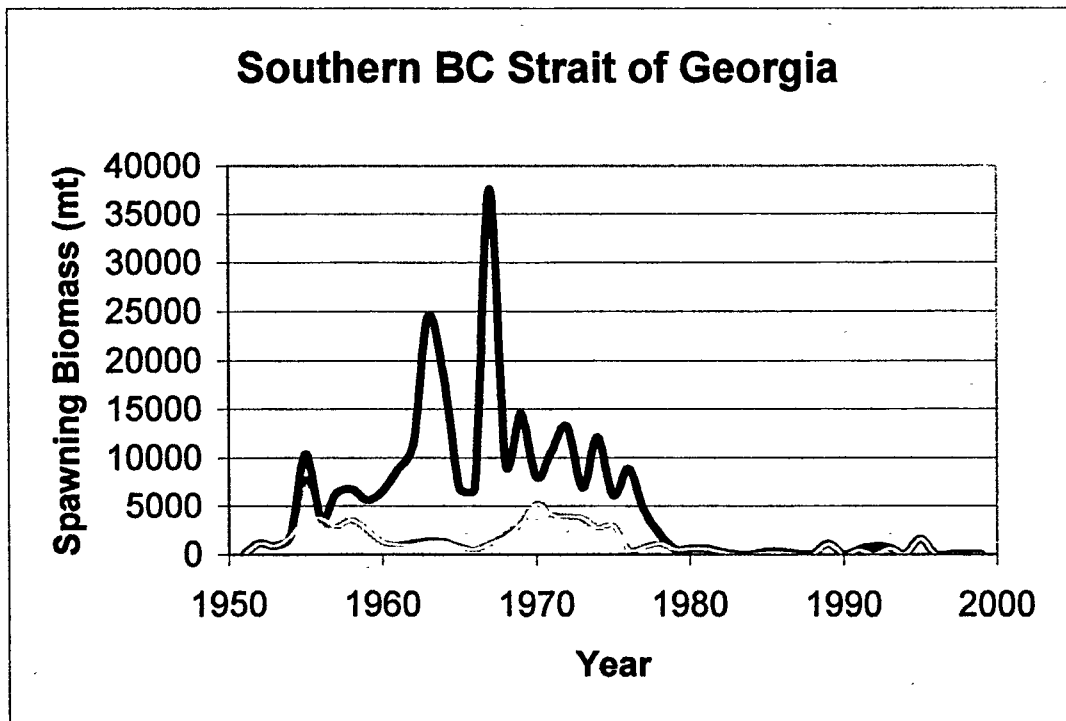
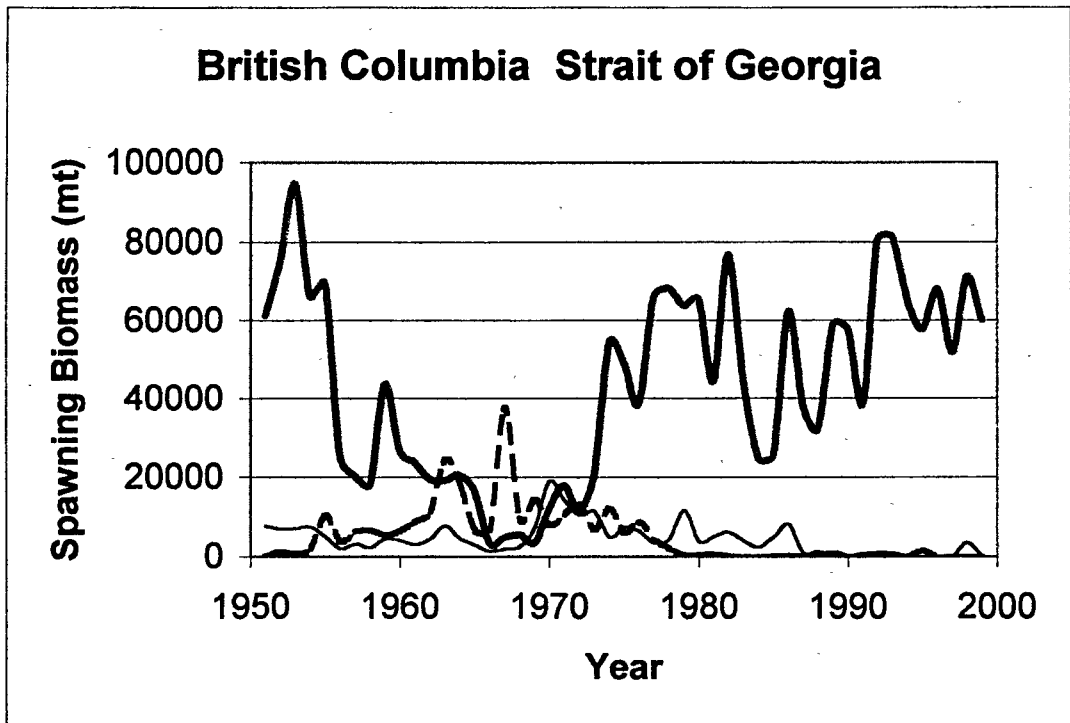


Figure 35. Spawning biomass estimates in the British Columbia portion of the Strait of Georgia. Low values are sometimes results of low or no surveys. Areas are defined in text. Top figure: heavy solid line Northwest area, broken line South area, and thin, solid line Northeast area. Bottom figure: heavy solid line Total, broken area Boundary Bay deleted, and thin solid line assessment area. Data from www.sci.pac.dfo-mpo.gc.ca/herspaw/default.htm (DFO 2000a).

period of time. Biomass in the assessment portion of the southern area was relatively low, increased in 1970 then decreased to relatively low levels after 1977 (Fig. 35). Because survey effort varied over the time period, available data do not support a more quantitative conclusion than was made by Hay and McCarter (1997a) about trends in herring spawning biomass in the southeastern portion of British Columbia Strait of Georgia region. Landings of herring were dominated by the Northwest and South portions prior to the collapse of the reduction fishery in the 1968 (Fig. 36). After the stocks recovered in 1973, landings were dominated by the Northwest portion. However landings were fairly high in the South portion in 1977 and 1978 (Fig. 36).

The Strait of Georgia (SG) population was at relatively high levels in recent years; however, spawn deposition decreased in the southeast parts of the SG (Hay and McCarter 1997a). Biomass in none of the British Columbia areas had downward trends as severe as observed for some of the Puget Sound populations (Table 5). Biomass was relatively high in all British Columbia areas in 1999 except WCVI.

Southeast Alaska—Alaska manages its sac-roe fisheries similarly to British Columbia (http://www.cf.adfg.state.ak.us/geninfo/finfish/herring/forecast/01_4cast.htm) (Larson et al. 2000). No exploitation is allowed if forecasted biomass in a management area falls below a threshold. If biomass is adequately above the threshold, allowable exploitation is set at 20%. If biomass is close to the threshold, allowable exploitation is set at a level that will not drop the surviving biomass below the threshold. There are four management areas in Southeast Alaska: Kah Shakes/Cat Island, Sitka Sound, Seymour Canal, and Craig. Estimates of biomass, forecasted biomasses and thresholds are shown in Table 9. The Kah Shakes/Cat Island and Prince William Sound spawning populations were considered depressed. Prince William Sound biomass decreased from 111,800 tons in 1992 to 28,100 tons in 1993 and has not recovered to high levels observed between 1980 and 1992. Herring returning to Prince William Sound in 1993 were abnormally small, had unusual behavior, and tests indicated the presence of Viral Hemorrhagic Septicemia (Funk 1995). The 1976, 1980, 1984, 1988, 1992, and 1994 year-classes dominated age compositions in both the Prince William and Sitka Sounds (Carlile, unpubl. data).

San Francisco and Tomales Bays—The only significant fishery for herring south of Puget Sound is on spawning populations in San Francisco and Tomales Bays, California (Suer 1987). Biomass estimates (Table 10) considerably fluctuated without a strong trend, since subtidal spawning areas were first included in the surveys in 1979, but the San Francisco Bay biomass averaged about 39% higher during the 1981-1990 period than during the 1991-2000 period. Combined San Francisco Bay and Tomales Bay estimates for 2000 were the third lowest since 1975.

Quantitative trend analysis

Musick (1999) presented guidelines based on productivity criteria for considering marine fish to be sufficiently at risk to warrant careful evaluation. These guidelines were developed in the belief that guidelines developed for other groups of animals were not appropriate for marine fish. The life-history characteristics indicate that herring are in the medium productivity category.

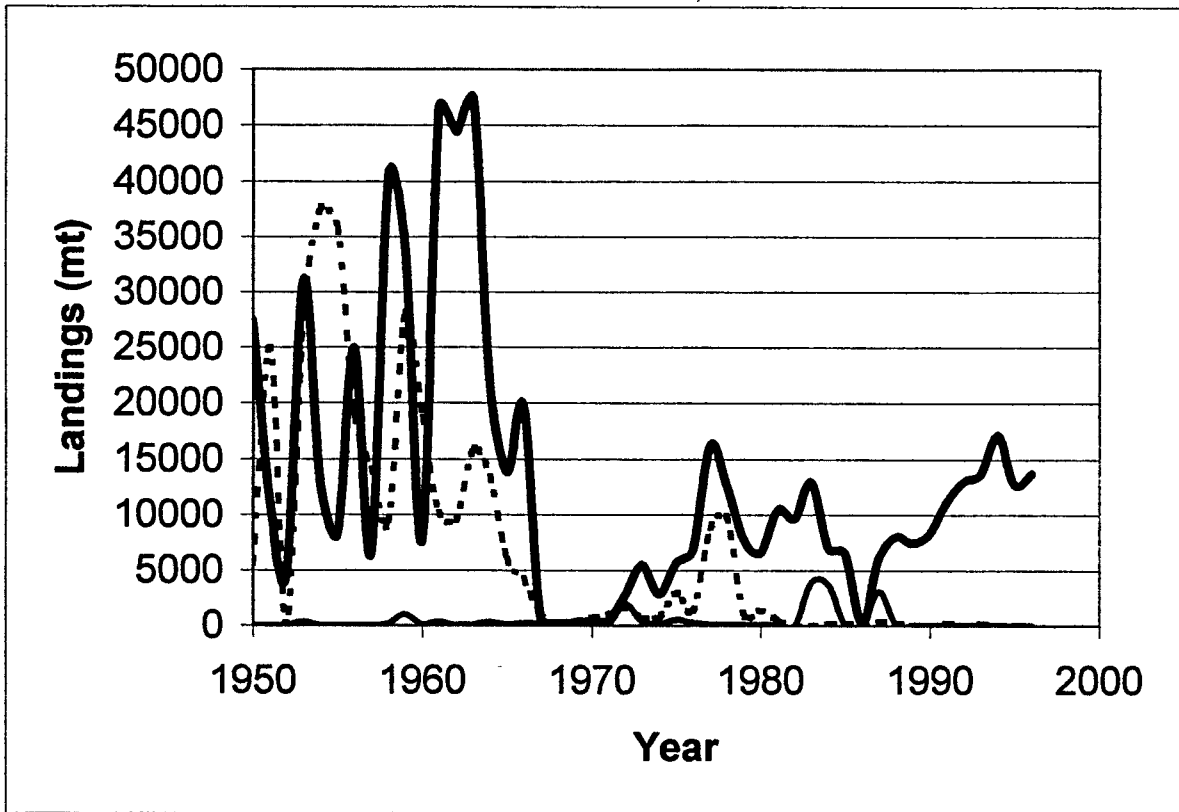


Figure 36. Landings of herring in British Columbia portion of Strait of Georgia. Solid, heavy line in Northwest part, broken line is South part, and solid, thin line is Northeast part. See text for definitions. Data from www.sci.pac.dfo-mpo.gc.ca/herspawn/default.htm (DFO 2000a).

Table 9. Biomass (tons), forecasted biomass for 2000 and 2001, threshold biomass, and status of herring by Southeast Alaska management area and Prince William Sound. (na: not available) Forecast and status data for 2000 from www.cf.adfg.state.ak.us/geninfo/finfish/herring/forecast/00_4cast.htm. Southeastern Alaska data for 1971-2000 from Carlile 2000.

Year	Area					Prince William Sound
	South Eastern Kah Shakes/ Cat Island	Sitka Sound	Seymour Canal	Craig		
1971	na	6686	na	na	na	na
1972	na	7058	na	na	na	na
1973	na	10097	na	na	na	na
1974	na	4681	na	na	na	28500
1975	na	6532	na	na	na	26000
1976	6124	3500	1944	na	na	22500
1977	4820	4890	4120	na	na	21100
1978	5821	2675	5754	na	na	18100
1979	11328	20250	2235	na	na	26900
1980	16640	39385	5695	616	na	42600
1981	20290	33506	2015	4409	na	52700
1982	17979	33863	1340	5410	na	44100
1983	17939	28950	4015	3836	na	49200
1984	17732	44330	1950	3080	na	57000
1985	11396	38475	3000	3203	na	69200
1986	11388	30443	4342	1534	na	61800
1987	9840	50216	4800	4311	na	68300
1988	7237	68075	3200	18364	na	88500
1989	3912	39135	3115	21530	na	100500
1990	8624	26804	2850	21571	na	92500
1991	11110	25408	2100	21072	na	96800
1992	9356	53868	1780	14645	na	111800
1993	7668	45513	3005	7585	na	28100
1994	5162	18779	3675	4961	na	16900
1995	7258	43077	1252	3539	na	18700
1996	4534	44516	1703	3654	na	21200
1997	6505	38273	4913	6083	na	25800
1998	12157	41623	4390	6600	na	30100
1999	2407	53728	4044	6729	na	na
2000	642	62888	4558	9264	na	na
Forecast for	4300	36000	3400	3600	na	23987
Threshold	6000	20000	3000	2000	na	22000
Status	Depressed	Moderate	Moderate	Moderate	na	Depressed
Forecast for	2382	47460	4349	9091	na	na

Table 10. Biomass estimates of herring spawning in San Francisco and Tomales Bays, California. Tomales Bay estimates included fish inside and offshore of Bodega Bay. The 1986 Tomales Bay estimate based on cohort analysis. The 1990 Tomales Bay estimate was composed of a 350 t hydro-acoustic estimate plus 95 t catch. Other estimates based on egg deposition surveys plus catch. Prior to 1979 subtidal areas not included and biomass was probably under-estimated (Spratt 1981). (Data: K. Oda, California Department of Fish and Game, 411 Burgess Dr., Menlo Park, CA. 94024. Pers. commun. October 2000).

Biomass (tons)		
Year	San Francisco Bay	Tomales Bay
1974	6200	6562
1975	27200	4728
1976	27100	7913
1977	26900	5083
1978	8700	22163
1979	36700	No Survey
1980	53000	6023
1981	65400	5576
1982	99600	7149
1983	59200	11040
1984	40800	1280
1985	46900	6586
1986	49100	6000
1987	56800	5798
1988	68900	2061
1989	66000	380
1990	64500	445
1991	51000	779
1992	46600	1214
1993	21500	4078
1994	39900	2463
1995	40000	3979
1996	99000	2059
1997	59570	1510
1998	20000	586
1999	39500	4069
2000	27400	2011

Musick recommended considering a species at risk if a species in the medium productivity category experiences a decline of 95% or more during the longer of 10 years or three generations. Generation length for herring is about five years. We conducted trend analyses of herring biomass during the past 15 years.

Enough data were available from six of the Puget Sound populations to conduct trend analyses. Trends were estimated using the following model:

$$B_{t+1} = \lambda B_t = B_0 e^{\mu} \quad (1)$$

where,

B_t = biomass in year t , and

λ = annual rate of biomass change.

Holmes (In prep.) recommended using running sums of biomass to estimate λ . The running sum of biomass at year t is

$$R_t = \sum B_{t+i}, \text{ where } i=0, \dots, L. \quad (2)$$

Let

μ = sample average of $\ln(R_{t+1}/R_t)$, and

$\sigma^2(\mu)$ = slope of sample variance of $\ln(R_{t+\tau}/R_t)$,

where slope is the linear regression estimate of the slope in the relationship between sample variance of $\ln(R_{t+\tau}/R_t)$ and τ , and τ varies from 1 to 4. The estimate of λ is then given by

$$\lambda = \exp(\mu + \sigma^2(\mu)/2). \quad (3)$$

Holmes (In prep.) found that the above procedures for estimating μ and $\sigma^2(\mu)$ were less biased than the respective maximum likelihood estimates: sample average and variance of $\ln(B_{t+\tau}/B_t)$. She recommended that L be set to less than 4 and used 3 in her examples. We also set L at 3.

We used the estimates of μ and $\sigma^2(\mu)$ to estimate several measures of risk, based on forecasting future stock trends. Declines to 5% of 1999 biomass in fifteen years (following Musick (1999), one ton, or one fish seemed to be significant measures to consider. A wild population of one fish would be for practical purposes extinct. A one ton population of herring would be sufficiently small to be considered very close to extinction and difficult to detect. We assumed that average weight of herring would be 0.2 lbs (Fig. 37b). Mean time (Time(F)) to reach a specified decline is $\ln(F)/\mu$, where F is fraction of starting population. We also estimated the probabilities of a 95% decline in 15 years, and declines to one ton or one fish in 10, 25, 50, and 100 years (PR(F,t)). We assumed that μ follows a log-normal distribution with variance $\sigma^2(\mu)$ following Holmes (In prep.).

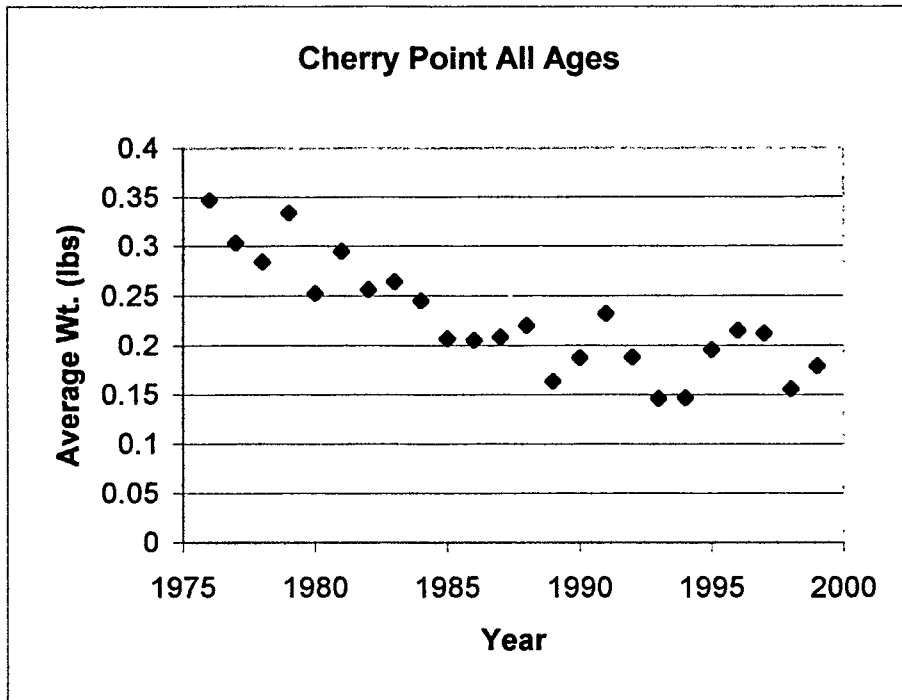


Figure 37a. Average weight of herring of all ages sampled from the Cherry Point population. (K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000.)

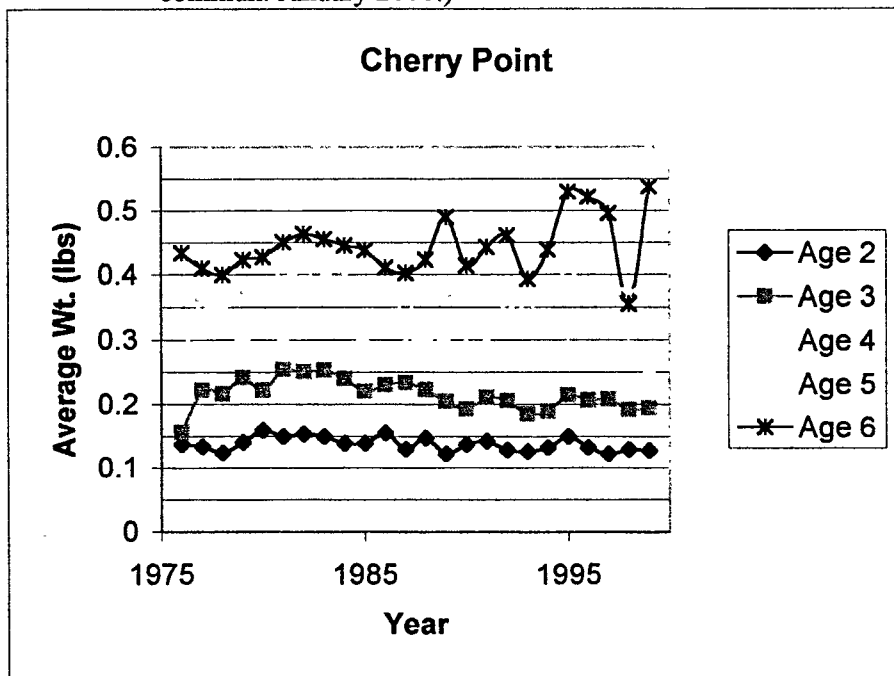


Figure 37b. Average weight at age of herring from the Cherry Point population. (K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000)

Under the assumptions of the model and if current conditions continue, the results (Table 11 and Fig. 36) indicate none of the populations are likely to decline 95% during the next 15 years, but indicate the time is 16 years for the Discovery Bay population. These estimates may also be considered the best estimates of the trend during the past 15 years. There is greater than 50% chance that the Cherry Point population will decline to 1 ton or less in 100 years, and greater than 50% chance that the Discovery Bay population will decline to one ton or less in 50 years. Chances are less than 50% that the other four populations will decline to one ton or less in 100 years. Holmes (In prep.) recommends caution in use of probabilities of extinction if the estimate of λ is close to one. Holmes (In prep.) doesn't provide a method for estimation of confidence limits of λ , but if the model holds, and μ is normally distributed, and if μ is more than 1.96 standard deviations lower than 0, it is significantly different than 0% at the 95% level of confidence. The results (Table 11) indicated that the only significant negative trend was for Discovery Bay. Since multiple tests were made, even if all of the assumptions hold the actual level of significance was less than 95%. These results indicated that the probability estimates should be interpreted with caution.

Population estimates in some of the spawning areas have always been small, and combined populations may produce more meaningful estimates of trends than individual populations. Projections indicated there is greater than 50% chance that biomass in North Sound (Cherry Point and Discovery Bay combined) will decline to 1 ton or less in 100 years (Table 11 and Fig. 38). Chances are less than 50% that biomass in South Sound (Quartermaster Bay, Port Orchard-Port Madison, Port Gamble, and Port Susan combined) (Fig. 39) or Puget Sound (North and South Sound combined) will decline to 1 ton or less in 100 years. As previously mentioned herring biomass in the southeast portion of the Canadian portion of Strait of Georgia (CSG) decreased as did the Washington portion of the Strait, but insufficient detailed data were collected by Canada to allow analysis (Hay and McCarter 1997). Biomass in the CSG is much larger than in Puget Sound and biomass in both the CSG and Georgia Basin DPS had an upward trend (Table 11).

Trends in Productivity

Here we consider two aspects of a population's productivity: recruitment of young fish into the population and mortality rate of adult fish. Age composition data are available since 1976 for the Cherry Point population, most of the populations for 1998, and for 15 years from the Port Gamble population. Age compositions for the Cherry Point population (Table 12), show the declining representation of older fish with time as described in the Wright petition. Numbers of age-2 fish were low during the first and last four years of the period. There were large fluctuations in numbers between 1980 and 1995 with relatively large values for 1980, 1993, and 1994. Because Puget Sound herring mature at age-2 or age-3, changes in numbers of 2-year-old fish could be due to differences in year-class strength and/or age at maturity. Numbers of fish older than 2 tended to decline with time. The ratio of 2-year-old fish to 3-year-old fish in the following year tended to increase after 1979, which suggests a reduction in the age at maturity.

The average age composition between 1987 and 2000 for Port Gamble fish (Table 13) was similar to Cherry Point fish, but the apparent year-class strengths were not correlated between the

Table 11. Results of trend analyses for Georgia Basin herring. CHPT = Cherry Point, DISCO = Discovery Bay, NS = North Sound (CHPT+DISCO), QM = Quartermaster Bay, PO-PM = Port Orchard - Port Madison, PG = Port Gamble, PT SUS = Port Susan, SS = South Sound (QM+PO-PM+PG+PT SUS), PS = Puget Sound, SG = Canadian portion of Strait of Georgia, and GB = Georgian Basin (PS+SG). Inf. = infinity. Last 15 years of observations used for analysis, which is described in text. Last observed biomass was in 1999 for SG and GB, and 2000 for other areas. Var(Mu) = variance of mu, Std(Mu) = standard deviation of mu. Time(x) = expected time for population decreasing by x. Pr(x,yr) = estimated probability of population decreasing by x in yr years. Pr(x ton, yr) = estimated probability of population to x ton in yr years.

	CHPT	DISCO	NS	QM	PO-PM	PG	PT SUS	SS	PS	SG	GB
Biomass (last observed) (t)	808	159	967	743	1756	2459	785	5743	6710	91987	98919
Mu	-0.113	-0.188	-0.126	0.013	-0.049	-0.017	0.030	-0.012	-0.052	0.056	0.043
Var(Mu)	0.097	0.006	0.078	0.046	0.202	0.013	0.005	0.005	0.011	0.015	0.012
Std(Mu)	0.311	0.077	0.279	0.214	0.449	0.114	0.071	0.071	0.105	0.121	0.109
Lambda	0.938	0.832	0.917	1.037	1.053	0.989	1.032	0.990	0.954	1.066	1.050
Time (0.05) (yr)	26.5	16.0	23.8	Inf.	Inf.	172.8	Inf.	204.7	57.3	Inf.	Inf.
Pr (0.05,15)	0.390	0.440	0.396	<.001	<.001	0.054	<.001	0.003	0.077	<.001	<.001
Time (1 ton) (yr)	59.3	27.0	54.7	Inf.	Inf.	450.5	Inf.	605.6	168.5	Inf.	Inf.
PR (1 ton, 10)	0.037	0.000	0.022	<.001	<.001	0.000	<.001	0.000	0.000	<.001	<.001
PR (1 ton, 25)	0.310	0.425	0.297	<.001	<.001	0.005	<.001	0.000	0.002	<.001	<.001
PR (1 ton, 50)	0.473	0.859	0.483	<.001	<.001	0.111	<.001	0.010	0.116	<.001	<.001
PR (1 ton, 100)	0.559	0.956	0.581	<.001	<.001	0.296	<.001	0.140	0.365	<.001	<.001
Time (1 fish) (yr)	140.9	76.1	128.0	Inf.	Inf.	981.9	Inf.	1435.8	344.7	Inf.	Inf.
PR (1 fish, 10)	0.000	0.000	0.000	<.001	<.001	0.000	<.001	0.000	0.000	<.001	<.001
PR (1 fish, 25)	0.047	0.000	0.032	<.001	<.001	0.000	<.001	0.000	0.000	<.001	<.001
PR (1 fish, 50)	0.255	0.111	0.242	<.001	<.001	0.002	<.001	0.000	0.001	<.001	<.001
PR (1 fish, 100)	0.441	0.712	0.450	<.001	<.001	0.089	<.001	0.008	0.108	<.001	<.001

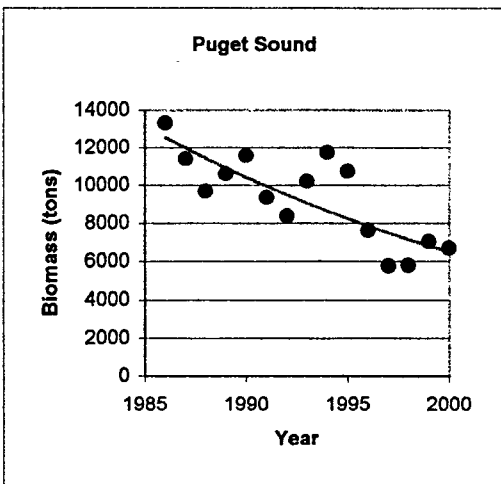
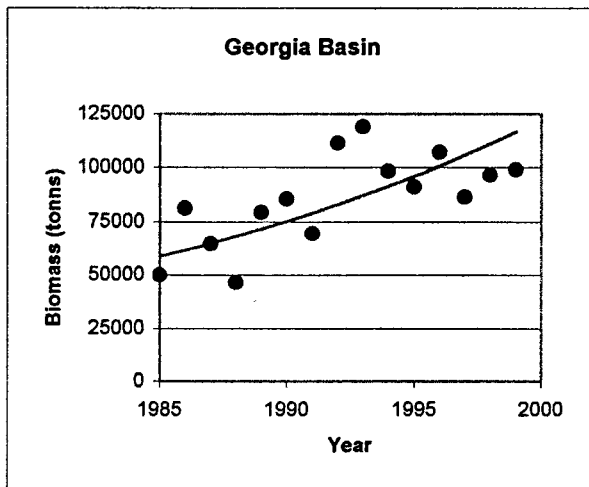
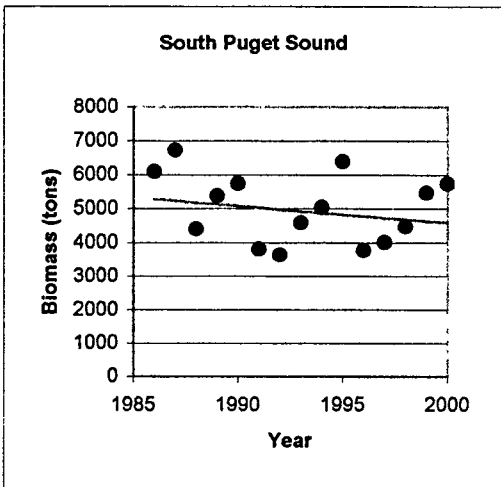
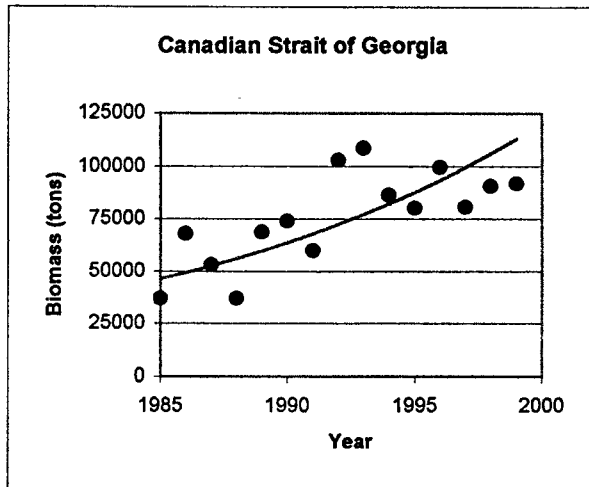
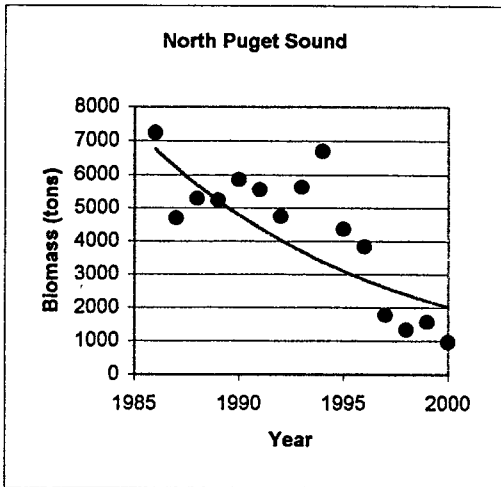


Figure 38. Estimated trends in biomass of North Puget Sound (Discovery Bay and Cherry Point), South Puget Sound (Quartermaster Bay, Port Orchard-Port Madison, Port Gamble, and Port Susan), Puget Sound (North Sound and South Sound), Canadian Strait of Georgia, Georgia Basin (Puget Sound and Canadian Strait of Georgia). Line showing trend using lambda and closed circles show observations. Canadian data converted from mt to tons. (Data from K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000).

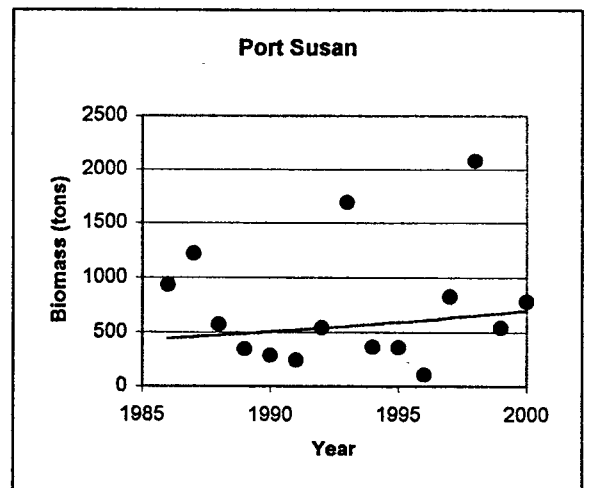
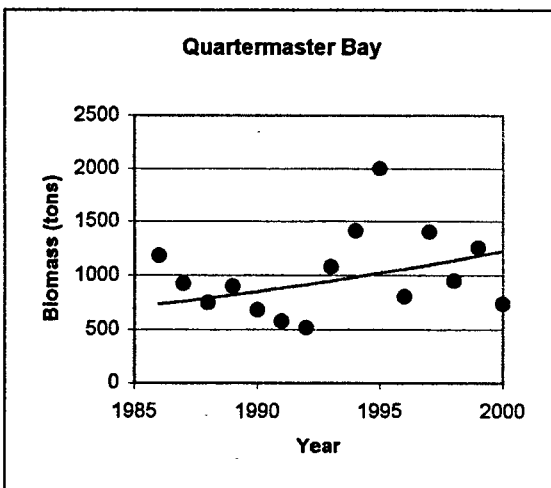
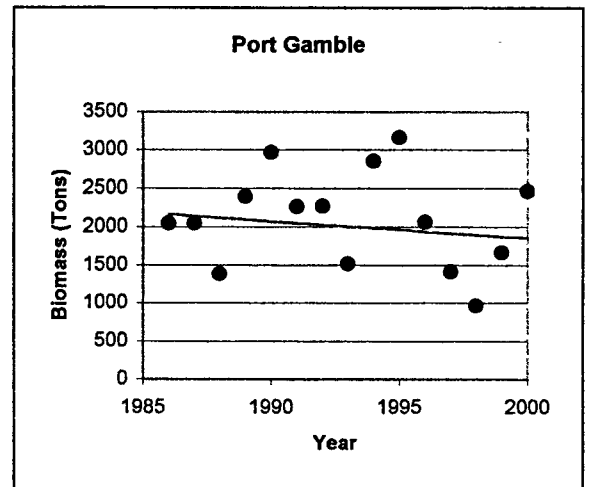
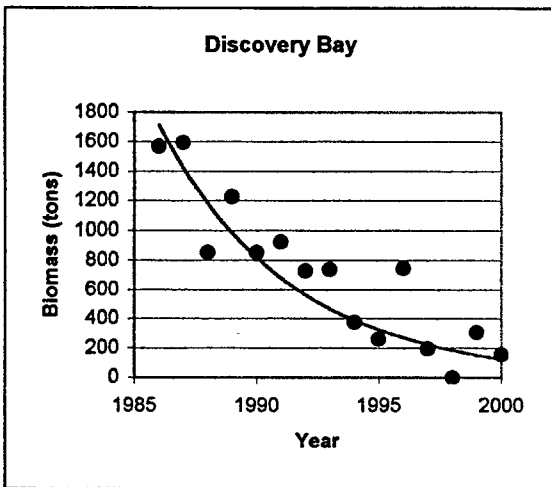
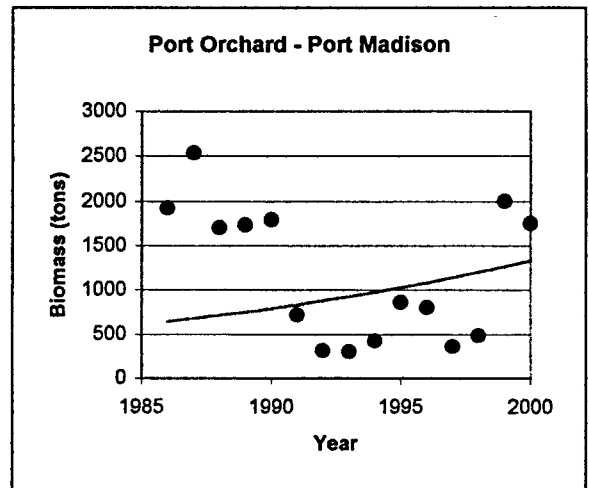
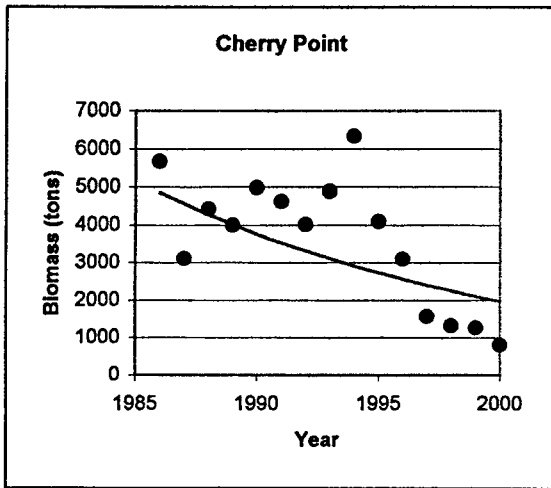


Figure 39. Estimated trends in biomass of six Puget Sound spawning aggregations of herring. Line shows trend using calculated lambda and closed circles show observations. (Data from K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000).

Table 12. Age and year of millions of herring in the Cherry Point population. (Data from K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. October 2000).

Year	Age (Years)							
	2	3	4	5	6	7	8	9+
1976	5.53	10.17	18.09	8.33	9.83	11.06	4.37	1.23
1977	13.91	22.41	6.15	7.91	5.20	6.81	6.66	4.10
1978	1.24	41.75	14.15	5.03	4.72	2.78	3.40	4.25
1979	3.82	8.07	25.75	10.04	3.53	4.24	1.73	2.63
1980	40.16	6.22	5.05	9.95	7.24	2.12	1.32	1.10
1981	5.99	20.71	4.89	3.16	5.27	1.39	0.34	0.42
1982	16.41	8.96	10.67	3.17	1.29	0.96	0.25	0.00
1983	24.70	12.50	8.66	10.92	2.62	0.67	0.79	0.18
1984	23.95	6.49	5.87	5.72	4.43	1.01	0.29	0.29
1985	23.90	21.67	6.91	1.45	0.95	0.61	0.17	0.00
1986	30.80	14.96	5.46	2.21	1.21	0.28	0.22	0.06
1987	12.58	11.03	4.26	1.10	0.45	0.15	0.09	0.12
1988	14.79	16.12	6.59	2.01	0.52	0.16	0.00	0.00
1989	34.10	7.89	5.00	1.91	0.05	0.05	0.00	0.00
1990	27.18	18.39	3.09	3.20	1.28	0.11	0.11	0.00
1991	10.61	16.76	7.82	2.67	1.80	0.20	0.04	0.00
1992	23.76	8.29	7.82	1.96	0.38	0.26	0.04	0.00
1993	55.34	6.77	2.21	1.41	0.87	0.27	0.07	0.00
1994	73.72	9.25	2.16	0.69	0.52	0.09	0.00	0.00
1995	20.26	18.08	2.22	0.50	0.71	0.13	0.00	0.00
1996	8.65	10.79	7.79	1.13	0.20	0.29	0.03	0.00
1997	3.86	6.05	4.36	0.44	0.13	0.00	0.00	0.00
1998	13.06	2.14	1.36	0.32	0.12	0.00	0.00	0.00
1999	4.18	9.13	0.65	0.16	0.01	0.00	0.00	0.00
2000	5.22	2.51	1.42	0.02	0.00	0.00	0.00	0.00

Table 13. Age and year of millions of herring in the Port Gamble population. Data were not available for missing years. (Data from K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. October 2000).

Year	Age (Years)							
	2	3	4	5	6	7	8	9+
1978	1.17	2.35	2.47	2.41	2.20	1.22	0.49	0.26
1979	0.00	4.46	2.29	2.78	0.84	0.84	0.00	0.00
1981	2.90	5.41	2.42	1.59	0.60	0.23	0.13	0.00
1987	14.54	8.48	2.20	2.33	0.00	0.00	0.00	0.00
1988	6.16	6.64	1.32	0.24	0.00	0.00	0.00	0.00
1989	22.30	5.58	3.12	1.12	0.00	0.00	0.00	0.00
1990	15.68	11.97	4.46	1.13	0.38	0.00	0.00	0.00
1991	6.70	10.23	5.68	1.48	0.75	0.22	0.00	0.00
1992	6.69	13.44	3.88	0.62	0.20	0.00	0.00	0.00
1993	18.05	4.11	1.70	0.26	0.10	0.00	0.00	0.00
1994	15.98	10.98	4.83	1.46	0.24	0.00	0.00	0.00
1995	35.32	8.22	2.97	0.69	0.00	0.06	0.00	0.00
1996	13.92	11.33	2.93	0.29	0.00	0.00	0.00	0.00
1997	13.56	4.74	0.58	0.13	0.00	0.00	0.00	0.00
1998	5.01	6.61	2.04	0.05	0.07	0.00	0.00	0.00
1999	17.48	7.91	1.53	0.13	0.00	0.00	0.00	0.00
2000	17.45	20.30	2.09	0.38	0.12	0.00	0.00	0.00

two areas. There was considerable variation in age compositions among 12 herring populations located in the Georgia Basin DPS in 1998 (Table 14). However either age-2 or age-3 fish dominated the composition in all areas. Older herring tend to appear and spawn before younger herring (Day 1987). Some of the differences in age composition could be results of the date of sampling effort relative to the timing of spawning of the different populations. Average weight at age tended to decrease after about 1983 (Fig. 37b). It is not known if the decrease was due to changes in growth in length or condition.

The combined-age average weight of the Cherry Point population declined sharply between 1976 and 1984, and gradually declined after 1984 (Fig. 37a). The decline mainly resulted from reduced numbers of older fish and partially resulted from reduced weight-at-age. The average biomass of Cherry Point herring decreased 83% from 10,973 tons in the 1976-1979 period to 1,815 tons in the 1996-1999 period (Table 15). If the average weight at age observed during the 1976-1979 period occurred during the 1996-1999 period the decline in biomass would have declined to 1,919 tons in the 1996-1999 which is very similar to the observed decline. The number of 2-year-old fish actually increased between the two periods, but the numbers of older fish decreased sharply.

Average exploitation rates tended to increase with age for the mature fish fisheries on the Cherry Point and Port Gamble populations (Fig. 40). Age composition data are not available for the sport bait fishery, but this fishery targets age-1.5-year-old fish. Exploitation rates of mature fish from the Cherry Point population decreased sharply when the non-treaty sac-roë fishery was closed in 1980 (Fig. 41). The treaty sac-roë fishery exploited the population at modest rates between 1986 and 1996. There was also a modest treaty-fishery on the Port Gamble population between 1987 and 1993 (Fig. 41). Exploitation rates are not available for the sport-bait fishery, but should be modest unless a relatively small population was heavily targeted. Estimates by WDFW of non-fishing related annual mortality rates of mature herring in Puget Sound increased sharply between 1976 and 1985 and slightly if at all since 1985 (Fig. 42). The mortality rates could include some fishing mortality caused by Canadian fisheries (Buchanan 1985b).

Because the Cherry Point population was abundant in the early-1970s, it is informative to backcalculate the number of recruits that would have been necessary to produce this level of abundance. Numbers of 3-year-old fish in the Cherry Point population were approximated for the 1971-1975 period using the numbers of 4 to 8-year-old fish in 1976 (Table 12) and the following assumptions: 1) annual rate of natural mortality was 0.2 (instantaneous rate =0.22) (Fig. 40), 2) relative age-specific fishing mortality was the same as during 1976-1980, 3) weight at age was same as during 1976-1980, 4) only the sac-roë fishery exploited Cherry Point herring, 5) the ratio of number of 2-year-old fish in year t to the number of 3-year-old fish in year $t+1$ was the same as during 1976-1980, and 6) fish did not survive beyond 9 years and the number of 9 year fish was the same as the 1976-1980 average. Results indicated that there were about 30, 62, 42, 22, and 31 million 3-year-old fish from 1971 to 1975. While these estimates must be considered first approximations, the numbers of 3-year-old fish during 1971 to 1975 probably averaged considerably higher than latter years.

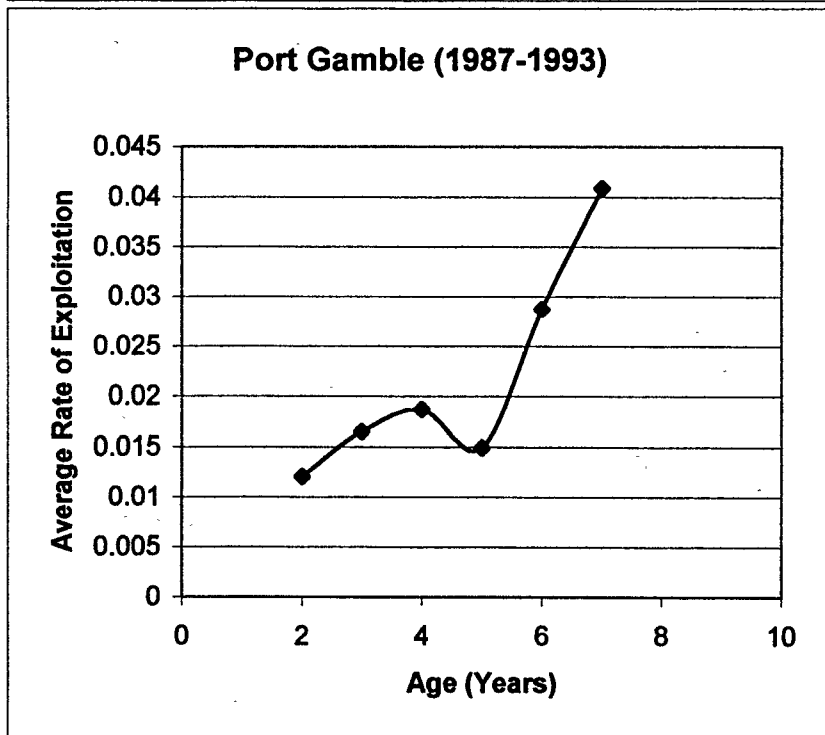
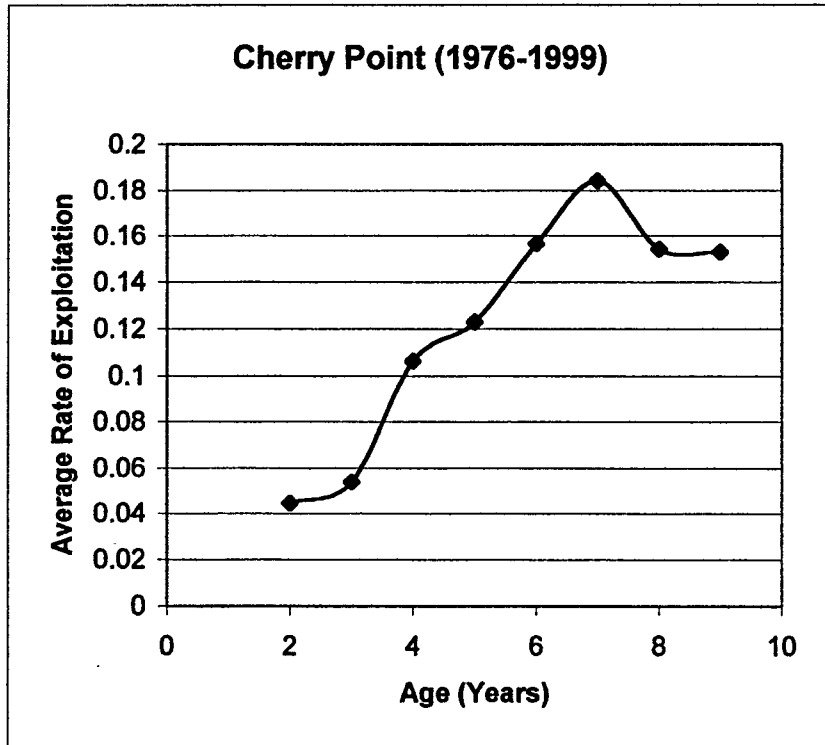


Figure 40. Average rate of exploitation by age on Cherry Point and Port Gamble herring populations, estimated by dividing number caught by number in population from data provided by WDFW (K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000).

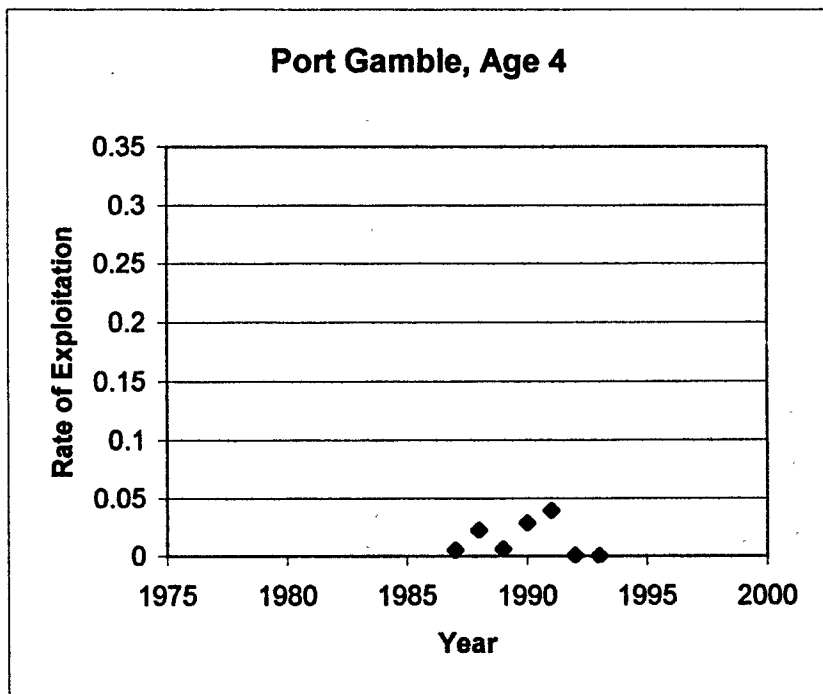
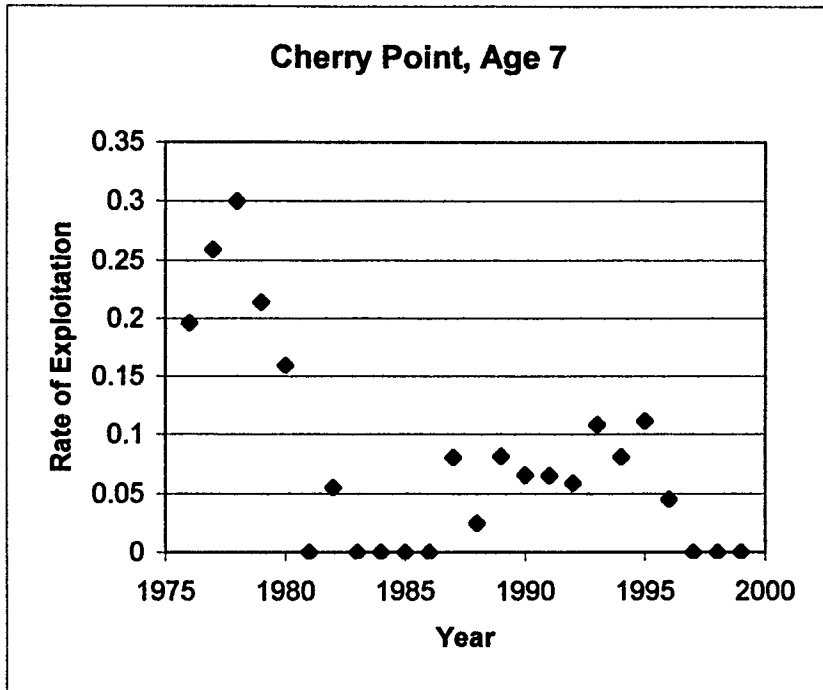


Figure 41. Annual rates of exploitation on the Cherry Point and Port Gamble herring populations. Exploitation by the sport-bait fishery is not included. Exploitation estimated by dividing number caught by number in population from data provided by WDFW (K. Stick, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000).

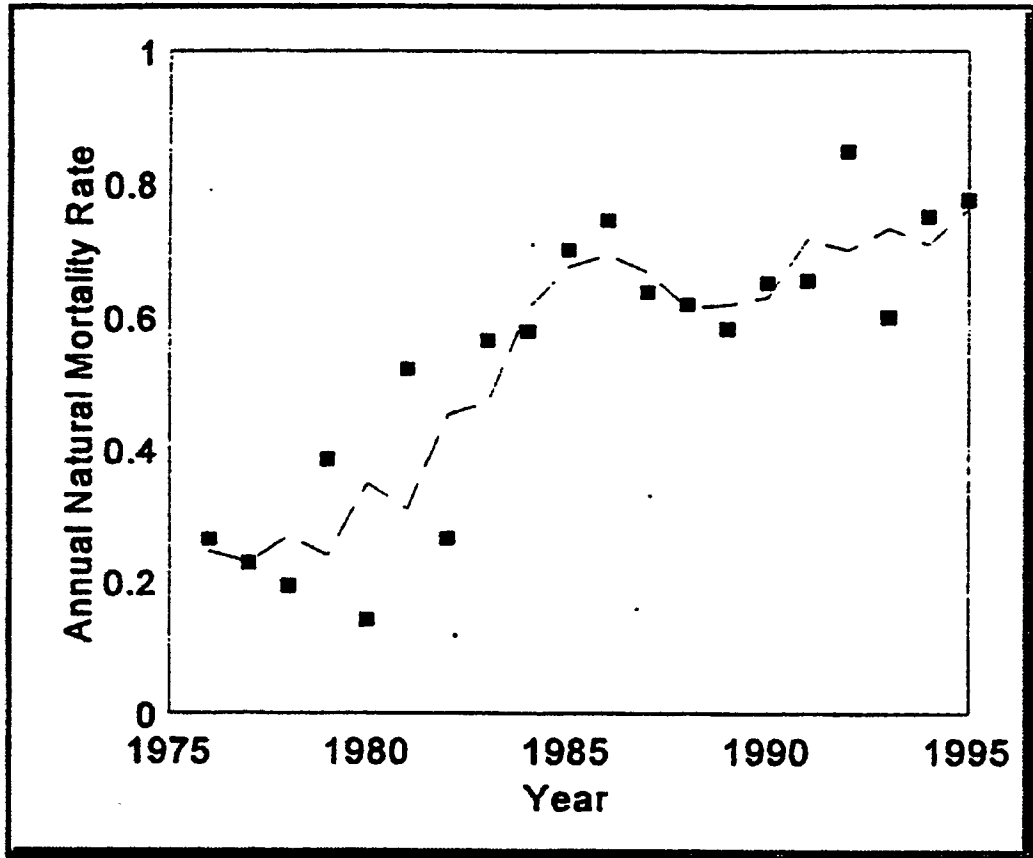


Figure 42. Annual natural mortality of Pacific Herring in Puget Sound. Figure 5 of Bargmann (1998).

Table 14. Age of millions of herring for 12 Puget Sound populations in 1998. (Data from M. O'Toole, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000).

1998 Age Composition								
Age (Years)								
Population	2	3	4	5	6	7	8	9+
Squaxin Pass	0.44	0.50	0.12	0.00	0.00	0.00	0.00	0.00
Quartermaster Harbor	4.97	4.97	1.62	0.16	0.00	0.00	0.00	0.00
P. Orchard-P. Madison	8.16	1.30	0.15	0.04	0.00	0.00	0.00	0.00
Port Gamble	5.01	6.61	2.04	0.05	0.07	0.00	0.00	0.00
Kilisut Harbor	1.68	1.56	0.61	0.05	0.02	0.00	0.00	0.00
Port Susan	5.13	15.23	5.44	0.31	0.00	0.00	0.00	0.00
Holmes Harbor	3.05	2.62	1.13	0.17	0.09	0.00	0.00	0.00
Skagit Bay	3.03	1.02	0.22	0.00	0.00	0.00	0.00	0.00
Fildalgo Bay	11.01	4.44	0.46	0.13	0.00	0.00	0.00	0.00
Samish-Portage Bay	6.53	5.17	0.99	0.00	0.00	0.00	0.00	0.00
Semiahmoo Bay	14.12	3.90	0.85	0.12	0.00	0.00	0.00	0.00
Cherry Point	13.06	2.14	1.36	0.32	0.12	0.00	0.00	0.00

Table 15. Sum of age compositions of Cherry Point Herring during the 1976-1979 and 1996-1999 periods. (Data from M. O'Toole, Washington Department of Fish and Wildlife, P.O. Box 100, La Conner, WA 98253, Pers. commun. January 2000).

Average Age	2	3	4	5	6	7	8	9+	Total
Number (Million Fish)									
1976-1979	6.13	20.60	16.03	7.82	5.82	6.22	4.04	3.05	69.64
1996-1999	7.44	7.03	3.54	0.51	0.12	0.07	0.01	0.00	18.70
Weight (tons)									
1976-1979	414.20	2193.98	2400.2	1436.54	1221.92	1473.56	1018.41	814.15	10972.9
1996-1999	479.15	707.32	489.04	93.68	27.65	17.02	1.55	0.00	1815.42
Tons/Million Fish									
1976-1979	67.62	106.51	149.69	183.60	210.06	236.79	251.99	266.71	157.58
1996-1999	64.41	100.65	138.15	182.92	236.06	236.04	214.58	0.00	97.06
Weight (tons) when 1976-1979 tons/million fish multiplied by 1996-1999 Number of fish									
	503.04	748.55	529.89	94.03	24.61	17.08	1.82	0.00	1919.00

Age compositions did not indicate that a decrease in abundance of older fish occurred in the British Columbia stocks that was comparable to the observed decrease in Puget Sound populations (Schweigert and Fort 1999). However, concern was expressed that fish were migrating from SG to the Central Coast Area (CCA), because estimates of natural mortality were considerably higher for SG than for the CCA. An analysis was made to examine the possibility and did not produce convincing results (Schweigert and Fort 1999). Weight-at-age decreased in all major British Columbia herring stocks since the mid- to late-1980s (Stocker and Kronlund 1998), which is consistent with the decline observed for the Cherry Point population (Figs. 37a & 37b). The 1972, 1974, 1985, 1987, 1989, 1994, and 1995 year-classes were relatively strong in SG. The 1972, 1985, and 1994 year-classes were relatively strong in WCVI (Schweigert and Fort 1999).

In summary, a combination of reduced recruitment of 3-year-old herring and increased non-fishery related losses of older fish appeared to be the primary causes of the decline in biomass of Cherry Point and perhaps other Puget Sound populations of herring. Reduced weight-at-age appeared to contribute little to the decline.

Risk Conclusions

The BRT utilized the process as presented by Wainwright and Kope (1999) to assess the three main risk categories: abundance and trends in population, productivity and variability as well as habitat quality change. The members of the BRT were asked to rate these risks for 1 to 5 with 1 representing very low risk and 5 as high risk of extinction in the near future due to this factor.

For the Georgia Basin DPS of Pacific herring, abundance was rated by the BRT as a modal score of 2. A score of 2 represents "Low risk. Unlikely that this factor contributes significantly to the risk of extinction by itself, but some concern that it may in combination with other factors." The range was between 1 and 2. A score of 1 represents "Very low risk. Unlikely that this factor contributes significantly to risk of extinction, either by itself or in combination with other factors." For trends in abundance, the unanimous score was also 2. For changes in habitat quality, the modal score was 2 with a range from 2 to 3. A score of 3 represents "Moderate risk. This factor contributes significantly to risk of extinction, but does not in itself constitute a danger of extinction in the near future." As a reference, other species that have been subsequently recommended for listing generally have scored in the 3 to 5 range for each factor.

Musick et al. (2000) have developed a method that compares information pertaining to the productivity of the DPS to criteria based on productivity of species and resiliency of populations. Because the risk matrix process assisted the BRT in determining that the Georgia Basin DPS of Pacific herring is not in danger of becoming extinct in the foreseeable future, the BRT utilized this method to assess whether the species might be "vulnerable" which is "(of special concern), not necessarily endangered or threatened severely, but at possible risk of falling into one of these categories in the near future" (Musick et al. 2000). The information available for use in this method is the time-at-maturity (Tmat) (2-4 yrs) and the maximum age of fish (Tmax) (4 to 10 years). Both of these parameters result in a "medium" productivity parameter (Table 16).

Table 16. Suggested values for productivity index parameters: intrinsic rate of increase r , von Bertalanffy k , fecundity (Fec), age at maturity (Tmat), and maximum age (Tmax) DPSs may be classified according to their production as High, Medium, Low, and Very Low. The parameters are suggested only as guidelines and may not be consistent within all DPSs because of the great diversity of life history strategies among fishes (Musick 2000).

Parameter	Productivity			
	High	Medium	Low	Very Low
r (yr - 1)	>.50	.16-.50	.05-.15	<.05
Von Bertalanffy k	>.30	.16-.30	.05-.15	<.05
Fec. (yr - 1)	> 10^4	10^2 - 10^3	10^1 < 10^2	< 10^1
Tmat	<1yr	<u>2-4 yr</u>	5-10 yr	>10 yr
Tmax	1-3 yr	<u>4-10 yr</u>	11-30 yr	>30 yr

The BRT then utilized this overall productivity value to determine if this species is “vulnerable” to becoming extinct. The IUCN defines a species as being vulnerable if its DPS has experienced a 20% decline in 10 years or 3 generations, whichever is longer (Musick 1999). The proposed American Fisheries Society (AFS) risk criteria (Table 17) indicates that a species with medium to high productivity, such as Pacific herring, would have to undergo a decline of at least 95% in 10 years or 3 generations, whichever is longer. The Georgia Basin DPS of Pacific herring does not approach this decline, so the BRT determined that this DPS does not meet the criteria for “vulnerable” at present. However, some populations such as Cherry Point and Discovery Bay within the DPS do meet the criteria.

Summary of Risk Assessment

The BRT utilized the methods presented in Wainwright and Kope (1999), West (1997) and Musick et al. (2000) to organize their conclusions regarding risk to the Georgia Basin DPS of Pacific herring. The BRT concluded, by a large majority, that the Georgia Basin DPS of Pacific herring are neither at risk of extinction nor likely to become so. However, most members expressed concern that they could not entirely rule out the possibility that this Georgia Basin DPS at present is likely to become in danger of extinction, especially because some stocks within the Georgia Basin, such as Cherry Point and Discovery Bay, have declined to such an extent that they may meet the IUCN criteria to be considered “vulnerable”. Although the BRT recognized that herring populations in north Puget Sound and Puget Sound proper may be vulnerable to extinction, these populations represent a relatively small portion of the overall DPS of herring in the Georgia Basin. Moreover, because of the moderate to high productivity of herring populations and the tendency of herring to stray among spawning sites, the BRT felt that there are reasonable possibilities at present for recolonization of depleted populations associated with specific spawning sites. The BRT also expressed caution that important changes in resource management practices (e.g., increased harvest levels) and in the ecosystem (e.g., increased numbers of marine mammals or predatory fish species), as well as increased habitat degradation, could result in increased extinction risk for Pacific herring in this DPS.

However, the BRT, emphasized that while the DPS is defined at a larger scale than the “stocks” that are managed in Puget Sound by WDFW, and that the Georgia Basin DPS does not appear at risk of extinction at present, local populations are the appropriate scale for fisheries management activities, and as McQuinn (1997) emphasizes, their “conservation is essential for the preservation of spawning potential and for the viability of coastal fisheries.”

Table 17. Decline thresholds for four categories of DPSs based on population resilience. If a decline reaches a threshold, the DPS would be listed as *vulnerable* and subjected to close scrutiny for further listing. (Musick 2000).

Productivity	Threshold	Decline (over the longer of 10 years or 3 generations)
High		.99
Medium		.95
Low		.85
Very Low		.70

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GLOSSARY

Allele

An alternative form of a gene that can occur at the same location (locus) on homologous (paired) chromosomes. A population can have many alleles for a particular locus, but an individual can carry no more than two alleles at a diploid locus.

Allozymes

Alternative forms of an enzyme that have the same function, are produced by different alleles, and are often detected by protein electrophoresis.

AFS

American Fisheries Society

Anthropogenic

Caused or produced by human action.

Benzo[a]pyrene (BaP)

An aromatic hydrocarbon with five benzene rings that is representative of HAHs.

Biochemical oxygen demand (BOD)

The depletion of oxygen associated with eutrophication from excess nutrient inputs or with discharge of organic matter.

Biological Review Team (BRT)

The team of scientists who evaluated a scientific information considered in the National Marine Fisheries Service status review.

Co-managers

Federal, state, and tribal agencies that cooperatively manage groundfish in the Pacific Northwest.

CPUE

Catch-per-unit effort

1,1,1-trichloro-2,2-bis-(p-chlorophenyl)ethane (DDTs)

Persistent contaminants of aquatic sediments and biota. Commercial formulations of DDTs are mixtures of individual chlorinated biphenyls. Prior to the 1975 congressional ban on DDT manufacture, DDTs were commonly used as pesticides

Distinct population segment (DPS)

A population, or group of populations of a vertebrate organism that is “discrete” from other populations and “significant” to the biological species as a whole.

DNA (deoxyribonucleic acid)

DNA is a complex molecule that carries an organism's heritable information. DNA consists of a polysugar-phosphate backbone from which the bases (nucleotides) project. DNA forms a double helix that is held together by hydrogen bonds between specific base pairs (thymine to adenine, guanine to cytosine). Each strand in the double helix is complementary to its partner strand in terms of its base sequence. The two types of DNA commonly used to examine genetic variation are mitochondrial DNA (mtDNA), a circular molecule that is maternally inherited, and nuclear DNA, which is organized into a set of chromosomes (see also allele and electrophoresis).

Dry weight (dw)

Refers to unit of chemical concentration for a sample in which all water has been removed.

Electrophoresis

Electrophoresis is the movement of charged particles in an electric field. This process has been developed as an analytical tool to detect genetic variation revealed by charge differences on proteins or molecular weight in DNA. Data obtained by electrophoresis can provide insight into levels of genetic variability within populations and the extent of genetic differentiation between them.

Endangered species

A species in danger of extinction throughout all or a significant portion of its range.

EPA

U.S. Environmental Protection Agency

ESA

U.S. Endangered Species Act

Evolutionarily significant unit (ESU)

An ESU represents a distinct population segment of Pacific salmon under the Endangered Species Act that 1) is substantially reproductively isolated from nonspecific populations and 2) represents component an important component of the evolutionary legacy of the species.

Euryhaline

Organisms that tolerate a wide range of salinities.

F statistics

A series of coefficients used to quantify the distribution of genetic variation within and among populations and groups of populations. Most often used is F_{st} , which describes overall differentiation among a group of populations, or more specifically, the correlation of genes among individuals in each population.

Fluorescent aromatic compounds (FACs)

Fish possess a significant capability, primarily in the liver, to readily metabolize PAHs and related aromatic compounds to more polar products (metabolites) that pass into the bile for excretion. These compounds are not detectable in customary PAH analytical procedures, but are determined by their fluorescence, most of which is retained during the metabolic transformations.

Genetic distance

A quantitative measure of genetic difference between a pair of samples.

Genetic drift

The occurrence of random changes in the gene frequencies of populations.

Georgia Basin

The semi-enclosed marine basin comprised of the Strait of Georgia, Puget Sound, and the Juan de Fuca Strait together with the lands that drain into these marine waters.

Haplotype

The collective genotype of a number of closely linked loci; the constellation of alleles present at a particular region of genomic or mitochondrial DNA.

Heterozygosity

A measure of allelic diversity at a locus (or averaged over several loci) whereby alternate alleles at a locus are different.

Heterozygous

The condition of having two different alleles at a given locus of a chromosome pair.

Higher molecular weight PAHs (HAHs)

In contrast to the LAHs, the HAHs are less water soluble and generally more tightly sorbed to sediment. HAHs are present in crude oil, fossil fuels and in combustion residue (e.g., soot) from all incomplete combustion processes, including natural processes such as forest fires. The HAHs have four to six aromatic rings, and are known more for their chronic toxicity than acute toxicity.

IUCN

International Union for the Conservation of Nature.

Locus (pl. loci)

The site on a chromosome where a gene is found; often used more or less synonymously with gene (cf. polymorphic locus, allozymes).

Lower molecular weight PAHs (LAHs)

Relative to the HAHs, the LAHs are more volatile and water-soluble. The LAHs have two to three aromatic rings, and are generally known for their acute toxicity. Sources of LAHs include all fossil fuels and discharges of products of their incomplete combustion, as well as crude oil.

Meristic trait

A discretely varying and countable trait (e.g., number of fin rays or basibranchial teeth); cf. traits with continuous variation (e.g., weight, length) or discrete variation (e.g., male, female, mature, immature).

Microsatellite

A class of repetitive DNA. Microsatellites are simple sequence repeats one to eight nucleotides in length. For example, the repeat unit can be simply "CA", and might exist in a tandem array (CACACACACA) 50 or more repeat units in length. The number of repeats in an array can be highly polymorphic

Mitochondrial DNA (mtDNA)

The DNA genome contained within mitochondria and encoding a small subset of mitochondrial functions; mtDNA is typically circular and 15-20 kilobases in size, containing little noncoding information between genes.

Morphometric trait

A discretely varying trait related to the size and shape of landmarks from whole organs or organisms analyzed by appropriately invariant biometric methods in order to answer biological questions.

Naphthalene (NPH)

An aromatic hydrocarbon with two benzene rings that is representative of LAHs.

NMML

National Marine Mammal Laboratory

Nuclear DNA (nDNA)

The DNA contained in the chromosomes within the nucleus of eukaryotic cells. The nuclear genome in Pacific salmon is approximately 4.6 billion base pairs in size.

NWFSC

Northwest Fisheries Science Center

Otolith

Crystalline calcium-carbonate structures within the inner ear of fish. These structures have distinctive shapes, sizes, and internal and surface features that can be used for age determination and species identification.

Parts per billion (ppb)

A unit of chemical concentration.

Phenanthrene (PHN)

An aromatic hydrocarbon with two benzene rings that is a significant component of crude oil.

Phenotype

The appearance (or other measurable characteristic) of an organism that results from interaction of the genotype and environment.

Polychlorinated biphenyls (PCBs)

Persistent contaminants of aquatic sediments and biota that are very widespread. Commercial formulations of PCBs are mixtures of individual chlorinated biphenyls (congeners) varying according to the numbers of chlorines and their ring positions on the biphenyl. Prior to the 1975 congressional ban on PCB manufacture, various mixtures of some 209 individual PCBs were used extensively in electrical transformers, capacitors, paints, waxes, inks, dust control agents, paper and pesticides.

Polycyclic aromatic hydrocarbons (PAHs)

The PAHs are widely distributed throughout the marine environment and commonly occur in sediments in urban coastal and estuarine areas. Sources include crude oil, petroleum products and residues from combustion of fossil fuels. They are composed of fused benzene rings, with or without alkyl substituents (e.g., methyl groups).

Polymorphic

Having more than one form (e.g., polymorphic gene loci have more than one allele).

Polymorphic locus

A locus characterized by more than one allele in a sample. If different alleles can be detected at a gene locus, the locus is considered polymorphic. If all alleles are of the same type, the locus is considered monomorphic. Many population genetic analyses are based on the frequency of different alleles at polymorphic loci.

Population

A group of individuals of a species living in a certain area that maintain some degree of reproductive isolation.

Principal component analysis (PCA)

An ordination technique for analyzing data from several variables, such as allelic frequencies or morphological data. The method finds linear trends (principal components) through the clouds of sample points in multidimensional space. These principal components account for the greatest amount of variation present in the data. The residual variance is removed from the data with the calculation of each successive principal component.

Protein electrophoresis

An analytical laboratory technique that measures differences in the amino acid composition of proteins from different individuals. Because the amino acid sequence of proteins is coded for by DNA, data provided by protein electrophoresis provide insight into levels of genetic variability within populations and the extent of genetic differentiation between them. See electrophoresis.

Puget Sound

A coastal fjord-like estuarine inlet of the Pacific Ocean located in northwest Washington State between the Cascade and Olympic mountains and covering an area of over 9,000 km² including 3,700 km of coastline.

RFLP

(restriction fragment length polymorphism) variations occurring within a species in the length of DNA fragments generated by a specific restriction endonuclease. Such variation is generated either by base substitutions that cause gain or loss of sites, or by insertion/deletion mutations that change the length of fragments independent of restriction site changes.

SCUBA

Self-contained underwater breathing apparatus.

Species

Biological - A small group of organisms formally recognized by the scientific community as distinct from other groups. legal - refers to joint policy of the USFWS and NMFS that considers a species as defined by the ESA to include biological species, subspecies, and DPSs.

Strait of Georgia

The body of water separating the southern portion of Vancouver Island and the British Columbia mainland. The strait extends from Cortes Island and Desolation Sound in the north to the San Juan Islands in the south.

Strait of Juan de Fuca

The body of water separating the southern portion of Vancouver Island and the Olympic Peninsula in Washington. The strait extends from the Pacific Ocean east to the San Juan and Whidbey Islands.

Threatened species

A species not presently in danger of extinction but likely to become so in the foreseeable future.

Total PAHs (TPAHs)

The summed total of all the individual PAHs detected in a sample.

Trophic

Pertaining to nutrition. A trophic migration would be a movement of fish to a feeding area.

WDFW

Washington Department of Fish and Wildlife, which co-manages groundfish fisheries in Washington State with WWTIT and other fisheries groups. The agency was formed in the early 1990s by combining the Washington Department of Fisheries and Washington Department of Wildlife.

WWTIT

Western Washington Treaty Indian Tribes, an organization of Native American tribes with treaty fishing rights recognized by the United States. WWTIT co-manages groundfish fisheries in western Washington in cooperation with WDFW and other fisheries groups.

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