Proceedings of a Synthesis Meeting:

The North Aleutian Shelf Environment and Possible Consequences of Offshore Oil and Gas Development

Anchorage, Alaska, 9–11 March 1982

Outer Continental Shelf Environmental Assessment Program
Juneau, Alaska

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

U.S. DEPARTMENT OF THE INTERIOR
Minerals Management Service

Proceedings of a Synthesis Meeting:

The North Aleutian Shelf Environment and Possible Consequences of Offshore Oil and Gas Development

Anchorage, Alaska, 9-11 March 1982

Edited by

Lyman K. Thorsteinson

Outer Continental Shelf Environmental Assessment Program

Juneau, Alaska

March 1984

United States
Department of Commerce
Malcolm Baldridge, Secretary

National Oceanic and
Atmospheric Administration
John V. Byrne, Administrator

United States
Department of the Interior
William P. Clark, Secretary

Minerals Management Service
William D. Bettenberg, Director

Notices

This report has been reviewed by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration's Outer Continental Shelf Environmental Assessment Program Office, and approved for publication. The interpretation of data and opinions expressed in this document are those of the authors and synthesis meeting participants. Approval does not necessarily signify that the contents reflect the views and policies of the Department of Commerce or those of the Department of the Interior.

The National Oceanic and Atmospheric Administration (NOAA) does not approve, recommend, or endorse any proprietary product or proprietary material mentioned in this publication. No reference shall be made to NOAA or to this publication in any advertising or sales promotion which would indicate or imply that NOAA approves, recommends, or endorses any proprietary product or proprietary material mentioned herein, or which has as its purpose an intent to cause directly or indirectly the advertised product to be used or purchased because of this publication.

Preface

The Outer Continental Shelf Environmental Assessment Program (OCSEAP) was established by a basic agreement between the National Oceanic and Atmospheric Administration and the Bureau of Land Management to conduct environmental research on Alaskan continental shelf areas identified for potential offshore oil and gas development. In 1982, the Minerals Management Service (MMS) assumed responsibility for federal offshore leasing and administration of the related environmental studies program. As a major portion of the Alaskan OCS studies program, OCSEAP's activities include review of existing data, planning and management of original research on all aspects of marine science, and transfer of information to MMS and other users. Scientific information is gathered and disseminated in journal articles, monographs, and books; digital data products; progress reports and final reports from individual research projects; and proceedings of disciplinary program reviews and interdisciplinary synthesis meetings.

OCSEAP synthesis meetings address environmental issues and resource use conflicts which may arise in a proposed oil and gas lease area. OCSEAP investigators, other scientists, OCSEAP management, MMS personnel, and representatives from state government, the petroleum industry, local residents, and other interest groups attend these meetings.

Synthesis reports are based on the proceedings of the meetings and include interpretation of data by scientists and others knowledgeable about the lease area or the environmental problems of offshore oil and gas development. Within OCSEAP, synthesis reports are the most direct avenue from scientists to decisionmakers. Interpreting a variety of scientific data so as to predict the possible effects of oil and gas development is complex. It requires a comprehensive and objective understanding of the environment that may be more difficult and time-consuming than the tasks some scientists have undertaken in the past. Nonetheless, active participation of scientists in this process is crucial and within OCSEAP it will continue.

This report evaluates available environmental data in light of proposed oil and gas development in the North Aleutian Shelf lease area, located just outside Bristol Bay in the southeastern Bering Sea. The planned OCS Lease Sale 75 encompassed a relatively small area (3.4 million acres) along the north side of the Alaska Peninsula, between Port Heiden and Unimak Pass and extending to 57° N. latitude. This sale was cancelled soon after the synthesis meeting was held and in July 1982 it was replaced by the North Aleutian Basin lease sale (Sale 92), encompassing 32 million acres, extending from Unimak Pass to Cape Newenham and including the entire Bristol Bay. Because of the limited areal extent of Sale 75, the meeting agenda focused on potential environmental problems and resource use conflicts resulting from oil and gas development only in the North Aleutian Shelf. The rich and varied biological resources of the entire southeastern Bering Sea, some with exceptionally high commercial value, were therefore not extensively reviewed or discussed at the meeting. As a result only a portion of the available data from the southeastern Bering Sea could be included in this report. Many environmental questions and issues pertaining to the North Aleutian Basin lease sale remain to be addressed. It is expected that future synthesis meetings will be held to review the substantially large data base which exists for the North Aleutian Basin.

M. J. Hameedi
Program Manager, Outer Continental Shelf
Environmental Assessment Program

Acknowledgments

This report was prepared with contributions and assistance from scientists and managers from the Outer Continental Shelf Environmental Assessment Program, the Minerals Management Service, and several other federal agencies, the state of Alaska, the petroleum industry, universities, and the public at large. Special thanks are due the workshop chairpersons and meeting participants who submitted text and graphic material for the report.

Executive Summary

Results and conclusions of a NOAA/OCSEAP synthesis meeting are summarized herein. Prediction of oil spill behavior and potential effects of several hypothetical oil spills on biota are based on OCS exploration and development scenarios established prior to the meeting by the Minerals Management Service. These scenarios and corresponding physical and biological assumptions formed at the meeting for analyses of potential impacts are described in the Introduction and in following chapters documenting the proceedings of individual workshops, respectively. Since the North Aleutian Shelf sale was deferred shortly after this synthesis meeting was held, many assumptions such as recoverable resource and spill estimates and hypothetical oil spill point sources, may differ from those described in this report and may not be consistent with those of future federal environmental impact statements or related risk assessments for the much larger North Aleutian Basin sale area or other lease offerings planned for the southeastern Bering Sea.

1. The oil and gas resources of the continental shelf north of the Alaska Peninsula and underlying the southwest portion of Bristol Bay were recently proposed for leasing (OCS Sale 75). The proposed North Aleutian Shelf sale included 605 tracts encompassing 1.4 million hectares (ha), ranging in depth from 25 to 100 meters (m) and extending 19 to 76 kilometers (km) north of the Alaska Peninsula. This sale, scheduled for October 1983, was cancelled in March 1982. However, the most recent OCS planning schedule (July 1982) shows much of Bristol Bay proposed as a lease offering in April 1985 (Sale 92).

2. Winds and tides drive the circulation of the shallow continental shelf waters of the North Aleutian Shelf lease area. Currents are weak and variable. Residual mean currents averaged over many tidal cycles and wind events are 1-6 cm/s.

3. Winds contribute considerable kinetic energy to the water column. Wind-driven currents are in the order of 10 cm/s at 5 m, and typically result in a well-mixed column in the upper 20–30 m of the water column. Offshore winds are highly variable but tend to be southerly during summer and northeasterly the rest of the year. Nearshore orographic effects result in a bimodal distribution of wind patterns originating in the northeast and southwest and influencing local circulation 20–40 km offshore.

4. Tides in the North Aleutian Shelf are dominated by a semidiurnal bulge that enters the Bering Sea through the central and western Aleutian straits and moves across the shelf as a free wave. Tidal amplitudes average 2 m across the open shelf, 3.3 m at Port Moller, and more than 6 m at the head of Bristol Bay.

5. The propagation of tidal waves onto the shelf accounts for 90% of the kinetic energy in the water column. Turbulence resulting from tidal currents, which range from 40 to 80 cm/s or more, causes mixing of the column from the bottom to about 50 m above the bottom. Wind and tidal influences result in a well-mixed water column inside the 50-m isobath.

6. The North Aleutian Shelf is a region of frequent local storms. During the summer months, winds are predominantly from the south, placing the nearshore region in the lee of the Alaska Peninsula. Storms are of much greater consequence in winter, when prevailing winds are from the north and generate severe waves in relatively unprotected coastal areas.

7. The northern waters of the North Aleutian Shelf are covered with ice during most winters. Maximum coverage usually occurs in March and April in average years and in February during heavy ice years. Sea ice can extend as far south as the Port Moller region.

8. Sediment concentrations are high in a surface-mixed zone where particle accumulation occurs above the pycnocline, low across a broad zone of low diffusivity between the pycnocline and upper limits of resuspension, and high in the zone 10–30 m above the sea floor where tidal resuspension of bottom sediments occurs.

9. The North Aleutian Shelf encompasses approximately 25,000 km^2 of Bristol Bay and contains portions of three oceanographic domains, each possessing quite different water column characteristics that can be distinguished for most of the year but which may be homogenously mixed in winter. Each is separated from the other by the year-round presence of hydrographic frontal structures.

   a. *Coastal Domain.* Coastal waters inside the 50-m isobath are generally warm, low in salinity, and vertically well mixed, lacking stratification.

   b. *Middle Shelf Domain.* Midshelf waters, extending between the 50- and 100-m contours, are strongly stratified into two layers.

   c. *Outer Shelf Domain.* Outer shelf waters, from the 100-m contour to the shelf break, are characterized by a stratified layer with pronounced fine structure, separating surface- and bottom-mixed layers.

10. The proposed North Aleutian Shelf lease area can be described as containing three broad-scale habitat types: offshore and coastal habitats corresponding in areal coverage to the oceanographically defined middle shelf and coastal domains, respectively, and estuarine habitat.

11. The offshore, or midshelf, habitat is characterized as a region of high primary productivity that is inefficiently utilized by planktonic herbivores, resulting in large quantities of sinking phytoplankton detritus. The detritus in turn supports a rich infaunal community and an abundance of demersal fish and crabs. Seabirds are distributed across the midshelf but are less abundant than elsewhere in the southeastern Bering Sea. Seabird abundance, especially that of shearwaters, is greatest along the 50-m isobath. Walrus, sea lions, spotted seals, and gray and belukha whales are seasonal migrants through midshelf waters. All, except the gray whale, occur most frequently in these waters in association with the ice edge.

12. The coastal habitat is noted for its high infaunal standing stocks, especially clams. The high abundance of these organisms is thought to be linked to their ability to utilize detrital inputs from sinking phytoplankton and an unknown contribution from coastal lagoons. Crabs and demersal fish, especially the juveniles of many species, are abundant in coastal waters. This habitat is used extensively from spring through fall by large schools of migrating or spawning forage fish, namely herring, capelin, eulachon, and sand lance, which constitute the major food source for several small seabird colonies along the coast. Major breeding seabird species include cormorants, kittiwakes, gulls, murres, and puffins. Harbor seals and sea otters are the dominant marine mammals of the coastal band, although gray whales, walrus, and sea lions are also present.

13. The bays and lagoons of the north coast of the Alaska Peninsula constitute a major portion of the total estuarine habitat in the Bering Sea. These areas are known for their high productivity. Izembek Lagoon contains the largest eelgrass stand in the world; daily eelgrass productivity there ranges from 3.3 to 8.0 g C/m^2. Microbial degradation of eelgrass detritus is a major lagoonal process affecting most trophic relationships and energy transfers among lagoonal inhabitants. Eelgrass leaves support large numbers of epiphytic organisms with a total biomass perhaps approaching that of the eelgrass itself. Food webs are very short in the lagoon and in most cases consist of fewer than six intermediate species. Shrimps, crabs, juvenile fish, and an abundance of other invertebrates are dominant species. The bays and lagoons are critical habitat for many species of shorebirds and waterfowl who use them for staging in spring and fall. Nelson and Izembek lagoons are especially important habitat for staging birds. Harbor seals and sea otters are dominant estuarine mammals, and gray whales feed within Nelson Lagoon in summer and early fall.

14. The weathering of oil released into the marine environment can be described by considering the mass conservative partitioning of the spilled oil into four compartments: the atmosphere, the sea surface, the water column, and the benthic sediments. The distribution of the oil within and between these compartments occurs by spreading, evaporation, dissolution, dispersion, and sinking, all of which are extremely incident and site specific, as well as interdependently related.

    a. *Atmosphere.* Evaporation begins immediately after a spill event, removing the low-molecular-weight volatile components from the slick. Evaporation is quite rapid and may account for as much as 60% of the mass of light crude and 17% of an oil of similar composition to Prudhoe Bay crude. Evaporation alters the composition of spilled oil, increasing its density and viscosity and decreasing the aqueous solubility and toxicity of the residual mass.

    b. *Sea Surface.* Spreading of spilled oil on the sea surface is controlled by the combined driving forces of gravity and surface tension counterbalanced by the retarding forces of inertia and viscosity. Spreading is responsible for the areal extent of contamination, and affects the rates of a number of other weathering processes that are surface related.

    c. *Water Column.* Water column turbulence provides the mixing energy for two competitive dispersion processes: the formation of water-in-oil (mousse) and oil-in-water emulsions. Spilled Prudhoe Bay crude forms mousse in 40–48 hours, a time when many volatile components have already been lost through evaporation. After mousse formation, further weathering is greatly hindered. Oil-in-water emulsions are formed as surface oil breaks up into small droplets which are incorporated into the water column where they dissolve or are degraded.

    d. *Benthic Sediments.* The ultimate repository of spilled oil is the benthic sediments. Limited information is available concerning the exact nature of this transport. In the North Aleutian Shelf, daily rates for the sinking of suspended particulate matter are in the order of 5–10 mg oil/m^2. Because the regional waters are relatively high in concentrations of particulate material, flocculation may be a major process removing oil from the water column.

15. Surface trajectories have been calculated for spilled oil released from several launch points within the North Aleutian Shelf at different times of the year. During the summer, June–August, surface trajectories tend to move in a northeasterly direction into inner Bristol Bay. In winter periods, December–May, trajectories are most likely to move in a westerly direction seaward in the southeastern Bering Sea. However, trajectory analysis indicates that it would be possible for oil launched from hypothetical spill points in the most northwesterly portion of the proposed lease area to strike the north coast of the Alaska Peninsula at all times of the year.

16. The beaches of the exposed Alaska Peninsula coastline are largely composed of coarse-grained sands of intermediate vulnerability and sensitivity to spilled oil as regards persistence of oil and contamination of indigenous biota. Lagoon and bay shorelines are much more sensitive and if substantial oiling were to occur, contaminants would remain for long periods of time and biological losses would be great.

17. Theoretically and empirically derived partitioning and weathering coefficients were used to describe expected time-dependent concentrations of total dispersed and dissolved oil in the water column below and around three hypothetical oil spill sites in or near the North Aleutian Shelf under typical summer conditions:

    a. *Amak Island.* A continuous spill of 2,000 bbl/d for 5 days would result in a slick size of 100 km^2. Total hydrocarbon concentrations exceeding 0.1 ppm would extend 400 m on either side of the slick and persist for at least 5 days. Under summer spill conditions and steady onshore winds (13% probability), approximately 80% of the spilled oil would be transported to the entrance of Izembek Lagoon in about 1 day. Of this, approximately 25% could enter the lagoon.

    b. *Cape Seniavin.* A continuous spill of 2,000 bbl/d for 5 days would result in similar distributions of oil concentrations in time and space as those described for the hypothetical Amak Island spill assuming the same wind and weather conditions used in that scenario. About 70% of the oil spilled 50 km offshore from Cape Seniavin would reach the coast in about 100 hours.

    c. *Rush Rock.* A tanker accident in the Cold Bay vicinity instantaneously releasing 200,000 bbl would result in a 168-km^2 slick. Total hydrocarbon concentrations greater than 0.01 ppm would impact an area of 407 km^2.

18. The North Aleutian Shelf encompasses a variety of habitats for this wildlife-rich portion of the southeastern Bering Sea. In general, the potential losses from hypothetical 10,000-bbl oil spills near Amak Island and Cape Seniavin described in 17(a) and (b) would not be of sufficient magnitude to imperil any population living there.

    a. *Amak Island and Cape Seniavin.* Oil spill impacts on regional biota from spills originating at these sites would be similar in many instances due to their relative closeness. The populations most at risk from oil spills and periods of greatest sensitivity are:

        i. *Shellfish.* Red king crab larvae for large portions of an entire year class are coastally distributed within the North Aleutian Shelf for extended periods of the summer each year.

ii. *Fish.* Herring, capelin, and other trophically important species spawn intertidally and subtidally in the nearshore zone of the North Aleutian Shelf during early summer months.

iii. *Birds.* Birds most vulnerable to oiling are those which are gregarious, spend most of their time on the surface, and dive rather than fly when disturbed. These include murres, puffins, and diving ducks such as eiders, scoters, and Oldsquaws. Most seabirds are long-lived with low reproductive turnover (usually only one egg), which exacerbates the problems of hydrocarbon exposure as compared to waterfowl whose large clutch sizes compensate for high natural mortality rates. Amak Island also supports the largest seabird colony in the North Aleutian Shelf area. Cormorants, murres, and Black-legged Kittiwakes are the most abundant breeding seabirds. Oiling of bays and lagoons could have substantial effects on the shorebirds and waterfowl staging, molting, or breeding there from spring through fall. Loss of vegetative cover could take many years to replace, and in areas such as Izembek and Nelson lagoons, populations of Dunlin, godwits, and other sandpipers, Steller's Eider, King Eider, Emperor Goose, Black Brant, and Taverner's Goose could be severely impacted.

iv. *Mammals.* The sea otter is the species most at risk from potential oil spills in midshelf and coastal habitats of the North Aleutian Shelf. Mortalities associated with accidental spills elsewhere indicate that in some cases pinnipeds and sea otters can be oiled. In the North Aleutian Shelf, sea otters, and to a lesser degree fur seals, would be susceptible to oiling with subsequent loss of thermoregulatory control, possibly leading to death. Amak Island and the nearby Sea Lion Rocks provide haulout and breeding habitat for the largest concentration of sea lions found in Bristol Bay. Harbor seals are also abundant in this area. Cetaceans appear to be able to detect and avoid spilled oil, although in an area of OCS activity their behavior may be modified by social interactions, feeding, agonistic behavior, migration, and human activity.

b. *Rush Rock.* Nearly half a million seabirds nest in the Cold Bay region. Dominant species include Glaucous-winged Gulls, Cassin's Auklets, and Horned and Tufted puffins. Oiling losses would be greatest in the summer months and impacts might persist for many years. Sea otters are also abundant in the nearshore waters south of the Alaska Peninsula and oiling losses from a 200,000-bbl spill would be great. Information regarding the range expansion of sea otters in the Aleutian Islands suggests that their recovery after a spill would be rapid. Alcids, petrels, and gulls are dominant breeding seabirds nesting at colonies on the Krenitzin Islands and Sandman Reefs. The extent of ice coverage in the Bering Sea dictates the movement of shorebirds and waterfowl to the Cold Bay region each year. Sea lions and sea otters are abundant year round in the nearshore waters south of the Alaska Peninsula.

19. Disruption of eelgrass beds could have deleterious effects on the coastal environment. Despite the high productivity of sea grasses, such as at Izembek Lagoon, return to normal state after disruption is slow because it involves ecosystem development.

20. Unimak Pass is one of the major migration corridors for bird and mammal populations entering and leaving the Bering Sea. An oil spill in Unimak Pass could potentially impact major portions of regional populations of birds and mammals. Major portions of populations of humpback, fin, and gray whales and northern fur seals are regular seasonal migrants through the pass. A spill large enough to significantly oil the pass in early spring or late fall would expose great numbers of fur seals and gray whales to hydrocarbon contaminants. Mortalities of fur seals during these periods would likely be high. Immense flocks of shearwaters feeding in Unimak Pass would be vulnerable to oiling. Nesting colonies of several hundred thousand Tufted Puffins on nearby Aleutian Islands might be decimated by heavy oiling of foraging adults.

21. Many of the coastal streams draining into the proposed lease area are the spawning grounds for salmon originating along the north coast of the Alaska Peninsula. Including these local stocks, approximately 88% of all salmon entering streams around the eastern Bering Sea migrate through North Aleutian Shelf waters.

22. Salmon passing through North Aleutian Shelf waters are a complex mixture of stocks of five species of salmon bound for streams and rivers located on the north coasts of Unimak Island and the Alaska Peninsula, around Bristol Bay, and further north along the Bering Sea coast. Salmon are present in the proposed lease area as seaward-migrating juveniles or returning adults from May through at least October.

23. The Kvichak and Naknek rivers are the major Bristol Bay producers of sockeye salmon; the Nushagak River, second in sockeye production, also has important runs of king, chum, and, in even-numbered years, pink salmon. Of all salmon stocks that pass through the lease area, those of Bristol Bay are overwhelmingly important numerically and in commercial value.

24. Of the five species of salmon inhabiting the Bering Sea, only sockeye salmon have been studied sufficiently to describe in some detail their seaward migration. Information on other species is fragmentary and has been obtained incidentally from the sockeye studies. Juvenile salmon are abundant within the North Aleutian Shelf from mid-May through at least September and probably even later. Chinook salmon are the first species to enter the area, followed in order by sockeye, chum, pink, and coho salmon.

25. Sockeye smolts emigrate from the Bristol Bay systems from mid-May to August with peak out-migrations occurring about 1 June, although this varies from system to system and year to year. Food is sparse in inner Bristol Bay and young fish move rapidly to the Port Heiden area where prey is more abundant. The fish move in a coastal band extending 65 km offshore. Major prey include euphausiids, copepods, cladocerans, and insects. Temperature affects the rates of juvenile growth and movement. Although little is known about other salmon species, it is thought that they follow the same migratory pathway as sockeye salmon and respond to similar environmental cues.

26. Amak Island and Cape Seniavin are relatively close to each other and based on what is known about juvenile salmon movement, the times of greatest potential impact would be similar at both hypothetical spill sites described in 17(a) and (b). Based on abundance estimates, juvenile chinook salmon would be in greatest abundance and therefore most vulnerable in May and June; sockeye salmon in July and August;

chum salmon in July through September; and pink and coho salmon in August and September. Judging from estimates of their rates of movements and modeled extent and duration of contamination in the water column, exposures would not exceed 4 days and some mortalities could be expected. Such losses would not be detectable within the natural fluctuations that have been observed in Bristol Bay salmon runs.

27. Studies examining the migratory behavior of adult salmon have dealt primarily with sockeye salmon. If salmon respond to the same environmental cues, other species are thought to follow the same migratory path. The center of abundance of this migratory band is 50-65 km offshore and may extend as far out as 165 km. Once reaching Unimak Island, adults move about 50 km/d.

28. Bristol Bay sockeye salmon fishing peaks around 4 July each year. Fishing for other species is staggered throughout the summer as the salmon become available; chinook salmon appear first, followed by sockeye, pink, chum, and coho salmon. The total catch of all salmon species from runs that migrate through the proposed lease area has had an annual ex-vessel value as high as $100 million.

29. The chronological order of appearance and months of peak adult salmon abundance at the Amak Island and Cape Seniavin spill sites are: June for chinook and sockeye; July and August for chum and pink; and July through September for coho. Adult exposures would probably last from 12 to 24 hours. Adult mortalities would not be detected in total run sizes due to large but naturally occurring fluctuations in annual returns caused by varying survival from fry to returning adults. Even substantial oil spill losses (perhaps 200,000-300,000 fish) would not be detected in the catch nor be harmful to Bristol Bay salmon runs that vary in total number from 15 to 50 million fish annually.

30. Local salmon stocks from natal streams directly adjacent to the North Aleutian Shelf would suffer the greatest impact if an oil spill were to occur at a time when adults were massing after having separated into individual spawning units.

31. The relative vulnerabilities of other fishery resources, including groundfish and commercial crabs, were also considered for the Amak Island and Cape Seniavin hypothetical spills. The eggs and larvae of many of these species are sensitive to oil concentrations as low as 200 ppb. However, because of their wide distribution in the Bering Sea and seasonality of occurrence in the North Aleutian Shelf, any mortalities associated with the hypothetical spills would probably be undetectable in future fishery harvests and not responsible for any long-lasting changes in species abundance. This is due to the small area of the spill zone as compared to the total area these fish and shellfish occupy in the Bering Sea. Red king crab were identified as a species being potentially susceptible to significant losses from oil spills originating in the North Aleutian Shelf.

32. Information regarding the status of fishery resources along the south side of the Alaska Peninsula is not as comprehensive as for Bristol Bay and the Bering Sea. Pacific salmon, flatfish, shrimps, Dungeness crab, and king crab are present in this region. The Tanner crab *Chionoecetes opilio* does not occur south of the Alaska Peninsula.

33. Young salmon migrate from local south coast Alaska Peninsula streams sometime between late April and mid-June. The most abundant species are pink and chum

salmon; because the course of their migration through salt water is not known, the numbers of young fish that might be in the Rush Rock spill area described in 17(c) on 22 June cannot be estimated at this time.

34. Adult pink, chum, and sockeye salmon bound for streams in the Bering Sea and eastern Aleutian Islands migrate along Unimak Island during June. These fish would have moved through the impacted zone of the hypothetical Rush Rock spill by 22 June. Local spawners do not appear in the Cold Bay region until mid-July. Thus, it appears unlikely that many adults would be present in the area at the time of this spill scenario. Other species of fish and crabs would be affected by an oil spill of this magnitude and biological losses would probably be great. However, population effects on a regional level would not be expected even though local stocks and fisheries could be severely impacted in the short term.

Contents

Figures

Figure		*Page*

Tables

1

Introduction

Lyman K. Thorsteinson

1.1 PROPOSED ACTION

The continental shelf underlying the eastern Bering Sea is among the most promising of potential petroleum provinces currently scheduled for offshore leasing by the U.S. Department of the Interior. The eastern Bering Sea shelf is quite broad, extending over 120 million ha, and remains largely unexplored for possible oil and gas deposits. Consequently, it has received special recognition in the Department of the Interior's planning schedule for Outer Continental Shelf oil and gas development (Hameedi 1982). As of April 1982, four Bering Sea planning units covering 46 million ha of seabed were identified on the OCS leasing schedule. Of these, the North Aleutian Shelf in southwestern Bristol Bay is the smallest (3.26 million ha), yet perhaps most controversial due to its close proximity to lucrative salmon and crab fishing areas, national wildlife refuges, and state of Alaska critical habitat areas (Fig. 1.1).

The sensitive nature of offshore oil and gas development in the North Aleutian Shelf is reflected in changing Department of the Interior leasing priorities and the on-again off-again nature of this lease area on OCS planning schedules during the past 10 years. A sale for the Outer Bristol Basin, OCS Sale 51, was originally scheduled for December 1977. The Area of Call included virtually all of Bristol Bay (about 13 million ha), out to Unimak Pass on the south and Cape Newenham on the north. This sale was cancelled in March 1977. The North Aleutian Shelf, Sale 75, was added to the planning schedule in June 1979 as a new lease area proposed for sale in April 1982. Sale 75 was later delayed to October 1983. Then, within days after the North Aleutian Shelf Synthesis Meeting, in March 1982, the Department of the Interior cancelled Sale 75. The most recent OCS planning schedule (July 1982) shows Bristol Bay in its entirety, as the North Aleutian Basin, Sale 92, proposed for leasing in April 1985.

Tentative tract selection for Sale 75 was completed 31 December 1980 and included 605 tracts covering 1.4 million ha (Fig. 1.2). The tracts range in depth from 25 to 100 m and extend 19 to 76 km seaward of the Alaska Peninsula. The maximum actual area to be offered was anticipated at slightly more than 400,000 ha (U.S. Department of the Interior 1980).

Two sedimentary formations having oil and gas potential are located in the North Aleutian Shelf (Fig. 1.3): the Bristol Bay Basin, a northwest-trending elongate structure which is expressed in almost equal proportions on the Alaska Peninsula and the North Aleutian Shelf; and the Amak Basin, lying almost entirely offshore. A U.S. Geological Survey (USGS) resource appraisal for Sale 75 suggests that the southwest portion of the Bristol Bay Basin shows greater promise of recoverable petroleum than its northeastern counterpart (Marlow *et al.* 1980). This appraisal is supported by a thicker sequence of Cenozoic deposits in the region and shows of oil and gas in exploratory wells on the peninsula adjacent to the offshore lease area (Science Applications, Inc. 1981). USGS estimates of reserves for the North Aleutian Shelf, although speculative, are that if petroleum hydrocarbons are found, there is a 95% chance they will amount to 0.1 billion bbl of oil and 0.1 trillion ft^3 of natural gas. There is a 5% chance the reserves will amount to 2.3 billion bbl of oil and 5.8 trillion ft^3 of gas. Mean

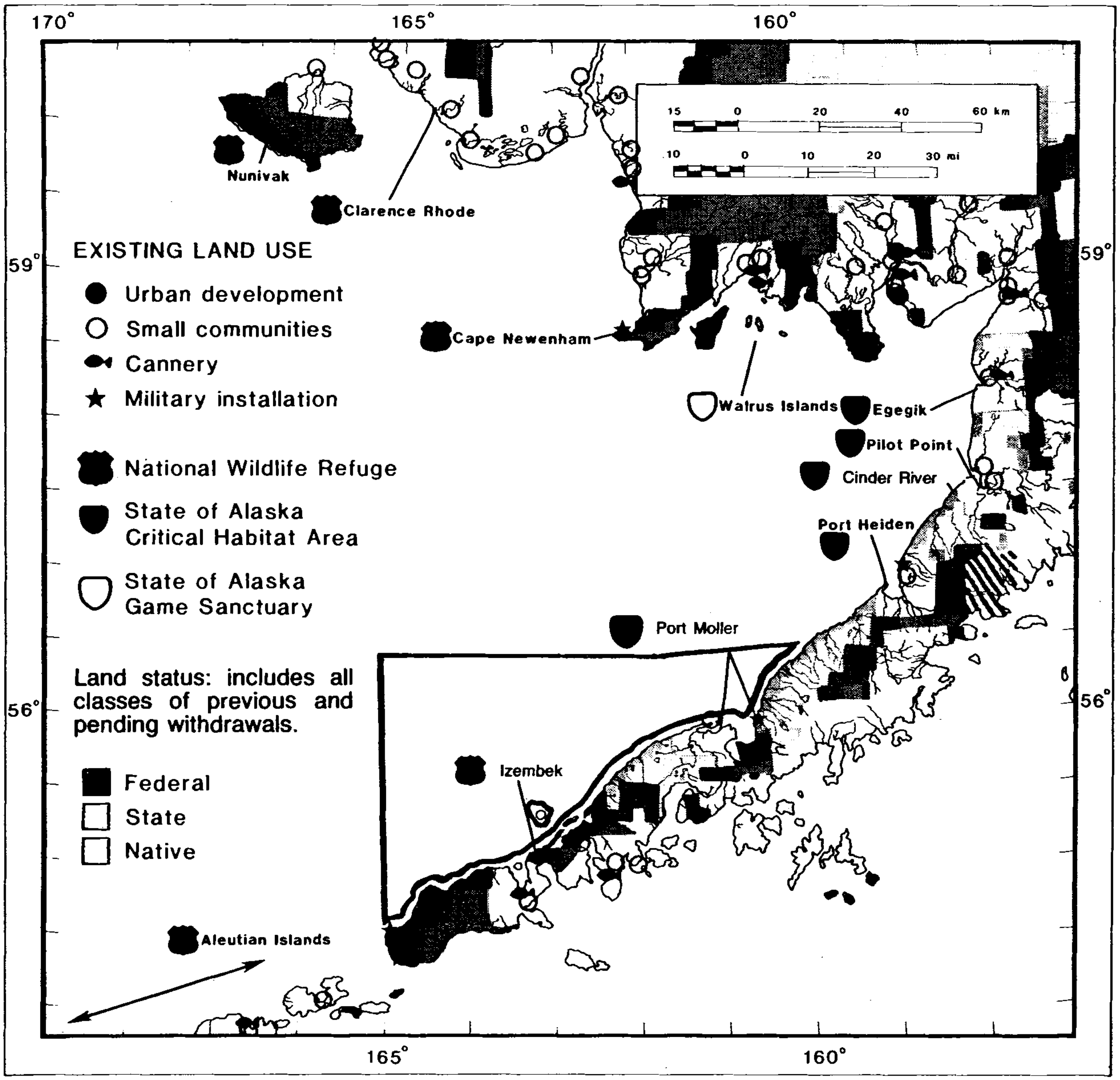


FIGURE 1.1—North Aleutian Shelf proposed lease area and existing land use patterns in adjacent coastal areas (Science Applications, Inc. 1981).

case estimates include 0.7 billion bbl of oil and 1.5 trillion ft^3 of gas. For OCS Sale 92, which includes all of Bristol Bay, oil and gas estimates would be much higher.

Overcoming the environmental constraints inherent to developing the North Aleutian Shelf appears to be well within the operational capabilities of semisubmersibles, drillships, and jack-up rigs (in shallow waters). Once leases are sold, how long the exploratory phase will last largely depends on the worldwide availability of rigs and on whether or not seasonal restrictions are imposed on exploratory drilling. Assuming rigs will be available, sea ice, fog, and storm waves will pose the most serious hazards and sources of delay to the safe conduct of exploratory activities.

Exploration-related industry will prefer to use existing facilities for shore-based servicing of rigs. Cold Bay and Dutch Harbor are currently the most plausible base sites. The Cold Bay airport already supports international jet transpor-

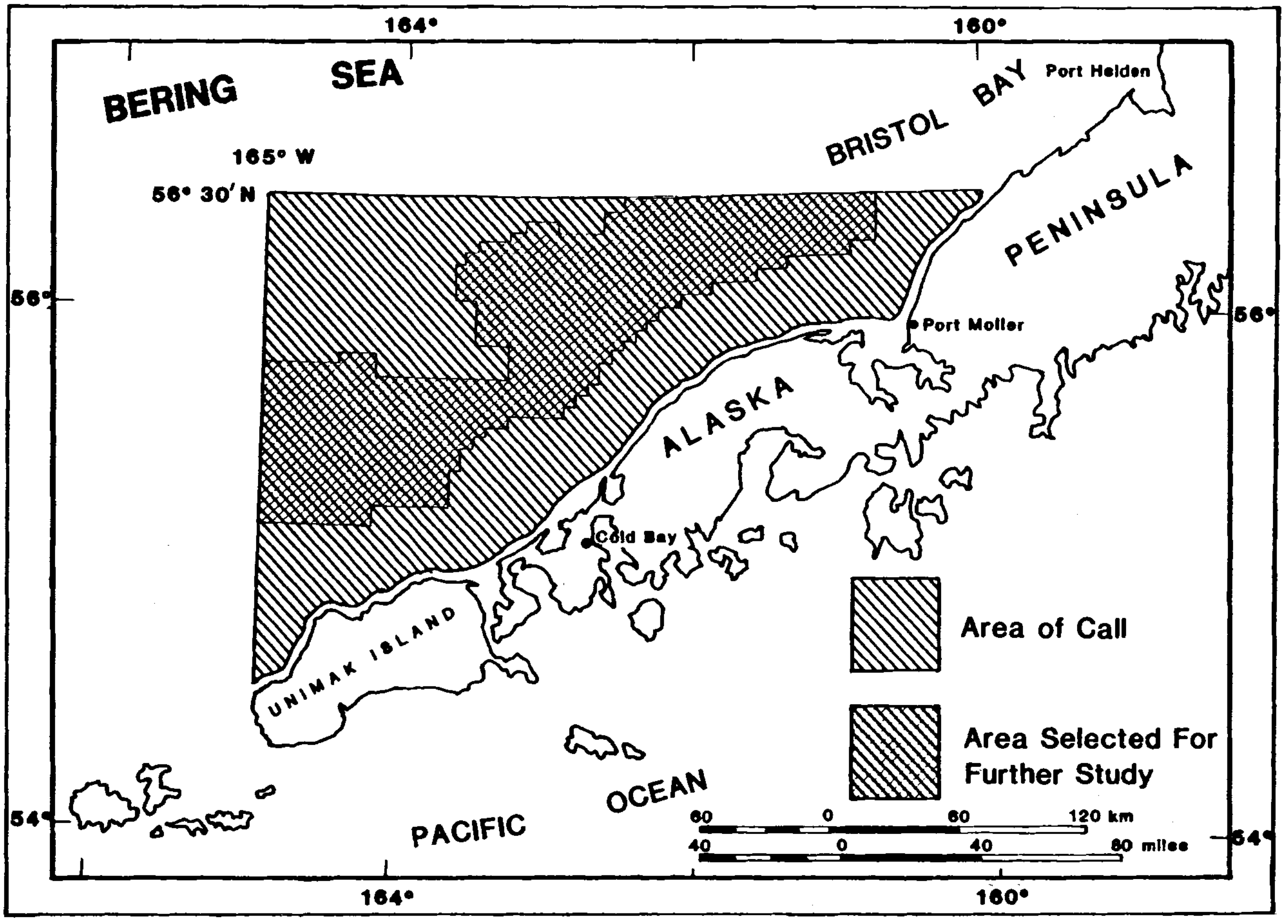


FIGURE 1.2—Area of the North Aleutian Shelf selected for further study.

tation and offers the best alternative for air transportation needs associated with possible oil and gas development in the North Aleutian Shelf. Dutch Harbor is closer to the lease area than Cold Bay by sea and its existing infrastructure offers better anchorage and marine servicing for supply boats. Both sites would be able to service rigs via long-range helicopter support. The possibilities of using Port Moller and Port Heiden during exploration are more remote. However, in the event of a commercial find, Port Moller is the only potential deepwater port along the north side of the Alaska Peninsula. The airstrip at Port Heiden could be used as a service base for helicopters during exploration.

Specific details on exploration, development, production, and transportation will be developed following discovery of commercial quantities of oil, and will be available from the Alaska Office of the Minerals Management Service. Details on the anticipated technology may be found in Dames and Moore's (1980) technology assessment for the North Aleutian Shelf.

1.2 ENVIRONMENTAL IMPLICATIONS OF OCS SALE 75

The North Aleutian Shelf lease area contains and is adjacent to several regions of high fishery and wilderness values. Nearby communities are remote, of small populace, and, in many respects, resource oriented. Although a cash economy predominates in the region, hunting, fishing, and gathering for subsistence are pervasive activities composing an important component of community lifestyles. Offshore oil and gas development in the North Aleutian Shelf will bring certain changes to the socioeconomic organization in the Alaska Peninsula and Aleutian Islands and may interfere with many

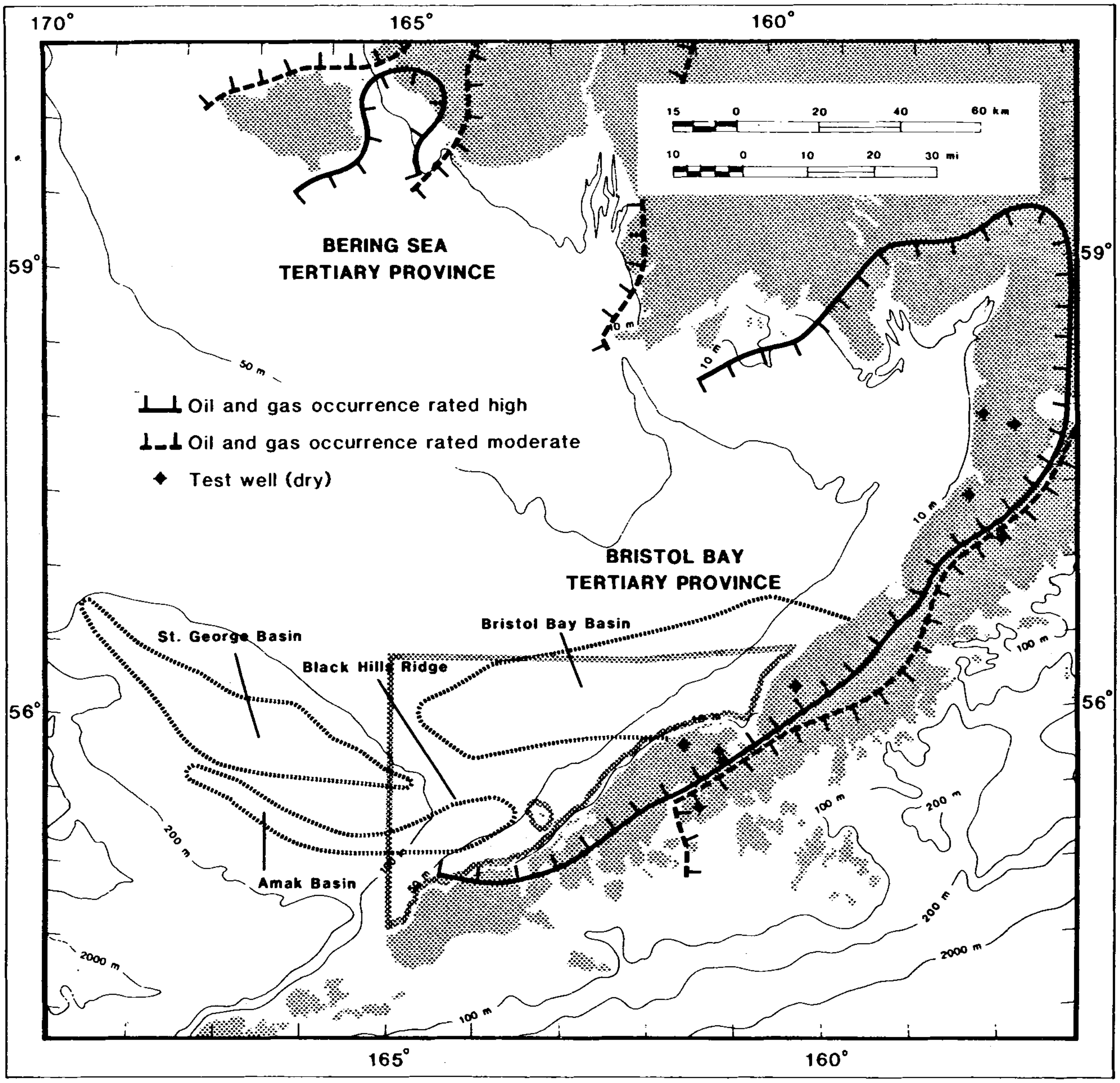


FIGURE 1.3—Potential oil and gas sedimentary formations in the North Aleutian Shelf (Science Applications, Inc. 1981).

traditional activities.

Bristol Bay has one of the richest fishing grounds in the world and the greatest concentrations of birds, fish, and marine mammals on the North American continent. The lack of previous oil drilling experience in the southeastern Bering Sea, where environmental conditions are severe and renewable resources are extremely valuable and potentially vulnerable, highlights the controversy surrounding oil and gas leasing in the area. The main features of the Bering Sea OCS and likely impacts of petroleum development are summarized in Figure 1.4.

1.2.1 At-Sea Conflicts With Fisheries

Experience in other regions has shown that just the appearance of oil exploration and production facilities in traditional fishing areas presents a conflict between the two industries. Offshore oil and gas development could impact fisheries through (1) preemption of fishing

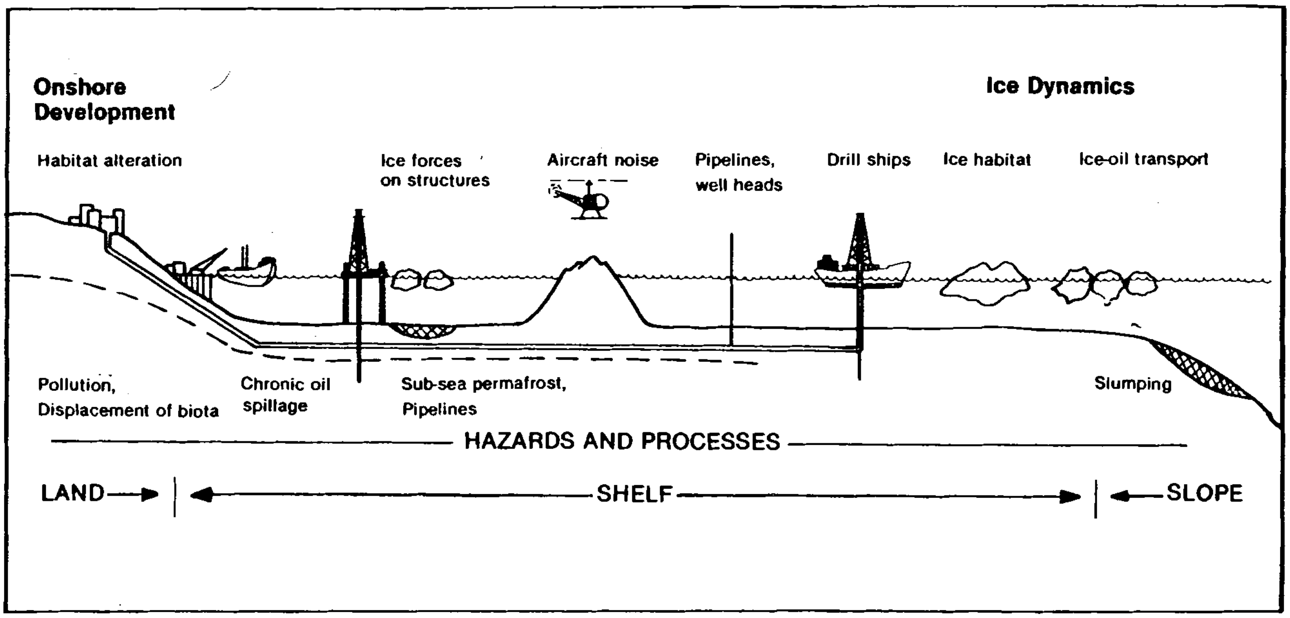


FIGURE 1.4—Main features of the Bering Sea Outer Continental Shelf and likely impacts of petroleum development.

grounds, (2) gear loss or damage, (3) contamination of gear or catch, or (4) competition for port facilities and labor.

The siting of onshore structures and facilities could preclude fishing in historically productive areas. The extent of losses would depend on the number and locations of structures and the size of safety zones required by regulatory agencies. Increased vessel support traffic and associated easements would hinder trawling, crabbing, and seining, with losses persisting through the life of the field. Oil spills would be a more transitory preemption of fishing grounds; fear of damage to gear and contamination of catch likely would preclude fishing activities in polluted waters.

The methods of capture used in the exploitation of major commercial fish and shellfish stocks in Bristol Bay are susceptible to a variety of losses or damages associated with offshore oil and gas development. Most species in this area are harvested from near-surface waters or directly off the sea bottom. This requires gears that (1) float at the surface with nets penetrating to predetermined depths (net fishermen), (2) sit on the sea floor (crabbers and longliners), or (3) drag along the bottom (trawlers). Although fishing gear is well attended in net fisheries, spilled oil could reach and contaminate nets during periods of decreased visibility such as at night or in fog. Fouled gear would be expensive and, in most cases, impractical to clean. Increased vessel support of offshore platforms in the North Aleutian Shelf and other Bering Sea lease areas could also increase the frequency of collisions with marking buoys and corresponding losses to fishermen. The gear overrun issue is most germane to regional crab fisheries where pots are fished for several months, then stored in offshore waters for the remainder of the year. Offshore structures and development-related debris offer a multitude of sources for entanglement and destruction of gear in trawl fisheries. Usually gear losses or damage translate into lost fishing time. With the exception of bottomfishing, Bering Sea fisheries are typically brief, intense, and reflective of fish migration patterns or protective quotas established by managing authorities. Lost fishing time or closures of oiled waters to fishing could result in substantial reductions in income to many.

Fish captured in oiled gear would be spoiled and unmarketable. Crab boats require circulating seawater intake to live storage tanks. If this system were exposed to oil, crabs would be rendered unsalable and much time would be lost in an already abbreviated fishing season in cleansing fouled tanks. Although a much larger fleet of at-sea processors operates to the west of the North Aleutian Shelf, several operate there. Shipboard fish processing requires clean seawater; if contaminated, it would destroy the pack's marketability.

Offshore oil and gas exploration and development in the North Aleutian Shelf (and St. George Basin) will stimulate growth of shore-based industries in Cold Bay and Dutch Harbor. This growth is expected to coincide with developing U.S. groundfish fisheries in the southeastern Bering Sea. Both industries will require expanded shore and harbor facilities and marine services during the next 10 to 15 years. Initially, dock space, warehouse and supply yards, living accommodations, and other marine services could be in short supply and expensive.

The presence of the petroleum industry may offer some employment opportunities to local residents. This possibility has been met with mixed reactions. Few actual new jobs will be created during exploration for local-priority hire. If oil is discovered, the segment of the labor force normally participating in regional fisheries may be drawn into more permanent and possibly more lucrative jobs with oil companies.

1.2.2 Coastal Resources

The coastal waters of the North Aleutian Shelf exhibit a great diversity of fish, wildlife, and habitat resources which are important to the character and economy of the area. This is evidenced in existing land use along the coast, where large tracts of acreage are set aside as national wildlife refuges and state critical habitats (Fig. 1.1). Inshore waters are critical spawning and nursery habitat for crabs. Hundreds of millions of salmon migrate through the lease area annually. Large numbers of whales and other marine mammals inhabit or migrate through the area, including summer resident gray and humpback whales and, less frequently, several other species of endangered cetaceans. The Bristol Bay-Alaska Peninsula region is one of the world's great bird migration crossroads and is used by hundreds of thousands of migrating waterfowl, seabirds, and shorebirds. Widespread environmental perturbations could jeopardize large portions of entire world or North American bird populations that seasonally congregate in the extensive wetlands and lagoons adjacent to the North Aleutian Shelf. These habitats are believed to be necessary for the continued survival of many species and, as such, are important features of the lease area whose ecological integrity must be maintained to preserve the value of coastal resources for commercial and subsistence use, recreational and aesthetic appreciation, and protection of regional lifestyles (Kramer *et al.* 1978).

The expansion and improvement of shore-based industries in support of OCS activities will use and likely modify coastal and marine habitats near the North Aleutian Shelf. Possible sources of modification to coastal habitats include construction activities; dredging operations and settling of dredged sediments; pipeline, platform, and offshore storage placements; discharges of drilling muds, cuttings, fluids, and formation waters; and increased noise and disturbance associated with aircraft and vessel support (Hameedi 1982). Because the North Aleutian Shelf lies close to several critical wildlife habitats, careful selection of development sites and transportation corridors is critical to mitigating potential impacts. Selection of sites and routes "will ultimately be determined by the needs of industry, the policies and control of local, state, and federal governments, and by evaluation of predicted environmental effects" (Hameedi 1982). Throughout the selection process the State of Alaska must provide protection of "ecologically sensitive areas, including but not limited to: estuaries, wetlands, river deltas, fish spawning grounds, intensive-use habitats, bird nesting areas, migration routes, wildlife wintering habitat, and sea mammal rookeries and hauling-out grounds" (Kramer *et al.* 1978).

1.2.3 Geologic Hazards

Prior to petroleum industry development in the North Aleutian Shelf, the regional geologic hazards must be evaluated. Although relatively aseismic in comparison to the Gulf of Alaska, earthquakes and associated ground accelerations, surface faulting, and sediment instability are likely events that will affect design and engineering features. Strong earthquake-generated ground accelerations could destroy or weaken OCS structures and rupture pipelines and storage tanks. Gas seeps and related seafloor instabilities are other sources of possible hazard to drilling in the North Aleutian Shelf. Drilling through gas deposits of unknown pressures could increase the probabilities of well blowouts and other accidents. Geohazards related to sedimentary processes include unstable deposits, rapid erosion and deposition, and dispersion of particulate pollutants. Because the North Aleutian Shelf lies adjacent to a chain of active volcanoes along the Aleutian Island-Alaska Peninsula arc, volcanic ejecta and directed blasts must also be considered in any hazard assessment.

A more thorough discussion of geohazards of the southeastern Bering Sea is available in the report on the St. George Basin Synthesis Meeting (Sackinger and Combellick 1982). As regards the North Aleutian Shelf, the severity of geohazards is not so great that they cannot be accommodated by proper site selection and state-of-the-art engineering design (Science Applications, Inc. 1981).

1.2.4 Accidental Oil Spills

There is always the threat of a major oil spill. Because of the potential for human error, the chances can be reduced, but not eliminated (Hileman 1981). The USGS estimates the probability of finding 0.7 billion bbl of oil (mean case) in the North Aleutian Shelf at 21%. If seasonal drilling restrictions are not imposed, exploration and development phases should occur rapidly. The average life of a North Aleutian Shelf field is expected to be 25-30 years (Dames and Moore 1980). Oil spill estimates for a field of this size and life-span have been projected by the USGS (statistics from Labelle, USGS, Reston, Va.) based on the frequency of spills in other areas where offshore oil and gas development has occurred. For the mean North Aleutian Shelf case one spill larger than 1,000 bbl and no spills greater than 10,000 bbl are expected over the life of the field. In comparison, the expectation for Sale 70 St. George Basin leases, with a mean case of 1.12 billion bbl, is most likely 4 to 6 spills over 1,000 bbl and 1 to 2 over 10,000 bbl; and for Norton Sound Sale 57, with a mean case of 0.48 billion bbl, is 2 spills over 1,000 bbl and 1 over 10,000 bbl (U.S. Department of the Interior 1982).

Spill estimates for Alaskan OCS lease areas may be conservative. Subsurface pressures are unknown and environmental hazards are frequently great, suggesting that probabilities for accidents may be greater than in established fields elsewhere (Hameedi 1982).

1.2.5 Chronic Pollution

Several potential sources of low-level chronic pollution during exploration have been identified (Hameedi 1982). Intermittent discharges (in time and quantity) associated with actual drilling operations are likely to be localized, in effect in the immediate area of the rig. Sources of chronic pollution from exploratory rigs include (1) discharges of muds, cuttings, fluids, formation waters, and other mining wastes during actual spudding; (2) separation of seawater from petroleum and storage in ballast systems; (3) freshwater distillation onboard rigs; (4) disposal of domestic and solid wastes; and (5) industrial wastes associated with blowout prevention.

The North Aleutian Shelf and St. George Basin have very similar tidal, wave, and storm surge characteristics. Impacts related to exploration sources of chronic pollution have been described for the St. George Basin (Hameedi 1982). Sessile benthos near the exploration site, especially infaunal organisms, are expected to be most severely affected by occasional discharges and settling particulates. For example, drilling a well to 2,000 m can be expected to produce 130 m^3 of cuttings and 60 m^3 of drilling muds (U.S. Department of the Interior 1980). Discharge standards are regulated by various government agencies.

Coastal and estuarine waters adjacent to the Alaska Peninsula and several Aleutian Island communities may experience substantial impact by changing land use patterns in support of the oil industry. Many of these communities already use coastal waters as receptacles for fish processing wastes from cold-storage facilities and floating processors. In coastal areas of poor flushing this organic loading may already be close to or exceeding the biological oxygen demand of the waters. Because the fishing industry is well represented in most of these communities, coastal waters may be further stressed by support industry for oil exploration, development, and production in the North Aleutian Shelf and other Bering Sea lease areas through increases in:

1. Discharges of domestic sewage and other oxygen-demanding wastes such as synthetic organics and fluids.
2. Solid (paper and paper products, metal cans, bottles and jars, plastics, rubber, metal squeeze tubes) and industrial (inorganic chemicals and minerals) wastes.
3. Sediment loads and turbidity in coastal waters and embayments due to changes in local land use practices, such as dredging and port facility expansion.
4. Noise due to increased human activities and vessel and air support.

The possibility of greater use of coastal waters as receptors for contaminants associated with OCS shore-based industrial growth could result in permanent habitat alterations, affecting local recreational, subsistence, and commercial fisheries (Hameedi 1982). Each habitat is characterized by its own species, carrying capacity for those species, levels of production, food web, nutrient cycles, and physical inputs (Bahr *et al.* 1978). The time scale of important events in these ecosystems is often seasonal, and at this level capable of being significantly altered by contaminating agents. Chronic discharges into marine waters, especially in embayments with poor flushing, may result in dramatic changes in species diversity and abundance. Increased levels of pathogens (viruses, bacteria) in fish and other marine organisms living in contaminated waters or sediments may be a consequence of chronic discharges, resulting in changes in local use of biota and maintenance of stocks (Hameedi 1982).

OCS-related development in Bristol Bay and nearby communities may lower air and water qualities through (1) increased use of ground and surface fresh water, (2) pollutant emissions from storage and loading facilities, and (3) increases in residental and commercial use of combustible fluids. All are factors that would affect aesthetic wilderness values often attributed to this region (Hameedi 1982).

1.3 THE MEETING

On 9-11 March 1982, OCSEAP principal investigators, other scientists conducting research in Bristol Bay, representatives of resource management agencies, and other interested parties, including those responsible for the Bristol Bay Management Plan, met in Anchorage, Alaska for the North Aleutian Shelf Synthesis Meeting. The meeting provided a forum for discussions on environmental concerns and multiple resource use conflicts and provided recommendations for the protection of marine and coastal resources from possible adverse effects of oil and gas development. At the meeting, available data were used to (1) describe the marine and coastal habitats and resources of the North Aleutian Shelf; and (2) discuss the environmental implications of the planned oil and gas development, including effects from hypothetical cases of oil spills and other pollution incidents.

The environmental consequences of three hypothetical oil spills were considered: 10,000 bbl of oil released over 5 days at Amak Island and Cape Seniavin as a result of well blowouts, and a tanker accident releasing 200,000 bbl of oil instantaneously near Cold Bay. For the sake of discussion, hypothetical spills occurred on 22 June. These topics were also presented to the Minerals Management Service in the preparation of the draft environmental impact statement for OCS Sale 75.

The following topics were discussed in workshops and plenary sessions of the synthesis meeting:

1. Pollutant transport and fate: oil spill trajectories, weathering and persistence of spilled oil, oil spill countermeasures and contingencies, dispersion and transport of drilling fluids and muds and other discharges into the marine environment, and other topics.
2. Fisheries: biology and distribution of salmon and other fishery resources; commercial, recreational, and subsistence values of the fisheries; resource and space use conflicts between the fisheries and petroleum industries; probable impacts of petroleum development and pollution events; and other topics.
3. Coastal and nearshore habitats and ecosystems: identification of biologically rich and critical areas or ecosystems; migratory corridors or staging areas for marine birds and mammals; potential sites for support

and supply bases, including those on the south side of the Alaska Peninsula; probable impacts of petroleum development and pollution events; and other topics.

1.4 REFERENCES CITED

BAHR, L. M., JR., J. W. DAY, JR., T. GAYLE, J. G. GOSSELINK, C. S. HOPKINSON, AND D. STELLAR.
1978. The construction of a conceptual model of the Chenier Plain coastal ecosystem in Louisiana and Texas. *In* J. B. Johnston and L. A. Barclay (eds.), Contributed papers on coastal ecological characterization studies, presented at the Fourth Biennial International Estuarine Research Conference, Mt. Pocono, Pa., 2-5 October 1977, p. 32-43. Off. Biol. Serv., U.S. Fish Wildl. Serv. FWS/OBS-77/37.

DAMES AND MOORE.
1980. North Aleutian Shelf technology assessment: OCS lease sale No. 75. Alaska OCS Socioeconomic Studies Program Tech. Rep. 63, 8 chap. (Available from U.S. Dep. Inter., Bur. Land Manage., Alaska OCS Office, Anchorage.)

HAMEEDI, M. J. (ed.).
1982. Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 162 p.

HILEMAN, B.
1981. Offshore oil drilling. Environ. Sci. Technol. 15(11): 1259-1263.

KRAMER, L. S., V. C. CLARK, AND G. J. CANNELOS.
1978. Planning for offshore oil development: Gulf of Alaska OCS handbook. Alaska Dep. Community and Regional Affairs, Juneau, 257 p.

MARLOW, M. S., H. MCLEAN, A. K. COOPER, T. L. VALLIER, D. W. SCHOLL, J. V. GARDNER, R. MCMULLIN, AND M. B. LYNCH.
1980. A preliminary summary of regional geology, petroleum potential, environmental geology, and technology for exploration and development for proposed OCS lease sale #75, North Aleutian Shelf, Bering Sea, Alaska. U.S. Geol. Surv. Open-File Rep. 80-653, 53 p.

SACKINGER, W. M., AND R. A. COMBELLICK.
1982. Environmental hazards to petroleum industry development. *In* M. J. Hameedi (ed.), Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981, p. 39-54. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

SCIENCE APPLICATIONS, INC.
1981. North Aleutian lease area. Twenty-one resource assessment sheets prepared for OCSEAP. SAI, Boulder, Colo.

U.S. DEPARTMENT OF THE INTERIOR, BUREAU OF LAND MANAGEMENT.
1981. Draft environmental impact statement: Proposed OCS oil and gas lease sale 57, Norton Sound. U.S. Dep. Inter., Bur. Land Manage., Alaska OCS Off., Anchorage, 256 p. + append.
1982. Final environmental impact statement: OCS proposed oil and gas lease sale 57, Norton Sound (February 1982). U.S. Dep. Inter., Bur. Land Manage., Alaska OCS Off., Anchorage, 331 p. + append.

U.S. DEPARTMENT OF THE INTERIOR, MINERALS MANAGEMENT SERVICE.
1982. Final environmental impact statement: Proposed oil and gas lease sale 70, St. George Basin (August 1982). U.S. Dep. Inter., Minerals Manage. Serv., Anchorage, 385 p. + append.

2

Transport and Fate of Spilled Oil

Carol-Ann Manen and Mauri J. Pelto

Workshop Chairman: M. J. Pelto. Participants: E. T. Baker, J. D. Cline, B. E. Kirstein, J. J. Leendertse, S.-K. Liu, J. E. Overland, J. R. Payne, and J. D. Schumacher.

2.1 INTRODUCTION

The North Aleutian Shelf lease area encompasses approximately 25,000 km² in the southwestern section of Bristol Bay. It is bounded by the Bering Sea to the north and west and by the glaciated, volcanic terrains of the Alaska Peninsula and Unimak Island to the south. Specifically, the lease area extends eastward along the north side of the Alaska Peninsula from Unimak Pass (long. 165°00′ W.) to Cape Seniavin (long. 159°30′ W.) and north to latitude 57°00′ N. (Fig. 2.1).

Water depths in the lease area reach 70 m in the northeast and 110 m in the southwest. Most of the area is overlain by stratified water characteristic of the middle domain described by Kinder and Schumacher (1981). The sea floor within the area is very flat and is typical of the shallow continental shelf of the southeastern Bering Sea. The annual weather patterns in the lease area develop as a result of strong seasonal pressure changes. The *Coastal Pilot* (U.S. Department of Commerce 1979:297) describes weather in this area as follows:

> The weather over the Bering Sea is generally bad and very changeable. Good weather is the exception, and it does not last long when it does occur. Wind shifts are both frequent and rapid. The summer season has much fog and considerable rain. In early winter, the gales increase, the fogs lessen, and snow is likely any time after mid-September. Winter is the time of almost continuous storminess.

Lastly, ice extends south over much of the area during heavy ice years.

2.1.1 Distribution of Properties

The North Aleutian Shelf lease area includes parts of each of the three hydrographic domains—coastal, middle, and outer—used by Kinder and Schumacher (1981) to describe the summer eastern Bering Sea shelf (Fig. 2.1). The coastal domain, inside of the 50-m isobath, is characterized by generally warm, low-salinity, vertically well-mixed water lacking stratification. A strong inner front, defined by an enhanced horizontal salinity gradient, separates the coastal domain from a middle shelf domain. The middle shelf domain is recognized by a strongly stratified two-layered structure extending to approximately the 100-m isobath. A middle front, at about the 100-m isobath, delineates the third or outer shelf domain. The outer shelf domain structure is characterized by a stratified layer with pronounced fine structure separating surface- and bottom-mixed layers. Beyond the shelf break, ocean water persists. Kinder and Schumacher (1981) suggest that this hydrographic structure is controlled by the gentle slope of the bathymetry interacting with boundary processes which include tidal and wind stirring, surface cooling, river runoff, and lateral exchange with oceanic water. During the winter, cooling of the surface water allows mixing of the water column to the bottom over the middle shelf domain and diminishes the definition of the domains and their bordering fronts. However, they tend to persist through winter.

Summer temperatures in the coastal domain range from 10°C nearest shore to 7°C near the boundary with the middle zone. Winter temperatures are from near freezing to 2°C, except near Unimak Pass where 4°C water is found. Salinities are generally less than 31 g/kg in the coastal domain and 32 g/kg offshore and near Unimak Pass. A seasonally varying current with properties—i.e., temperature and salinity—similar to those of the water on the shelf south of the Alaska Peninsula flows through Unimak Pass and then northeastward parallel to the north shore of the peninsula. This current has been identified as a source for some of the freshened water on the North Aleutian Shelf where freshened water occurs in quantities not accountable for by local runoff (Fig. 2.1).

2.1.2 Circulation and Hydrography

Dynamic height calculations indicate northeastward currents, generally, within the coastal zone north of the Alaska Peninsula. The freshwater, methane, and sediment plumes which have been tracked along the Alaska Peninsula also indicate a net northeasterly flow (Baker 1983; Cline *et al.* 1982). A long-term mean northeasterly current of 2–5 cm/s has been measured along the shelf north of the Alaska Peninsula and is believed to be continuous with a weak current past Nunivak Island (Kinder and Schumacher 1981). Near Port Moller, currents were found to be of even lesser net magnitude with no evidence of intensification of the current near the coast. Close inshore, within 50 km, currents ranged from 1 to 6 cm/s (Schumacher and Kinder 1982) (Fig. 2.1).

Superimposed on the net northeasterly flow is a fluctuating flow resulting from atmospheric forcing (winds). Because the winds are so highly variable, their contribution to net circulation is difficult to quantify, but they do contribute kinetic energy to the water column in the frequency band 0.1 to 0.5 cycles per day (Schumacher and Kinder 1982). Also, the alongshore component of winds is highly correlated with both onshore and alongshore components of surface and subsurface currents. During an event recorded in August 1980, when the wind was toward the southwest, there occurred an offshore transport at about 1% of the wind speed at a depth of 5 m. When winds blew toward the northeast, a similar transport took place in the onshore direction. Deeper water moved off- and onshore to compensate, but at a much lower speed. Alongshore transport at depth was poorly correlated with the surface current and occurred at a speed only one-fourth to one-third that at the surface. In this case, with a persistent alongshore wind of 10 m/s, any material suspended in the water column would be transported off- or onshore at a speed of approximately 8–10 cm/s (Fig. 2.2). The surface slick would be moved to the right of the wind vector as the surface is dragged along by the water beneath.

2.1.3 Tidal Currents and Mixing

Tides in the study area are dominated by a tidal bulge which enters the Bering Sea through the central and western Aleutian straits and progresses as a free wave onto the Bering Sea shelf. It is dominantly a mixed semidiurnal tide over the southeastern portion of the shelf. On the open shelf the tidal amplitudes average 2 m. Toward the head of Bristol Bay the largest amplitudes exceed 6 m. The tidal range at Port Moller averages 3.3 m, compared to a range of 6.9 m at the Naknek River entrance (Brower *et al.* 1977).

The propagation of tidal waves onto the Bering Sea shelf accounts for approximately 90% of the kinetic energy in the water column. On the North Aleutian Shelf, where the net currents are only 1–4 cm/s and the typical wind-driven currents are 10 cm/s at 5 m, the tidal currents are 40–80 cm/s or more. Turbulence resulting from tidal currents causes mixing of the water column from the bottom to about 50 m above the bottom. When this is added to the wind mixing, which extends down to a depth of 20–30 m depending on wind velocity, the result inside the 50-m isobath is a well-mixed water column (Coachman and Charnell 1979).

Tidal currents in Bristol Bay are nearly reversing along the Alaska Peninsula and become more cyclonic and rotary offshore. National Ocean Survey current tables show a change in maximum ebb currents from 20–25 cm/s up to 30–40 cm/s in June near Amak Island. Near Port Moller, the tidal current speeds are as high as 100 cm/s (U.S. Department of Commerce 1980). Residual currents generated by the tidal current interacting with changes in bathymetry and stratification have been calculated for the area

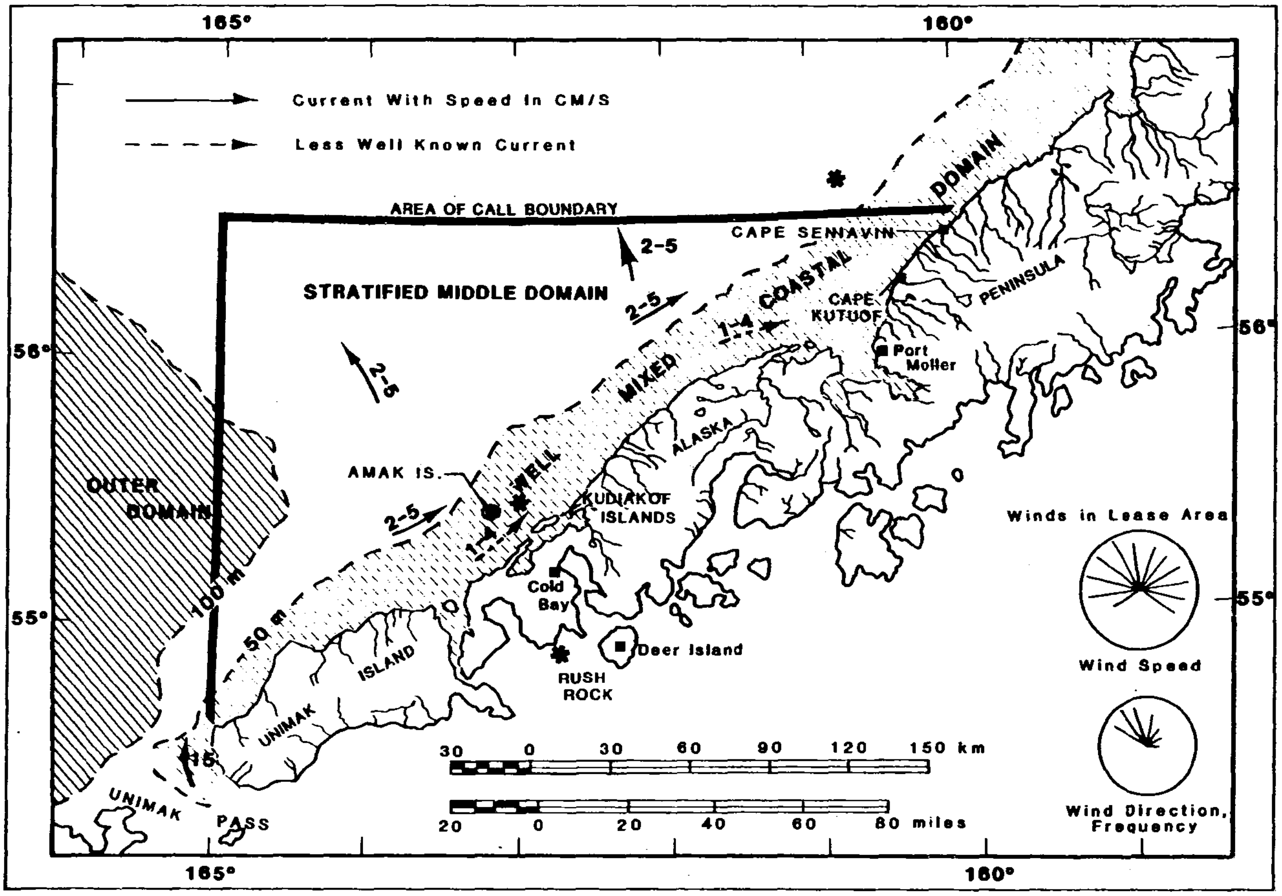


FIGURE 2.1—Physical features of the North Aleutian Shelf lease area under typical summer conditions. The wind roses are those used by Liu and Leendertse (1982) in the development of the oil spill trajectories. Asterisks (*) indicate hypothetical oil spill sites (*see* section 2.4, p. 27).

near Port Moller. At a depth of 2.0 m, the calculated tidal residual current is approximately 3-4 cm/s, spatially highly variable, and directed to the northwest (Liu and Leendertse 1981a).

2.1.4 Winds

Offshore over much of the North Aleutian Shelf, winds are likely to blow from any direction, but with a slightly greater tendency to be from the south during the summer. In the summer, storm centers (lows) tend to cross the eastern Bering Sea shelf to the north of the lease area, thereby causing a slight bias toward southerly winds (Overland 1981). These southerly winds are generally light; approximately 5 m/s during the summer. In the winter, the low pressure systems pass to the south of the lease area with a resulting tendency for air flow from the north (northerly winds) to predominate. These winds are much stronger; the mean wind is between 10 and 15 m/s and there is a 25% probability of winds exceeding 14 m/s during November. Although the most likely wind during June is from the southwest, after September northerly and northeasterly winds are more probable (Overland 1981). Near shore, the winds are more nearly bimodal, from the northeast in the winter and southwest in the summer, an effect caused by the mountains (Schumacher 1982).

Of all the factors to be considered in assessing risk from oil spills, the climatology of winds may be the most important. Winds are also a primary factor in determination of wave height and assessment of hazards, and are a principal cause of the nontidal currents responsible for transport of spilled oil should accidents occur.

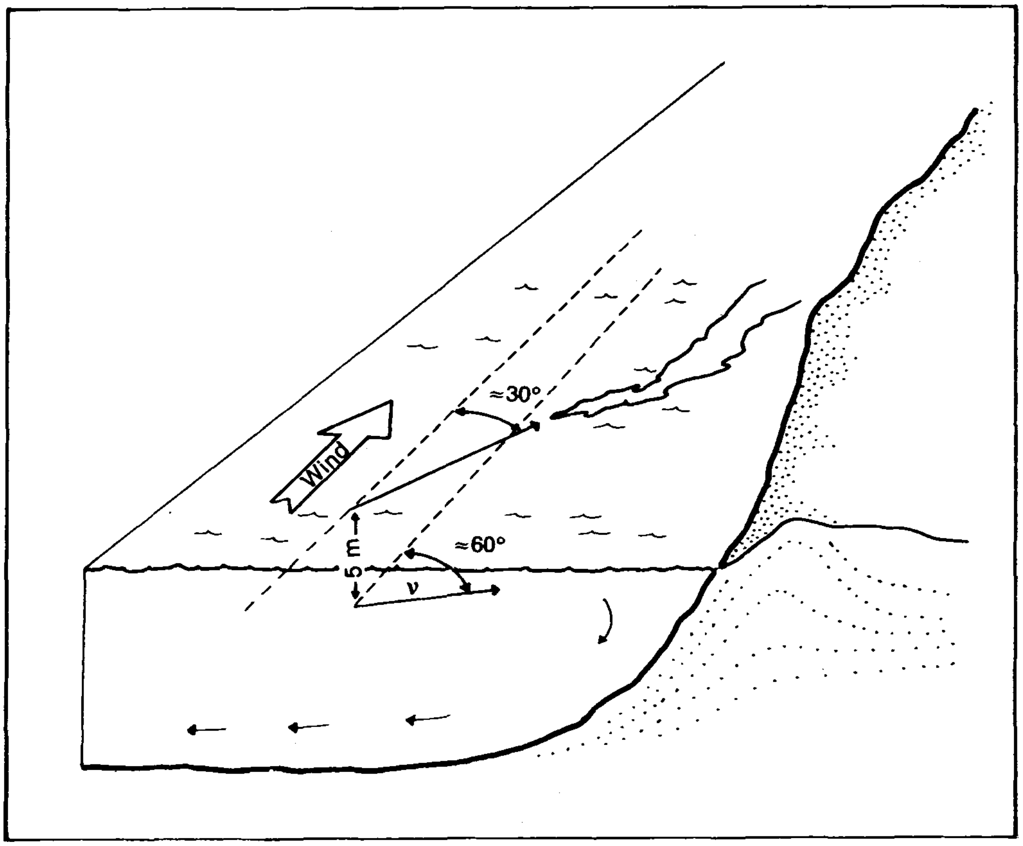


FIGURE 2.2—Effect of alongshore wind on onshore and offshore transport. The subsurface current (ν) is directed sharply onshore. The surface current is moving downwind at an angle of 30° to the right of the wind. Angles shown are typical, but highly dependent on local conditions.

2.1.5 Waves

The North Aleutian Shelf is characterized by severe waves generated by local storms. The most critical parameters controlling wave climate for the area are fetch, storm duration, and shallow-depth conditions. During the summer, winds are predominantly from the south, placing the nearshore portion of Bristol Bay in the lee of the Alaska Peninsula. As a result, most waves are generated locally and are not very severe. However, during the winter the prevailing winds are northerly at 10–15 m/s. The increased fetch and wind speed have a significant effect on wave height and period. The maximum observed wave height in June is 5.5 m; 50% of the observed waves are less than 1.5 m in height, with correspondingly small periods. During November the maximum observed wave height is 9.0 m; 60% of the observed waves are greater than 2.0 m in height and the average period is 7 seconds (Brower *et al.* 1977).

2.1.6 Ice

The mean limits of 5/8 ice cover lie just to the north and well to the south of the lease area. As a result, one can expect to encounter ice in the area in most winters, with March and April the months of greatest probability of occurrence and the greatest coverage. Data collected from 1972 to 1980 indicate a 20% probability of finding ice in the area in March, with 70% coverage. Along the northern part of the lease area, 100% coverage was found in 20% of the months (March) of record (Stringer and Henzler 1981).

The maximum extent of ice cover tends to occur in February in heavy ice years and in March in average ice years. The occurrence of heavy and light ice years appears to correlate with yearly shifts in storm tracks; light ice years are associated with the more westerly storm tracks, the cyclone centers moving preferentially up the western Bering Sea in their northerly path (Overland and Pease 1982).

2.1.7 Suspended Sediment Distributions

Circulation and mixing processes inferred from salinity and temperature distributions are also evident from suspended sediment data and from the distribution of bottom sediments. In the coastal domain there is strong evidence that net transport is to the northeast, that resuspension occurs due to tidal currents, and that fine-grain materials are transported offshore beyond the frontal zone forming the boundary between the coastal and middle domains (Baker 1983).

Particle gradients in the vertical direction are low or nonexistent in the coastal domain, with concentrations decreasing rapidly with distance offshore. As a result of the high tidal energy environment of the coastal domain, suspended particles are in a state of transit with little deposition occurring except for larger grain sizes (mean > 125 μm). Scour channels as deep as a few meters and 200 or more meters in width have been noted (B. Molnia, pers. commun. 1982).

Seaward of the coastal zone, at depths greater than 50 m, the particles are typically distributed into three distinct layers. High and locally variable concentrations (0.5–2 mg/liter) are found in the surface-mixed layer, often with marked particle accumulation at the top of the pycnocline. Concentrations in the bottom 10–30 m of the water column are also high (1–2 mg/liter) and variable because of tidal resuspension of the bottom sediments. Between these boundary layers is a broad and geographically uniform zone of low concentrations (about 0.5 mg/liter) separated from the boundary layers by zones of low diffusivity.

In studies of vertical sediment transport by means of traps, sand grains >32 μm in diameter composed 20–40% of the accumulation in the three deepest traps; sand in the inshore trap was about 60% of the total. The remainder in each trap was principally silt and clay < 32 μm in diameter and small amounts of fecal pellets and diatom tests > 32 μm in diameter (Baker 1983).

2.2 TRANSPORT OF SPILLED OIL

Transport of oil on the ocean's surface is the result of the complex interaction of (1) currents which are superposition of tides, tide-induced residual flows, local wind-driven flows, currents generated by pressure gradients, and currents induced by oceanic circulation; (2) Stokes' drift component of the surface wind wave field; (3) ice; and (4) the time-dependent behavior of weather (wind) patterns. The oil spill trajectory model developed by Liu and Leendertse (1979, 1981a, 1981b, 1982) and used herein to compute the probable location of oil slicks combines these physical processes through several submodels including (1) a three-dimensional model of tides and circulation which incorporates field observations of bottom pressure, mass distribution, ice coverage, and currents; (2) a gravity-wave or Stokes' drift component which results in a surface drift speed of about 1.6% of the wind speed in the direction of wave propagation; and (3) a two-dimensional stochastic weather (wind) model to simulate the evolutary behavior of wind field changes according to a Monte Carlo procedure using a transitional matrix derived from 19 years of weather data.

For oil spill risk analyses, a stochastic weather model (as opposed to a deterministic one) is required. It provides the essential statistical parameters in the subsequent computation of the conditional probabilities of spill-risk. The reliability of the stochastic weather model has been tested. A comparison of simulated winds with long-term wind data from a land-based weather station at Nome showed that simulated wind came within 3% of the observed average wind speed and direction (given in 22.5° segments) during summer and winter months (Liu and Leendertse 1981a).

The trajectories shown in Figures 2.3 and 2.4 were computed using the oil spill trajectory model. Each figure illustrates a general tendency of probable oil transport direction and distance and the probability density distribution associated with the stochastic process. The dots on each trajectory (Fig. 2.4) represent the location at the end of the day, and each 30-day trajectory was computed according to the evolution of weather type as well as dynamic effects such as tidal circulation, vertical density structure, and shore effects.

The model reflects that during the summer, winds are predominantly from the southwest and therefore spilled oil will move in an easterly direction toward Bristol Bay (Fig. 2.3). The model also reflects that oil released from any point within the sale area during the summer or fall could reach the Alaska Peninsula within 30 days. Under winter conditions with predominantly northeasterly winds, spilled oil will move toward the northwest out into the Bering Sea at a mean speed 2–3 times greater than that indicated for summer conditions (Fig. 2.4). Oil released under typical winter conditions from points northwest of about 56°30′ N. and 163°30′ W. (Fig. 2.4b) would move out into the Bering Sea without approaching shore.

The trajectories pictured indicate a general tendency; the outermost trajectories in each case do not indicate the limits of areal risk due to the asymptotic nature of the probability distribution. They do reflect, based on 19 years' data, certain predominant movements of storms through the region for each particular time period. Areas covered by the low probability of risk may still be hit by a particular combination of storm track, intensity of wind, and time of spill.

Winter trajectory calculations include the effect of ice which is present in the areas during some years (*see* section 2.1.6). Ice in the Bering Sea moves under the influence of winds and currents in a manner very similar to the motion of water because the ice is generally loose enough that ice-ice interaction is weak. Therefore, there is no obvious evidence in the model trajectories in Figure 2.4 of processes or motions different from those of the water column alone.

2.3 PARTITIONING OF THE OIL

Once oil is released into the marine environment, it is accessible to many physical, chemical, and biological processes that change the quantity and composition of a surface slick. The fate of oil released into the marine environment can be described by considering the distribution of the oil into four compartments: the atmosphere, the sea surface, the water column, and the benthic sediments (Fig. 2.5). The distribution of the oil between these compartments occurs by spreading, evaporation, dissolution, dispersion, and sinking. Distribution is essentially complete within 10 days of the time of the spill.

For the purpose of this workshop, Prudhoe Bay crude oil was used as the spilled oil. This decision was based on the intermediate chemical composition of the oil and the probability of Prudhoe Bay crude being released into subarctic marine waters during transportation. The aliphatic fraction of Prudhoe Bay crude is an evenly repeating series of n-alkanes and branched and cyclic hydrocarbons; the aromatic fraction is not skewed to either high or low molecular weight compounds; the polar fraction is limited. Idiosyncratic characteristics of Prudhoe Bay crude include a relatively high asphaltic fraction (36.3%), intermediate levels of organometallics, and a comparatively low API gravity (27.0). Differences in composition among crude and refined petroleum products are reflected in both weathering and toxicity.

2.3.1 Physical and Chemical Processes Affecting Spilled Oil

Spreading

Oil spilled on a perfectly smooth, quiet surface will spread, under the combined driving forces of gravity and surface tension, counterbalanced by the retarding forces of inertia and viscosity. As the viscosities of oil and water are temperature dependent, and the interfacial tensions at air-oil-water interfaces are influenced by the physical and chemical properties of the oil, the spreading process is thermodynamically favored. The net effect is that oil spreads out rapidly into a thin film or sheen followed by formation of thicker lenses of oil which spread more slowly into the sheen. This was first documented reliably during experimental spills by Jeffrey (1973), who showed that 80 to 90% of the total area of the oil spill consisted of a thin slick or sheen and about 10% was thick slick.

Most of the oil mass, however, resides in the thick slick. The thicker lenses are not spread by surface tension because there is no air-water interface accessible to them, the interface being entirely covered by the sheen of oil. Rather, the thicker oil spreads as a result of hydrostatic or gravitational forces which tend to cause the

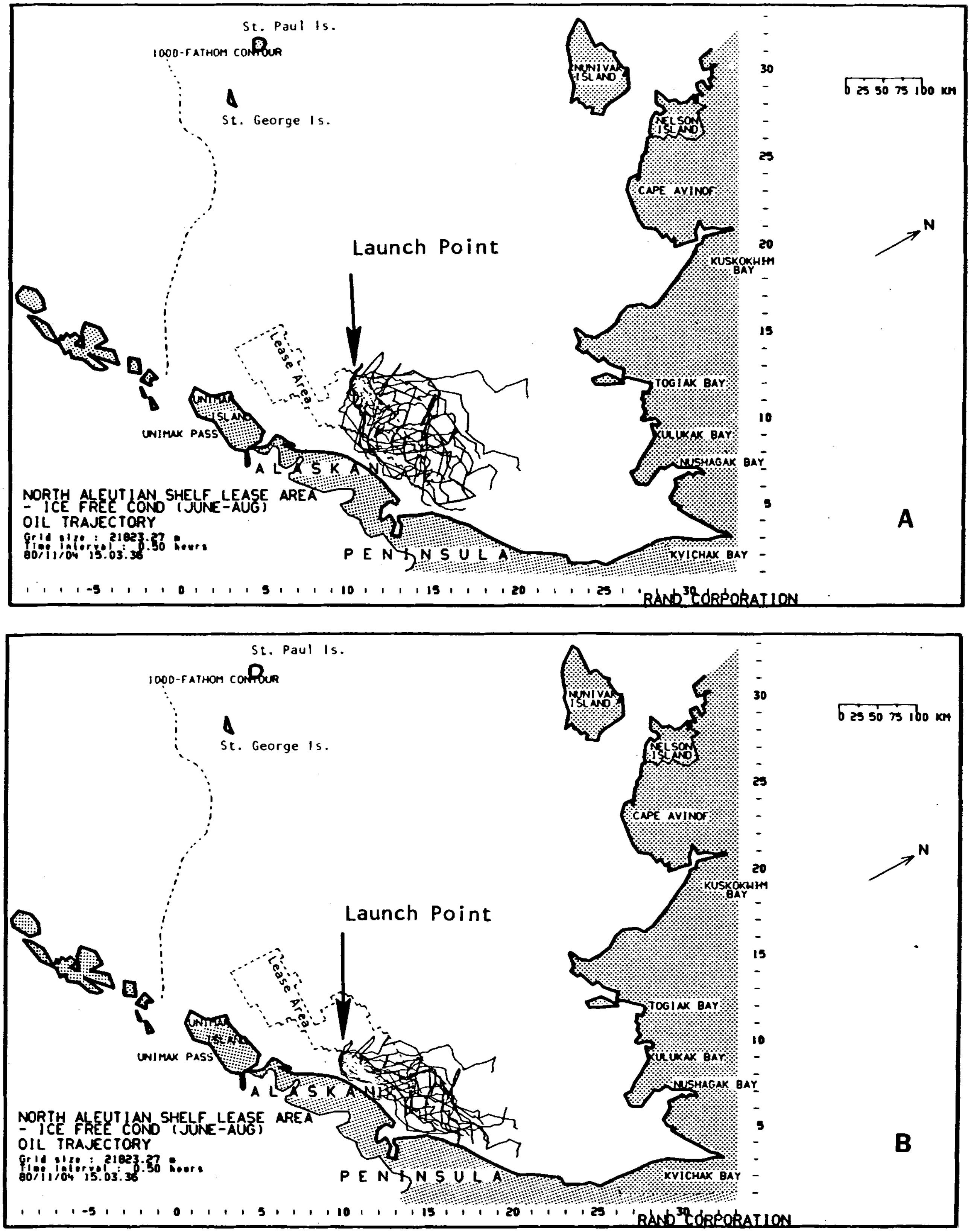


FIGURE 2.3—Calculated 30-day trajectories for spilled oil under stochastic summer weather conditions. *A* and *B* differ only in the selection of the launch points. The weather patterns used in the development of the trajectories were the same in both cases (Liu and Leendertse 1982).

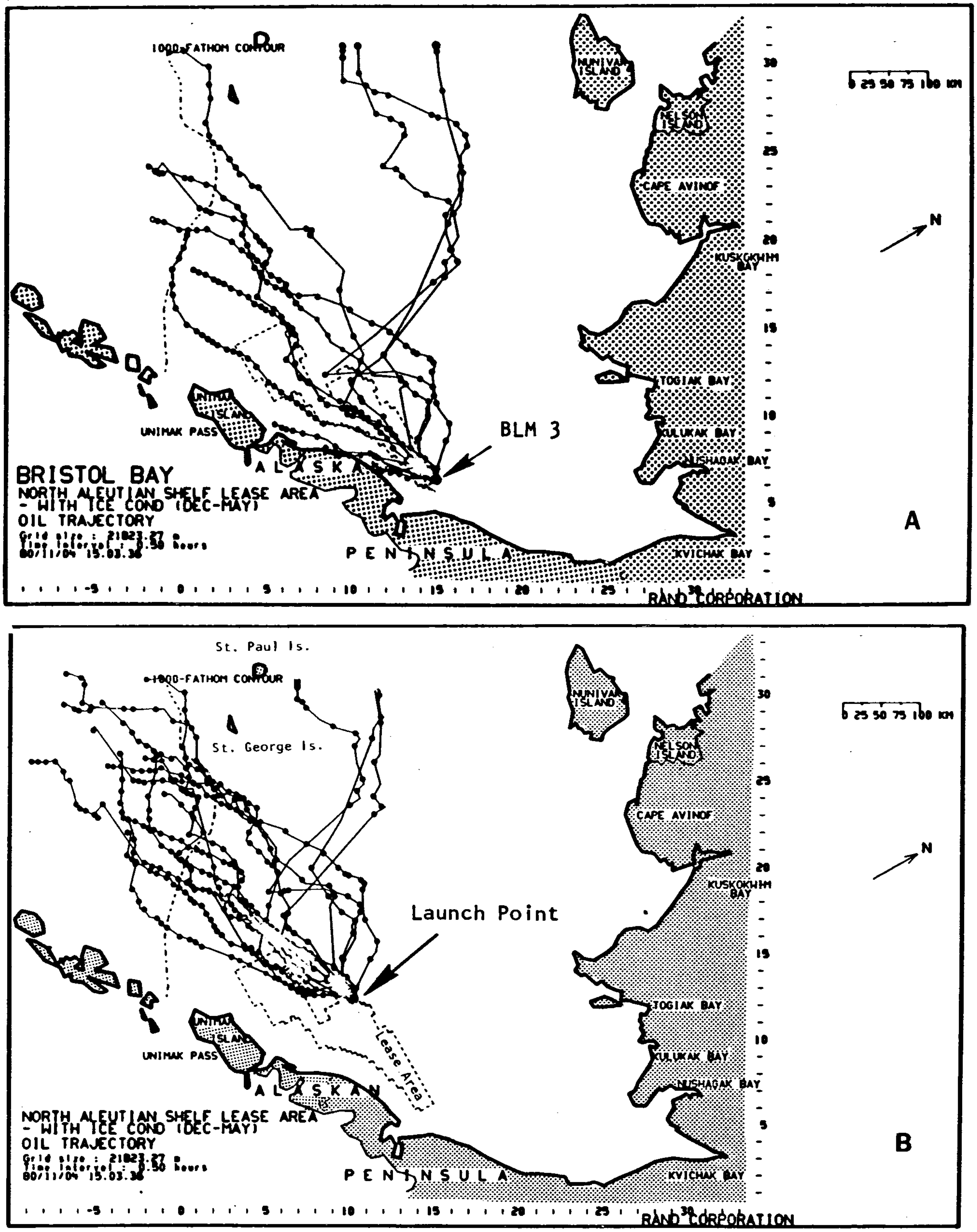


FIGURE 2.4—Calculated 30-day trajectories for spilled oil under stochastic winter weather conditions. *A* and *B* differ only in the selection of the launch points. The weather patterns used in the development of the trajectories were the same in both cases (Liu and Leendertse 1982).

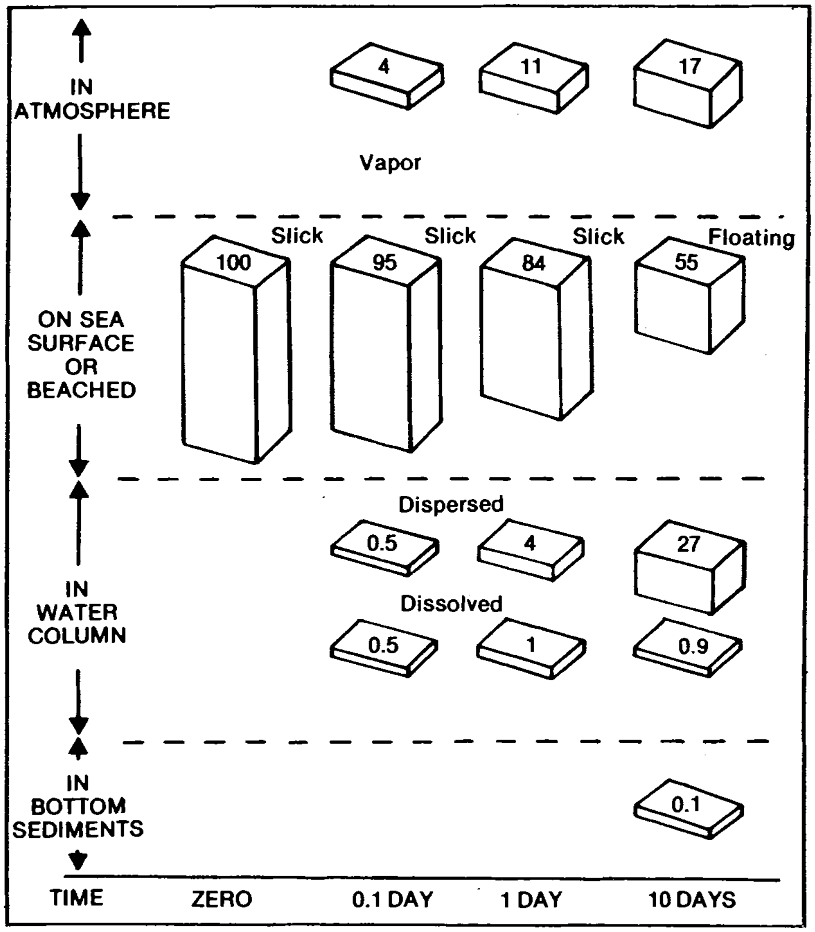


FIGURE 2.5—Speculative mass balance for Prudhoe Bay crude oil. Distribution of an initial 100 volumes of oil, assuming wind of 5 m/s and temperature of 0°C, at various times after the release. (Based on a similar diagram by J. N. Butler, Harvard University. Payne *et al.* 1983.)

thickness of the oil to become constant on the water surface. This gravity-driven process is much slower, particularly under high wave conditions when the hydrostatic gradient between thick and thin oil slicks is countered at times by the elevation difference of the oil on the waves. In this case, the amount of oil present in the thin area may be insufficient to form concentrations in the water that are of toxicological significance.

The mixing energy of the wind and waves will break the slick up into discontinuous patches. The areal extent of the patches is estimated to be an order of magnitude greater than the sums of the areas of the separate patches (Stolzenbach *et al.* 1977). Areas of some historical spills are illustrated in Figure 2.6. These spills can be compared with the areas calculated by Liu and Leendertse (1982) and Payne *et al.* (1984) for the spills considered in this workshop.

Spreading of the slick controls the extent of the area contaminated and influences a number of other processes; for example, evaporation, dissolution, and photo-oxidation, all of which are related to surface area.

Evaporation and Dissolution

Even as the oil spreads, evaporation takes place (Fig. 2.7). Evaporation removes benzene, toluene, and other low-molecular-weight volatile components, and may account for the loss of up to 60% of the mass of a spill of a light

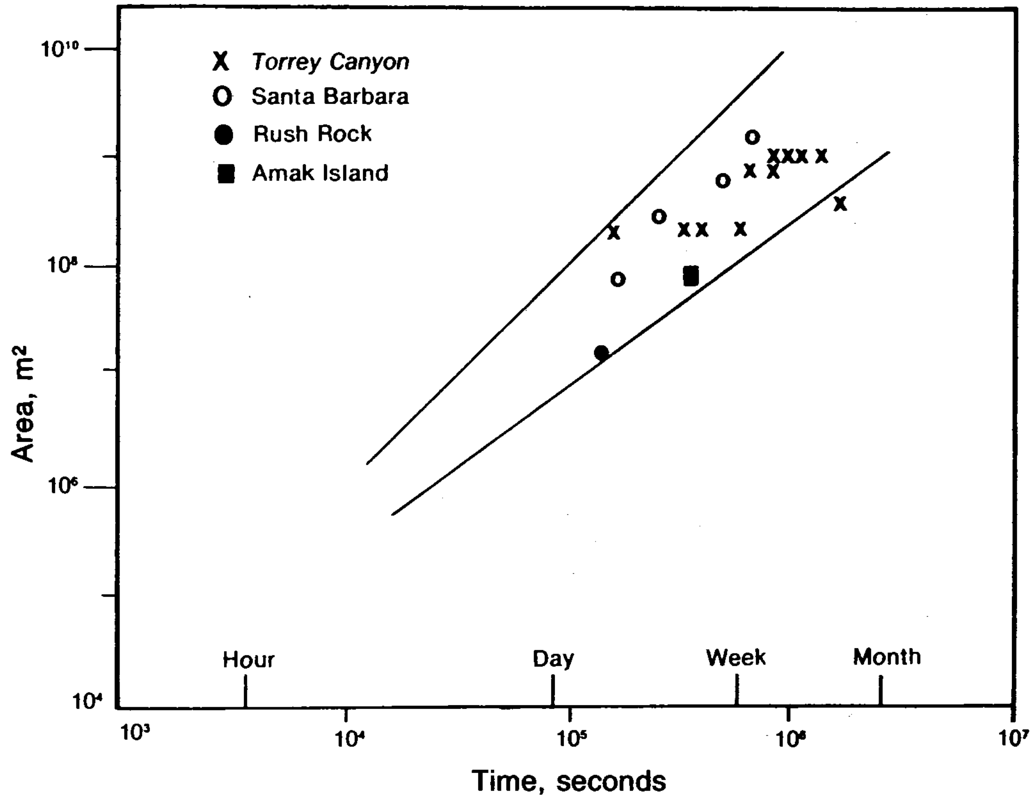


FIGURE 2.6—Comparison of theoretical (Rush Rock and Amak Island) and observed (*Torrey Canyon* and Santa Barbara) slick sizes. Straight lines define a general spreading model (Liu and Leendertse 1982). Values indicated for Amak Island and Rush Rock are from Payne *et al.* (1984). Area indicated for Rush Rock is at 41 hours, and for Amak Island is 5 days.

crude oil, such as Louisiana crude. However, these volatile components are estimated to account for only 17% of the mass of Prudhoe Bay crude (Fig. 2.5). Evaporation affects the spilled oil by altering its composition, increasing its density and viscosity, and decreasing the aqueous solubility and toxicity of the residual mass.

The evaporation rate per unit area depends on the oil vapor pressure, which is in turn a function of temperature and oil composition; and a kinetic or transport term which is best expressed as a mass transfer coefficient, dependent primarily on the level of atmospheric turbulence above the spill, as controlled by wind speed (Fig. 2.7). Evaporation rate also depends to a lesser extent on fetch, surface roughness, and the gas phase molecular diffusivity of the evaporating hydrocarbon. The preferential loss of volatiles causes an enhancement in concentration of the nonvolatiles and, therefore, increasing oil density, viscosity, and surface tension (Fig. 2.8). Lastly, the evaporation rate also depends on slick thickness; thick slicks undergo slower compositional changes because of the greater evaporative loss necessary to accomplish a given concentration change.

Dissolution competes with evaporation, which is concerned with the same volatile fractions and is controlled by the same physical and environmental factors. Dissolution, however, is not very rapid; evaporation will deplete the slick of most volatile components before they have a chance to dissolve. Those components that have dissolved may subsequently evaporate upon exposure to the atmosphere with the slick absent. The combined evaporation from the slick and from the water column results in the incorporation of relatively small lasting quan-

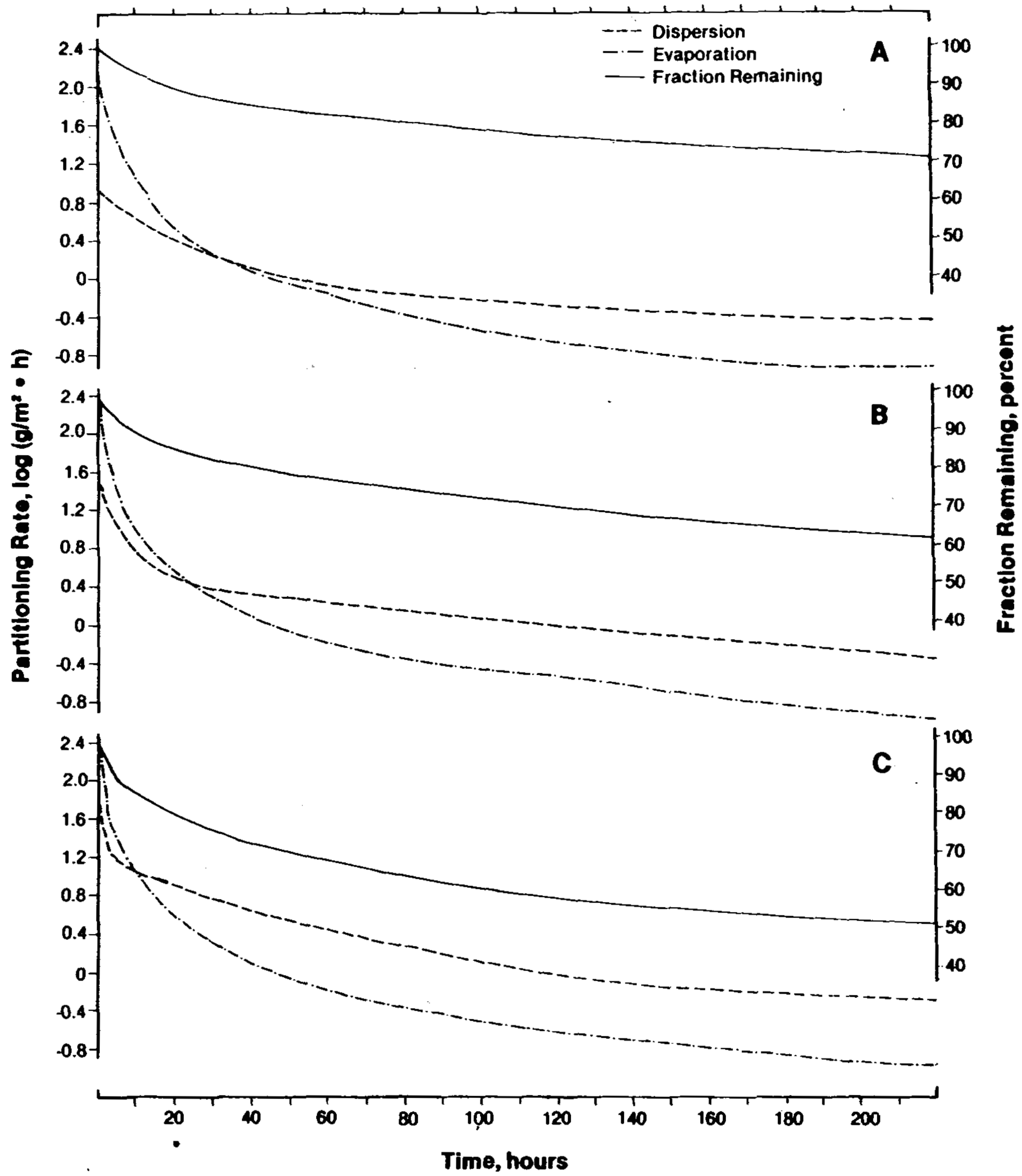


FIGURE 2.7—Effect of wind speed on the partitioning rates of Prudhoe Bay crude oil. Wind speeds depicted are *A*, 5 m/s; *B*, 10 m/s; and *C*, 20 m/s. Increasing wind speed changes both the evaporation and dispersion rates and thus has a profound effect on the rate at which material is removed from the slick (Payne *et al.* 1984).

tities of volatile hydrocarbons into the water column (McAuliffe 1977).

It should be emphasized that those petroleum hydrocarbons which are most toxic—the aromatics, especially benzene and toluene—are those which are most volatile. Therefore, the standing concentration of dissolved hydrocarbons in the water column is important in assessing the effect of spilled oil on the biota.

Dispersion

Water column turbulence provides the mixing energy for two competitive dispersion processes, the formation of water-in-oil and oil-in-water emulsions. In general, light oils tend to form oil-in-water emulsions and heavy oils tend to form water-in-oil emulsions.

Oil-in-water emulsions are formed as a slick breaks up into small droplets. Some of the drop-

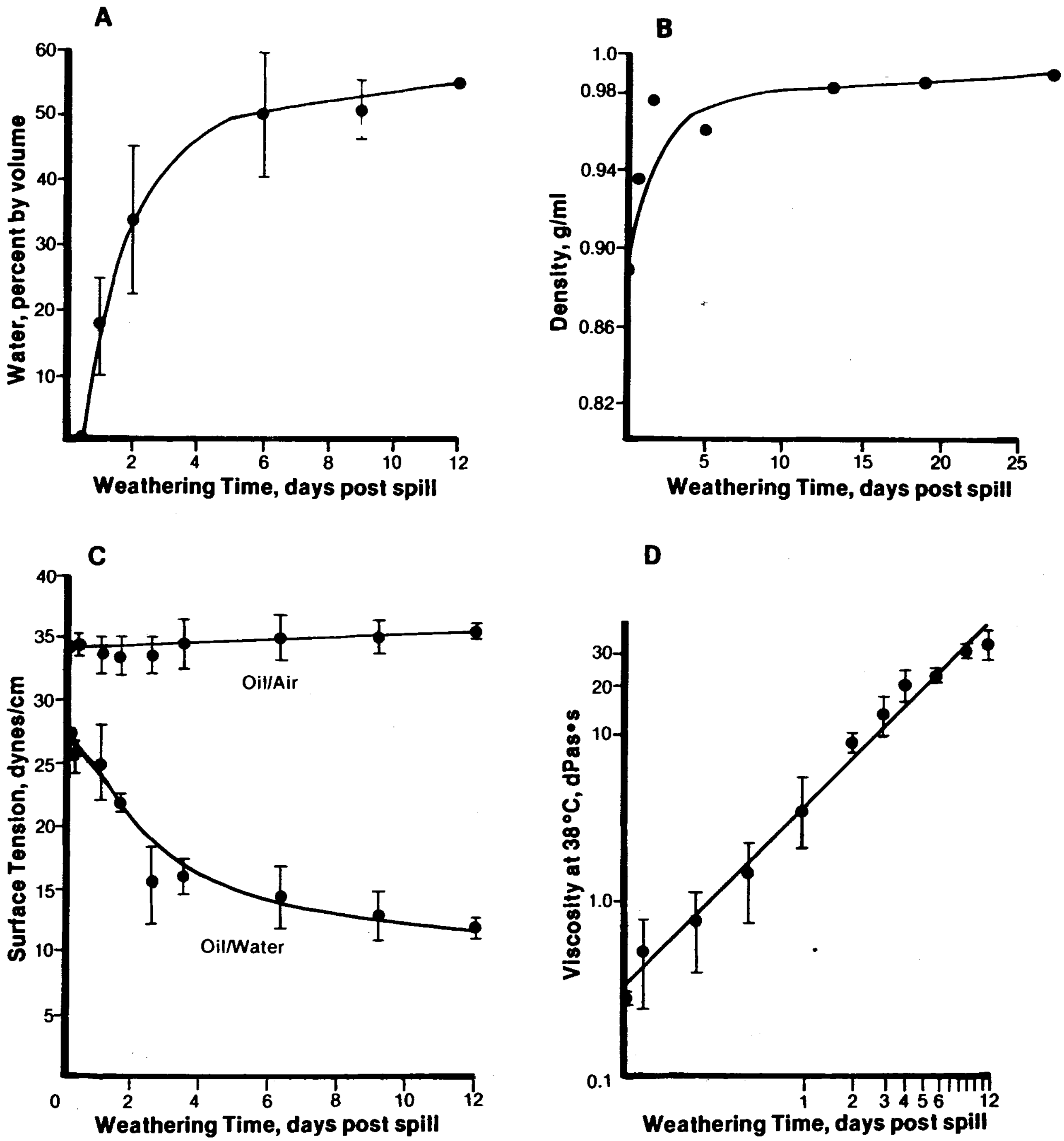


FIGURE 2.8—Physical changes in Prudhoe Bay crude oil as a function of time: *A*, percent water; *B*, density; *C*, surface and interfacial tensions; *D*, viscosity. Measurements were made on Prudhoe Bay crude oil spilled in outdoor, flowing seawater wave tanks at Kasitsna Bay, Alaska (Payne *et al.* 1983).

lets have a sufficiently small rising velocity that they are semipermanently incorporated into the water column where they later dissolve and are degraded. The larger droplets, with higher rising velocities, tend to resurface and recoalesce with the slick. The principal resistance to dispersion is the water-oil interfacial tension which is typically 20 to 30 dynes/cm (Fig. 2.8), enough to require a significant input of energy for the formation of a surface area of small droplets.

Dispersants reduce the oil-water interfacial tension and thus accelerate the dispersion process. Figure 2.7 shows the relation between wind speed and dispersion, with time. During the first hour, a wind speed of 5 m/s will cause the dispersion of fresh Prudhoe Bay crude oil at a rate of 8.5 g/(m^2 • h); a wind speed of 10 m/s will increase the dispersion rate to 29 g/(m^2 • h); and so on, with increasing wind speed.

The second type of emulsion, water in oil, is usually referred to as mousse. In this case, water droplets 5 to 20 μm in diameter are retained within the oil. The amount of water incorporated into the oil in this fashion may be four to five times the original volume of the oil. The ability of an oil to incorporate water depends on the composition of the oil. No mousse can be generated from distillants such as gasoline or kerosene. Light oils may form fluid or unstable emulsions. More viscous oils, such as Prudhoe Bay crude, will form stable emulsions. However, because evaporation is so efficient in removing the volatiles from spilled oil, thereby increasing the viscosity, almost any crude oil is capable of forming mousse. If the oil in question has a high asphaltic fraction and is released into a low-temperature environment, mousse formation will occur even in calm seas. For example, Prudhoe Bay crude oil spilled in a calm sea state at 6°C formed a stable mousse within 40-48 hours (Fig. 2.8).

Once mousse has formed, weathering processes decrease dramatically and, if the parent oil contained high concentrations of asphaltenes, waxes, organometallics, and other surfactants which act to keep the contained water droplets from coalescing, the mousse may be very stable and long lived. Mousse has been reported to be stable up to 2 years in the laboratory (Davis and Gibbs 1975).

The mechanical breakup of mousse may be one process that forms tar balls. Analyses of tar balls show that the more volatile compounds, up to nC-15 to C-17, have been lost. The fate of tar balls is believed to be their breakup and sinking as a result of adherence of sand or the settling of marine organisms.

Sinking

The ultimate repository of spilled oil is the benthic sediments. However, information on what percentage of spilled oil is deposited in the benthos, and by what means it gets there, is limited. Estimates of the amount of oil in the sediment after a spill range from 1 to 100%. Measurement is difficult due to the flocculant nature of the sedimented oil.

Because of their low density, oil droplets can be expected to behave in a fashion "hydraulically equivalent" to fine mineral grains, clay floccules, or organic particles. Fine sedimentary matter tends to accumulate at density discontinuities in the water column, such as the thermocline, as well as just above the sea floor. The suspended material tends to be transported in these horizontal layers, known as nepheloid layers, across the shelf and toward depositional sites on the continental slope or rise.

During their residence in the water column, suspended sediments (and presumably small oil droplets) are subject to ingestion by zooplankton and incorporation in fecal pellets. A great deal of controversy exists concerning the role of organisms in sedimenting oil. Given the patchiness of zooplankton populations, it can safely be assumed that this mechanism is of varying importance in the sedimentation of oil.

In the absence of vertical advection, an oil droplet will not sink until its density exceeds that of seawater at a given temperature and salinity. This can occur only through one of two processes: loss of lighter, more volatile components (weathering) (Fig. 2.8), or flocculation with heavier particulate matter until the aggregate density of the floccules exceeds seawater density. In either case the oil will sink at the same rate as other material of similar size and density dispersed in the water column. The accumulation rate of vertically settling material into sediment traps has been measured at 0.1 to 32 mg/(m^2 • d) on the North Aleutian Shelf (Baker 1983). "Typical" sedimentation rates are 5 to 10 mg/(m^2 • d). Flocculation with heavier particulate matter may be a major process removing oil from the water column in the lease area because of the high particle concentrations measured there. Concentrations in the shallowest areas sampled (about 25 m deep) are sometimes as high as 6 mg/liter, but typically are about 1 mg/liter. Particle concentrations at the seaward edge of the North Aleutian Shelf are generally 0.5-1 mg/liter (Baker 1983).

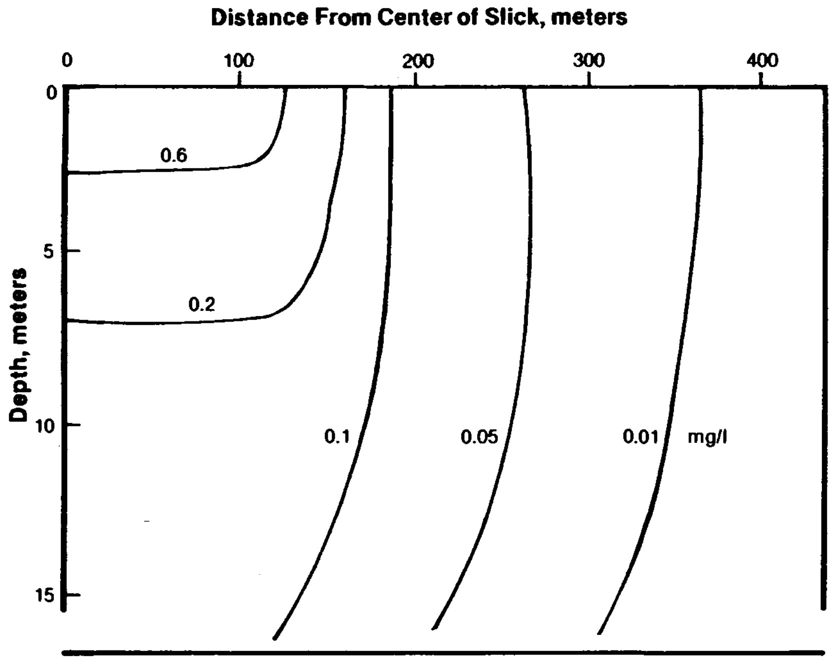


FIGURE 2.9—Theoretical concentration curves of dissolved and dispersed oil in the water column under and around a surface slick of Prudhoe Bay crude oil at 12 hours. The dilution curves are symmetrically distributed around a slick 200 m wide. This solution assumes a persistent wind of 5 m/s (Pelto *et al.* 1983).

These water column sediment loading estimates and sedimentation rates can be combined with possible oil loading capacities to estimate the amount of oil that might be accommodated and sedimented on the North Aleutian Shelf. The oil capacities measured for a variety of deposited sediments range from 117 to 1,200 mg/g of sediment (Payne *et al.* 1984). Oil loading capacities range from 2 to 180 mg/m² of water column, assuming all particles are loaded to the fullest extent found for each sediment type. "Typical" loadings possible are approximately 25–50 mg/m². Assuming flux to the benthos to be similar for both oiled and nonoiled suspended particulate material, the deposition rate for oil would be between 1.0 and 10 mg/(m² • d) in the shallowest areas (Baker 1983).

Once oil has reached the benthos, the length of time it may remain there in sufficient quantity to affect benthic organisms depends on the original concentration of oil deposited and the energy of the benthic environment. A field experiment conducted in a moderate-energy environment (Kachemak Bay, Alaska) indicated that while 100 ppm of Cook Inlet crude oil mixed into the benthic sediments was completely degraded after 1 year, 50,000 ppm was unchanged in quantity and composition (Griffiths and Morita 1980). The grounding of the *Amoco Cadiz* off the coast of France in March 1978 provided more field data. Intertidal sediments near the spill site contained in excess of 1,000 ppm shortly after the spill; this concentration had decreased to approximately 2 ppm by the following March (Calder and Boehm 1981). Due to the comparatively light benthic oil concentration calculated above and the comparatively high energy of the North Aleutian Shelf benthic environment as indicated by sand grain sizes greater than 32 μm, it is thought that the maximum residence time of the sedimented oil in this area will be 1 year.

2.3.2 Vertical and Horizontal Distribution of Dispersed Oil

Estimations of the vertical and horizontal distribution of oil (the areal extent of water contaminated with greater than 0.1 ppm of hydrocarbons, the lower limit of marine larval and adult acute toxicity), are a primary requirement for assessing the impact of spilled oil on the biota. Unfortunately these numbers are difficult to come by, as the vertical and horizontal distribution of oil depends on the composition of the oil spilled and the environmental conditions under which the spill occurs. That is, the vertical and horizontal distribution of spilled oil is site and incident specific in the extreme. Efforts to derive general information have focused on laboratory studies and spills of opportunity, such as *Amoco Cadiz* and Ixtoc I. Field experiments in the Canadian Arctic and the Gulf of Maine are providing more information and a reasonable link between the laboratory studies and spills of opportunity.

Theoretical Approach

Experimentally derived dispersion rates and partition coefficients for Prudhoe Bay crude oil into seawater (Payne *et al.* 1984) were used to model the concentration contours of total dissolved and dispersed hydrocarbons in the water column under and around a long, narrow slick (Pelto *et al.* 1983). If the only relevant transport processes are vertical and horizontal diffusion, as would be the case with a stable water column under a narrow slick in water of a depth which is small with respect to the length of the slick, water column concentrations can be modeled with a two-dimensional diffusion equation.

$$\frac{\partial C}{\partial t} = K_Z \frac{\partial^2 Z}{\partial Z^2} + K_Y \frac{\partial^2 Y}{\partial Y^2} \qquad [1]$$

Equation [1] was solved by using a finite difference scheme such as described by Wang and Anderson (1982). The difference equation solved was:

$$C_{ji}^{N+1} = C_{ji}^{N} + \Delta t \cdot K_Z (C_{j,i+1}^{N} + C_{j,i-1}^{N} - 2C_{j,i}^{N})/\Delta Z^2 + \Delta t \cdot K_Y (C_{j+1,i}^{N} + C_{j-1,i}^{N} - 2C_{j,i}^{N})/\Delta Y^2 \qquad [2]$$

The vertical and horizontal diffusion coefficients were chosen on the basis of area of interest and local conditions. Cline *et al.* (1982) calculated a vertical diffusivity of 185 cm²/s from salinity data collected near Port Moller. The water column in the area examined was well mixed. Alternatively, a value of 25 cm²/s has been calculated by Liu and Leendertse (1982) for typical partially stratified water such as in the lagoons of the Beaufort Sea coast. Computed values for horizontal diffusivities range from 5.5×10^3 in the New York Bight to 2.8×10^6 cm/s in the Bering Sea shelf (Okubo 1971, Coachman and Charnell 1979). Wilson *et al.* (1981), using drogues, measured horizontal diffusion in Harrison Bay (American Beaufort). They reported values of 780 to 8,400 cm²/s for diffusion in the transverse axis of the ellipses studied. In the solution illustrated herein, K_Y = 18,500 cm²/s and K_Z = 185 cm²/s in order to depict dilution curves in the shallow, partly stratified water of the North Aleutian Shelf (Fig. 2.9).

In this scenario, the spilled oil forms an elongated slick 200 m wide and of indefinite length. Concentrations of hydrocarbons high enough to cause death of organisms exposed for 96 hours would extend out to 400 m from the center of the slick and down to depths of more than 15 m. However, because of the assumptions made in this model, the resultant water column concentrations are at or near the theoretical maximum limits for the time indicated. In the real world, tides and variation in wind direction and persistence are enough to cause advection, which will significantly decrease the concentrations below the values predicted by the model.

This model was used to examine the concentrations of hydrocarbons in the water column below and around a slick of increasing size, such as that caused by a continuous spill. In this case, it was assumed that there was no horizontal shearing in the water column and that a persistent wind moved a slick originating at *X* past the point of observation (*Y*), which is a cross section through the water column 2 hours downstream of *X* (Fig. 2.10). The hydrocarbon concentrations in the water column at *X* 12 hours after the slick first reaches *Y* (14 hours after the spill starts) are similar to those in Figure 2.9. However, because advection and convection processes are ignored in this treatment and new oil is entering the water column

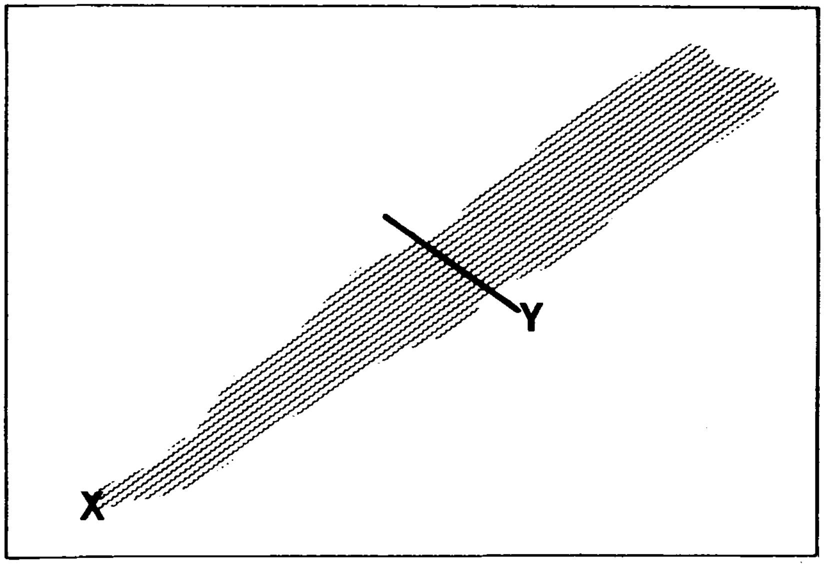


FIGURE 2.10—Surface slick formed by a continuous oil spill. Oil released at point *X* moves downwind past the point of observation (*Y*) under the influence of a persistent wind. There is no disruption of the slick path by tides or currents.

at a constant rate, hydrocarbon concentrations continue to increase for as long as the release lasts (Fig. 2.10).

Experimental Approach

A more realistic, and more difficult to model, scenario assumes a constantly regenerating water column, where all transport processes—advection, convection, dispersion, and diffusion—are considered. Mesocosm experiments are presently being conducted at Kasitsna Bay, Alaska under ambient weather conditions but most of the data are from spills of opportunity.

Payne *et al.* (1983) examined Prudhoe Bay crude oil spilled in flowing seawater (15 l/min) outdoor wave tanks at Kasitsna Bay, Alaska. Time-series data were taken for changes in oil density, percent water incorporated, oil-water interfacial surface tension, and oil viscosity (Fig. 2.8), as well as the total concentration of oil in the moving water column under the slick (Fig. 2.12). The lower and intermediate molecular weight aromatic hydrocarbons dissolved rapidly into the water column, reaching concentrations of approximately 480 ppb in 12 hours (Fig. 2.12). The concentration then decreased exponentially over the next 12 days. The decrease represents the net balance from the combined processes of dissolution from the slick or dispersed oil droplets, evaporation from the slick and through the air-sea interface, and water column turnover. Only the higher molecular weight (and less volatile) components, such as the alkyl-substituted naphthalenes and phenanthrenes, have a long lifetime in the water column. Also, with the slight turbulence, approximately equal to a wind of 2 m/s, present in these tanks, Prudhoe Bay oil formed a stable emulsion within 48 hours after the spill (Fig. 2.8).

The values derived from this experiment must be considered in terms of the environmental parameters of the experiment, including water currents, turbulence, and the composition of the experimental oil. For example, both higher and lower water column concentrations have been measured in real spill situations. Concentrations up to 10,000 ppb were measured within the plume near the Ixtoc I blowout (Fiest and Boehm 1980), compared to 950 ppb in the top 3–9 m beneath experimental surface spills in the New York Bight (McAuliffe *et al.* 1981); and 331 ppb at the outside edge of the Ixtoc I blowout plume (Fiest and Boehm 1980), compared to 2–300 ppb in the vicinity of the Ekofisk Bravo blowout in the North Sea (Grahl-Nielsen 1978; Mackie *et al.* 1978). The water column concentrations reported from the Ixtoc I blowout may be higher when compared to data from other spills because the subsurface release of the oil and associated gases resulted in a great deal of turbulence and a correspondingly high rate of dispersion.

The Baffin Island Oil Spill Project (BIOS) reported maximum hydrocarbon concentrations in the water column of 1,000–3,000 ppb from a surface spill of Lago Media crude under flat calm conditions. These concentrations were reached within 2 hours of the release of the oil and lasted through 24 hours. At no time was oil detected at depths greater than 3 m below the surface; most of the oil was confined to the top meter (Green *et al.* 1982). These concentrations are probably a direct consequence of the mild weather at the time of the spill and the restricted circulation of the bay in which the spill took place and most closely approach both the conditions and the results considered in the above "Theoretical Approach."

2.4 OIL SPILL SCENARIOS

The workshop was assigned three situations to consider: (1) an instantaneous 200,000-bbl spill at Rush Rock, south of the Alaska Peninsula near Cold Bay; (2) a continuous spill of 2,000 bbl/d for 5 days near Amak Island; and (3) a continuous spill of 2,000 bbl/d for 5 days at a point 50 km offshore of Cape Seniavin. All three scenarios take place in June so that summer weather conditions prevail. That is, the air temperature is approximately 6°C, water temperature is approximately 7°C, and winds are from the south at 5 m/s.

2.4.1 Rush Rock

An instantaneous spill of 200,000 bbl near Rush Rock would describe a meandering path under the combined influence of winds and currents. Winds over this area show no strong directional preferences and are extremely variable. Brower *et al.* (1977) calculated a 90% probability that a given wind will persist for less than 2 days. The currents near Rush Rock are not well known, although a weak net flow to the southwest has been postulated on the basis of measurements at Unimak Pass and Shelikof Strait (Schumacher 1982). The effect of the weak net current in an open area such as Rush Rock is thought to be secondary to the effect of the winds.

As a result of the spreading process described above, 200,000 bbl of Prudhoe Bay crude oil would cover an area of 16.8 km^2 after 41 hours in the presence of a 5 m/s wind. If, in turn, this breaks into patches, the maximum area covered by the slick could be 168 km^2. Potentially lethal concentrations of hydrocarbons, greater than 0.01 ppm, would cover an area of 407 km^2 (the theoretical maximum limit).

For the purposes of this workshop, steady winds of mean speed persisting long enough to result in landfalls were postulated. By assuming minimum times to landfalls, impacts would be maximized. The closest landfall to Rush Rock is Sandy Cove (15 km) (Fig. 2.13). Oil spilled at Rush Rock could reach Sandy Cove in approximately 25 hours, assuming that the wind was from the southeast and that it persisted for 25 hours or more. The combined probability of direction and persistence is 1.21% (Table 2.1).

TABLE 2.1—Estimated travel time of oil released at Rush Rock under probable June weather conditions. A persistent wind of 5 m/s is assumed in the time calculations.

Landfall	Distance (km)	Time (h)	Wind	Probability of Wind— Direction	Persistence	Final Probability
Sandy Cove	15	25	SE	11%	≤11%	1.21%
Thin Point	18	28	S	12%	≤8.5%	1.02%
Deer Island	17	30	SW	12%	≤8%	0.96%
Kenmore Head	24	41	E	13%	≤5%	0.65%

SOURCE: Liu and Leendertse 1982.

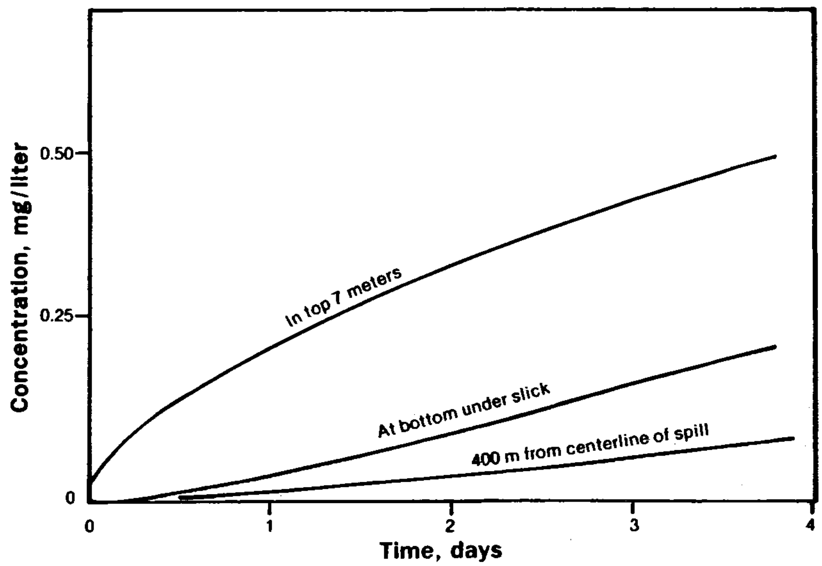


FIGURE 2.11—Increasing hydrocarbon concentrations under oil slick at point *Y* (*see* Fig. 2.10), assuming that the spill persists, the wind is steady, and there are no tides or currents. These concentrations are at or near the theoretical maxima for times indicated (Pelto *et al.* 1983).

Other possible landfalls are Thin Point, 1.02%; Deer Island, 0.96%; and Kenmore Head, 0.65%. In all cases, landfalls would occur within 25-41 hours of the spill, given the above assumptions.

The amount of oil available for stranding, approximately 160,000 bbl, could smear hundreds of miles of coast. The remainder will have evaporated (11%) and small fractions will have been dissolved (1%) and dispersed (4%) in the water column (Fig. 2.5). The precise amounts and locations of the stranded oil are impossible to predict at this time. In any case, the stranded oil could continue to shed significant concentrations of hydrocarbons into the water column for several years, depending on the ambient energy of the stranding area (Boehm *et al.* 1982; Owens *et al.* 1982).

2.4.2 Amak Island

Under the usual summer wind conditions, a wind of 5.0 m/s from 234°, oil spilled near Amak Island would describe a meandering path toward the east at 4.5 cm/s (Fig. 2.14). The computed speed includes the effect of the wind as well as the waves caused by the winds plus the retarding effect of tidal residual currents which are toward the west-southwest in the vicinity of Amak Island. The slick would be elliptical in shape and would cover 1.3 km² by the end of day 1, 3.08 km² by the end of day 2, and so on. By the end of day 5 the slick would cover an area of 10.5 km² if continuous, and 100 km² if broken into patches, which is more probable. Even though the total area oiled will continue to increase after this time, the loss of the most toxic compounds from the oil by 5 days and the breakup of the slick by dispersion will combine to decrease the area impacted.

The concentrations of hydrocarbons in the water column were calculated for a point 2.0 km downwind from the origin and assuming a wind speed of 5.0 m/s. The area covered by the slick between the origin and 2.0 km downstream would be 0.5 km². Potentially lethal concentrations, greater than 0.01 ppm, would extend out 400 m on either side of the slick, indicating that a minimum area of 0.8 km² would be severely impacted for the 5 days of the spill (Figs. 2.9 and 2.10).

If the wind blows steadily onshore, a 13% probability, the slick will reach shallow water between the 20-m contour and the surf zone at the entrance to Izembek Lagoon in 27 hours (Fig. 2.14). In the surf zone, both horizontal and vertical dispersion will be greatly increased as the result of the mixing energy of the surf zone.

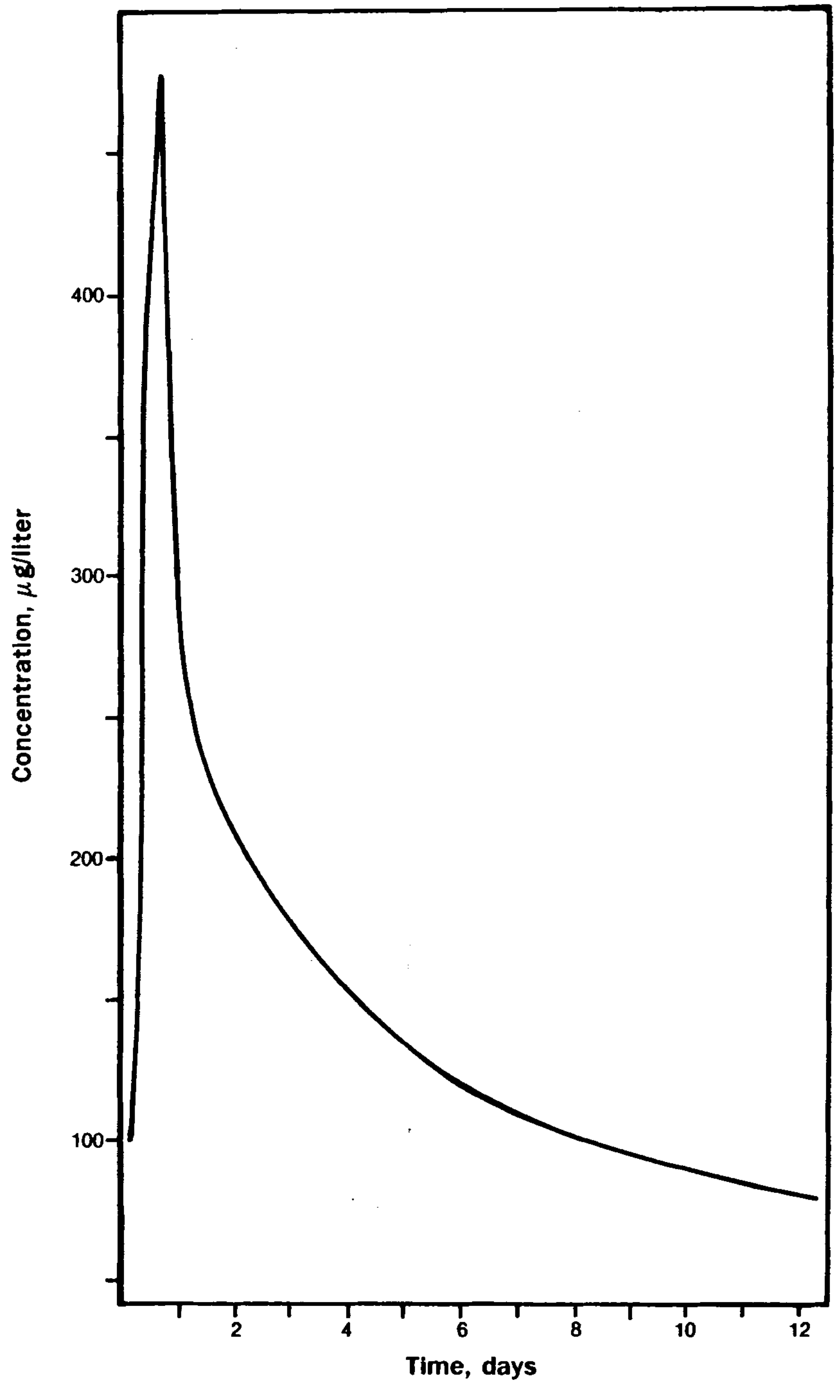


FIGURE 2.12—Observed concentrations of petroleum hydrocarbons in a moving water column under a slick of Prudhoe Bay crude oil. Oil was spilled in outdoor flowing seawater wave tanks at Kasitsna Bay, Alaska (Payne *et al.* 1983).

The floating oil will be mixed with the water column and subjected to onshore and alongshore transport to a greater or lesser extent depending on the energy and current regimes of this area, which are unknown. The workshop chose to assume that, given a wind which would blow the oil toward shore, approximately 20% of the oil that reaches the surf zone (5.1×10^4 liters/d for 5 days) would enter Izembek Lagoon. This amount of oil (26×10^4 liters total) would

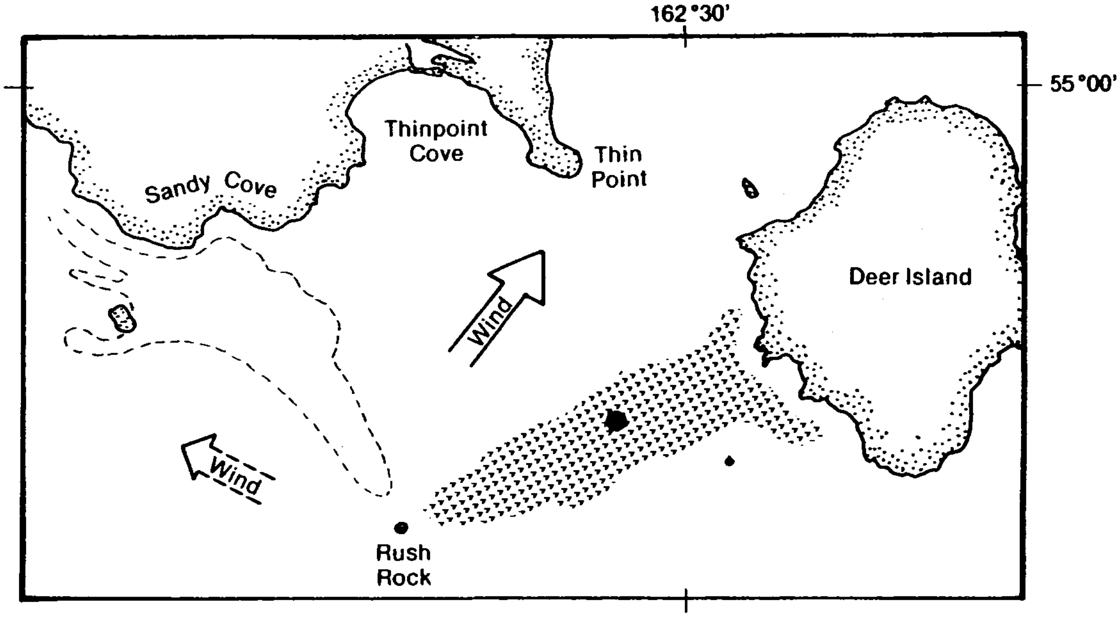


FIGURE 2.13—Probable landfalls of oil spilled at Rush Rock under June weather conditions. See Table 2.1 for conditions and probabilities. The direction of the spill path is directly dependent on the direction of the wind.

cover an area of 0.25 km² to a depth of 0.1 cm. A small but unquantified part would be blown ashore as a wind-blown spray.

2.4.3 Cape Seniavin

Conditions near Cape Seniavin are sufficiently similar to those near Amak Island that many of the same assumptions apply. Again, mean summer wind conditions will move the slick along the coast to the northeast in a meandering path. The calculated concentrations of hydrocarbons illustrated in Figures 2.9, 2.10, and 2.11 for Amak Island will apply to this case as well. The presence of a pycnocline at 20 m will not have any significant real effect on the distribution of oil from a surface spill.

At Cape Seniavin, an onshore wind would bring the oil slick to shore in something over 100 hours. By this time weathering will have reduced the floating oil to approximately 70% of its original volume and the floating oil would still have to pass through a surf zone to make a landfall.

2.5 SUMMARY

The movement of oil spilled on the North Aleutian Shelf would respond directly to and be controlled by ambient wind speed and direction. During the summer months (June to August) the prevailing winds are southerly at 5 m/s. Oil released in this season would move toward the northeast, into Bristol Bay at a speed of approximately 6 km/day. The probabilities are high that oil released from any site within the North Aleutian Shelf lease sale area in this season would make a landfall on the north side of the Alaska Peninsula within 30 days of release. In the winter, the prevailing winds are northerly and northeasterly at speeds of 10–15 m/s. Oil spilled at this time (December to May) would move toward the west-southwest, out into the Bering Sea, at speeds of 10–15 km/day. There are significant but low probabilities that oil released from sites within the North Aleutian Shelf lease sale area during this season would come ashore. Oil released during the winter from the most northwesterly sites in the area would probably not come ashore within 30 days.

If an oil similar in composition to Prudhoe Bay crude oil is spilled on the North Aleutian Shelf under typical summer conditions, approximately 11% of the spilled oil would have evaporated and 5% would have entered the water column within 24 hours of the spill. By 10 days, when

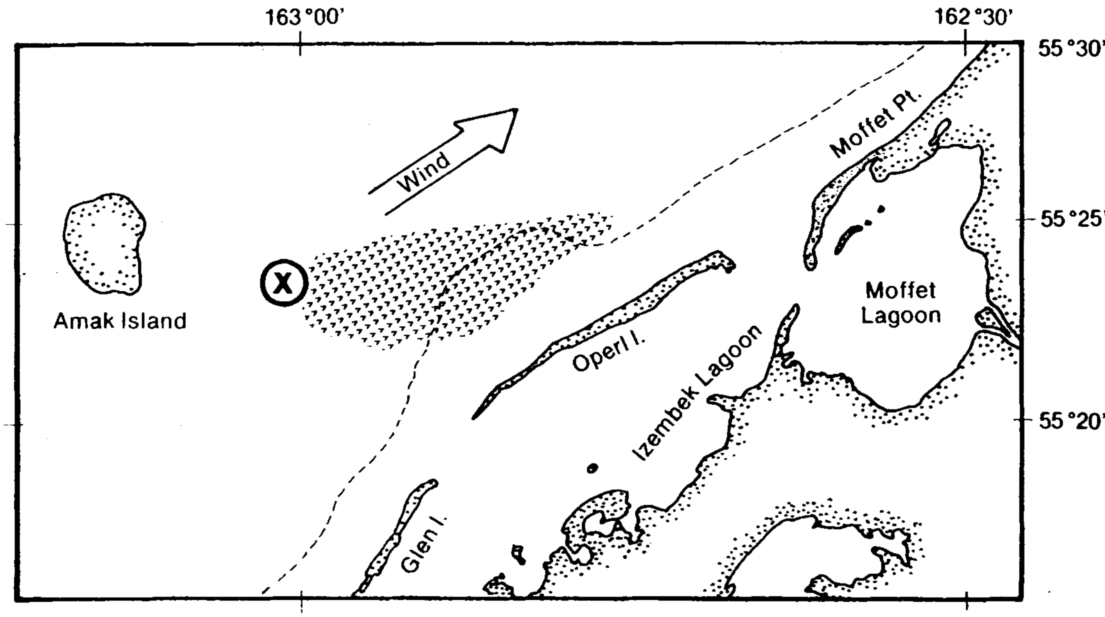


FIGURE 2.14—Probable path of oil spilled near Amak Island under June weather conditions. The wind is assumed to be persistent from the most probable direction.

partitioning is almost complete, 17% would have evaporated, 55% would remain in the slick, and 28% would be dispersed in the water column. At this point (10 days) almost all of the volatile components, including many of the toxic components, would have evaporated. In fact, most of the volatile compounds would be gone from the slick and from the water column within 4 days (100 hours). Alternatively and very possibly, the spilled oil would form a stable water-in-oil emulsion (mousse) within 48 hours, at which point any further partitioning would be dramatically decreased.

The concentrations of oil in the water column

TABLE 2.2—Summary of three deterministic oil spill scenarios. All three scenarios take place in June so that summer weather conditions prevail; that is, the air temperature is approximately 6°C, water temperature is approximately 7°C, and winds are southerly at 5 m/s.

Spill Location and Size	Slick Size	Concentration Under Slick	Area With Concentrations >0.01 ppm	Probability of Stranding*	Quantity Stranded
Rush Rock†					
3.2×10^6 liters	168 km^2	<550 ppb	407 km^2‡	<1.21%	2.6×10^6 liters within 25 h
Amak Island					
3.2×10^5 liters/day for 5 days	100 km^2	650 ppb from source to 2.0 km	min. 0.8 km^2 for 5 days	<13% within 27 h	2.6×10^5 liters for 5 days
Cape Seniavin					
3.2×10^5 liters/day for 5 days	100 km^2	650 ppb from source to 2.0 km	min. 0.8 km^2 for 5 days	<1% within 100 h	1.1×10^6 liters for 5 days

* Probabilities were calculated for closest landfalls.

† Instantaneous spill.

‡ This concentration would probably not be present over 48 hours.

under and around a long, narrow slick were modeled with a two-dimensional diffusion equation. Using experimentally derived dispersion rates and partition coefficients, and vertical and horizontal diffusion coefficients calculated for the North Aleutian Shelf, concentrations of hydrocarbons greater than 0.01 ppm would extend approximately 100 m out from the edges of a slick 200 m wide and down to depths of 15 m at a time point 12 hours after the spill. If oil continues to be added to the slick and if the water column is stationary, it was further calculated that the maximum concentration from the source of the spill to a point 20 km downstream would not be greater than 650 ppb for the 5-day period of the spills considered. These concentrations are very conservative; in the real world advection caused by tides and variations in wind direction and persistence would significantly decrease these concentrations.

The characteristics of the oil spill scenarios considered by the workshop, a massive spill from near Rush Rock and somewhat smaller spills continuing for 5-day periods from near Amak Island and Cape Seniavin, are presented in Table 2.2. There is a possibility of oil entering Izembek Lagoon from a spill occurring near Amak Island. Because of uncertainties about the magnitude and directions of coastal processes at the entrance(s) of the lagoon, it is impossible at this time to make a realistic estimate of the amount of oil actually entering this sensitive ecological area.

2.6 REFERENCES CITED

BAKER, E. T.
1983. Suspended particulate matter distribution, transport, and physical characteristics in the North Aleutian Shelf and St. George Basin lease areas. Draft final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Natl. Ocean Serv., Off. Oceanogr. Mar. Serv., Ocean Assess. Div., Juneau, 134 p.

BOEHM, P. D., D. L. FIEST, AND P. HIRTZER.
1982. Chemistry: 2. Analytical biogeochemistry-1981 study results. (BIOS) Baffin Island Oil Spill Working Rep. 81-2, 354 p.

BROWER, W. A., JR., H. W. SEARBY, J. L. WISE, H. F. DIAZ, AND A. S. PRECHTEL.
1977. Climatic atlas of the Outer Continental Shelf waters and coastal regions of Alaska. Arctic Environmental Information and Data Center, Univ. Alaska, Anchorage, 443 p.

CALDER, J. A., AND P. D. BOEHM.
1981. The chemistry of *Amoco Cadiz* oil in the Aber Wrac'h. *In Amoco Cadiz*: fates and effects of the oil spill. Proceedings of the international symposium, Centre Océanologique de Bretagne, Brest (France), November 19-22, 1979, p. 149-158. Centre National pour l'Exploitation des Océans, Paris.

CLINE, J. D., K. KELLY-HANSEN, AND C. N. KATZ.
1982. The production and dispersion of dissolved methane in the southeastern Bering Sea. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 99 p.

COACHMAN, L. K., AND R. L. CHARNELL.
1979. On lateral water mass interaction—a case study, Bristol Bay, Alaska. J. Phys. Oceanogr. 9: 278-297.

DAVIS, S. J., AND C. F. GIBBS.
1975. The effect of weathering on a crude oil residue exposed at sea. Water Res. 9: 275-285.

FIEST, D. L., AND P. D. BOEHM.
1980. Subsurface distributions of petroleum from an offshore well blowout: the IXTOC-I blowout, Bay of Campeche. *In* Proceedings of the symposium on preliminary results from the September 1979 RESEARCHER/PIERCE IXTOC-I cruise, Key Biscayne, Florida, June 9-10, 1980, p. 169-189. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Boulder.

GRAHL-NIELSEN, O.
1978. The Ekofisk Bravo blowout: petroleum hydrocarbons in the sea. *In* C. C. Bates (ed.), The proceedings of the conference on assessment of ecological impacts of oil spills, 14-17 June 1978, Keystone, Colorado, p. 476-487. Am. Inst. Biol. Sci., Washington, D.C.

GREEN, D. R., B. HUMPHREY, AND B. FOWLER.
1982. Chemistry: 1. Field sampling and measurements-1981 study results. (BIOS) Baffin Island Oil Spill Project Working Rep. 81-1, 111 p.

GRIFFITHS, R. P., AND R. Y. MORITA.
1980. Study of microbial activity and crude oil-microbial interactions in the waters and sediments of Cook Inlet and the Beaufort Sea. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 361 p.

JEFFREY, L. M.
1973. Large scale experiments on the spreading of oil at sea and its disappearance by natural factors. *In* Proceedings of joint conference on prevention and control of oil spills, p. 469-474. Am. Pet. Inst., Washington, D.C.

KINDER, T. H., AND J. D. SCHUMACHER.
1981. Circulation over the continental shelf of the southeastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. I, p. 53–75. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

LIU, S.-K., AND J. J. LEENDERTSE.
1979. A three-dimensional model for estuaries and coastal seas: Vol. VI, Bristol Bay simulations. Rand Corp., Santa Monica, Calif., R-2405-NOAA, 121 p.
1981a. Oil-spill analysis and simulation for the proposed oil-lease sale area in the St. George Basin, Alaska. Rand Corp., Santa Monica, Calif., WD-1026-NOAA, 75 p.
1981b. A 3-D oil spill model with and without ice cover. Rand Corp., Santa Monica, Calif., P-6620, 23 p.
1982. Personal communication to M. J. Pelto.

MACKIE, P. R., R. HARDY, AND K. J. WHITTLE.
1978. Preliminary assessment of the presence of oil in the ecosystem at Ekofisk after the blowout, April 22–30, 1977. J. Fish. Res. Board Can. 35: 544–551.

MCAULIFFE, C. D.
1977. Evaporation and solution of C_2 to C_{10} hydrocarbons from crude oils on the sea surface. *In* D. A. Wolfe (ed.), Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms, p. 363–372. Pergamon Press, New York.

MCAULIFFE, C. D., G. P. CANEVARI, T. D. SEARL, J. C. JOHNSON, AND S. H. GREENE.
1981. The dispersion and weathering of chemically treated crude oils on the sea surface. *In* Petroleum and the marine environment, Petromar 80, p. 573-590. Graham & Trotman, Ltd., London.

OKUBO, A.
1971. Oceanic diffusion diagrams. Deep-Sea Res. 18: 789–802.

OVERLAND, J. E.
1981. Marine climatology of the Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. I, p. 15–22. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

OVERLAND, J. E., AND C. H. PEASE.
1982. Cyclone climatology of the Bering Sea and its relation to sea ice extent. Monthly Weather Rev. 110(1): 5–13.

OWENS, E. H., J. R. HARPER, C. R. FOGET.
1982. Shoreline countermeasures-1981 study results. (BIOS) Baffin Island Oil Spill Working Rep. 81-4, 123 p.

PAYNE, J. R., B. E. KIRSTEIN, G. D. MCNABB, JR., J. L. LAMBACH, R. REDDING, R. E. JORDAN, W. HOM, C. DE OLIVEIRA, G. S. SMITH, D. M. BAXTER, AND R. GAEGEL.
1984. Multivariate analysis of petroleum weathering in the marine environment-sub arctic. Volume I-Technical results. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep. 21 (entire volume; paginated by chapter).

PAYNE, J. R., B. E. KIRSTEIN, G. D. MCNABB, JR., J. L. LAMBACH, C. DE OLIVEIRA, R. E. JORDAN, AND W. HOM.
1983. Multivariate analysis of petroleum hydrocarbon weathering in the subarctic marine environment. *In* Proceedings of 1983 oil spill conference (prevention, behavior, control, cleanup), p. 423–434. Am. Pet. Inst., Washington, D.C. (API Pub. 4356).

PELTO, M. J., C. A. MANEN, AND B. E. KIRSTEIN.
1983. A two-dimensional numerical model for predicting the concentrations of oil under a slick. *In* Proceedings of sixth arctic marine oil spill program technical seminar, June 14–16, 1983, Edmonton, Alberta, p. 20–23. Environ. Prot. Serv., Edmonton.

SCHUMACHER, J. D.
1982. Transport processes in the North Aleutian Shelf. Draft final rep. prepared for OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 90 p. + append.

SCHUMACHER, J. D., AND T. H. KINDER.
1982. Dynamical characteristics of three low-frequency current regimes over the Bering Sea shelf. Unpubl. manuscr., 32 p. + figs. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., PMEL (Pac. Mar. Environ. Lab.), 7600 Sand Point Way N.E., Seattle, WA 98115.

STOLZENBACH, K. D., O. S. MADSEN, E. E. ADAMS, A. M. POLLACK, AND C. K. COOPER.
1977. A review and evaluation of basic techniques for predicting the behavior of surface oil slicks. M.I.T. Dep. Civ. Engineering Rep. 222.

STRINGER, W. J., AND R. D. HENZLER.
1981. The frequency and percent coverage of sea ice in the St. George Basin. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 14 p.

U.S. DEPARTMENT OF COMMERCE.
1979. Coastal pilot #9, Pacific and Arctic coasts. U.S. Dep. Commer., NOAA, Natl. Ocean Serv., Washington, D.C.
1980. Tidal current tables, Pacific coast of North America and Asia. U.S. Dep. Commer., NOAA,

Natl. Ocean Serv., Rockville, Md., 260 p.

WANG, H. F., AND M. P. ANDERSON.
1982. Introduction to groundwater modeling: finite difference and finite element methods. W. H. Freeman, San Francisco, 237 p.

WILSON, D. E., J. C. H. MUNGALL, S. PACE, P. CARPENTER, H. TEAS, T. GODDARD, R. WHITAKER, AND P. KINNEY.
1981. Numerical trajectory modeling and associated field measurements in the Beaufort Sea and Chukchi Sea nearshore areas. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1981, 5: 299-378.

3

Coastal Habitats and Species

David A. Armstrong, Lyman K. Thorsteinson, and Carol-Ann Manen

Workshop Chairman: D. A. Armstrong. Participants: K. J. Frost, G. Getter, P. J. Gould, S. C. Jewett, A. Johnson, R. D. Jones, Jr., K. Pitcher, C. A. Manen, C. P. McRoy, J. Michel, G. Oliver, and S. T. Zimmerman.

3.1 INTRODUCTION

The proposed North Aleutian Shelf lease area and nearby waters encompass a great diversity of habitat types. These range from high-energy nearshore and open-water systems to shallow, eelgrass-dominated lagoons and coastal embayments. In many instances the brackish headwaters of these bays contain large meadows of mixed stands of salt marsh vegetation and are surrounded by sand dune upper-beach environment. Most are of low-level gradient and when tidally exposed provide a broad expanse of wetlands and mud flats. In aggregate, the North Aleutian Shelf lease area provides requisite habitat for numerous resident and migratory species of wildlife, many of them representing significant portions of North American or worldwide populations.

The planned action for the North Aleutian Shelf will surely result in environmental trade-offs, especially if commercial quantities of oil and gas are discovered. Any attempt to identify all possible sources of pollution would be spurious without detailed information about the size of OCS reserves and industry development scenarios, including coastal sites targeted for shore-based growth. During exploration and post-discovery periods the greatest threat of pollution is from large oil spills. Less catastrophic, but as yet of unknown long-term consequences, would be regulated discharges from drill ships, platforms, or support facilities. Although it is not currently practical to discuss all potential pollution sources, it is possible to describe the broad-scale ecology of the North Aleutian Shelf and the dominant physical and biological features that may be affected by offshore oil and gas activities, specifically the extraction, transportation, and storage of crude oil.

3.1.1 Coastal Vulnerability

Beach morphology provides a framework by which biological habitat and physical transport processes can be tied (Hayes and Gundlach 1979). A general knowledge of the geomorphology and major features of coastal transport is also necessary in planning contingency measures to limit damage during an oil spill. An Oil Spill Vulnerability Index (OSVI) has been developed on the basis of knowledge gained in studies of the effects of several oil spills, literature review, and as part of a systematic sampling program to rapidly classify large sections of Alaskan coastline according to their relative vulnerability to spilled oil (Hayes and Gundlach 1979). The method relates oil persistence to shoreline features and coastal processes (Table 3.1). Because floating oil striking a shoreline behaves differently on different beaches, the OSVI combines geological information on beach erosion-deposition cycles and sediment characteristics including type, size, and composition, with physical information on waves, alongshore transport, wind, general weather conditions, and effects of ice where applicable. This classification scheme has been modified as it pertains to Bering Sea coastline to include information on biotic communities and major land use patterns. Although this improves the mapping technique, beach ratings are still determined according to the OSVI classification scheme. A new index called the Environmental Sensitivity Index (ESI) equivalent to the OSVI is used with the modified classification (Gundlach *et al.* 1981).

Some 10,055 km of Bristol Bay coastline from Cape Newenham to Cape Sarichef, along with the western shoreline of Unimak Island south to Scotch Cap, have been surveyed and map-

TABLE 3.1.—Classification of Alaska shorelines in order of increasing vulnerability to oil spill damage.

Vulnerability Index	Shoreline Type	Natural Cleanup Efficiency and Recommended Oil Spill Countermeasure
(Lowest)		
1	Exposed rocky headlands.	Wave reflection keeps most oil off shore. Cleanup not necessary.
2	Eroding wave-cut platforms.	Wave swept. Most oil removed by natural processes within weeks.
3	Fine- to medium-grained sand beaches.	Oil does not penetrate into the sediment, facilitating mechanical removal. Otherwise, oil may persist several months.
4	Coarse-grained sand beaches.	Oil may sink and/or be buried, making cleanup difficult. Under moderate- to high-energy conditions, natural processes may remove oil from most of the beach face within months.
5	Exposed tidal flats (low biomass).	Most oil does not adhere to or penetrate the compacted tidal flat. Cleanup usually unnecessary.
6	Mixed sand and gravel beaches.	Oil may undergo rapid penetration and burial. Under moderate- to low-energy conditions, oil may persist for years.
7	Gravel beaches.	Same as 6. Cleanup should concentrate on the high-tide swash area. A solid asphalt pavement may form under heavy oil accumulations.
7a	Exposed tidal flats (moderate biomass).	Same as 7. Cleanup not necessary where oil accumulation is low. Removal of sediment should be avoided. Use of heavy machinery would tend to mix oil into sediments.
8	Sheltered rocky shores.	Areas of low wave action. Oil may persist for many years. Cleanup not recommended unless oil concentration very heavy.
8a	Eroding peat scarps.	Oiled organic material should be removed rapidly to prevent spread of oil to bottom sediments or into marsh areas behind the delta front.
9	Sheltered tidal flats.	Areas of low wave action. Oil may persist for years. Cleanup not recommended unless oil accumulation very heavy. First priority should be protection, using booms or oil sorbents.
10	Marshes.	Oil may persist for years. Cleanup by burning or cutting recommended only if area heavily oiled. First priority should be protection, using booms or oil sorbents.
(Highest)		

SOURCE: Hayes and Gundlach 1979.

ped according to their relative vulnerability to spilled oil (Michel *et al.* 1982). Significantly large proportions of this shoreline were classified as marshes (26%) and sheltered flats (12%). Relatively little of the coastline was categorized as rocky headlands (1.6%) and coarse sand beaches (8%), which are primarily located off the Black Hills region. Only 3.4% of the coast was gravelly at Port Moller and near Amak Island. Thus, using the OSVI/ESI classification scheme, most of the North Aleutian Shelf coast has a great capacity to incorporate and retain oil and should be considered as high in environmental risks. In the ecological descriptions presented in this chapter, OSVI indices are given only where relevant to a particular habitat type.

3.1.2 North Aleutian Shelf Habitats

The North Aleutian Shelf encompasses a wide variety of habitats supporting a diverse array of marine life. The habitats considered for workshop purposes included the midshelf; exposed coastal waters; protected nearshore waters; and other habitats, including Amak Island, Unimak Pass, and pertinent regions on the south side of the Alaska Peninsula. These habitats provide important refuge to many resident and migratory species of fishes, birds, and marine mammals. Numerous accounts and reviews of the distribution and abundance of major species are available (Hood and Calder 1981; Hameedi 1982) and several have been prepared specifically to address planned OCS oil and gas development in this lease area (Higgens 1978; Gusey 1979; Alaska Department of Fish and Game 1980; U.S. Department of Commerce 1980a, 1980b; Science Applications, Inc. 1981). The importance of the area's wildlife resources may be gauged by their commercial worth, ecological roles, or scarcity and subsequent designation as endangered species.

A habitat is simply defined as that place where an organism lives. Each habitat can be characterized by its species, carrying capacities, levels of production, food webs, nutrient cycles, and physical inputs (Bahr *et al.* 1978). Plant associations serve as the best guide to habitats and the pattern of vegetation types should correlate with patterns in climate, soil, and fauna (Daubenmire 1968). The activities of a given animal are most significantly described in terms of the vegetation and substrate types it frequents or uses at different times of the day or season. The following presentation is not intended to be a comprehensive account of the North Aleutian Shelf ecosystem, but a description of regional habitats based on dominant biota and the physical factors affecting their occurrence.

3.2 MIDSHELF WATERS

The physical oceanography of the southwestern portion of Bristol Bay has been extensively studied and described (Kinder and Coachman 1978; Coachman and Charnell 1979; Schumacher *et al.* 1979; Kinder and Schumacher 1981). For all practical purposes the North Aleutian Shelf encompasses two well-defined and regularly identifiable water masses (20–30 km wide) at approximately the 50- and 100-m isobaths. Midshelf waters include the offshore region between the 50- and 100-m contours. This area has been described as the middle shelf domain (Iverson *et al.* 1979; Kinder and Schumacher 1981). The midshelf encompasses virtually the entire bounded portion of the proposed lease area. It is a strongly stratified, two-layered structure characterized by sluggish circulation and considerable settling of sediments and, presumably, suspended particulate matter.

3.2.1 Plankton

Community structure and production have been well studied in the southeastern Bering Sea. Water column processes have been investigated for 5 years by PROBES (Processes and Resources of the Bering Sea Shelf; Goering and McRoy 1981). An annual primary production rate of 400 g C/m² has been reported for midshelf waters (Goering and McRoy 1981). Of this, 65% is produced in April, May, and June (Niebauer *et al.* 1981). A value of 400 g C/m² is high compared to the average annual shelf productivity of 183 g C/m² in other oceans (Platt and Subba Rao 1975). Daily phytoplankton production rates as high as 5–10 g C/m² have been measured during bloom periods (Whitledge *et al.* 1980), which are also high when compared to the daily productions of 0.4–0.9 g C/m² for other oceans (Mann 1982).

Diatoms account for the majority of phytoplankton found in open water habitat of the

North Aleutian Shelf. Spring bloom-formers, especially *Thalassiosira* spp., are the most abundant plankton in early May. Successional species of *Rhizosolenia alata* and *Chaetoceros* spp. become midsummer dominants. Other common diatom and dinoflagellate species are listed by Selkgregg (1974).

The presence of an oceanographic front at 100 m separates middle and outer shelf (100–200 m) waters. This front and the apparent lack of a strong advective mechanism across the area are thought to confine large herbivorous zooplankton (*Metridia lucens, Calanus plumchrus, C. cristatus,* and *Eucalanus bungii bungii*) west of the 100-m isobath, thereby reducing the food web transfer of energy to the pelagic community of the midshelf (Cooney and Geist 1978; Iverson *et al.* 1979; Cooney 1981; Vidal and Smith 1982).

Dominant midshelf zooplankton are small copepods (*Acartia longiremis* and *Calanus marshallae*) that fail to graze much of the diatom production in these waters (Dagg *et al.* 1982). Cooney (1981) estimated that greater than 90% of primary production landward of the 100-m front is available to benthic communities. Others (Cooney and Coyle 1980; Dagg *et al.* 1982) estimate that between 10% and 30% of the daily production is consumed by midshelf copepods and euphausiids. The higher value is similar to consumption rates of zooplankton over the outer shelf, but, because primary production rates are higher in the midshelf, 2 to 3 times more material is lost to the benthos. In accordance with the higher midshelf consumption estimate are annual zooplankton growth rates of 7–10 g C/m² (Cooney 1981).

3.2.2 Benthos

PROBES has described the midshelf of the North Aleutian Shelf as having relatively high annual primary productivity but perhaps low consumption by herbivorous zooplankton. If so, then a large proportion of sinking organic material reaches the benthos to support diverse and abundant infaunal and epifaunal communities.

Although benthic species exhibit patchy distributions, it is often possible to predict their occurrence based on associated sediment particle size, sediment sorting ranges, and depth (Feder *et al.* 1981). Water mass characteristics (temperature and salinity) also affect community structure but are difficult to separate. However, they can be considered as fairly homogenous between frontal zones and across-the-midshelf benthic trends can be described (Haflinger 1981).

A large gradient in grain size, sorting, and sand and silt content is found in the vicinity of the 40- to 50-m frontal zone (Burrell *et al.* 1981). Such gradients stem from the turbulent nature of seawater at the front which results in deposition of coarser-grain sediment landward and finer sediment seaward. Midshelf sediment collections indicate that shelf sediments are mostly silty sands (Fig. 3.1). Mean grain size tends to decrease from 1 to 5 ϕ (0.5 to 0.0625 mm) with increasing depth (Earth Technology Corporation 1983). Poorest sorting occurs in shallow (< 50 m) and deep waters (> 100 m) (Fig. 3.2). Similar sediment characteristics were reported by Feder *et al.* (1981a) in conjunction with benthic grab sampling. Midshelf sediments can be collectively described as approximating 85% sand, 6–12% silt, and 3–7% clay. This corresponds to an average grain size of 2.67 ϕ and a sediment-size class falling between fine and very fine sand. Sediments from the midshelf region of the North Aleutian Shelf are moderately to poorly sorted.

Infaunal standing stock biomass estimates for the midshelf approximate 120 g/m² (Sonntag *et al.* 1980; Feder and Jewett 1981; Haflinger 1981) (Fig. 3.3). Unless indicated otherwise, all biomass estimates reported herein are based on determinations of wet weight. Dominant groups and species are described.

Bivalve molluscs are the dominant infaunal group of the midshelf region. Feder *et al.* (1981) report that 33 species were collected from the southeastern Bering Sea. Twelve were found in at least 18% of the stations sampled by grab: *Nucula tenuis* (77% occurrence), *Axinopsida serricata* (56%), *Thyasira flexuosa* (39%), *Nuculana fossa* (36%), *Yoldia scissurata* (28%), *Tellina lutea* (28%), *Cyclocardia crebricostata* (25%), *Y. amygdalea* (23%), *Macoma calcarea* (23%), *Clinocardium ciliatum* (21%), *Spisula polynyma* (20%), and *Serripes groenlandicus* (18%). Biomass estimates averaged approximately 8 g/m². Larger values (60–2,200 g/m²) were reported at similar depths in inner Bristol Bay and near Nunivak Island (Feder *et al.* 1981).

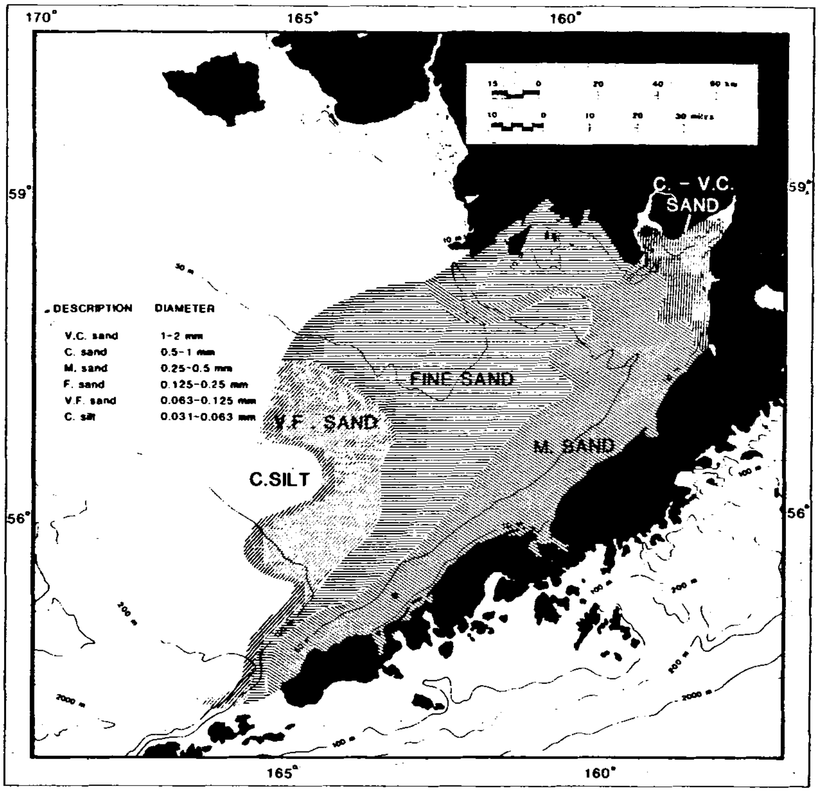


FIGURE 3.1—Sediment size across the North Aleutian Shelf (Science Applications, Inc. 1981).

Feder *et al.* (1981) focused their attention on eight species of bivalves based on their representation of major trophic types or their potential for commercial harvest. *Nucula tenuis, Nuculana fossa, Y. amygdalea, T. lutea,* and *M. calcarea* are the most abundant deposit-feeding clams. They are typically found in areas of weak circulation and moderate sedimentation (2.25–3.0 ϕ) and coarse silt (4.25–5.0 ϕ) between 25 and 100 m (Feder *et al.* 1981). Filter-feeding *Cyclocardia crebricostata, Clinocardium ciliatum,* and *Spisula polynyma* are also found in these sediment regimes. *Tellina lutea* and *S. polynyma* populations are in great abundance and have been considered for potential fisheries. Distribution of these species by substrate and depth characteristics in which they occur is presented in Table 3.2.

Other common infauna and sessile slow-moving epifauna found in midshelf waters were described by Feder *et al.* (1981). Extensive sampling resulted in collection of animals representing 11 phyla, 55 families, and 142 species. The 11 most common species were marine snails (*Solariella obscura, S. varicosa, Margarites olivaceus, Natica clausa, Polinices pallida*); the opisthobranch gastropod *Cylichna alba*; the sand dollar *Echinarachnius parma*; brittle stars (*Diamphiodia craterodmeta* and *Ophiura sarsi*); the sea cucumber *Cucumaria calcigera*; and the tunicate *Boltenia ovifera*. This group averages approximately 114 g/m^2 across the midshelf. Their distribution by sediment parameters and depth is given in Table 3.3.

Cluster analysis illustrates broad trends in infaunal cross-shelf zonation (Haflinger 1981). Haflinger's analysis identified four distinct faunal domains, including those organisms ubiquitously distributed in the southeastern Bering Sea (Group 1) and those dominating the midshelf region (Groups 6 and 7). The mobility of each organism and their trophic representation are also indicated (Table 3.4). The primary food source for the benthic communities must be derived from water column productivity, both in association with ice (in years when present) and open water. The presence of large numbers of deposit- and suspension-feeding detritivores, including clams, may reflect this detrital fallout. The abundance of these organ-

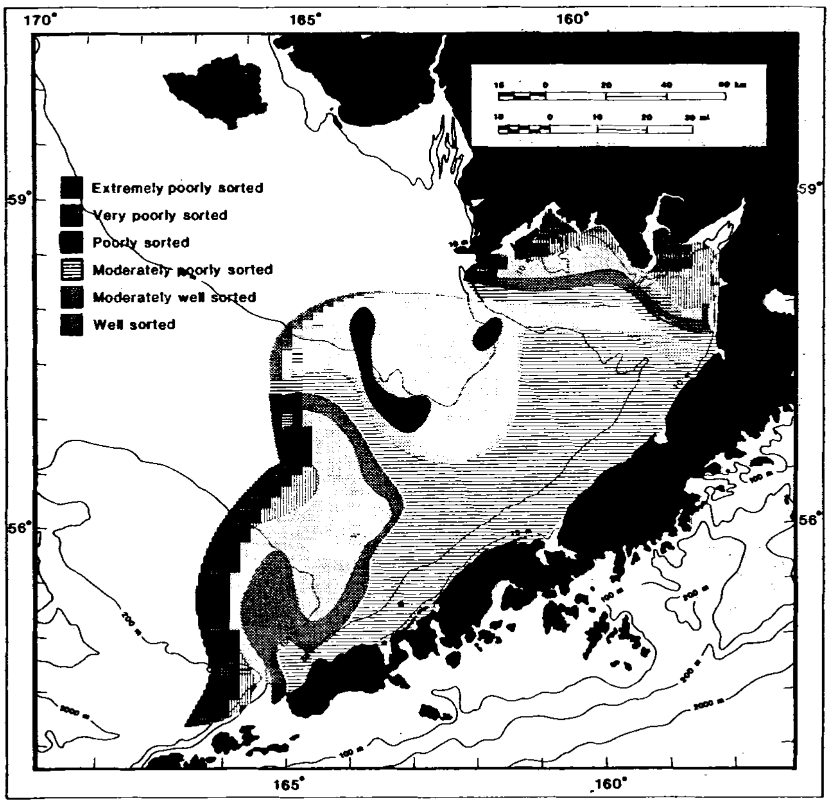


FIGURE 3.2—Sediment sorting across the North Aleutian Shelf (Science Applications, Inc. 1981).

isms is also responsible for the presence of the commercial quantities of crustaceans and demersal fish and marine mammals in the midshelf region. All must be feeding on polychaetes, bivalves, and other benthic foods occurring there (Pereyra et al. 1976; Feder 1978; Braham *et al.* 1982; Fay 1982).

Estimated biomasses of invertebrate epifaunal species across the midshelf indicate that red king crab (*Paralithodes camtschatica*), Tanner crabs (*Chionoecetes opilio, C. bairdi*), and the sea star *Asterias amurensis* are dominant forms in this part of the North Aleutian Shelf (Table 3.5). Red king crab biomass in this area is 40 times greater than in shallower waters. Tanner crabs are generally not found landward of the 50-m isobath, and although *C. opilio* abundance is high this reflects their distribution in the westernmost portion of the lease area. *Asterias amurensis* composed almost 13% of the total biomass for the midshelf compared to over 84% more coastally.

3.2.3 Demersal Fish and Crab Resources

The National Marine Fisheries Service (U.S. Department of Commerce 1980a) summarized patterns of abundance for the commercially important groundfish and crab resources of the North Aleutian Shelf. Groundfish species having a relatively high proportion of their total biomass between 50 and 100 m in survey data reviewed (1975, 1976, and 1979) were yellowfin sole (*Limanda aspera*), rock sole (*Lepidopsetta bilineata*), arrowtooth flounder (*Atheresthes stomias*), Pacific halibut (*Hippoglossus stenolepis*), sablefish (*Anoplopoma fimbria*), and Pacific cod (*Gadus macrocephalus*). These and other fisheries resources are discussed in Chapter 4, including descriptions of the biology of king and Tanner crabs occurring in the midshelf region.

Information on the distribution and abundance of king crab in Bristol Bay is more comprehensive than for any other decapod fished by U.S. fleets (Otto 1981). The centers of distribution for red king crab and Tanner crab *C. bairdi* are located in, or overlap with, the North Aleutian Shelf year round. The distribution of *C. opilio* also extends into the lease area but to a lesser degree than *P. camtschatica* and *C. bairdi*.

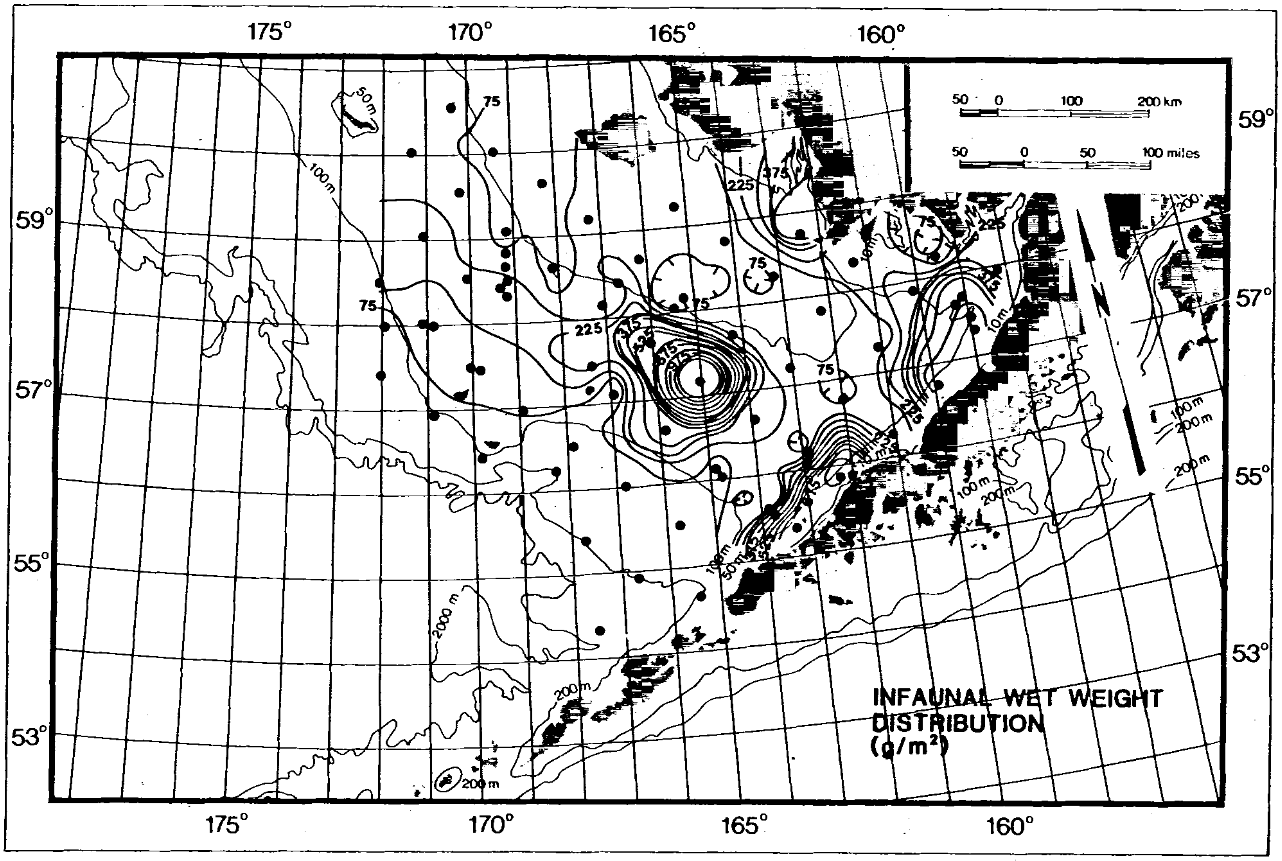


FIGURE 3.3—Wet weight (g/m²) of infaunal standing stock over the southeastern Bering Sea shelf (Haflinger 1981).

Female and small male king crab are found closer to shore and farther east of large males beyond the Port Moller region (Otto *et al.* 1980). (Males < 110 mm carapace length and females < 89 mm are classified as small.) Very small juvenile red king crab are rarely caught in midshelf waters. Catch data suggest juvenile crab up to 60 mm in carapace length (about 3 years old; Weber 1967) are absent from the midshelf and are likely near shore.

Red king crab molt, mate, and release larvae in midshelf waters. Females carry eggs for up to 11 months as embryos develop through naupliar stages to prezoeae (Marukawa 1933). Larvae are hatched and develop near shore from Unimak Island into upper Bristol Bay in depths from 40 m to about 70 m (Armstrong *et al.* 1981). Because adult distribution and the fishery occur over a much broader area of the midshelf, it is striking to realize how restricted larvae of the species are; they are virtually absent from the outer and most of the midshelf domains. Larvae are significantly reduced in abundance 20-30 km farther offshore from nearshore stations of high numbers, and the increase from western Unimak Island to Port Moller may be two orders of magnitude.

Eggs normally begin to hatch in early April (Sato 1958; International North Pacific Fisheries Commission 1960, 1963, 1965; Haynes 1974), although female king crab may vary in time of hatch between widely separated populations from Unimak Island to Port Moller. Interannual timing of the onset of hatch and seasonal occurrence of pelagic larvae can vary by as much as a month.

Larvae pass through four zoeal stages and molt every 2½ to 3 weeks (Marukawa 1933; Armstrong *et al.* 1981), spend about a month as glaucothöe, and then metamorphose to first instars about mid-July to August (Kurata 1960; Weber 1967). Horizontal transport of king crab larvae by currents is thought to move them appreciable distances from the origin of hatch, and implies that recruitment of juveniles to a given area might depend on larvae hatched elsewhere, including areas south of the Alaska Peninsula (Hebard 1959; Haynes 1974). Hebard (1959) calculated that larvae hatched at Amak Island could be transported over 96 km (60 mi) to the northeast and metamorphose at Port Moller (net current of 0.02 m/s moving northeasterly along the North Aleutian Shelf). Haynes (1974) adds credence to the possible transport of larvae from south of the peninsula by showing a northerly dispersion of king crab larvae off the southwest tip of Unimak Island, and a northeast shift in areas of larval abundance from the Black Hills into Bristol Bay (May–July 1969 and 1970).

While a general pattern to larval king crab distribution has been described, the extent to which the population continues from Port Moller northeast into Bristol Bay is unknown. Haynes (1974) indicated that most of a larval year-class would occur from Port Moller east by midsummer as metamorphosis approaches. If this is true, young-of-the-year (0+) crab may predominantly settle out to the east of the lease area. Neither studies by Haynes (1974) nor Armstrong *et al.* (1981) have comprehensively sampled larvae in time and space to confirm this. Furthermore, information is not available on where 0+ king crab metamorphose and settle on the bottom. Metamorphosis may occur along an extensive reach in shallow water between Amak Island and Port Moller, or perhaps farther northeast in upper Bristol Bay. During an OCSEAP survey in June and August 1982,

TABLE 3.2—Sediment parameters and locations of dominant midshelf bivalves on the North Aleutian Shelf.

Species	Sediment Size	Sediment Sorting	% Mud (Range)	Depth (m)	Distribution Relative to NAS
Nucula tenuis	Very fine sand to medium silt (91%)	Poorly sorted (75%)*	0–70	50–100 (92%)	Throughout
Nuculana fossa	Very fine sand to medium silt (84%)	Poorly sorted (96%)	0–60	75–150 (94%)	Northeastern portion, but patchy throughout
Yoldia amygdalea	Very fine sand to medium silt (89%)	Poorly sorted (89%)	0–50	75–100 (92%)	Central portion
Cyclocardia crebricostata	Fine to very fine sand (76%)	Moderately well sorted (58%)	0–20	25–75 (99%)	Northeastern portion, and inner Bristol Bay west of Amak Island
Clinocardium ciliatum	Very fine sand to coarse silt (98%)	Poorly sorted (100%)	0–70	50–75 (97%)	Everywhere except southwestern portion north of Unimak Island
Spisula polynyma†	Fine sand to to coarse silt (98%)	Moderately well to poorly sorted (59%)	0–50	50–100 (94%)	Three patches: Unimak Island, Amak Island–Black Hills, and Port Moller–Bristol Bay
Tellina lutea†	Fine sand (70%)	Well to poorly sorted (83%)	0–40	<25–50 (78%)	Northeast corner
Macoma calcarea	Medium silt (94%)	Poorly sorted (98%)	0–50	50–100 (97%)	Everywhere except north of Unimak Island

SOURCE: Feder *et al.* 1981, p. 473.

* Each percentage in parentheses refers to the major concentration of a species at the given parameter.

† *Spisula polynyma* and *Tellina lutea* are large clams that were not collected quantitatively for all sizes. Distributions for only the small, young individuals of the two species are represented for the three parameters.

few 0+ and 1+ crab were captured, and only in depths of 30–70 m, from Amak Island to Cape Seniavin.

Only *C. bairdi* (not *C. opilio*) has large populations distributed across the the North Aleutian Shelf. Sexually mature female and juvenile *C. bairdi* tend to occur in a sweeping arc that begins northwest of the Pribilof Islands along the 150- to 200-m isobath, extends down through the St. George Basin, and continues northeast off Unimak Island beyond Port Moller.

Larvae of *C. bairdi* are more ubiquitously dispersed than those of king crab. High larval abundance occurs over the midshelf near the 50-m isobath (Armstrong *et al.* 1981; Lewis Incze, unpubl. data). Tanner crab larvae hatch about mid-April and have two zoeal stages (Kon 1967, 1970; Haynes 1973) of about 1 month

TABLE 3.3—Sediment parameters and locations of dominant infauna and slow-moving epifauna taken by Van Veen in midshelf waters of the North Aleutian Shelf.

Species	Sediment Size	Sediment Sorting	% Mud (Range)	Depth (m)	Distribution Relative to NAS
Solariella obscura (Snail)	Medium to fine sand (59%)*	Very well to moderately well sorted (52%)	0–70	<25–75 (82%)	Patchy in northeastern and northwestern portions
S. varicosa (Snail)	Fine sand to medium silt (64%)	Poorly sorted (67%)	0–70	50–100 (75%)	Northcentral portion
Margarites olivaceus (Snail)	Medium to fine sand (80%)	Poorly sorted (79%)	0–40	25–50 (66%)	North of Port Moller
Natica clausa (Snail)	Medium sand to coarse silt (63%)	Poorly to very poorly sorted (56%)	0–50	100–175 (56%)	Northwest corner and north of Port Moller
Polinices pallida (Snail)	Fine sand to coarse silt (72%)	Very well to moderately well sorted (52%)	0–70	50–75 (62%)	Throughout midshelf
Cylichna alba (Opisthobranch gastropod)	Medium sand to medium silt (98%)	Moderately well to poorly sorted (62%)	0–70	25–100 (72%)	Throughout, >50 m
Echinarchnius parma (Sand dollar)	Medium to fine sand (69%)	Well to moderately well sorted (72%)	0–40	<25–75 (99%)	Throughout midshelf, from northeast corner of Unimak Island
Diamphiodia craterodmeta (Brittle star)	Fine sand to coarse silt (86%)	Poorly sorted (88%)	0–70	75–100 (79%)	Northwest corner and north of Amak Island
Ophiura sarsi (Brittle star)	Fine to very fine sand (82%)	Poorly sorted (97%)	0-70	50-100 (83%)	Northwest corner, and small patch just north of Port Moller (~ 50 m)
Cucumaria calcigera (Sea cucumber)	Very fine sand to coarse silt (98%)	Poorly sorted (99%)	0-60	50-75 (98%)	Central portion, north of Amak Island
Boltenia ovifera (Tunicate)	Coarse to medium silt (100%)	Poorly sorted (100%)	0-50	50-75 (100%)	Small patch west of Amak Island and northeast

SOURCE: Feder *et al.* 1981, p. 473.

* Each percentage in parentheses refers to the major concentration of a species at the given parameter.

duration each (Adams 1979; Incze *et al.* 1982). Megalopae metamorphose to benthic juveniles in late August to mid-September, for a total larval duration of about 4 months in midshelf waters (Incze *et al.* 1982).

TABLE 3.4—Major species and their mobility and trophic representation in the infaunal domains of the midshelf North Aleutian Shelf.

Group and Scientific Name	Common Name	Feeding Type*	Mobility Type†
GROUP 1:			
Byblis gaimardi	Ampelisciid amphipod	SF	S
Capitella capitata	Capitellid polychaete	DF	M
Haploscoloplos elongatus	Orbiniid polychaete	DF	M
Harpinia gurjanoe	Gammarid amphipod	SF	M
Magelona pacifica	Magelonid polychaete	DF	DM
Nephthys ciliata	Nephthyid polychaete	DF/P	M
Nucula tenuis	Bivalve mollusc	S	M
Phloe minuta	Sigalionid polychaete	S	M
Praxillella praetermissa	Maldanid polychaete	DF	S
Tharyx sp.	Cirratulid polychaete	DF	S/DM
GROUP 2:			
Axinopsida serricata	Bivalve mollusc	SF	S
Chaetoderma robusta	Bivalve mollusc	SF	M
Clinocardium ciliatum	Bivalve mollusc	SF	F
Diamphiodia craterodmeta	Brittle star	DF/P	M
Drilonereis falcata minor	Nereid polychaete	DF	M
Eudorella emarginata	Cumacean	SF/S	M
Heteromastus filiformis	Capitellid polychaete	DF	M
Maldane sarsi	Maldanid polychaete	DF	M
Nephthys punctata	Nephthyid polychaete	P	M
Nuculana pernula	Bivalve mollusc	DF	M
Ophiura sarsi	Brittle star	DF/P	M
Scalibregma inflatum	Marine snail	DF	M
Solariella varicosa	Marine snail	DF	M
Terebellides stroemii	Terebellid polychaete	DF	S
Thyasira flexuosa	Bivalve mollusc	SF	M
GROUP 3:			
Artacama proboscidea	Spinosphaerid polychaete	DF	M
Bathymedon nanseni	Gammarid amphipod	DF/S	M
Brada villosa	Flabelligerid polychaete	DF	DM
Eudorella pacifica	Cumacean	SF/S	M
Eudorellopsis integra	Cumacean	DF/S	M
Macoma moesta alaskana	Bivalve mollusc	SF	M
Polynoe canadensis	Polynoid polychaete	DF	M
Pontoporeia femorata	Gammarid amphipod	SF	S/DM
Priapulus caudatus	Priapulid	P	M
Yoldia amygdalea	Bivalve mollusc	SF	M
Y. hyperborea	Bivalve mollusc	SF	M

SOURCE: Haflinger 1981, p. 349–354.

* P = predator, S = scavenger, DF = detrital feeder, SF = suspension feeder.

† M = motile, DM = discreetly motile, S = sessile.

3.2.4 Birds

Seabirds constitute an important component of the southeastern Bering Sea in terms of numbers and interactions with the marine communities in which they reside. The magnitude of breeding and nonbreeding seabird populations in the southeastern Bering Sea, areas of greatest abundance, and potential sensitivity to oil spill impact have been reviewed by Strauch and Hunt (1982).

About 45 species of seabirds occur in the Bering Sea and Aleutian area and 12 of these species have populations exceeding one million animals (Sowls *et al.* 1978; Hunt *et al.* 1981a). Several dominant species, including Black-legged Kittiwakes, shearwaters, and Tufted Puffins, arrive in the lease area in early April to feed before moving to nesting colonies (with the exception of shearwaters). These same species leave the Bering Sea by October and are essentially absent for about 6 months. Other species such as cormorants, Northern Fulmars (*Fulmarus glacialis*), murres, and auklets are year-round residents; their regional abundance shifts with season, reflecting breeding periods or retreats from ice to open water.

In the southeastern Bering Sea most breeding seabirds are found in a few, tremendous aggregations called megacolonies (Hunt *et al.* 1981b). Megacolonies are found on major islands or island groups that afford both protected nesting habitat and proximity to rich feeding grounds. The largest colonies of seabirds are located on the Pribilof Islands, around Cape Newenham, and on St. Lawrence and St. Matthew islands, well outside of the North Aleutian Shelf area.

Nonbreeding species may be more widely distributed over the Bering Sea shelf, and have been reported in flocks of tens to hundreds of thousands. These species are distributed in relation to important oceanographic features of the shelf (Hunt *et al.* 1981a) that demark zooplankton and fish communities which are amenable to seabird feeding strategies. In the North Aleu-

TABLE 3.5—Estimated biomass and abundance of dominant epifauna in the midshelf (>40–100 m) of the North Aleutian Shelf.

Species	Common Name	Mean Biomass (g/m^2)	Percentage of Total Biomass
Neptunea ventricosa	Snail	0.063	1.31
N. heros	Snail	0.118	2.45
Pagurus trigonocheirus	Hermit crab	0.075	1.56
Paralithodes camtschatica	Red king crab	0.919	19.07
P. platypus	Blue king crab	0.118	2.45
Hyas coarctatus alutaceus	Decorator crab	0.028	0.59
Chionoecetes (hybrid)	Tanner crab	0.072	1.51
C. opilio	Tanner crab	1.071	22.23
C. bairdi	Tanner crab	0.256	5.31
Erimacrus isenbeckii	Korean hair crab	0.073	1.51
Asterias amurensis	Sea star	0.611	12.69
Evasterias echinosoma	Sea star	0.006	0.12
Leptasterias polaris acervata	Sea star	0.062	1.29
Lethasterias nanimenis	Sea star	0.012	0.26
Strongylocentrotus drobachiensis	Green sea urchin	<0.001	0.01
Gorgonocephalus caryi	Basket star	0.080	1.66
Styela rustica macrenteron	Tunicate	0.350	7.26
Halocynthia aurantium	Tunicate	0.112	2.34
Total:		4.026	83.62

SOURCE: Jewett and Feder 1981.

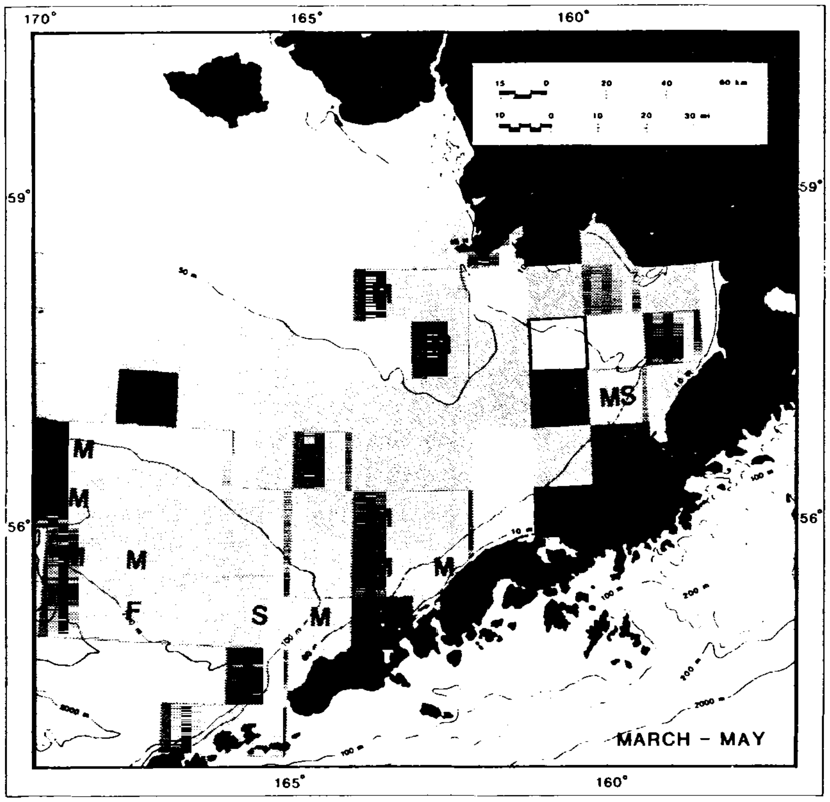


FIGURE 3.4—Pelagic densities of major seabird species across the southeastern Bering Sea: March–May (Science Applications, Inc. 1981).

PELAGIC DISTRIBUTION
birds/km²

- 0
- 0.1–15.0
- 15.1–75.0
- >75.0

Species with densities of 16.1 or more birds/km²

F - Northern Fulmar
S - Shearwaters
P - Storm-Petrels
K - Black-legged Kittiwakes
M - Murres
A - Small Auklets
T - Tufted Puffin

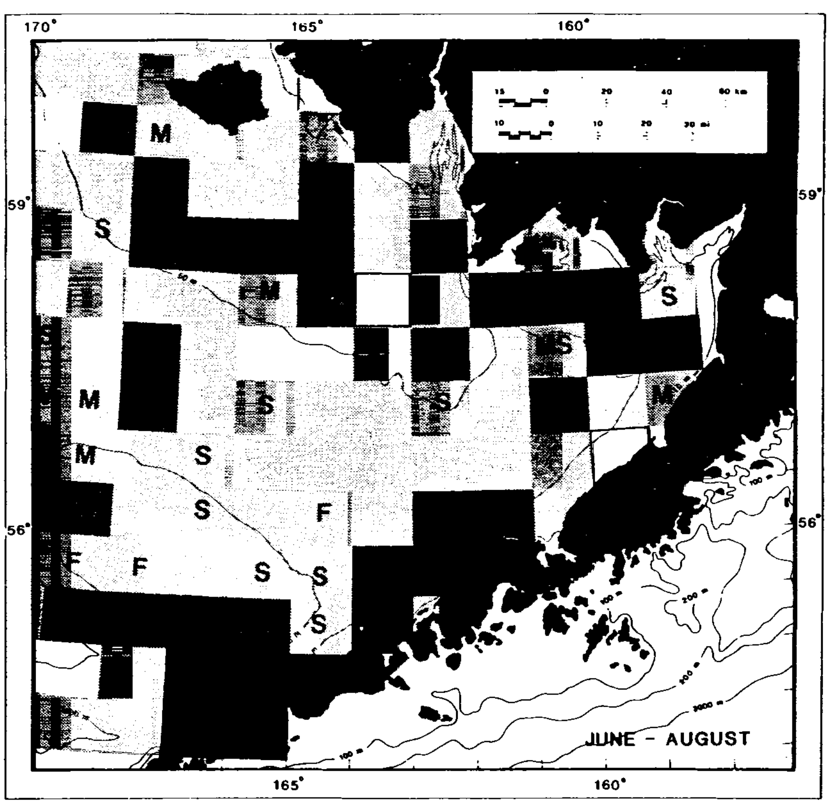


FIGURE 3.5—Pelagic densities of major seabird species across the southeastern Bering Sea: June–August (Science Applications, Inc. 1981).

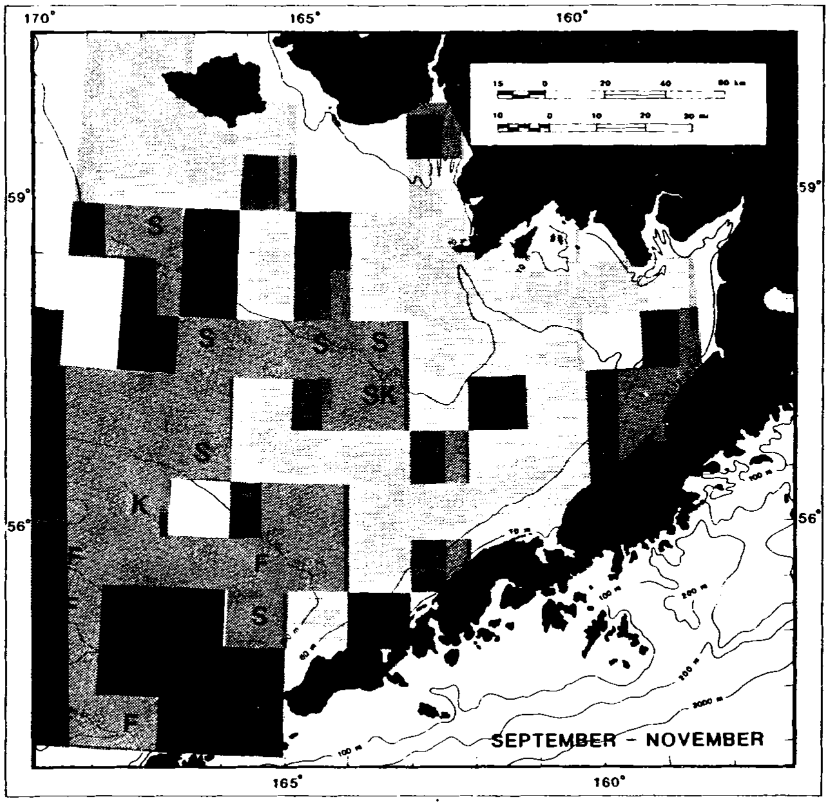


FIGURE 3.6—Pelagic densities of major seabird species across the southeastern Bering Sea: September–November (Science Applications, Inc. 1981).

tian Shelf, Short-tailed and Sooty shearwaters (*Puffinus tenuirostris* and *P. griseus*) are the most important nonbreeding seabirds. These species nest in the Southern Hemisphere. Populations totaling 8 to 20 million migrate to the Bering Sea where they feed from June to September in flocks of 100,000 to a million birds (Sanger and Baird 1977a; Hunt *et al.* 1981a; Gould *et al.* 1982). Shearwaters are most abundant near or inside the 50-m isobath (Hunt *et al.* 1981a). The persistent abundance of these birds at this front of water convergence and complete mixing implies a feeding dependence on the area.

Other dominant seabirds include Northern Fulmars, Black-legged and Red-legged kittiwakes (*Rissa tridactyla* and *R. brevirostris*), murres (*Uria* spp.), and petrels (*Oceanodroma* spp.), whose populations range from several hundred thousand to several million. These species are seasonally most abundant on 100- to 200-m and deeper waters over the shelf break, and less common over the midshelf (Figs. 3.4–3.6). Schneider and Hunt's (1982) summary of density data for seabirds clearly shows a preponderance of occupancy time (in bird days/km^2) on waters deeper than 100 m and at the shelf break (Table 3.6). Seasonal density estimates for major species substantiate this trend (Table 3.7). As another example, petrels have a mean density of 10–13 birds/km^2 between 100 and 200 m, but only 3 birds/km^2 over the midshelf (Hunt and Strauch 1982). Again, an important exception is the shearwaters that are abundant over the midshelf near the 50-m contour. A maximum of 50–100 birds/km^2 (all seabirds) has been reported over the midshelf region in general (Hunt *et al.* 1981a).

The lack of high densities of seabirds over the midshelf probably reflects species-specific limitations in food supply and distance to major colonies. The great dependence of some birds on relatively few types of food organisms makes them more susceptible to food-limited perturbations, when quantity and location are not optimal. Feeding strategies can be divided into two categories: surface feeders such as fulmars, Fork-tailed Storm-Petrels, and kittiwakes; and subsurface feeders, including murres, auklets, puffins, and shearwaters (Hunt *et al.* 1981c; Schneider and Hunt 1982). Surface feeders display more varied reproductive success rates, possibly reflecting the influence of severe weather on both their ability to forage and the presence of food at the surface. Schneider and Hunt (1982) provide a summary of the distribution and change of bird biomass over the midshelf which they relate to food consumption measured as carbon flux. Again, reduced abundance of birds over the midshelf was evident when compared to deeper shelf areas (11.6 and 21.2 kg/km², respectively), but, based on the observed allometric relationship between weight and metabolism, the food requirement was only 37% lower over the midshelf. A relatively small difference in daily aggregate carbon transfer was evident between the middle and outer shelf (30 vs. 48 mg C/m² from April to August), but there was a three-fold decrease in trophic transfer to surface-feeding birds of the midshelf (Fig. 3.7). Schneider and Hunt (1982) suggest that reduced carbon flux to comparatively smaller herbivorous zooplankton of the midshelf results in less food for surface-feeding birds, and, in turn, lower abundance.

The majority of seabird diets consists of crustaceans and fish. In many instances fish represent almost all consumption. Seabird trophics have been most extensively studied at the Pribilof Islands (Hunt *et al.* 1981c). Use of crustaceans is greatest among shearwaters that consume up to 70% euphausiids (frequency of occurrence) in summer and may switch to amphipods (60%) in fall (Sanger and Baird 1977b; Hunt *et al.* 1981c). Auklets forage extensively on crustaceans (up to 88% of gut contents by volume), including calanoid copepods characteristic of "oceanic" species found in greatest abundance beyond the 100-m frontal system. Hunt *et al.* (1981c) concluded that Least Auklets (*Aethia pusilla*) are so dependent on *Calanus marshallae* for food that the birds are restricted to nesting on islands near the outer shelf domain where these copepods are abundant. Most other seabirds feed principally on small fish (greater than 70% by volume), notably walleye pollock (*Theragra chalcogramma*). Kittiwakes feed heavily on first-year pollock, which are most abundant in the deeper waters south and northwest of the Pribilof Islands. The diets of Common Murres (*Uria aalge*) and Tufted Puffins (*Lunda cirrhata*) are chiefly composed of pollock (56% and 41%, respectively); however, other fish, including capelin and Pacific sand lance, are also important prey for

TABLE 3.6—Occupancy time of seabirds over midshelf, outer shelf, and slope waters of the southeastern Bering Sea.

Family and Species	Midshelf	Outer Shelf	Slope
Procellariids			
Northern Fulmar	349 ± 5	851 ±36	1,004 ±30
Fork-tailed Storm-Petrel	197 ± 9	961 ±39	620 ±65
Sooty and Short-tailed Shearwaters	897 ±26	615 ±46	595 ±21
Larids			
Black-legged Kittiwake	85 ± 4	294 ± 5	255 ± 8
Red-legged Kittiwake	14 ± 1	113 ± 3	782 ±21
Alcids			
Thick-billed Murre	265 ±16	544 ±21	216 ±10
Least Auklet	28 ± 3	22 ± 2	12 ± 2
Crested and Parakeet Auklets	10 ± 1	9 ± 1	29 ± 8
Tufted Puffin	50 ± 1	123 ± 2	1 ± 3

SOURCE: Schneider and Hunt 1982.

NOTE: Occupancy time is in bird-days/km² ± $(m)(s^2/DF)$, where m is average days/month (30.6), s^2 is the within-group (month) variance, and DF is the associated degrees of freedom (sample size minus 1).

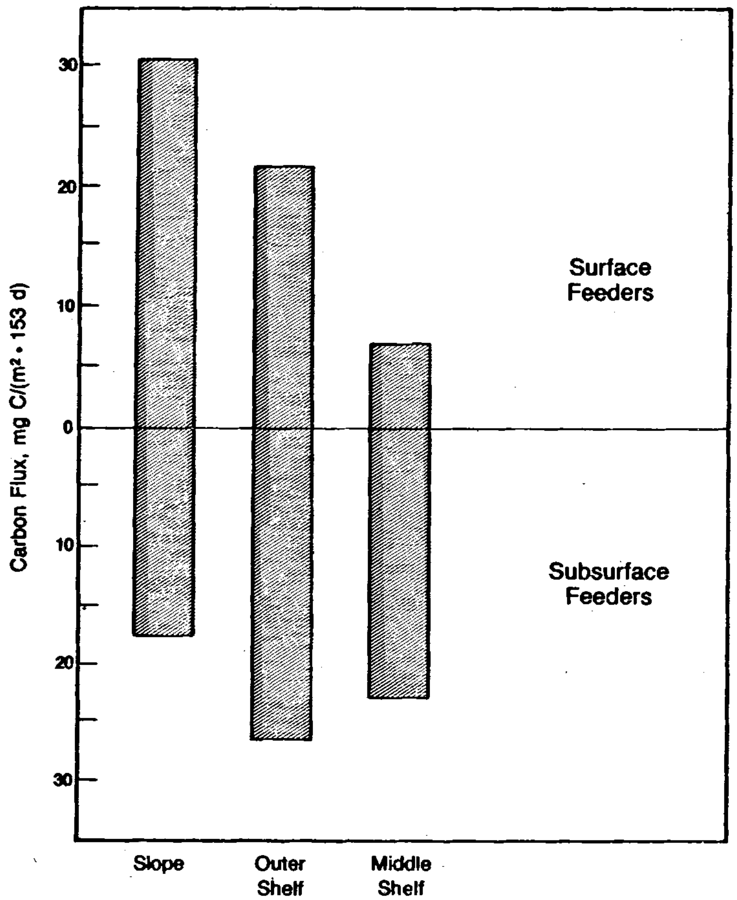


FIGURE 3.7—Carbon flux to seabirds for period April through August (averaged data for 1975–79). Surface feeders were Northern Fulmar; Forked-tailed Storm-Petrel; and Black- and Red-legged kittiwakes. Subsurface feeders were Sooty and Short-tailed shearwaters; Thick-billed Murre; Least, Crested, and Parakeet auklets; and Tufted Puffin. (Adapted from Schneider and Hunt 1982.)

TABLE 3.7—Seabird density indices (birds/km²) for seasons and habitats in the eastern Bering Sea.

	Winter*			Spring			Summer			Fall		
	CS	SB	OC	CS	SB	OC	CS	SB	OC	CS	SB	OC
Fulmar	1	3	2	3	11	2	3	16	3	12	35†	9
Shearwaters	0	0	0	3	3	+‡	81†	13	3	35	104	2
Storm-Petrels	0	3	1	1	2	2	2	7	2	1	6	3
Larus gulls	+	1	+	1	2	1	1	1	+	1	2	+
Kittiwakes	+	+	1	1	2	1	2	2	1	3	5	1
Alcids	16	2	2	34	20	5	15	17	2	9	3	2
Murres	14	0	0	19	2	1	9	1	+	4	1	+
Tufted Puffin	0	0	0	1	1	1	1	2	1	2	1	+
Total birds	31	9	6	63	43	13	114†	59	12	67	157†	17

SOURCE: Hunt *et al.* 1981a.

NOTES: Data are derived from combined shipboard and aerial surveys.

Habitats include continental shelf (CS), shelf break (SB), and oceanic (OC) waters.

* Based on a single aerial survey and no shipboard surveys.

† These densities are highly biased from sightings of large flocks.

‡ All densities have been rounded to nearest whole number; "+" indicates less than 0.5 birds/km².

these and other seabirds (Hunt *et al.* 1981c; Strauch and Hunt 1982).

Inter-annual variation in type and quantity of food supply can affect reproductive success and foraging habits of birds. Use of euphausiids by murres and kittiwakes increased tenfold in 1978 over 1977, and replaced fish to a large extent as a mainstay food. The lower energy content of euphausiids compared to fish may have contributed to low reproductive success of Black-legged Kittiwakes in the Pribilof Islands, where chicks fledged per nest decreased from about 0.53 in 1977 to 0.33 in 1978 (Hunt *et al.* 1981b, 1981c). The fate of seabird colonies is linked to the population dynamics of very few prey species of fish; although birds may be able to switch prey items to a degree, the quality of food (as calories per unit weight) is as important as quantity to the breeding success of colonies.

Although birds of the midshelf consume only about 0.03% of primary productivity (Schneider and Hunt 1982), total food consumption by seabirds of the eastern Bering Sea has been estimated at 5.8–11.5 × 10^5 t, of which 1.5 × 10^5 t are walleye pollock (Hunt *et al.* 1981b). The impact of seabirds on pelagic communities is probably greatest around megacolonies, Unimak Pass, and areas of the North Aleutian Shelf where immense shearwater populations forage.

3.2.5 Mammals

At least 20 species of marine mammals are known to occur in the North Aleutian Shelf lease area. A broad coverage of their distribution and abundance, as well as a general discussion of possible impacts from offshore oil and gas development, has been presented by Braham et al. (1982). Only those species most common to the midshelf region are discussed here.

Endangered gray whales (*Eschrichtius robustus*) are seasonal visitors to the midshelf and are most likely to be present during fall (mid-October to late December). During this period the southbound migration route for gray whales is poorly documented but appears to be less coastal and more diffuse than in spring (Frost *et al.* 1983). Large portions of the population migrating from northern feeding grounds in the Chirikov Basin and southern Chukchi Sea may move directly across the midshelf region en route to Unimak Pass. The primary motivation of the whales during southward migration appears to be directed movement but some feeding may occur.

Gray whales feed predominantly on ampeliscid amphipods which form dense mats in certain parts of the northern Bering and Chukchi seas. They also consume polychaetes, small bivalves, gastropods, mysids, and herring (Zimushko and Lenskaya 1970; Frost and Lowry 1981; National Marine Fisheries Service [NMFS], unpubl. data). It is not known whether or not feeding is occurring when gray whales are found in midshelf waters.

Belukha whales (*Delphinapterus leucas*) are the most numerous and widely distributed cetaceans in northern oceans. In Alaska there appears to be two stocks. One ranges throughout the northern Gulf of Alaska and a second, much larger stock, ranges seasonally through the Bering, Chukchi, and Beaufort seas. The latter stock is variously estimated at 9,000–16,000 (Interagency Task Group 1978) and 15,000–18,000 (Lowry et al. 1982). About 1,000–1,500 belukhas live in Bristol Bay during at least part or all of the year (Brooks 1954; Lensink 1961; Alaska Department of Fish and Game [ADF&G], unpubl. data).

During the coldest winter months, belukhas are occasionally, but not commonly, seen by coastal residents of Bristol Bay in small groups of 1 to 5 whales (Brooks *et al.* 1954; ADF&G, unpubl. data). Lensink (1961) states that during winter months they are confined to the outer regions of the bay, where they are believed to occur in close association with seasonal ice (Lensink 1961). Belukhas are probably most common in midshelf waters during winter in relatively heavy ice years.

Winter food habits of belukhas are poorly described. During summer months pelagic and semidemersal fish (herring, capelin, salmon, pollock, and cod) constitute major prey, and may be significant dietary components in winter (Lowry *et al.* 1982).

Over 70% of the world's population of northern fur seals (*Callorhinus ursinus*) breeds and pups on the Pribilof Islands (Kajimura *et al.* 1979, 1980; U.S. Department of Commerce 1980c; Kosloff 1981; Braham *et al.* 1982). From late May through early November most of these

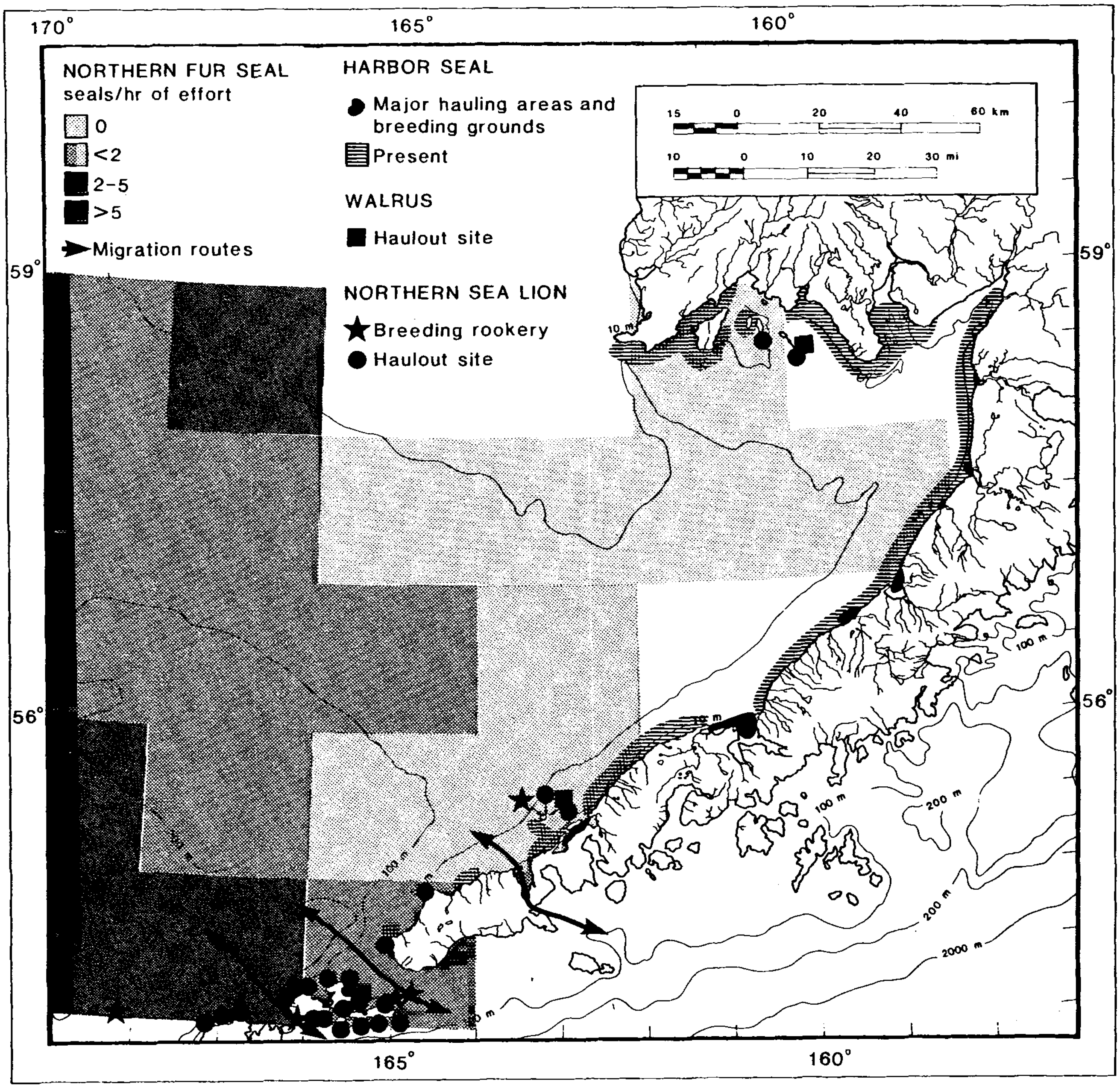


FIGURE 3.8—Distribution and abundance of harbor seals and northern fur seals across the southeastern Bering Sea shelf. Haulout areas and breeding sites for seals, sea lions, and walrus are indicated (Science Applications, Inc. 1981).

animals are found in the Bering Sea. During the summer, adult females and subadult animals range far from the Pribilof Islands in search of prey. Most of these seals appear to move south toward the shelf break, but others disperse widely over the shelf, including into midshelf waters (Fig. 3.8). The proportion of the population foraging within this lease area during summer and fall months is unknown, but is probably far smaller than over the shelf break. Adult males start abandoning their rookery territories in early August and return to the sea to forage, having fed little since late May. They, too, may migrate into and forage in midshelf waters. Most fur seals depart the Bering Sea between August and mid-November, although an unknown number of adult males may overwinter in Bristol Bay (Braham *et al.* 1982).

Fur seals feed primarily at night and early in the morning. In areas where food species remain in upper water layers in daylight, fur seals are known to feed actively throughout the day. Their major foods usually remain the same each year, changing only in rank of importance. In the Bering Sea their diet consists of squid, pollock, capelin, herring, and deep sea (bathylagid) smelt (Lowry *et al.* 1982).

Harbor seals (*Phoca vitulina*) and spotted seals (*P. largha*) are closely related and although morphological dissimilarities exist, they are typically differentiated by their choice of breeding habitat. Harbor seals pup and molt on land, whereas spotted seals do so on ice. Harbor seals are largely coastal in occurrence, although some movement is associated with advancing or retreating ice. These animals would generally not be encountered in midshelf waters (Frost *et al.* 1982) (Fig. 3.8).

Published information on the distribution of spotted seals is limited to general descriptive accounts of their distribution (Scheffer 1958; King 1964; Shaughnessy and Fay 1977) or of their distribution in the Bering Sea ice front in spring (Fay 1974; Burns and Harbo 1977; Burns *et al.* 1981). The population of spotted seals in the Bering-Chukchi region has been estimated at 280,000-300,000 (Burns 1978). In late winter and spring, the entire Bering-Chukchi population is concentrated in or near the ice front (Burns 1978), with major pupping and breeding concentrations in the Bristol Bay-Pribilof Islands region, Karaginski Bay, and the Gulf of Anadyr. Spotted seals are therefore infrequent visitors to the midshelf region, and their occurrence there is related to heavy ice years. In an aerial survey for spotted seals conducted 8-23 April 1976 almost 2,915 km² of the North Aleutian Shelf were flown (Burns and Harbo 1977). Nearly 600 seals were observed, of which 48 were pups. The magnitude of this winter variability in abundance has not been described.

Spotted seals feed predominantly on fish, especially rockfish, smelts, herring, salmonids, sculpin, and Pacific cod (Lowry *et al.* 1982). These organisms compose roughly 90% of their diet. Shrimps and crabs are eaten less frequently (Braham *et al.* 1982).

Steller sea lions (*Eumetopias jubatus*) are year-round inhabitants of the North Aleutian Shelf and are regularly found in midshelf waters (Scheffer 1958; King 1964; Schusterman 1981; Frost *et al.* 1983). Their pelagic occurrence is most likely related to food searching. Pollock compose roughly 80% (wet-weight volume) of the sea lion diet. Other fish and invertebrates make up the rest of their diet. Capelin, herring, Pacific cod, shrimps, and crabs are dominant prey (Braham *et al.* 1982; Lowry *et al.* 1982).

During the winter, groups of sea lions are commonly encountered along the southern fringe of the pack ice. These animals are predominantly adult and subadult males (Calkins *et al.* 1981). Other sea lions move to the eastern Aleutian Islands and northeastern Pacific Ocean during winter months.

Sea lion populations have followed a downward trend in the eastern Aleutian Islands since the late 1970's. Frost *et al.* (1983) report low and possibly declining sea lion numbers on Amak Island and the Sea Lion Rocks during the past 20 years. A similar trend has been observed in the Pribilof Islands where the number of breeding adults on Walrus Island has declined from 3,000 to 5,000 in the 1960's to 900 in 1981. It was suggested that there may also be an increased number of sea lions in Bristol Bay during the summer (Frost *et al.* 1983), and there has been an increase in use of the ice front during the winter over this same time period (G. Oliver, pers. commun.). The causes for these apparent changes are unknown; however, the apparent decline in the eastern Aleutians corresponds to a concurrent increase in commercial groundfish fisheries and competition for preferred foods (Braham *et al.* 1980). Fowler (1982) has recently suggested that entanglement with net fragments in areas of intense foreign fishing may be a significant source of mortality for fur seals and the same may be true for sea lions. Frost *et al.* (1983) suggest that because of reduced pollock stocks in other areas, increasing numbers of sea lions are moving through Bristol Bay to feed on the large herring and capelin resources occurring there seasonally.

Between January and March a major concentration of walrus (*Odobenus rosmarus*) forms in the area south of Cape Newenham from about 160° to 162° W. longitude and 57° to 58° N. latitude (Kenyon 1972; Krogman et al. 1979; Fay and Lowry 1981). The actual size of this concentration is not known, but probably contains about one-fourth of the total Alaskan walrus population of 250,000 animals (Fay 1982). As the ice edge recedes in April and May, females and young animals stay with the ice. A group of about 15,000 subadult and adult males remains in Bristol Bay (J. Taggert, pers. commun.). These males exhibit a highly synchronous behavior of going to sea to feed for about 7 days, then returning to haulout areas to rest for 2 to 4 days. It is during these feeding excursions that walrus are most likely to be found in midshelf waters. Bivalve molluscs are the most important prey of walrus and this in part explains their use of the midshelf region where clam densities are high (Fay and Lowry 1981; Fay 1982).

The total number of sea otters (*Enhydra lutris*) in the North Aleutian Shelf has been estimated at 17,000 animals and is probably nearing a maximum level (Schneider 1981). The southern limit of the pack ice forms the northern limit of the sea otter range. Otters extend their range to the north and east during periods when the area remains ice free; they are forced to reduce this range during years of extensive ice formation (Schneider and Faro 1975). Generally, the sea otter range does not extend much to the northeast of Port Heiden (Schneider 1981).

Sea otters are usually found near shore in the lease area but have been known to range as far as 80 km offshore (Schneider 1981). Their pelagic excursions are most common during summer and are probably related to food searching in midshelf waters. The diets of these animals have not been comprehensively examined; preliminary results of an ongoing OCSEAP study indicate that otters may feed predominantly on yellowfin sole (R. Cimberg, pers. commun.). Other prey include crabs, snails, and bivalve molluscs in unknown proportions.

3.3 EXPOSED COASTAL WATERS

In the North Aleutian Shelf lease area, exposed coastal waters habitat comprises all unprotected inshore waters (< 50 m deep) from Unimak Island to Port Heiden. Typically this habitat encompasses a coastal band about 25 km wide. PROBES fieldwork along the 50-m isobath has identified a narrow front approximately 10 km wide (Schumacher *et al.* 1979). Coastal waters shoreward of this front are vertically homogenous and very turbulent due to wind and tidal mixing. The turbulence results in complex organic particulate and sediment settling rates. All but the very large particles are transported beyond 50 m before sinking to the bottom. The prevailing circulation is to the northeast with current velocities ranging between 2 and 5 cm/s.

The unprotected shoreline is composed, for the most part, of large segments of coarse-grained sand beaches which correspond to an ESI rank of 4. (ESI 1 signifies a coastal morphology least sensitive to spilled oil and 10 signifies most sensitive.) This is especially true of the beaches just east of Port Heiden, between Izembek Lagoon and Bechevin Bay, and between Izembek Lagoon and Port Moller. Interspersed with the coarse-grained sand beaches are small sections of mixed sand and gravel beaches (ESI 6). Unimak Island beaches are more varied, although coarse-grained sand beaches predominate. Other beach types found along Unimak Island occur in short segments and include mixed sand and gravel beaches (ESI 6), wave-cut platforms (ESI 2), and gravel beaches (ESI 7).

Coarse-grained beaches usually display a short, steep beach face with a wide backshore. Beach sediments are loosely compacted and the beach morphology responds rapidly to changing wave and tidal conditions. Beach vegetation is dominated by American dune grass (*Elymus* sp.), forming a dense carpet on the sand dunes backing beaches. Because of the physical composition of these beaches (and their low species densities and diversities) they have been classified as moderately vulnerable to spilled oil.

3.3.1 Plankton

Coastal patterns of circulation greatly influence the composition of inshore phytoplankton communities. Because few plankton collections have been obtained inside the 50-m isobath and because species dominance and succession change rapidly (a few days to weeks), only characteristic assemblages can be described.

Before the spring bloom, dinoflagellates and *Phaeocystis* are the most numerous cells (Goering and Iverson 1981). Spring blooms include *Chaetoceros debilis*, *C. scolopendra*, and

Thalassiosira nordenskioldii. Summer assemblages normally consist of *Chaetoceros* spp., *Corethron hystrix*, *Dentricula* sp., *Nitzchia neriata*, *Rhizosolenia hebetata* forma *semispina*, and *Skeletonema costatum*. Inshore standing crop densities uniformly range from 1×10^5 to 1×10^9 cells/m. Annual production of phytoplankton is about 120 g C/m^2 (Iverson and Goering 1979).

In years of ice coverage, the ice-edge community contains large numbers of chain-forming diatoms, many of which form flat, ribbon-shaped colonies (Alexander and Cooney 1979). This community is dominated by *Thalassiosira* spp., but *Nitzchia* spp., *Fragilariopsis* spp., *Achmanthes* spp., *Navicula* spp., *Chaetoceros* spp., and *Detonula* spp. are also numerically abundant (Goering and Iverson 1981). The same holds true for ice-edge communities occurring over midshelf waters.

Zooplankton abundance in coastal waters is low as reflected in early and midsummer biomass estimates, averaging about 37 g/m^2 (Motoda and Minoda 1974). Copepods are small and dominated by *Calanus glacialis*, *Acartia longiremis*, and *C. marshallae*. As in the midshelf, these organisms are unable to graze much of the diatom production, resulting in an efficiency of transfer to secondary producers of about 3% or 2.8 g C/m^2 (Cooney 1981; Dagg *et al.* 1982; Vidal and Smith 1982). *Thysanoessa raschii* is the dominant coastal euphausiid, preferring low-salinity water. Amphipods are represented by *Parathemisto* spp. and *Hyperoche* spp., chaetognaths by *Sagitta elegans*, and pteropods by *Limacina helicina helicina* and *Clione limacina limacina*. Although most coastal standing stock estimates are similar to those described for the midshelf, amphipods, chaetognaths, and pelagic snails are generally less abundant coastally.

3.3.2 Benthos

Infaunal biomass is higher in nearshore than in midshelf waters and other parts of the southeastern Bering Sea shelf. Haflinger (1981) attributed the high coastal biomass to detrital energy inputs from adjacent lagoons and river discharges. Infaunal wet weight exceeds 675 g/m^2 near Izembek Lagoon and Port Heiden or about 30 g C/m^2 (Fig. 3.3). Cluster analysis of infaunal collections indicates an inshore group that dominates to about 50 m (Haflinger 1981). The inshore group is found in gravel-sand substrate and is dominated by the amphipods *Corophium crassicorne* and *Haustorius eous*, the sand dollar *Echinarachnius parma*, the polychaetes *Ophelia limacina* and *Spiophanes bombyx*, and the bivalves *Spisula polynyma* and *Tellina lutea*. Feder and Jewett (1981) also reported high infaunal biomass along the 50-m isobath (exceeding 200 g/m^2 wet weight) from Amak Island to upper Bristol Bay.

Bivalve molluscs are the dominant coastal infaunal group. Biomass estimates of 140 and 573 g/m^2 have been reported for Izembek Lagoon and Port Heiden, respectively (McDonald *et al.* 1981). *Tellina lutea*, *Cyclocardia crebricostata*, and the surf clam *S. polynyma* are dominant in the poorly sorted, mostly sand-bottomed sea floor characteristic of this habitat. The surf clam stock off Port Heiden was estimated to have an exploitable biomass of 329,179 t (723 million lb) with an annual maximum sustainable yield of 17,775 t (28 million lb) at depths between 26 and 35 m (Hughes and Bourne 1981).

Few systematic surveys have been conducted on inshore infauna, although sparse data suggest high biomass levels. Baxter (1975) describes major species by habitats between 0 and 50 m from samples collected in Bristol Bay (Table 3.8). In 1982, OCSEAP sponsored a field program that included a benthic survey as part of sea otter and juvenile king crab feeding studies. Astarte clams, starfish, hermit crabs, and sand dollars were dominant epifauna inside the 50-m contour. Razor clams (*Siliqua alta*) are thought to be abundant in the high-energy waters between Unimak Island and Port Heiden. The size of this population is unknown. Ongoing OCSEAP studies will greatly enhance what is known about infaunal standing stocks and potential biomass in the inshore coastal band.

Jewett and Feder (1981) reported on epifaunal invertebrates collected along the 50-m isobath. The greatest biomass in the small number of samples collected was recorded near Amak Island off Izembek Lagoon. Wet-weight values in this area were in excess of 9 g/m^2 with red king crab, Tanner crabs, and the starfish *Asterias amurensis* being most abundant. Gastropods were also abundant, composing 6–8% of the total observed biomass (Pereyra *et al.* 1976; MacIntosh and Somerton 1981). Marine snails included *Neptunea ventricosa*, *N. lyrata*, and *Plicifusus deformis.*

Red king crab are an important benthic component of the nearshore environment. Female and juvenile red king crab are abundant year round in these waters, although adults exhibit an offshore migration associated with winter and feeding. Adult males move into the shallow North Aleutian Shelf to mate each spring, after which they return to greater depths.

King crab population cycles suggest that year-class success may be largely due to the initial survival of pelagic and settling larvae. Peak hatch of eggs occurs sometime around May (as early as 1 April) in depths ranging from 20 to 70 m from Unimak Island into Bristol Bay (Armstrong *et al.* 1981). Larval densities increase dramatically from western Unimak Island to Port Moller. By August most larvae have metamorphosed and settled from the water column and have taken up a benthic existence. Survival from predation for these small crabs is believed to be greatest in gravelly, rocky, clam-shell substrates where juveniles can hide. Such habitat is patchy in distribution in the coastal waters of the North Aleutian Shelf and may be most extensive off Port Moller where juveniles have been caught in greatest numbers. Juvenile crabs, up to 60 mm in carapace length, or about 3 years of age, are resident to the coastal North Aleutian Shelf.

The nearshore abundance of small crabs from Port Moller into Bristol Bay is unknown. Available larval information suggests that the greater part of any year class may settle out to the east of the proposed lease area. Available data are inadequate to assess where 0+ king crabs metamorphose to the benthos. Metamorphosis may occur in all shallow waters between Amak Island and Port Moller, or perhaps farther north-

TABLE 3.8—Habitat determinations and representative infauna and epibenthos from 10- to 50-m depths in Bristol Bay.

	Sand	Sand-Mud	Mud	Rocky
Echinoderms	*Echinarachnius* *Leptasterias*	*Leptasterias*		*Leptasterias* Sea urchin
Crustaceans	*Crangon* *Telmessus*	*Crangon* *Telmessus*	*Pandalus* *Telmessus*	*Sclerocrangon* *Balanus*
Pelecypods				
Clinocardium	*californiense*	*californiense*		
Macoma	*lama*	*brota* *lama* *obliqua*	*calcarea*	
Mya	*priapus*	*priapus* *elegans*	*elegans*	
Mytilus				*edulis*
Serripes	*groenlandicus*	*groenlandicus*		
Siliqua	*alta*	*alta*		
Spisula	*polynyma*	*polynyma*		
Tellina	*lutea*	*lutea*		
Gastropods				
Beringius				*kennicottii*
Littorina				
Margarites		*olivaceus*		*pupillus*
Neptunea				*lyrata* *heros* *ventricosa*
Thais				*lima*

SOURCE: Baxter 1975.

east in upper Bristol Bay.

Tanner crab, *C. bairdi*, are found coastally but are more abundant in depths greater than 50 m. Preliminary results from the 1982 OCSEAP cruise indicate juvenile abundance increases dramatically between 50 and 70 m of depth, especially between Amak Island and the Black Hills region. (*See* 3.2.3 and Chapter 4 for descriptions of larval dispersal, development, and general distribution and abundance).

3.3.3 Fish

The exposed coastal habitat of the North Aleutian Shelf is a known nursery area for several species of fish (based on juvenile abundance). Yellowfin sole are the dominant demersal fish. Juvenile halibut are also abundant. Others including rock sole, butter sole (*Isopsetta isolepis*), Bering sole (*Hippoglossoides robustus*), pollock, Pacific cod, starry flounder (*Platichthys stellatus*), arrowtooth flounder, Pacific sand lance (*Ammodytes hexapterus*), sculpins, and various other flatfish are also abundant as evidenced in catch data (R.V. *Miller Freeman* Cruise Report for RP-4-MF-82A, Leg I).

As is the case for Pacific salmon, the nearshore waters of the North Aleutian Shelf are traversed extensively by huge schools of coastally spawning and migrating forage fish. Of these, capelin (*Mallotus villosus*), Pacific herring (*Clupea harengus harengus*), boreal smelt (*Osmerus eperlanus*), and eulachon (*Thaleichthys pacificus*) are most numerous (Warner and Shafford 1981). Capelin are probably the most abundant forage species in spring and summer months. Major capelin spawning areas are located along the exposed coastline between Lieskof Cape, Port Moller, and Cape Seniavin. Capelin spawn both offshore and intertidally. In Bristol Bay major herring spawning grounds are located around Cape Newenham, although smaller numbers are known to spawn intertidally at Port Moller and Port Heiden. Stock definition information for these spawning fish is not available. Boreal smelt and eulachon are anadromous species that spawn in rivers in the Meshik-Port Heiden regions of the North Aleutian Shelf. Herring, boreal smelt, and eulachon are especially abundant in the Port Heiden region between mid-April and July.

3.3.4 Birds

Numerous marine birds are resident species of the nearshore coastal band of the North Aleutian Shelf. Ecological groupings have been used to describe their abundance, consolidating birds into groups as they were most frequently observed in between Unimak Pass and Port Moller (Arneson 1981). Few swans (*Olor* spp.) or jaegers (*Stercorarius* spp.) were observed in aerial surveys; for data analysis their numbers have been combined with their nearest phylogenetic relatives, geese and gulls, respectively. Dabblers (or dabbling ducks) resident in the nearshore coastal band include Mallard (*Anas platyrhynchos*), Gadwall (*A. strepera*), Pintail (*A. acuta*), Green-winged Teal (*A. crecca*), Northern Shoveler (*A. clypeata*), European Wigeon (*A. penelope*), and American Wigeon (*A. americana*). Divers (or diving ducks) include Canvasback (*Aythya valisineria*), Redhead (*A. americana*), Ring-necked Duck (*A. collaris*), Greater Scaup (*A. marila*), Lesser Scaup (*A. affinis*), Common Goldeneye (*Bucephala clangula*), Barrow's Goldeneye (*B. islandica*), and Bufflehead (*B. albeola*). Sea ducks include Oldsquaw (*Clangula hyemalis*), Harlequin Duck (*Histrionicus histrionicus*), Steller's Eider (*Polysticta stelleri*), Common Eider (*Somateria mollissima*), King Eider (*S. spectabilis*), Spectacled Eider (*S. fischeri*), White-winged Scoter (*Melanitta deglandi*), Surf Scoter (*M. perspicillata*), and Black Scoter (*M. nigra*). Mergansers include Common Merganser (*Mergus merganser*) and Red-breasted Merganser (*M. serrator*). Raptors include hawks, eagles, falcons, and owls. Seasonal bird densities (all species) describing coastal use are depicted in Figure 3.9. The following descriptions of seasonal use of nearshore habitats have been reported from multiyear surveys of the Alaska Peninsula in 1976 and 1977 (Arneson 1981).

Over 200,000 birds were recorded in spring surveys along the Alaska Peninsula. Coastal waters and sandy beaches were preferred habitats and most heavily used by sea ducks (Steller's Eider, Black Scoter, and Common Eider), gulls (kittiwakes), and shorebirds (Black-bellied Plovers). Approximately 10,000 birds were observed in each habitat. Numerical composition in coastal waters included almost 7,000 sea ducks, 2,000 gulls, and 500 diving ducks.

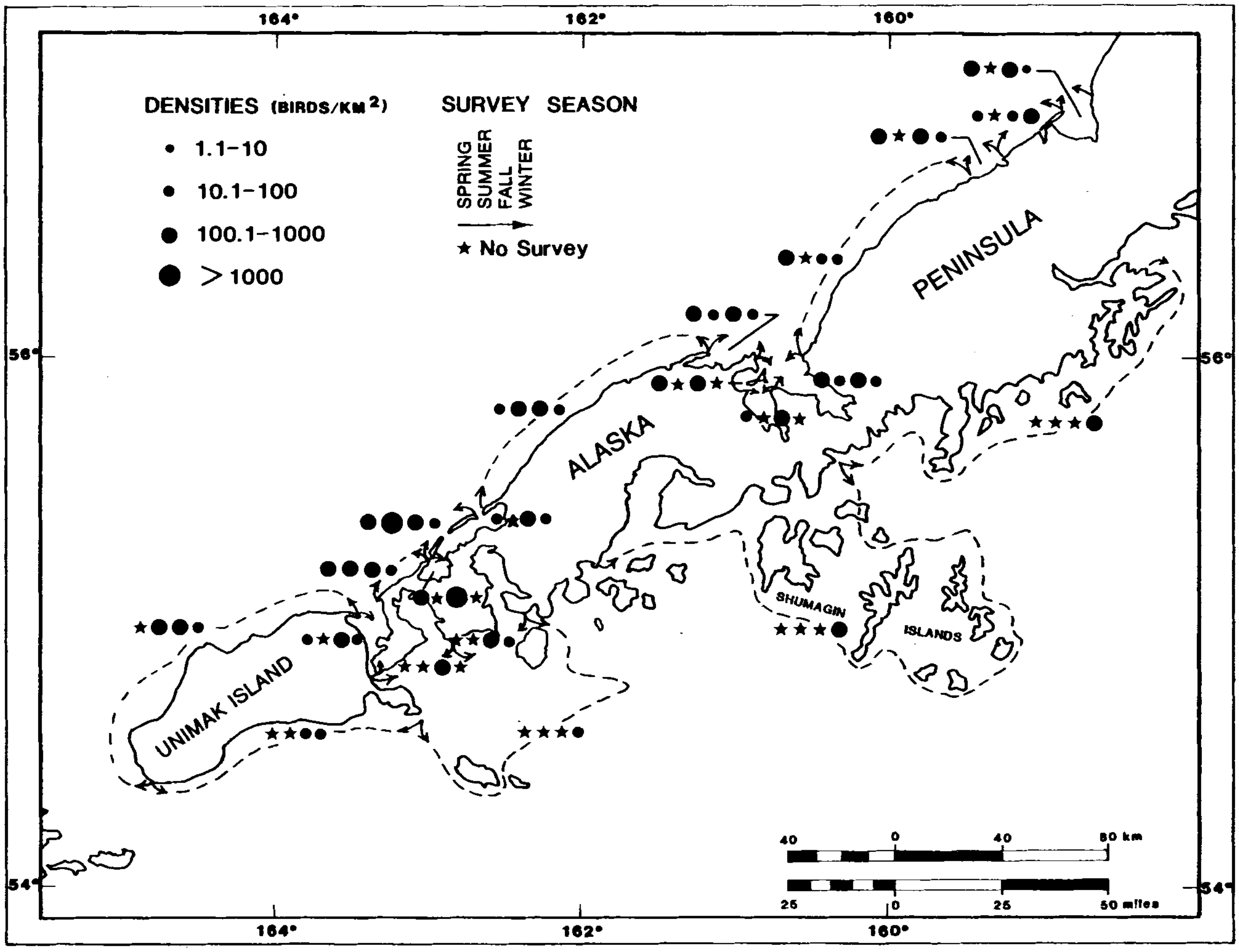


FIGURE 3.9—Total bird density by section along north and south coasts of Alaska Peninsula during four seasons as determined by aerial surveys. Densities read from left to right: spring, summer, fall, winter. Spring, fall, and winter surveys were coastal; summer surveys were pelagic. (Adapted from Arneson 1981.)

All other groups were represented by less than 500 birds. Exposed sandy beaches are typical of the North Aleutian Shelf coastline from the eastern corner of Unimak Pass to Port Heiden. Over 86% of the birds seen on these beaches were Glaucous-winged and Mew gulls (8,250 birds). Other groups identified included shorebirds (850 birds) and terns (300 birds). No birds were observed on the exposed rocky beaches of Unimak Island. Jaegers and gulls were the most abundant group along the sandy beaches of Unimak Island (625 birds); terns accounted for all other observations (75 birds). The mean density of birds along the North Aleutian Shelf during spring was 141 birds/km² (Table 3.9).

The greatest density of birds reported in summer was 432 birds/km² of which approximately 90% (402 birds/km²) were shearwaters. Short-tailed Shearwaters were most abundant in large flocks northeast and southwest of Amak Island near the 50-m contour. It was estimated that several million birds were pelagically distributed, and densities east of Amak Island of approximately 1,375 birds/km² were reported. Gulls were the next most abundant group with highest densities just north of Nelson Lagoon (65 birds/km²). Glaucous-winged Gulls and sea ducks predominated near Port Moller. Murres were the most abundant alcid with greatest densities reported southwest of Amak Island (33 birds/km²). Terns were observed in all sections but only in small numbers.

Over 21,000 birds were observed during fall months. Most (over 16,000) were seen very near shore and almost 5,000 sightings were made of birds on exposed sandy beaches. Few observations (<200) were made from the exposed rocky beaches of Unimak Island. Sea ducks (Steller's, King, and Common eiders) were most abundant in exposed inshore waters (83% of total), followed by gulls and jaegers (9%), and swans and geese (4%). Shorebirds (Rock Sandpipers) were the predominant species on exposed sandy beaches (73%). Gulls (Glaucous-winged Gull, kittiwakes, Mew Gull) and jaegers (13%), geese and swans (Black Brant, Emperor Goose, Canada Goose) (12%), and passerine species (13%) composed remaining sandy beach groups.

TABLE 3.9—Bird densities* over North Aleutian Shelf coastal waters by season.†

	Spring (1977)	Summer (1976)	Fall (1976–77)	Winter (1977)
Loon	1.1-10	10.1-100	1.1-10	1.1-10
Grebe	1.1-10	0	1.1-10	1.1-10
Tubenose	0	100.1-1,000	1.1-10	0
Cormorant	1.1-10	10.1-100	0.1-1	1.1-10
Goose and Swan	10.1-100	0	100.1-1,000	1.1-10
Dabbler	10.1-100	0	10.1-100	1.1-10
Diver	1.1-10	0	0.1-1	1.1-10
Sea Duck	10.1-100	0.1-1	10.1-100	10.1-100
Merganser	0.1-1	0	1.1-10	1.1-10
Raptor	1.1-10	0	1.1-10	1.1-10
Crane	1.1-10	0	0	0
Shorebird	1.1-10	10.1-100	10.1-100	1.1-10
Gull and Jaeger	10.1-100	10.1-100	10.1-100	10.1-100
Tern	0.1-1	10.1-100	1.1-10	0
Alcid	1.1-10	10.1-100	1.1-10	1.1-10
Corvid	1.1-10	0	1.1-10	1.1-10
Other Passerine	1.1-10	0	0.1-1	1.1-10
Other Bird	1.1-10	0	0.1-1	0

SOURCE: Arneson 1981.

* Densities (birds/km²):

• = 0; ● = 0.1-1; ● = 1.1-10; ● = 10.1-100; ● = 100.1-1,000.

† Spring = April, May; summer = June, July, August; fall = September, October, November; winter = December, January, February, March.

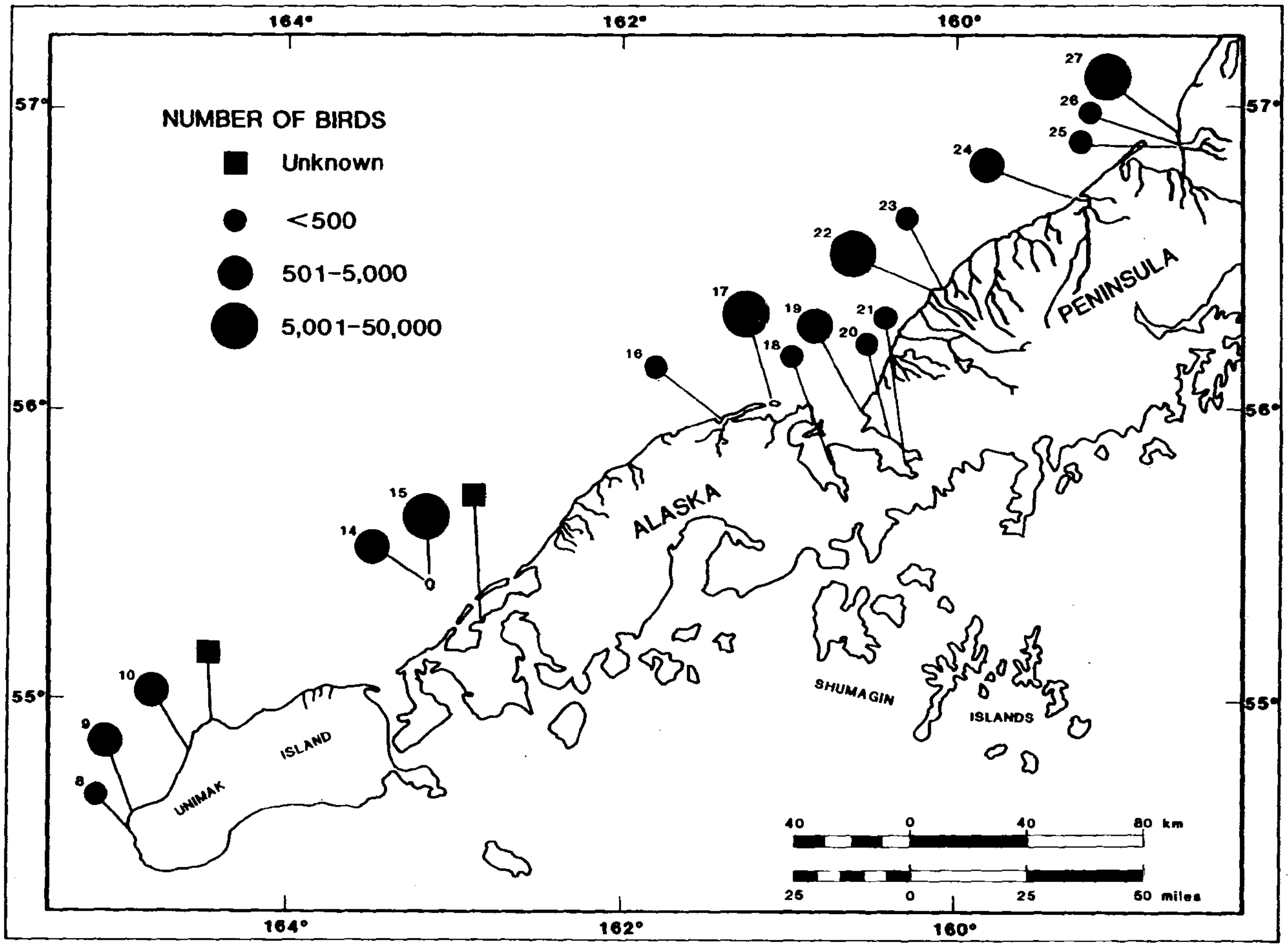


FIGURE 3.10—Seabird colonies in the North Aleutian Shelf area. (Adapted from Science Applications, Inc. 1981.)

Snow Buntings (*Plectophenax nivalis*) were abundant on beaches, feeding on beach rye (*Elymus sp.*).

Scoters (Black, White-winged, and Surf), eiders (Steller's, King, and Common), Oldsquaw, and Harlequin Duck were the most abundant sea ducks (33 birds/km²) during winter months. Gulls and jaegers (13 birds/km²), geese (3 birds/km²), and alcids (2 birds/km²) were also present. Of the more than 10,500 bird observations recorded, 82% were sea ducks, and 4% gulls and jaegers. Sea ducks were in greatest densities southwest of Port Heiden (182 birds/km²); gulls and jaegers were most frequently observed on sandy beaches. The fewest bird sightings were reported from rocky beaches, although this is where Red-faced Cormorants were most numerous.

Several small-sized seabird colonies are located along the exposed north coast of the Alaska Peninsula (Fig. 3.10). They are found near major spawning and nursery areas for local forage stocks—herring, capelin, and smelt. The colonies are thought to be small because (1) they lack suitable cliff-nesting habitat required by many seabird species, and (2) of the great distance between the colonies and the continental slope and shelf break areas where large quantities of preferred foods are found. Cormorants, gulls, and Black-legged Kittiwakes are the most abundant breeding birds (Table 3.10). They nest on flat ground, a readily available habitat along this part of the coast. They are also piscivorous. Mew and Glaucous-winged gulls; Double-crested, Red-faced, and Pelagic cormorants; Black-legged Kittiwakes; and Arctic and Aleutian terns are the major breeding species. Breeding phenologies and species-specific nesting characteristics are shown in Table 3.11. Seabird species are generally long-lived (10–30 years) and have very small clutches (1–3 eggs). Nest mortalities are greatest in the egg stage, and once hatched, survival of chicks to fledglings is great. Seabird diets in the southeastern Bering Sea have been summarized by Strauch and Hunt (1982).

Seasonal distributions of pelagic seabirds in relation to the oceanographic front located near the 50-m contour have been studied by Hunt *et al.* (1981a). In this sense the data collected were obtained slightly offshore the more coastal work of Arneson (1981). Hunt *et al.* (1981a) found that bird densities between 0 and 50 m were greatest in summer and fall (Table 3.11). Shearwaters and murres are the most abundant species. The Short-tailed Shearwater is the most abundant single species between June and September and is found in greatest concentrations near or within the 50-m isobath. Both Common and Thick-billed murres are present but estimates for each species are limited for they are difficult to tell apart in the field. Murres are the most abundant seabirds in the coastal band during winter.

3.3.5 Mammals

Like midshelf waters, the coastal habitat is used seasonally and most extensively by gray whales, belukhas, phocid seals, fur seals, walrus, sea lions, and sea otters. Of these, gray whales, harbor seals, and sea otters are the most visible and numerous mammals of the nearshore area. Gray whales, walrus, and possibly belukhas are present from early spring to late fall. Other mammals, although occasionally present, occur much less frequently in this part of the North Aleutian Shelf. Their abundance in the southeastern Bering Sea has recently been summarized with respect to OCS activities (Science Applications, Inc. 1981; Braham *et al.* 1982).

After entering the southeastern Bering Sea in spring and early summer, gray whales hug the west coast of Unimak Island and continue upon a coastal migration through the North Aleutian Shelf beyond Port Heiden (Pike 1962; Rice and Wolman 1971; Braham *et al.* 1977; Leatherwood and Evans 1982; Hessing 1983). Most animals are en route to summer feeding grounds in the northern Bering and southern Chukchi seas; however, a small number remain along the northern shores of the Alaska Peninsula throughout the summer (Leatherwood and Evans 1982; NMFS, unpubl. data). Although whale use of this area is not well documented, most observations have been made of animals in shallow waters between Bechevin Bay and Port Moller (NMFS, unpubl. data) (Fig. 3.11). The importance of these apparently traditional feeding areas, particularly Nelson Lagoon, has not been investigated. It is presumed the whales feed on ampeliscid amphipods and other benthic foods. Gray whales may be present in coastal waters as late as November.

Belukhas are usually characterized as a nearshore and estuarine species. During winter

TABLE 3.10—Seabird colonies along exposed North Aleutian Shelf coastline.

Colony Number and Name	Cormorants	Black-legged Kittiwakes	Other Gulls	Murres	Other Puffins	Other Alcids	Seabirds	Total
8 Unimak	50	0	0	0	0	0	0	50
9 Sea Lion Point	750	0	0	0	0	0	0	750
10 Cave Point	1,000	0	0	0	0	0	0	1,000
16 Dowitcher Island	0	0	300	0	0	0	0	300
17 Nelson Lagoon Island	20	0	13,000	0	30	0	1,400	14,450
22 Cape Seniavin	1,700	3,500	500	0	0	0	0	5,700
23 Unnamed Cape	50	100	0	100	0	0	0	250
24 Seal Islands	0	0	1,500	0	0	0	0	1,500
Total:	3,570	3,600	15,300	100	30	0	1,400	24,000

SOURCE: Sowls *et al.* 1978.

months they are occasionally, but not commonly, seen by coastal residents (Brooks *et al.* 1954; ADF&G, unpubl. data). However, they are believed to occur in close association with seasonal ice and their occurrence in exposed inshore waters of the North Aleutian Shelf would

TABLE 3.11—Estimated phenologies, nesting habitats, average clutch sizes, and birds fledged of major seabirds nesting along exposed North Aleutian Shelf coastline.

Seabird	NH: Nesting Habitat	$\bar{X}$ CS: Clutch Size	$\bar{X}$ BFN: Birds Fledged/Nest*	Phenology (Mar. Apr. May. Jun. Jul. Aug. Sept. Oct.)
Red-faced Cormorant	Cliff	1-4	2	E C; L; H; F
Black-legged Kittiwake	Cliff ledges	2	1	E E C C; L; H; F
Glaucous-winged Gull	Flat ground	2-3	1	E EC C; L; H; F
Aleutian/Arctic Terns	Sandy/rocky beaches	2	1	E C E C; L; H; F
Black-billed Murre	Cliff ledges	1	0.6	E EC C; L; H; F
Common Murre	Cliff ledges	1	0.6	E E C C; L; H; F
Ancient Murrelet	Talus and burrows	--	--	E 2E CCC; L; H; F
Cassin's Auklet	Talus and burrows	--	--	E; L
Tufted Puffin	Burrows in grassy slopes near cliff tops	1	0.8	E E C C; L; H; F

SOURCES: Hunt *et al.* 1981b; Strauch and Hunt 1982; U.S. Fish and Wildlife Service, unpubl. data.

KEY: ▬, presence on colony; L, laying; E, egg observed; H, hatching; C, chick observed; F, fledging.

* Data on clutch size and fledging were obtained by Hunt *et al.* (1981a) from Pribilof Island colonies and may not represent actual conditions of North Aleutian Shelf colonies. Clutch size and fledging undergo extreme annual fluctuations (complete failures in some years) in response to predation, food availability, weather, age of breeding birds, and other conditions, and vary from colony to colony.

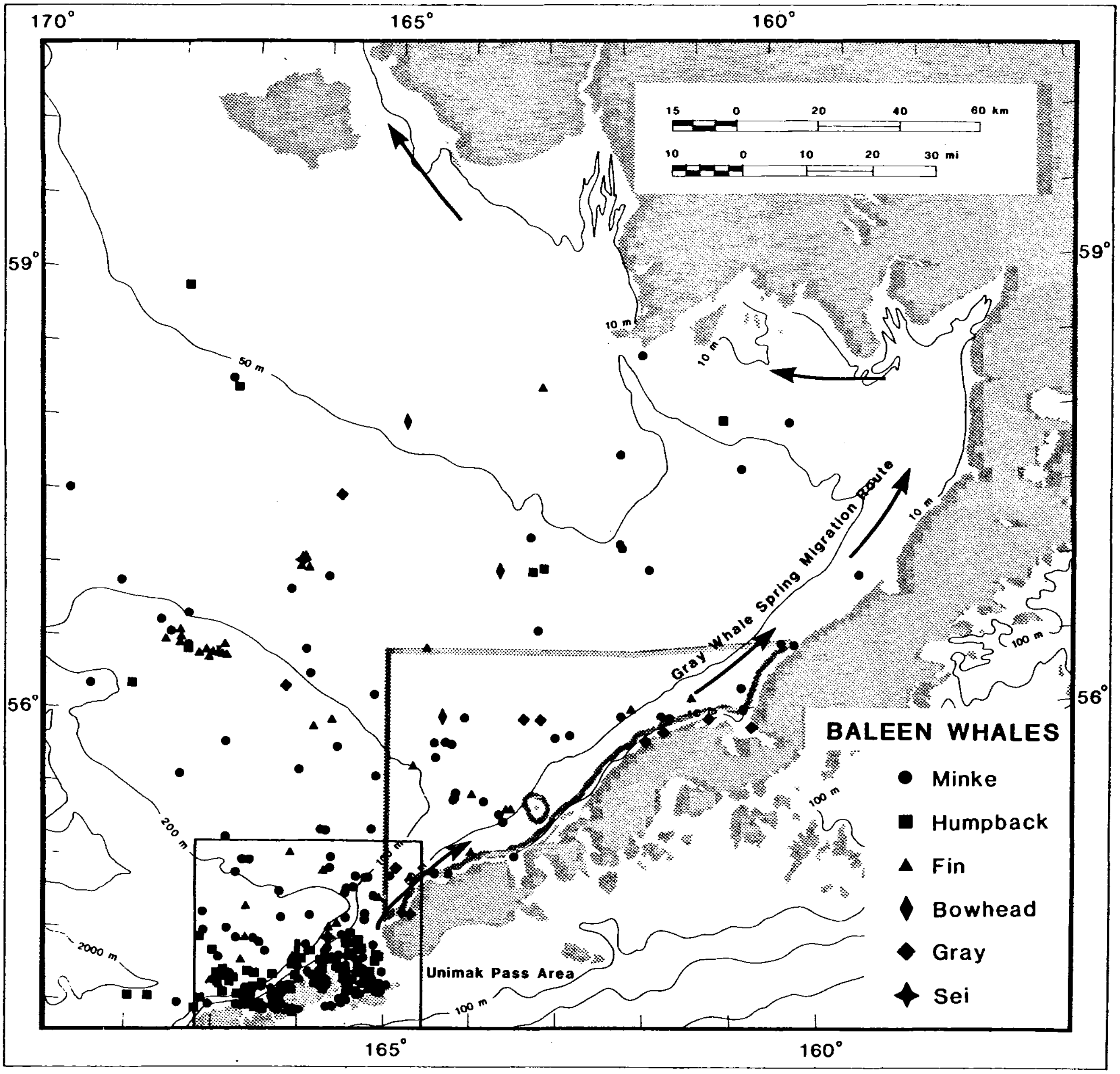


FIGURE 3.11—Gray whale spring migration route and cetacean use of North Aleutian Shelf waters and Unimak Pass (Science Applications, Inc. 1981).

normally be restricted to particularly cold years of heavy ice coverage (Lensink 1961). Belukhas move from the ice edge to coastal waters as they become free of ice, in March and April (Brooks 1955; ADF&G, unpubl. data). This is especially true at or near the mouths of large rivers in inner Bristol Bay, where groups of belukhas numbering in the hundreds are frequently found. Belukhas remain at the mouths or ascend the rivers to feed on concentrations of anadromous species such as smolting salmon and spawning smelt (Brooks *et al.* 1954; Brooks 1955; Lensink 1961; Klinkhart 1966). Pollock, capelin, herring, other fish, and squid compose the bulk of their diet (Lowry *et al.* 1982). Presumably their diet in winter, a time when belukhas would most likely occur in the lease area, also consists of fish.

Harbor seals are by far the most abundant phocid species. Although they are year-round residents of the coastal North Aleutian Shelf, in years of heavy ice they may winter to the west in the eastern Aleutian Islands (K. W. Pitcher, pers. commun.). At least 30,000 animals, an estimated 10–15% of the Alaskan population, are distributed in this coastal area. Spotted seals are very infrequent inhabitants of the coastal North Aleutian Shelf, occurring there only in years of extreme ice coverage (Burns 1970; Fay 1974; Burns and Harbo 1977; Burns *et al.* 1981; NMFS, unpubl. data).

Several locations along the North Aleutian Shelf coastline are regularly used by harbor seals for hauling out (Fig. 3.8). Haulouts are used for resting, molting, and care of young. Seals haul out on sandbars and other areas exposed by the tides and more animals have been observed hauled out at low than high tides (Everitt and Braham 1980). Peak use of haulout areas occurs during the molt in June and July and apparently tapers off in September and October when the seals spend more time in the water. There are six major haulouts: Izembek Lagoon (approximately 5,000 seals); Port Moller (up to 8,000); Seal Islands (up to 3,500); Port Heiden (up to 10,500); Cinder River, farther into Bristol Bay (up to 4,500); and Nanvak Bay (up to 2,900) (Everitt and Braham 1980).

Food habits of harbor seals in this part of Bristol Bay are poorly documented (ADF&G, unpubl. data). Based on a few observations and studies conducted elsewhere in Alaska, harbor seals appear to be largely piscivorous, consuming large quantities of pollock, Pacific sand lance, Pacific cod, capelin, smelts, and cottids (Lowry *et al.* 1982). These seals are also known to feed on shrimps, Tanner and king crabs, octopus, halibut, squid, and greenlings.

Sea lions are also quite abundant due to the presence of major haulout and breeding rookeries at Amak Island and Sea Lion Rocks, respectively (Frost *et al.* 1983). The population of the rookery is estimated at 2,500 animals. Sea lions also haul out at several principal areas on Unimak Island, including Sea Lion Point/Cape Sarichef, Oksenof Point, and Cape Mordvinof. Sightings from Unimak Island have been taken during March–August; as many as 4,000 animals were recorded in 1960 and less than 100 in 1975–77 (Frost *et al.* 1983) (Fig. 3.8). Sea lions are found in greatest pelagic concentrations in front of the bays and lagoons along the Alaska Peninsula. They breed shortly after the birth of single pups (Pitcher and Calkins 1981) between June and August and animals are dispersed throughout coastal waters during the remainder of the year. Major prey items composing their diets include pollock, flatfish, capelin, herring, salmon, cod, cottids, and other fish (Lowry *et al.* 1982). Among invertebrates, squids are the major food item.

Relative to the total number of northern fur seals occupying rookeries on and pelagically distributed around the Pribilof Islands during summer, very few of these animals are found along the coast of the Alaska Peninsula (Schusterman 1981; Frost *et al.* 1983). During the summer, adult females and subadults range widely from the islands but are most abundant in the slope and shelf break regions in the vicinity of the Pribilofs, where they feed on pollock. After August, adult males may be found foraging coastally but are most abundant to the west of the proposed lease area. In addition to pollock, major prey include capelin, herring, cottids, other fish, and squid (Lowry *et al.* 1982).

Walrus are generally associated with the ice edge in the southeastern Bering Sea (Fay 1982). In April and May most animals retreat with the receding ice. However, a group of about 15,000 subadult and adult males remains in Bristol Bay. This group hauls out on Round Island and other of the Walrus Islands during May through October. Total numbers hauling out increase until July or August and decrease in autumn (Frost *et al.* 1983). During the summer these walrus forage at sea for periods lasting up to a week and upon returning to Round Island or other haulout sites, sleep for several days. Feeding excursions often take the walrus into the coastal North Aleutian Shelf habitat where they have been known to haul out at Cape Seniavin, near Port Moller, and at Amak Island (Frost *et al.* 1983). Areas of high clam densities along the north coast of the Alaska Peninsula are foraged extensively in April and May (Frost and Lowry 1981). It has been estimated that over 80% of the walrus diet consists of infaunal benthos.

The sea otter population of Bristol Bay is

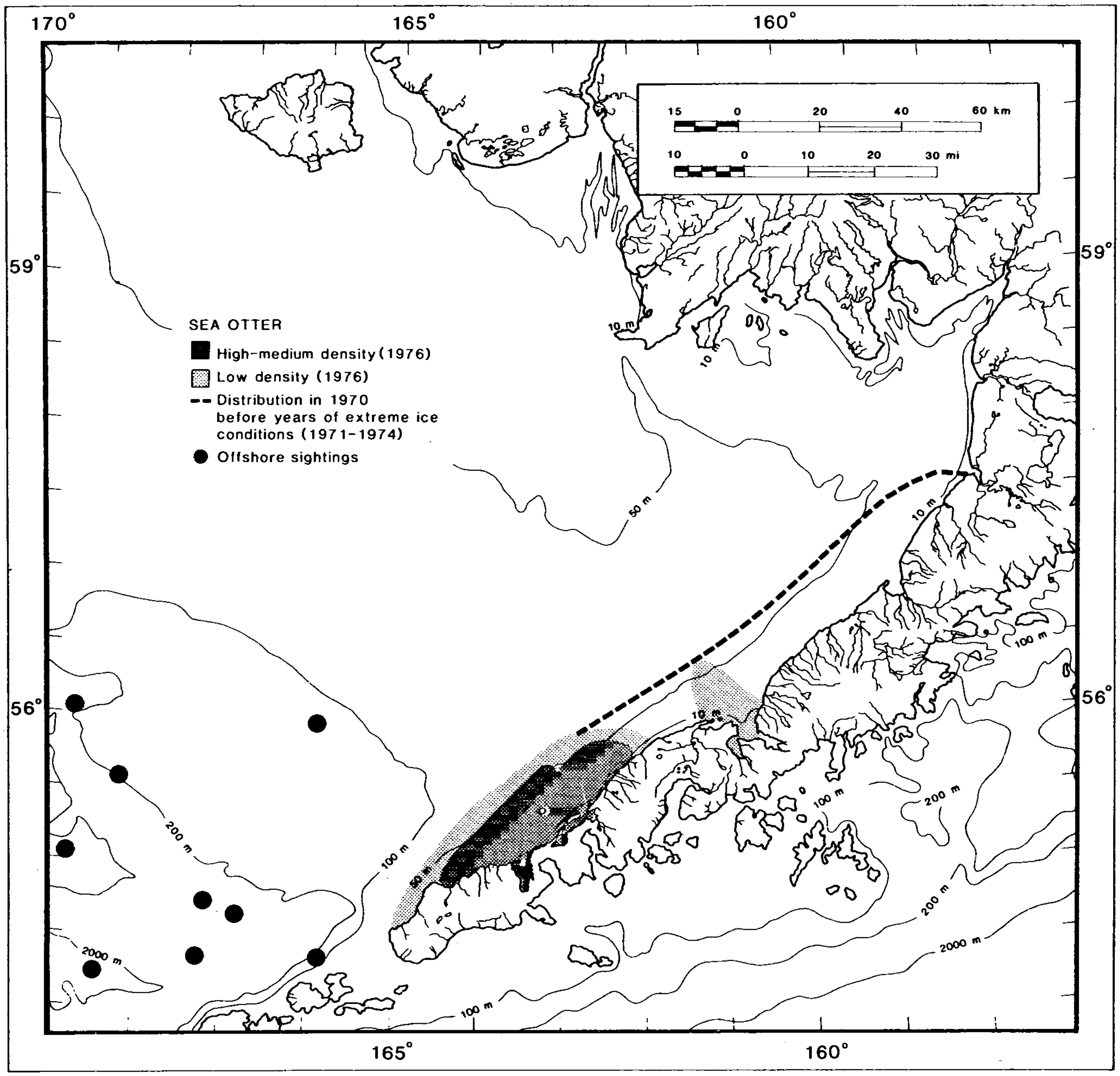


FIGURE 3.12—Distribution and abundance of sea otters in the coastal North Aleutian Shelf (Science Applications, Inc. 1981).

unique to the coastal North Aleutian Shelf (Fig. 3.12). This is largely due to their pelagic distribution and their association with a sandy rather than rocky/kelpy coastline, as found in other parts of Alaska. Sea otters are usually found inside the 50-m isobath and are most abundant from mid-Unimak Island, west beyond Izembek Lagoon (Schneider 1981). Historically this population has ranged as far into Bristol Bay as Ugashik Bay. Today otters are found in very low densities east of Port Moller. They are found very close to the coast from Bechevin Bay to Port Moller in large rafts of as many as 1,000 animals. Densities of 3.1 otters/km^2 in water 0–20 m deep, 5.8 otters/km^2 in water 20–40 m deep, and 0.5 otters/km^2 in water 40–60 m deep have been observed (Schneider 1981). The North Aleutian Shelf population has been estimated at 17,000 animals (Schneider 1981) but may be as great as 20,000 (R. Cimberg, pers. commun.). The sea otter diet in this area is currently being studied by OCSEAP. Preliminary results, based on relatively few scat samples collected at Cape Glazenap near Izembek Lagoon, suggest that yellowfin sole, bivalve molluscs, and several species of large epibenthos (e.g., crabs and shrimps) are major prey.

3.4 STANDING STOCKS AND MAJOR TROPHIC RELATIONSHIPS IN MID-SHELF AND COASTAL HABITATS

The resolution of biological data used in the prediction of standing stocks and trophic consumptions needed for depth zonation comparisons across the North Aleutian Shelf does not exist. The high benthic standing stocks resulting from midshelf phytoplankton fallout and coastal detrital inputs are reflected in the abundances and dietary roles of benthic organisms able to utilize these sources of organic carbon.

Copepods and euphausiids in midshelf and coastal areas subsist entirely on phytoplankton. Detritus appears to form the major food of the dominant regional infauna and several epibenthic species. Laevastu and Livingston (1980) have reviewed the detrital contribution to the generalized diets of major benthic groups and estimated consumption by dominant shelf infauna and epifauna (percent wet-weight contributions) as follows:

Infauna	*Percent*
Phytoplankton	75
Copepods	10
Euphausiids	10
Epifauna	5
	100

Epifauna	*Percent*
Infauna	40
Phytoplankton	24
Euphausiids	18
Copepods	18
	100

Phytoplankton detritus represents a major food of both groups, 75% and 24%, respectively. In aggregate, these generalized diets underscore the role of phytoplankton detritus in regional food webs and energy transfers. No estimate of lagoonal detrital input into coastal waters or its utilization by indigenous benthos is currently available. Such coastal inputs are hypothesized to be responsible for a large nearshore razor clam population.

Recent investigations using fisheries simulations have estimated the total finfish biomass over the eastern Bering Sea shelf (0–200 m) at approximately 32.7 t/km^2 (Laevastu and Livingston 1980). Benthic, infaunal, and epifaunal contributions to this estimated production and the dietary importance of benthic organisms are available from catch summaries and volumetric food habit analyses of major demersal and semidemersal species or species groups (Pereyra *et al.* 1976; Laevastu and Favorite 1981; Niggol 1982). Major species or species groups and the relative importance of benthos and demersal fish in their diets have been summarized as follows (Laevastu and Livingston 1980):

Species/ Ecological Group	*Relative Importance of Benthos in Diet (% Wet Weight)*
Predatory benthos	99.0
Crabs	71.0
Shrimps	75.0
Halibut, turbot	72.0
Yellowfin sole	56.5
Flathead sole	60.0
Other flatfish	61.0
Cottids	35.0
Pacific cod	24.5
Pollock	1.5

Pelagic fish and squid are large consumers of copepods, euphausiids, and other pelagic fish species. For example, 91% of the squid diet is filled by prey from zooplankton and other pelagic organisms, 89% of the salmon diet, 97% of the herring diet, and 97% of capelin and smelt diets. This is also apparent in the pollock diet and affects this species' distribution and abundance in the southeastern Bering Sea; pollock occur in highest densities in slope and shelf waters where plankton production is more efficiently cropped by pelagic herbivores.

The standing stocks of various marine birds occurring over the Bering Sea shelf during summer have been estimated at between 10.6 and 20 million birds (Sanger 1972) with a biomass of 5,920–11840 t (Strauch and Hunt 1982). Using seabird abundance estimates for the North

Aleutian Shelf, and information regarding their food habits, food consumption rates, and average yearly residences (Hunt *et al.* 1981c), it is possible to predict the order of magnitude of annual prey consumption by major seabirds in the proposed lease area (Table 3.12). These estimations correspond to an estimated annual consumption of roughly 34,000 t of finfish from the lease area as compared to a value between 500,000 and 750,000 t for the entire Bering Sea. Given the relatively small size of North Aleutian Shelf colonies this represents a significant trophic removal. Fish comprise almost 53% of the major seabirds' diets, although other food groups vary seasonally in importance to individual species. Murres consume the largest quantities of fish, of which pollock are most important in their diet.

Standing stock values cannot be derived for mammal populations in the lease area *per se* due to the sporadic and nonsystematic nature of the available data. It has been estimated that marine mammals consume about 2.3 million t of finfish annually in the Bering Sea (Laevastu and Favorite 1981). Pollock, capelin, and herring are the principal species consumed. Mammals who are most reliant on benthos, epifauna, and demersal species for food include gray whales (benthic amphipods and other organisms), walrus (bivalve molluscs), and sea otters to an unknown extent. Other dominant mammals of the lease area rely on pelagic fish. A simplified representation of a coastal North Aleutian Shelf food web is shown in Figure 3.13.

3.5 PROTECTED NEARSHORE WATERS

The bays and lagoons of the north side of the Alaska Peninsula are among the most expansive and biologically productive estuarine systems in the state. The lagoons are partially shielded from coastal inundations by sandy barrier islands and protective sandspits located at their entrances. Circulation patterns inside bays and lagoons are complex, influenced by winds and tides, and, although unstudied, the net transport is apparently outward. The influence of exported nutrients and detritus on the coastal ecology remains unknown but is suspected to be substantial on nearshore benthic standing stocks.

ESI's for the sheltered bays, lagoons, and associated wetland and marsh environments are very high (9–10). These areas must be ranked as highly vulnerable to spilled oil from possible OCS development in the North Aleutian Shelf because of the inherent capacities of lagoon and bay shorelines to incorporate and retain spilled oil, their shallow bathymetrics and poor flushing characteristics, and, most importantly, their unquestionable biological value, especially to migratory shorebird and waterfowl resources.

Bechevin Bay, located just east of Unimak Island, encompasses an area of approximately 244 km². The bay is connected to the Bering Sea by at least two shallow entrances less than 5 m deep. The entrance between Chunak Point and Cape Krenitzin is the only one with any width, approximately 3.2 km. The northern three-fourths of Bechevin Bay is shallow mud flats

TABLE 3.12—Estimated annual prey consumption (in metric tons) by major seabirds in the North Aleutian Shelf assuming a conservative study stock of 10.6 million seabirds.

	Prey Consumed				
Seabird Species	Euphausiids	Amphipods	Cephalopods	Pollock	Other Fish
Northern Fulmar	130	130	650	1,430	260
Shearwaters	4,380	4,380	4,380		1,460
Storm-Petrels	1,710		1,710		1,710
Black-legged Kittiwake	390	390		650	1,170
Murres	3,420	3,420	3,420	11,970	11,970
Small Auklets	960	640		160	640
Tufted Puffin		160	160	1,280	1,440
Total:	10,990	9,120	10,320	15,490	18,650

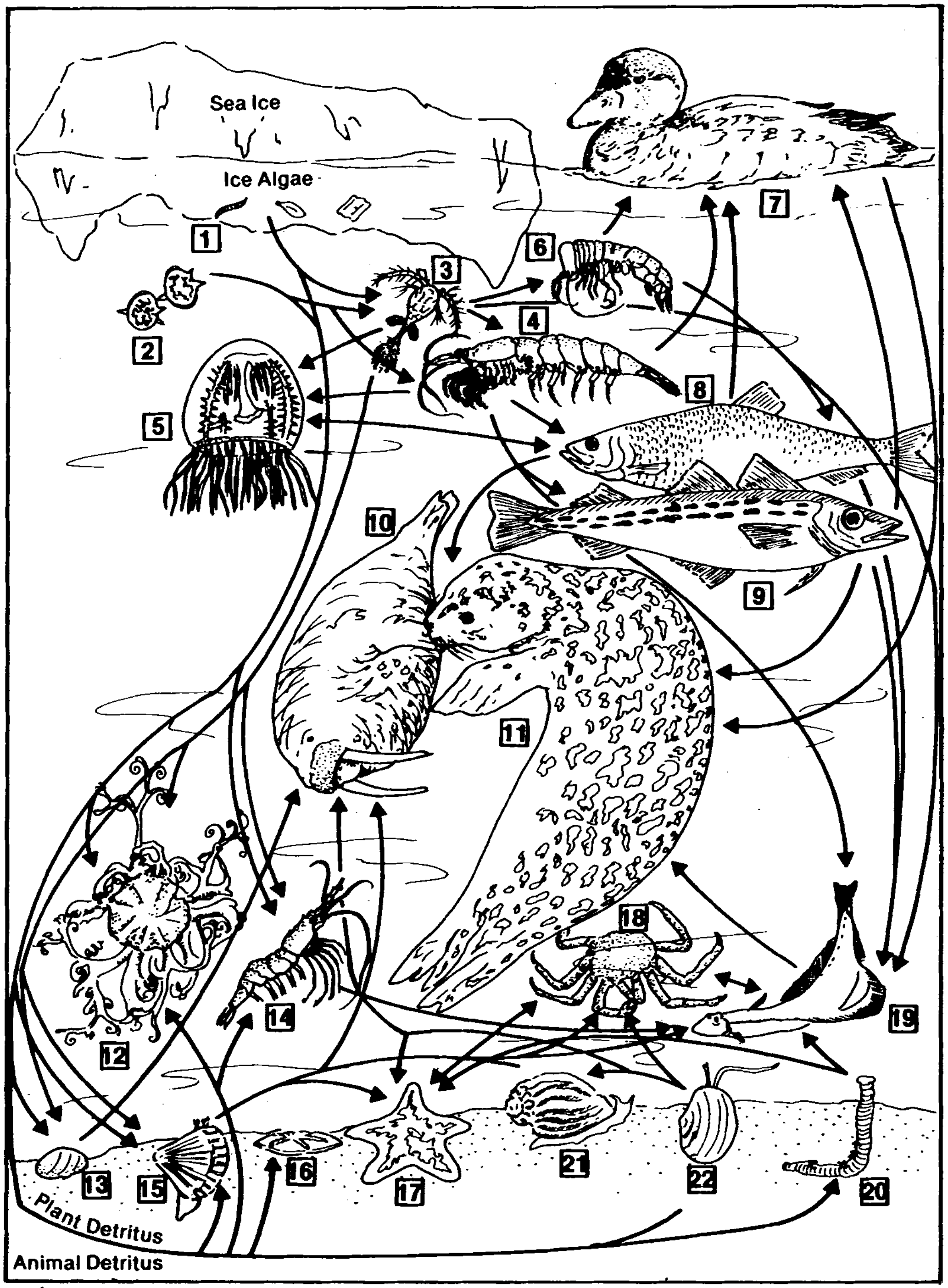


FIGURE 3.13—Bering Sea food web. Organisms depicted: 1, ice algae; 2, phytoplankton; 3, copepods; 4, mysids and euphausiids; 5, medusae; 6, hyperiid amphipods; 7, seabirds; 8 and 9, pelagic fish; 10, walrus; 11, seals; 12, basket stars; 13, ascidians; 14, shrimps; 15, filter-feeding bivalves; 16, sand dollars; 17, sea stars; 18, crabs; 19, bottom-feeding fish; 20, polychaetes; 21, predatory gastropods; 22, deposit-feeding bivalves. (Adapted from McConnaughy and McRoy 1979a.)

with tidal channels not exceeding 10 m in depth. The southern portion of the bay, below Rocky Point, contains the northern terminus of False Pass and is relatively deep, often greater than 130 m. Net transport is to the north with tidal flows measured off Rocky Point at 0.9 m/s on the flood and 0.7 m/s on the ebb (U.S. Department of Commerce 1981); beyond this, little is known of the bay's circulation. The shoreline of Bechevin Bay comprises many substrate types, with mud, sand, and gravel beaches predominating (Sears and Zimmerman 1977). Bedrock and boulder patches are also in evidence. These beach faces correspond to intermediate ESI rankings (5–7). Only protected mud flats (ESI's 9 and 10) such as those found in Hook Bay are classified as highly vulnerable to spilled oil. The wide entrance to Bechevin Bay would render oil spill countermeasures via booming or other conventional techniques ineffective methods for preventing the entrance of floating oil into the bay.

Izembek Lagoon is situated near the northwestern end of the Alaska Peninsula and is separated from the Bering Sea by two barrier islands, the Kudiakof Islands, and two long sandspits. Three large passes, 2–3 km wide and 10–13 m deep, provide the lagoon free exchange with the Bering Sea. Because there is little freshwater influence from streams emptying into Izembek Lagoon, salinities between the lagoon and coastal waters differ by less than 1 ‰ (McRoy *et al.* 1972). The lagoon has a surface area of 218 km^2; 78% is tidal flats, and 22% is tidal channels. The tidal channels vary in depth from 0.5 to 6.5 m. Average tidal excursions (0.98 m mean height) flood approximately 68% or 1.7×10^8 m of the total lagoon volume, and net transport of organic and mineralized nutrients is to the coast (McRoy *et al.* 1972). Lagoonal circulation has not been described but is undoubtedly responsive to local winds in addition to tidal flows in channels. The lagoon is encircled by about 195 km of protected mud and sandy coastline. The coarse-grained sandy beaches behind the barrier islands and sandspits have been assigned intermediate ESI rankings of 4 and 5. With few exceptions, the rest of the lagoon has been classified as highly sensitive to spilled oil (ESI's 9 and 10), due in part to the presence of large stands of eelgrass (*Zostera marina*).

The Port Moller-Nelson Lagoon complex, located on the north-central Alaska Peninsula, covers 1,100 km^2 and includes Port Moller, Nelson Lagoon, Mud Bay, and Herendeen Bay. The area is typified by a fairly regular coastline of sand beaches, low terraces, and alluvial fan deposits (Gill *et al.* 1981). Port Moller is the single largest estuary along the Alaska Peninsula, representing 44% of estuarine habitat found there. The Port Moller region is generally ice free between late April and early October. The adjacent Bering Sea is ice free between late March and early January. In winter the Bering Sea ice front usually extends south to the vicinity of Port Moller.

Nelson Lagoon, Mud Bay, and Herendeen Bay are well protected by sandspit peninsulas, barrier islands, and Port Moller coastline. Inner Port Moller is also relatively well protected, compared to the entrance of the estuary which is wide open to the coast (Table 3.13).

The entire shoreline of the region has been classified according to its vulnerability to spilled oil (Table 3.14). Estuarine headwaters and backwaters are consistently ranked as high environmental risks, largely because of the presence of extensive mud flats and fringing stands of wetland vegetation (grasses and sedges).

With the exception of the deep headwaters of Herendeen Bay, the Port Moller-Nelson Lagoon complex is characterized by a shallow bathymetry and areas of extensive shoreline. At

TABLE 3.13—General physiographic features of the Port Moller-Nelson Lagoon complex.

			Areal Estimates (km^2)			
Bay	Number of Entrances	Width (km)	Surface Area	Mud Flats	Depth 0-9 m	Tidal Channels
Port Moller	1	15	242	218	24	--
Nelson Lagoon	5	0.5–4.5	66	59	7	--
Mud Bay	2	1.1	308	62	92	154
Herendeen Bay	1	1.8	484	194	194	96

mean low water, approximately 230 km² of intertidal mud and sand flats are exposed. Ovei 90% of Nelson Lagoon is exposed at low tides. The mean diurnal tide range is 5.4 m (Gill and Sanger 1979).

Port Heiden is located to the northwest of Port Moller along the Alaska Peninsula and covers roughly 374 km². Five barrier islands provide limited protection. The narrowest channel between barrier islands is 200 m, with others ranging to 5 km. Estimates for several prominent physiographic features of Port Heiden include the following areal approximations: grassy marsh, 112 km²; mud flats, 150 km²; channel water (less than 10 m), 93 km²; and brackish influence of the Meshik River, 19 km². The vulnerability of the Port Heiden shoreline to spilled oil is generally very high (ESI's 9 and 10). The mud flats are ranked as moderately high environmental risks (ESI 7A). Vulnerability indices are lowest for the shoreward-facing beaches of the barrier islands (ESI's 4 and 5).

3.5.1 Vegetation

Within the concept of ecosystem structure and function, the pattern of vegetation types should correlate with patterns in climate, soil, and fauna (Daubenmire 1968). Each of the North Aleutian Shelf estuaries has a significantly different dominant plant association. Three genera represent the major macrophytes reported from Bristol Bay, including the filamentous green alga *Chaetomorpha* sp. found in well-sorted sediments, and *Fucus* sp. and *Ulva* sp. attached to stone (Redburn 1976). For instance, Port Heiden is dominated by wetland grasses and sedges, and Izembek Lagoon harbors one of the largest eelgrass meadows in the world.

TABLE 3.14—Representative ESI ranges for predominant beach types in the Port Moller-Nelson Lagoon complex.

Bay	North Shore	South Shore	East Shore	West Shore
Port Moller	7/10	9/10	2/7	5/7
Nelson Lagoon	9/10	9/10	6/7/9	9/10
Mud Bay	9/10	6/9	6/7/9	9/10
Herendeen Bay	9/10	9/10	2/7	6/7/9

With the exception of Izembek Lagoon, quantitative data on primary production are not available for North Aleutian Shelf estuarine waters. The descriptions provided in the following summary are based on identification of characteristic plants (Selkgregg 1974; U.S. Department of the Interior 1981), sparse field observations on intertidal biota (O'Clair *et al.* 1981), and estuarine community structure observed for similar plant assemblages in Cook Inlet (MacDonald *et al.* 1980).

Little information is available describing the marine flora of Bechevin Bay. Three major eelgrass stands are located in the northern portion of the bay behind protective sandspits. The physiography of Bechevin Bay does not allow the establishment of large algal growth such as the kelp forests often found at deep rocky coastlines along the south side of the Alaska Peninsula. Brackish water plants are not present in Bechevin Bay, although some rock weed (*Fucus* sp.), red algae (*Porphyra* sp.), and green algae (*Ulva* sp. and *Chaetomorpha* sp.) may be submerged in shallow waters. Phytoplankton production has not been studied in the bay. Beach ryegrass (*Elymus arenarius mollis*) and sandwort (*Arenaria* spp.) dominate low-lying bluffs and dunes and sandy strand communities, respectively (Selkregg 1974).

Izembek Lagoon is without doubt the best studied embayment along the North Aleutian Shelf and perhaps in Alaska. Eelgrass covers 68% of Izembek Lagoon's intertidal area or about 115 km², making this the largest single stand known. Sea grass systems comprise areas of some of the highest aquatic plant biomass in the world (Zieman and Wetzel 1980; Mann 1982). Eelgrass biomass in Izembek Lagoon is about 1,000–1,200 g dry weight/m² (about 430 g C/m²) (McRoy 1970; Barsdate *et al.* 1974), which is comparable to values for *Z. marina* and other genera in both temperate and tropical waters (Table 3.15) (McRoy and McMillan 1977; Zieman and Wetzel 1980). The biomass of *Z. marina* throughout the entire lagoon is about 1.4×10^5 t dry weight (3.1×10^8 lb). McRoy (1970) calculated a daily turnover of 2% of this biomass.

Daily productivity values for eelgrass within Izembek Lagoon range from 3.3 to 8.0 g C/m² (McRoy 1966, 1970), about twice the daily phytoplankton productivity of 2–4 g C/m² offshore (Dagg *et al.* 1982), and several times greater than the phytoplankton productivity of 0.08 g C/m² within the lagoon (McRoy *et al.* 1972).

In addition to direct production by eelgrass, there is a poorly studied component of production associated with eelgrass epiphytes. In Izembek Lagoon these are primarily diatoms (e.g., *Isthmia nervosa*) (McRoy and McMillan 1977), which at periods of maximum development may constitute 50% of the total eelgrass leaf plus epiphyte dry weight (McRoy and McMillan 1977). Studies elsewhere have indicated epiphytic production equal to 18–20% that of sea grass (Harlin 1980). A symbiotic relationship between eelgrass and epiphytes was suggested by McRoy and Goering (1974), who demonstrated the direct transfer of both carbon and nitrogen from *Z. marina* leaves to associated epiphytes. Eelgrass nutrition was derived primarily from the root and rhizome system, and transfer was envisaged as a leaky passage of both organic and inorganic compounds to both autotrophic diatoms and heterotrophic bacteria.

Total annual eelgrass production within the lagoon has been estimated at 4.6–5.1 × 10⁵ t (about 1.1 × 10⁹ lb) based on a 165-day growing season, of which carbon, nitrogen, and phosphorus are estimated at 166,000 t, 7,400 t, and 1,600 t, respectively (Table 3.15) (McRoy 1970; Barsdate *et al.* 1974). Some of this production is consumed directly by herbivorous grazers and some is recycled within the lagoon, but most is exported as particulate or dissolved material to coastal waters.

After slight trophic-related losses of *Z. marina* production within the lagoon, most is exported offshore as particulate or dissolved material. During transport from the lagoon, freshly detached eelgrass is actually enriched in nitrogen and other elements and, in general, particulate export is equal to annual production (Table 3.15) (Barsdate *et al.* 1974). Significant amounts of both total carbon (12%) and phosphorus (24%) are exported as dissolved compounds that result in an enriched plume near shore off Izembek Lagoon (Fig. 3.14). Although such enrichment contributes to regional productivity in adjacent nearshore waters, the largest nutrient export from Izembek Lagoon is the particulate/detrital eelgrass that constitutes most of the 4.6 × 10⁵ t produced annually (Barsdate *et al.* 1974).

The contribution of this material to the productivity of nearshore populations for several hundred kilometers along the North Aleutian Shelf is unknown but probably great. Processes that reduce eelgrass leaves to successively smaller fragments by grazers and microflora are reviewed by Klug (1980). Particulate eelgrass and associated bacteria and fungi compose much of the detritus consumed by invertebrate infauna and epifauna that, in turn, transfer eelgrass carbon to large fish, crabs, birds, and mammals (McConnaughey and McRoy 1979a, 1979b). The role played by bacteria and fungi as both decomposers and food in the detrital pathway is critical (Fenchel 1977; Klug 1980), and susceptible to oil toxicity. Numerous studies indicate that a large portion of the energy assimilated by detritivores comes from micro-

TABLE 3.15—Annual budget for carbon, nitrogen, phosphorus, copper, and silica in Izembek Lagoon by weight (metric tons) and by percent of amount incorporated in the calculated annual production of eelgrass.

	Carbon		Nitrogen		Phosphorus		Copper		Silica	
	Weight	%	Weight	%	Weight	%	Weight	%	Weight	%
Annual production	166,000	100	7,400	100	1,660	100	3.45	100	386	100
Gain while floating	--	--	1.4	0.02	0.08	0.05	0.009	0.26	23.7	6.1
Avian herbivory	−4,980	−3.0	−222	−3.0	−50	−3.0	−0.10	−3.0	−12	−3.0
Loss from beached eelgrass	−158	−0.095	−7.0	−0.094	−1.6	−0.096	−0.0033	−0.096	−0.37	−0.096
Particulate export	160,862	96.9	7,172	96.9	1,609	97.0	3.36	97.4	397	102.8
Dissolved export	19,600	11.8	96	1.3	495	29.8	−260	−7,536	−1,010	−262
Total export	180,462	108.7	7,268	98.2	2,104	126.7	−257	−7,449	−613	−159

SOURCE: Barsdate *et al.* 1974.

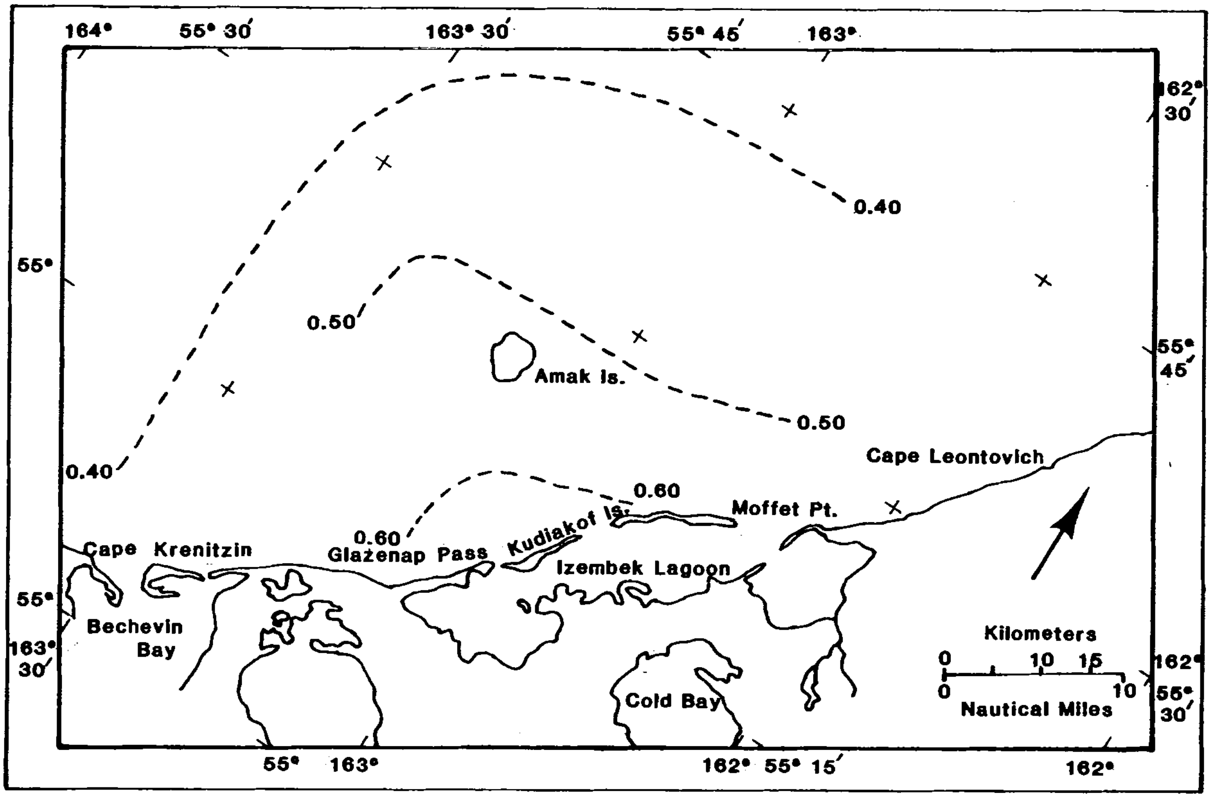


FIGURE 3.14—Dissolved reactive phosphorus distribution (μg-atoms P/liter) in the Bering Sea adjacent to Izembek Lagoon, June 1968 (R V *Acona* cruise 066) (Barsdate *et al.* 1974).

organisms on detritus (Newell 1965; Fenchel 1970, 1972; Hargrave 1970; Mann 1972; Rice 1981).

Within the lagoon, eelgrass serves five primary functions (Kikuchi 1980): (1) It is a dense vegetation that greatly increases substrate area for epiphytic fauna and flora. (2) Water currents and waves are attenuated in eelgrass stands, thereby providing less turbulent habitat for animals. (3) Eelgrass promotes settlement of organic particles and accumulation of sediment. (4) Excessive illumination is reduced which provides a shaded microenvironment with more constancy in temperature than unprotected and intertidal areas. (5) Dense vegetation provides refuge from predators and feeding grounds for invertebrates and juvenile fish, and spawning habitat for some fish.

Little information is available regarding primary production in the Port Moller-Nelson Lagoon complex. O'Clair *et al.* (1981) have described the vegetation at Port Edward at the northeast end of Cape Rozhof near the entrance of Port Moller, and at Middle Point along the western shore of Port Moller. At Point Edward, green algae (*Enteromorpha intestinalis*), diatoms, and red algae (*Porphyra* sp. and *Cryptosiphonia woodii*) were identified. A small eelgrass stand was located at Middle Point. Only two sites were studied in the entire complex, and given the wide expanse of mud flats found there, algal production must be high. Michel *et al.* (1982) described numerous areas of marsh habitat and sheltered tidal flats. Wetlands vegetation (e.g., *Triglochin, Elymus, and Carex*), filamentous green algae, and seaweeds (*Fucus*) probably predominate in these areas in varying degrees.

Port Heiden is essentially a large, laterally expansive wetlands with fringing marshes associated with sheltered tidal flats and deltas. American beach rye (*Elymus arenarius*) is found farthest from the salt water. Sedge and grass communities are dominant species across the flats. Sedges (*Carex* spp.) dominate backwater areas where freshwater influence is greatest, with mixed stands of *Carex* and beach grasses

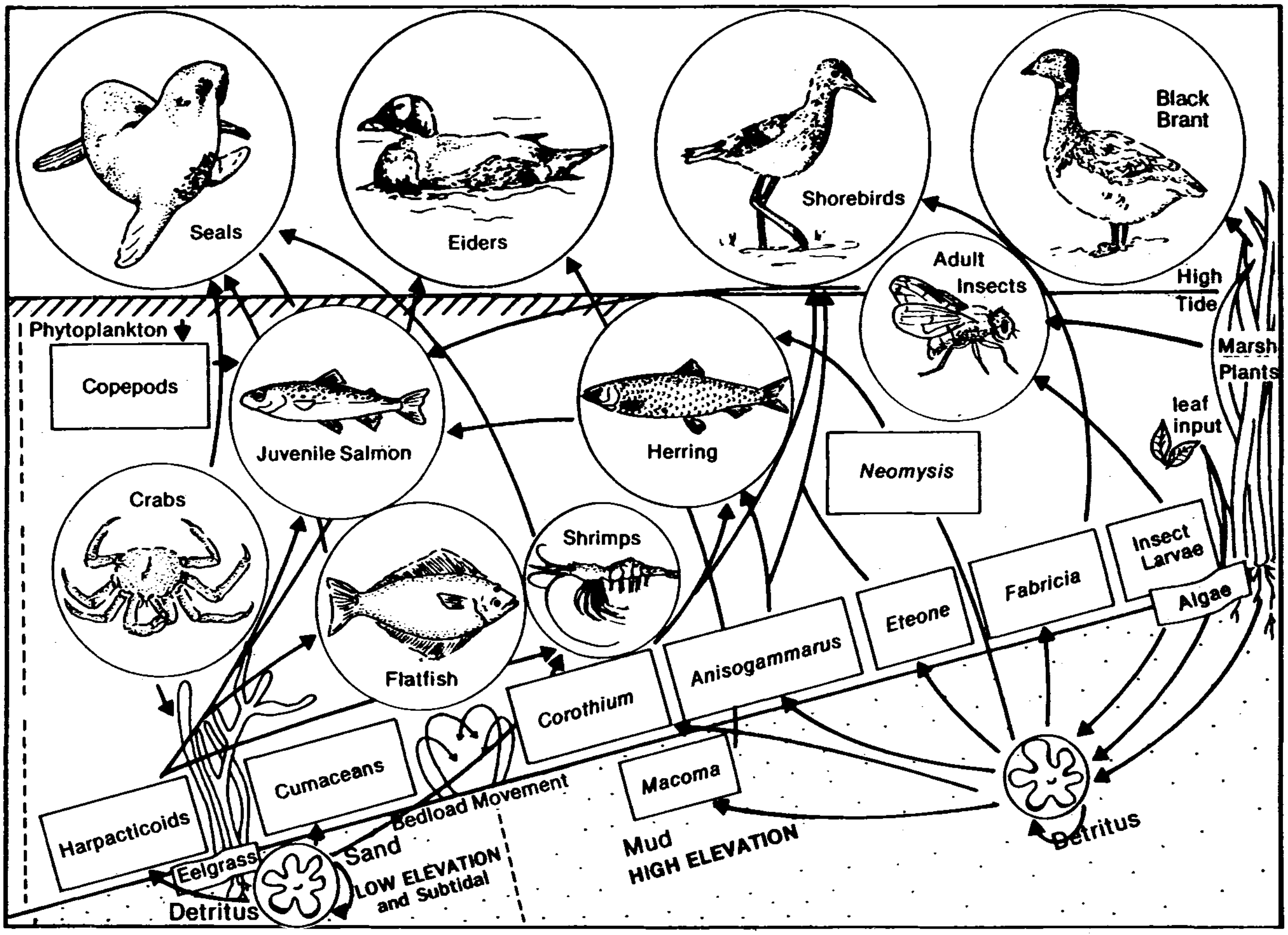


FIGURE 3.15—Food webs and important processes relating trophic levels at an idealized North Aleutian Shelf estuary. (Adapted from Levings *et al.* 1983.)

(e.g., *Triglochin* spp., *Agrostis* spp., and *Scolochloa* spp.) occurring together in varying abundance closer to the water's edge. Other grasses may be present (i.e., *Puccinellia* spp. and *Potentilla* spp.). Brackish waters in stream mouths support green algae and, occasionally, brown marine algae (U.S. Department of Commerce 1981). Filamentous green algae and brown rockweed algae probably occur in various abundances on Port Heiden mud flats.

3.5.2 Invertebrates

The transfer of eelgrass, carbon, and presumably other forms of primary production to birds, mammals, and large fish generally requires 0–2 intermediates by grazing and perhaps several more by the detrital route (McConnaughey and McRoy 1979b). These are seasonally short food webs and are capable of supporting high vertebrate productivity, as evidenced in Izembek Lagoon. Besides a bacterial component, several of the major invertebrate groups common to the North Aleutian Shelf are briefly described below. In addition to plant material these species form a very significant, albeit undetermined, component of any trophic pathways that can be described for estuaries along the north coast of the Alaska Peninsula (Fig. 3.15). Descriptive information has been drawn from Barnes (1968) and Blake (1975).

Nemerteans

Nemerteans are bottom-dwelling, elongate, and often flattened worms, commonly called proboscis worms. They live in shallow waters beneath shells and stones, in algae, or burrow in mud and sand. Nemerteans are entirely carnivorous and feed primarily on annelids, although they also eat other small living or dead invertebrates.

Sipunculids

Sipunculids are often called peanut worms. They are bottom dwellers living from the high tide mark to great depths. They are sedentary, live in sand and mud, and are deposit feeders on the sand and silt of their burrows.

Pelecypods and Gastropods

Pelecypods are bivalve molluscs, including clams and mussels; gastropod molluscs include marine snails. Bivalves are found primarily over soft bottom habitats (sands and muds). They are most commonly filter feeders, trapping food (bottom detritus) on their gills. Marine snails can be herbivorous or carnivorous; some are scavengers, whereas others are suspension feeders or parasites.

Annelids

Annelids include both polychaete and oligochaete worms. Polychaetes can be planktonic (e.g., *Nereis*); sedentary tube-dwellers (e.g., owenids, eunicids, and sabellid and serpulid fan worms) or permanent-burrow dwellers (e.g., glycerids, lumbrinereids, ophelids, and capitellids); or crawlers (e.g., nereids, syllids, and phyllodocid scale worms). Some species are carnivorous, feeding on small invertebrates including other polychaetes. Some nereid polychaetes are browsers and herbivorous scavengers, feeding on algae and detrital plant material. Deposit-feeding polychaetes (e.g., capitellids, sabellids, and terebellids) feed on organic material that settles to the bottom and accumulates between mineral particles. Filter feeders (e.g., serpulid and sabellid fan worms, spionids, and owenids) lack a proboscis and feed on plankton and detritus. Oligochaetes are virtually an unstudied group of marine worms in this part of Alaska.

Crustaceans

Common crustaceans include cirripeds, copepods, isopods, amphipods, mysids, cumaceans, and decapods. Cirripeds, or barnacles, are the only crustaceans that are sessile as adults. They are filter feeders, eating copepods, isopods, amphipods, and other food particles suspended in the water column.

Copepods are very small, shrimp-like crustaceans ranging from less than 1 mm to several millimeters in length and may be free-living or parasitic. Of the three free-living orders of copepods, the calanoids are largely planktonic, the harpacticoids are largely benthic, and the cyclopoids contain both planktonic and benthic species. The bottom-dwelling harpacticoids and some cyclopoids crawl or burrow through the substrate, and many harpacticoids live between sand grains. Most calanoid copepods are filter feeders subsisting on phytoplankton; several species feed on larger organisms in addition to their diatom consumption and a few species are predaceous. Harpacticoids are not known to be filter feeders; they are probably predaceous or graze directly on diatoms. Marine copepods exist in enormous numbers and are patchily distributed. They form a major part of the diet of many marine animals.

Most isopods are 5 to 15 mm in length and resemble sow bugs in appearance. Isopods can crawl, climb, burrow, and even swim, and as scavengers can be herbivorous, but most are omnivorous. They have completely dispersed with filter feeding.

Amphipods are shrimp-like in appearance and resemble isopods in size. This group includes the common beach fleas. Most amphipods can swim, and although most are scavenging detritus feeders, some are filter feeders. The majority of hyperiid amphipods are pelagic; the majority of the gammarid amphipods are benthic. Swimming takes place between intervals of crawling and burrowing. Caprellid amphipods, commonly called skeleton shrimp, are especially adapted for climbing.

Mysids also look like tiny shrimps and are usually 1.5 to 3 cm in length. Most mysid species are filter feeders, several are detrital scavengers, and others carnivores. Mysids may occur in large swarms and may live in algae and tidal grasses.

Cumaceans are about the same size as mysids, but with their inflated carapaces look like tiny horseshoe crabs. Most cumaceans inhabit the bottom where they live buried in sand and mud. They are filter feeders and characteristically exhibit a swarming behavior.

Decapods include the more familiar shrimp and crab species. Many burrow in the sand and mud. The decapod group displays a variety of feeding types, including carnivores, detrital filter feeders, and ominivorous scavengers.

3.5.3 Zooplankton and Micronekton

Most available information on nearshore community composition has been obtained from Izembek Lagoon and may not be extrapolated to other coastal systems. Zooplankton, mostly calanoid copepods, appear to be imported into the bays and lagoons on tidal excursions. Several species of gammarid amphipods, harpacticoid copepods, and hydrozoan jellyfish are dominant micronekton. The copepods *Acartia clausi, Pseudocalanus* spp., *Centropages abdominalis, Eurytemora pacifica, E. herdmani,* and *Tortanus discaudatus,* and the cladocerans *Podon* and *Evadne* are characteristic fauna of the brackish coastal lagoons and estuaries around Bristol Bay (Cooney 1981). At Izembek Lagoon several marine snails, a sea star, and a caprellid amphipod (*Caprella alaskana*) were found on eelgrass (McConnaughey and McRoy 1979b). For the most part these organisms feed directly on the eelgrass, eelgrass detritus, planktonic algae, or epiphytic algae.

3.5.4 Infauna and Epibenthos

With the exception of O'Clair's (1981) intertidal survey and other previously mentioned studies in Izembek Lagoon, little has been done to characterize North Aleutian Shelf estuarine habitats. Bechevin Bay has received only superficial biological sampling in association with coastal sensitivity rankings (Michel *et al.* 1982). Little more than a qualitative description of species groups can be given and that has been largely obtained from embayments farther east than the North Aleutian Shelf, in Bristol Bay (Baxter 1975).

At Bechevin Bay intertidal densities of dominant amphipods (*Eohaustorius* sp.), polychaetes (*Scolelepsis* sp.), and clams (*Macoma* sp.) were low to moderate (7.5–13.4 animals/108 cm). Cumaceans and oligochaetes were also moderately abundant in exposed tidal areas. Mussels and littorine snails were reported in rocky areas, as well as barnacles, amphipods, and polychaetes. Isopods were abundant in shallow backwaters behind protective sandspits.

In a study designed to examine the channeling of eelgrass carbon through a detrital food web to lagoonal fauna, McConnaughey and McRoy (1979b) quantitatively sampled for species abundance and trophic structures in Izembek Lagoon. Although biomass estimates have not been published, dominant infauna and epibenthos and associated food habits have been described (Table 3.16).

Telmessus cheiragonus, the horse crab, is probably the dominant lagoon animal in terms of biomass. This crab's diet consists of 37% eelgrass and 22% detritus, along with some algae and various animals. According to McConnaughy and McRoy (1979b:267):

> Large detrital particles are ingested by various deposit-feeders and sediment ingestors. The echiuroid worm *Echiurus echiurus alaskensis*, the bivalve *Macoma inconspicua*, and the shrimps *Crangon septemspinosa* and *C. dalli* are typical of animals feeding on the sediment surface. Various amphipods, isopods, crabs, gastropods, and polychaetes also feed on large detrital particles. Detritus feeders can reach especially high densities where eelgrass detritus accumulates in beach wracks and intertidal mats. *M. inconspicua* and certain amphipods reach densities of thousands per square meter in these shallow environments. There they fall prey to huge numbers of migratory shorebirds. Detritus-feeders probably provide the major route to carbon transfer from eelgrass to large demersal and benthic fishes, sea stars, crabs, birds, and mammals.

Polychaete worms were most abundant in intertidal surveys within Izembek Lagoon (O'Clair *et al.* 1981). Spionid worms (*Rhynchospio* sp.) and unidentified maldanid species were the most numerous on a low-gradient mud flat in Moffet Lagoon. At Blaine Point, 43 species of polychaetes composed 60% of the collected biomass. Most abundant were syllid, phyllodocid, spionid, and sabellid worms. The sabellid worm *Fabricia sabella* was most abundant at the Izembek study site. Isopods (*Edotea* sp. and *Saduria entomon*), amphipods (*Pontoporeia affinis* and an unidentified eysianassid), and nemerteans were also abundant in Moffet Lagoon. Eelgrass was present at Blaine Point and species diversity was higher there than at other lagoonal study sites. In addition to polychaetes, molluscs were abundant. Bivalves (*Macoma* sp., *Axinop-*

sida serricata, and others); gastropods (*Margarites* sp., *Haloconcha reflexa,* and *Littorina* sp.); several pycnogonids (*Nymphon grossipes, Amnothea latifrons,* and *Proxichilidrim femoratum*); mysids; cumaceans; amphipods (*Corophium* sp. and an unidentified caprellid); decapods (*Crangon* sp.); and several priapulid worms, echinoderms, and ascideans were present. The bivalve *Macoma balthica,* a caprellid amphipod, and a stalked sea anemone were other dominant invertebrates at the Izembek site.

Species diversity was high at Port Moller intertidal study sites. Polychaetes were most abundant numerically and the bivalve *Macoma balthica* most abundant by biomass (wet weight). Abundant polychaetes included *Arenicola gracialis* and *Capitella capitata.* The bivalve mollusc *Axinopsida serricata* was abundant at Port Edward but not Middle Point. Other common organisms were isopods, amphipods, bivalves (*Mytilus edulis* and *Mya* sp.), several marine snails, cumaceans, and harpacticoid copepods.

As is the case for Bechevin Bay, the infauna and epibenthos of Port Moller remain unstudied. However, this component of other protected waters of Bristol Bay has been characterized by habitat and depth (Baxter 1975). Because both Bechevin Bay and the Port Moller areas each have shallow and deepwater zones, and because the characterization is based on collections from nearby bays, species compositions listed are probably applicable (Table 3.17).

The benthic community of Port Heiden has been sampled as part of OCSEAP intertidal studies (Zimmerman and Merrell 1976). The dominant benthic forms in protected waters in this region are the bivalves *Mya* sp. and *Macoma* sp., and the polychaete *Arenicola* sp. (S. Zimmerman, pers. commun., April 1983). Other infaunal species representative of mud flats and shallow intertidal areas (0–10 m) are probably also abundant in Port Heiden.

3.5.5 Fish and Pelagic Crustaceans

Lagoonal fish and their diets have been studied only in Izembek Lagoon (McConnaughey and McRoy 1979b). Dominant lagoonal animals include sticklebacks, greenlings, rock sole, sculpins, gunnels, and crangonid shrimps

TABLE 3.16—Dominant infauna and epibenthos of Izembek Lagoon and their diets.

Scientific Name	Common Name	Diet
(Sponge)	Sponge	Planktonic algae
(Maldanid worm)	Maldanid worm	Planktonic algae
Rhynchospio sp.	Spionid worm	Planktonic algae
Pagurus hirsutiusculus	Hermit crab	Detritus, epiphytic algae, worms
Mya arenaria	Clam	Planktonic algae, zooplankton
Nephthys caeca	Nephthyid polychaete	Sediment, detritus, epiphytic algae
Balanus sp.	Barnacle	Planktonic algae, zooplankton
Arenicola glacialis	Arenicolid polychaete	Sediment, protozoans
Evasterias sp.	Sea star	Bivalves, hermit crabs, worms
Nucella lamellosa	Snail	*Balanus* sp.
Echiurus echiurus alaskensis	Echiuroid worm	Detritus, sediment
Macoma inconspicua	Clam	Detritus, planktonic algae, epiphytic algae, protozoans
Telmessus cheiragonus	Brachyuran horse crab	Eelgrass, detritus
Crangon sp.	Shrimp	Detritus, sediment, epiphytic algae, amphipods, seaweeds, planktonic algae

SOURCE: McConnaughy and McRoy 1979b.

(Table 3.18).

Other fish are undoubtedly found in other North Aleutian Shelf bays and lagoons year round or at certain times of the year. For instance, incidental to an OCSEAP study on the diet of juvenile crabs, Pacific sand lance and several species of juvenile flatfish and crangonid shrimps were found to be abundant in the tidal channels of Port Moller (*Miller Freeman* Cruise Report, Leg I, June 1982). The extent to which seaward-migrating salmon passing through Bristol Bay utilize the coastal bays and lagoons is not known. Herring are known to spawn in Port Moller, yet little is known regarding this stock. Adults are present seasonally in May and June and juveniles for a short period of time after hatching.

3.5.6 Birds

Four small seabird colonies are located inside Port Moller and three in Port Heiden (Fig. 3.10). Estimates of total breeding seabirds tally little more than 2,000 in Port Moller and about 5,700 in Port Heiden (Table 3.19). Glaucous and Glaucous-winged gulls are dominant breeders, especially in Port Heiden. Seabird phenologies and food habits already discussed for coastal colonies are applicable to the estuarine colonies.

Whereas seabirds are in relatively low abundance in the North Aleutian Shelf compared to other areas of their southeastern Bering Sea range, shorebird populations are large and highly dependent on the expansive estuaries and littoral areas for feeding habitat from summer through fall. Winter is also a critical season for some seabirds, such as young-of-the-year sea ducks which are inexperienced in food acquisition. The ice edge becomes an extremely important habitat in winter for marine birds, and also in spring when it acts as a concentration and feeding area. Reviews of shorebird biology have been given by Gill *et al.* (1977, 1981), Gill and Jorgensen (1977), and Gill and Handel (1981), who document seasonal increases and declines in shorebird populations as they move to estuaries and other coastal habitats in the spring,

TABLE 3.17—Habitat determinations and representative infauna and epibenthos from 0- to 10-m depths in Bristol Bay.

	Sand	Sand-Mud	Mud	Rocky
Vegetation			Eelgrass	*Fucus*
Echinoderms	*Leptasterias* *Echinarachnius*	*Leptasterias*		Sea Urchin
Crustaceans	*Crangon*	*Crangon* *Telmessus*	*Telmessus*	*Sclerocrangon* *Balanus*
Pelecypods				
Clinocardium		*nuttallii*		
Macoma	*lama*	*balthica*		
Mya			*arenaria*	
Mytilus				*edulis*
Siliqua	*alta*	*alta*		
Spisula	*polynyma*	*polynyma*		
Tellina	*lutea*	*lutea*		
Gastropods				
Beringius				*kennicottii*
Littorina				*sitkana*
Margarites				*pupillus*
Natica		*aleutica*		
Neptunea				*lyrata*
Thais				*lima*

SOURCE: Baxter 1975.

depart for nesting grounds farther to the north through summer, and return in late summer and early fall for staging before migrations. Some populations remain for the entire 7-month period of April to October.

Critical habitat for shorebirds comprises shallow-water estuaries and passes where broad intertidal areas are bordered by a coastal fringe of dunes, sand beaches, and vegetated lowlands. The most important areas immediately adjacent to the lease area are Bechevin Bay (and False Pass), Izembek Lagoon, the Port Moller-Nelson Lagoon complex, and Port Heiden (Fig. 3.16) (Gill and Handel 1981). Up to 52 shorebird species have been recorded from the North Aleutian Shelf; dominant species and migration periods are listed for this lease area by Gill and Handel (1981). Dunlins (*Calidris alpina*) and Western Sandpipers (*C. mauri*) account for about 80% of the total shorebird numbers in the Bering Sea-Bristol Bay area (Gill *et al.* 1979).

Two periods of migration characterize shorebird movements in the southeastern Bering Sea. The spring migration brings some birds to estuaries in early April for a few days or weeks to feed and wait for the ice to retreat before moving north to breeding grounds. Although portions of Port Moller may be ice-fast during April in cold years, as in 1976, birds still use littoral areas there for feeding. Peak shorebird movement occurs within 2 weeks of May; thus, the spring migration is rather short and direct (Gill and Handel 1981). During spring migration some numerically abundant species such as Western Sandpiper (*C. mauri*) and Dunlin (*C. alpina*) move over the eastern Alaska Peninsula

TABLE 3.18—Major fish and shrimp of Izembek Lagoon and their diets.

Scientific Name	Common Name	Diet
Gasterosteus aculeatus	Threespine stickleback	Land plants and animals, amphipods, zooplankton
Pungittius pungittius	Ninespine stickleback	Land plants and animals, amphipods, zooplankton
Hexagrammos stelleri	Whitespotted greenling	Shrimp, epiphytic algae, fish, worms, amphipods, *Caprella alaskana, Telmessus cheiragonus*, cumaceans, fish, zooplankton
H. octogrammus	Masked greenling	Worms, amphipods, *C. alaskana*, fish, shrimp, epiphytic algae
Hippoglossus stenolepis	Pacific halibut	Worms, amphipods, *C. alaskana*
Pallasina barbata	Tubenose poacher	Zooplankton, amphipods, *C. alaskana*
Lepidopsetta bilineata	Rock sole	Worms, amphipods, zooplankton
Theragra chalcogramma	Pollock	Amphipods, *C. alaskana*, cumaceans, zooplankton
Crangon septemspinosa	Crangonid shrimp	Detritus, sediment, epiphytic algae, amphipods, seaweeds
C. dalla	Crangonid shrimp	Detritus, sediment, epiphytic algae, planktonic algae
Microcottus sellaris	Brightbelly sculpin	Worms, amphipods, snails, eelgrass, fish
Pholis lacta	Crescent gunnel	*Caprella alaskana*, amphipods, zooplankton, isopods, fish
Myoxocephalus polycanthocephalus	Great sculpin	Worms, amphipods, isopods
Heptacarpus camtschatica	Caridean shrimp	No data

SOURCE: McConnaughy and McRoy 1979b.

and make little use of Unimak Pass (Fig. 3.16).

Fall shorebird migration is more protracted and is prefaced by several weeks to a couple of months spent on intertidal areas within estuaries. There, species feed, accumulate fat, and often molt in preparation for migration south. Fall migration may commence in late June and continue through September. Gill and Jorgensen (1977) reported that most species had left the Port Moller-Nelson Lagoon area by early October. The route of the southern migration, again, seems to take many shorebird species overland to the Gulf of Alaska and not through Unimak Pass (Gill *et al.* 1979).

Little nesting and reproduction by shorebirds occurs in or around the estuaries of the North Aleutian Shelf. Gill and Jorgensen (1977) reported that only four species, including Least Sandpiper and Dunlin, nested in large numbers (but still less than several hundred pairs). While breeding *per se* is not extensive, this area and others of the southeastern Bering Sea support the main Alaska or North American populations of 10 shorebird species including Dunlin, Western Sandpiper, and Bar-tailed Godwit (Table 3.20).

Not only does the North Aleutian Shelf provide some nesting habitat, it is of paramount importance to shorebirds as a migration, molting, and staging area in late summer and fall (Gill *et al.* 1981). Several important studies in Nelson Lagoon and Mud Bay have elucidated both temporal abundance of shorebirds in the estuaries, and preferred habitats on which they feed (Gill *et al.* 1977, 1981; Gill and Handel 1981). A significant increase in shorebird abundance in Nelson Lagoon begins in either late June for some species like Western Sandpiper, or July to August for Dunlin and Bar-tailed Godwit. Abundance of most species is greatest in September and by early October populations depart for southern habitats. A total shorebird population of 500,000 to 1 million is estimated in North Aleutian Shelf estuaries in September.

Use of littoral areas by shorebirds was studied by Gill and Jorgensen (1977) in Nelson Lagoon where a variety of habitats (mud flats, mixed sand and mud flats, sandy beaches, etc.) is present. Mud and mixed mud and sand flats are the most prevalent substrates of the lagoon, and the largest percentage of shorebird populations were found in such areas. Invertebrates constitute the major food supply on littoral flats, and adequate feeding by juveniles and post-breeding adults is critical to successful staging.

Protected waters along the north side of the peninsula are used twice a year by huge waterfowl populations for feeding and staging. Addi-

TABLE 3.19—Port Moller and Port Heiden seabird breeding colonies.

Colony Number and Name	Cormorants	Black-legged Kittiwakes	Other Gulls	Murres	Other Puffins	Other Alcids	Seabirds	Total
Port Moller								
18 Gull Island	0	50	100	0	50	30	0	230
19 Entrance Point	0	0	0	0	0	0	1,400	1,400
20 Left Triangle	0	0	50	0	0	0	0	50
21 Unnamed Island	150	0	200	0	0			
Total:	150	50	350	0	50	30	1,400	2,030
Port Heiden								
25 Crescent Island	12	0	0	0	0	0	0	12
26 Meshik	0	0	0	0	0	0	160	160
27 Chistiakof Island	50	0	5,500	0	0	0	0	5,550
Total:	62	0	5,500	0	0	0	160	5,722
Grand total:	212	50	5,850	0	50	30	1,560	7,752

SOURCE: Sowls *et al.* 1978.

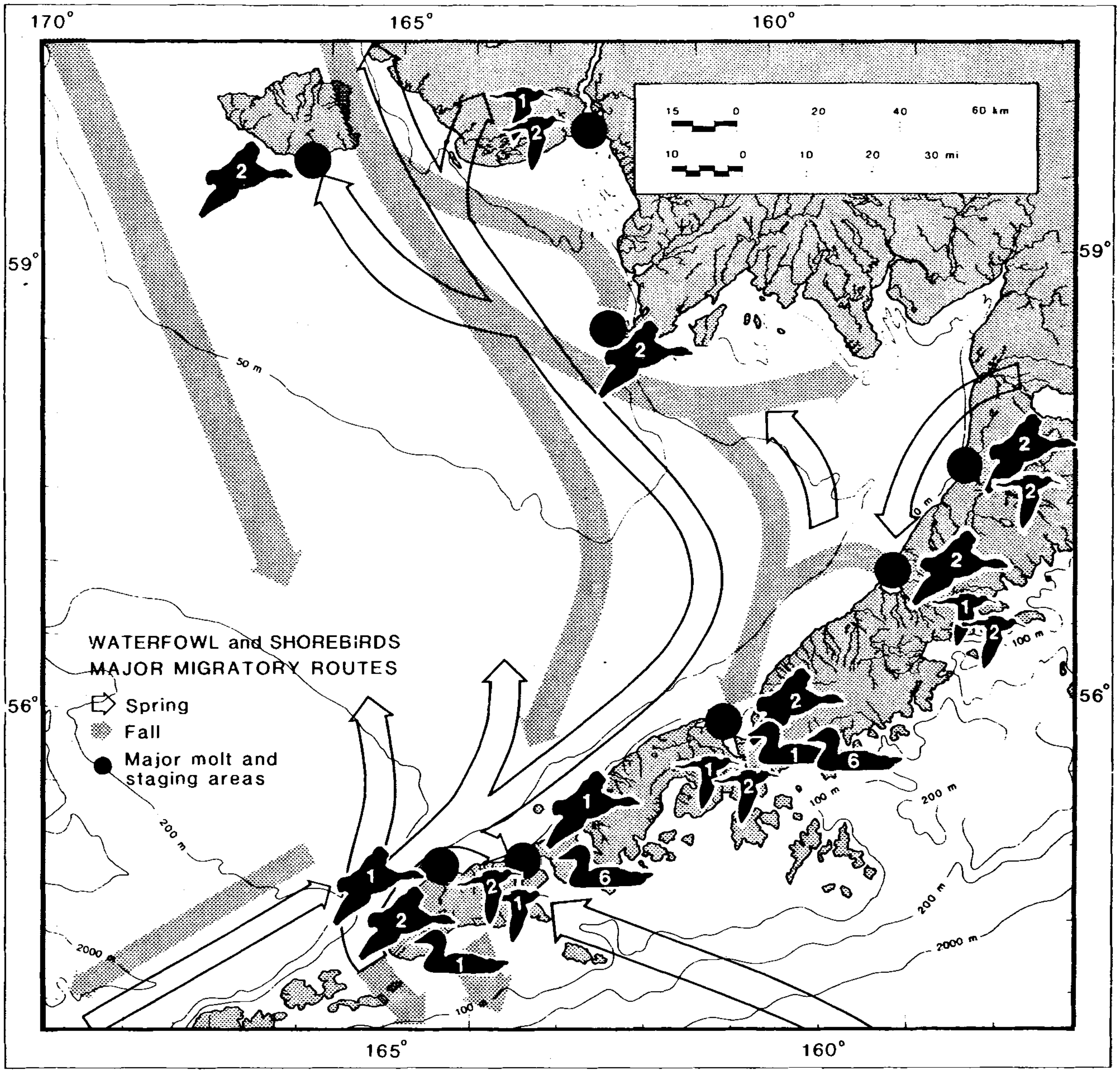
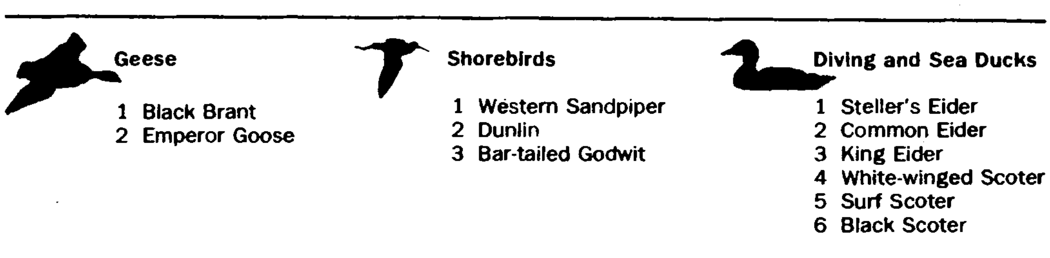


FIGURE 3.16—Major spring and fall waterfowl and shorebird migratory routes in and near the North Aleutian Shelf lease area (Science Applications, Inc. 1981).



tionally, they are used for nesting and wintering by several species. False Pass, Izembek Lagoon, Port Moller-Nelson Lagoon, and Port Heiden comprise tens of thousands of hectares of productive littoral habitat (Fig. 3.17). For some species the link to such estuaries is crucial as entire North American populations may use these areas.

The two periods of principal waterfowl migration occur in early spring and late fall. In early April, waterfowl numbers increase at the southern end of the Alaska Peninsula in Izembek Lagoon and adjacent estuaries (King and Dau 1981) where they feed and stage in preparation for flights to more northerly nesting grounds (Fig. 3.17). The waterfowl follow retreating ice through Bristol Bay and forage on plants and animals in littoral areas of estuaries and in nearshore waters along the coast. Hundreds of thousands of geese, Black Brant, eiders, and dabbling ducks occur in Izembek and Nelson lagoons. As with shorebirds, the North Aleutian Shelf is not used extensively for nesting, and spring migrants move north to breeding grounds near Cape Newenham and the Yukon Delta (Fig. 3.16).

Fall migrations for some species (e.g., Black Brant and Steller's Eider) are first directed to molting and staging areas of the North Aleutian Shelf. Late-arriving geese and Black Brant that reach Izembek Lagoon in late August and early September have already molted and use the habitat for staging prior to a southerly migration in October and even November (King and Dau 1981; J. Sarvis, U.S. Fish and Wildlife Service, pers. commun.). Steller's Eiders, however, arrive at Nelson Lagoon to molt and stage before moving to the south side of the peninsula for winter (Petersen 1980, 1981). Canada Geese and Black Brant leave Izembek Lagoon in early November after accumulating fat reserves for extended flight, while Steller's Eiders, Emperor Geese, and some other species winter more locally in Alaska.

The extreme dependence of certain waterfowl species on the lagoons is reflected in the high percentages of North American populations that use Nelson and particularly Izembek lagoons. The entire world population of Black Brant (150,000 birds) stages in Izembek Lagoon in September and October, as do most Emperor Geese (90,000 birds), Cackling Canada Geese (65,000 birds), adult female Steller's Eiders (100,000 birds), and other sea ducks. Nelson Lagoon is of great importance to numerous waterfowl species, in particular juveniles and males of Steller's Eider (100,000 birds), Pintail, Greater Scaup (which is the most abundant

TABLE 3.20—Shorebird species whose main Alaska (*) or North America (†) breeding or postbreeding populations occur in the eastern Bering Sea region.

Breeding	Postbreeding
†Black Turnstone (*Arenaria melanocephala*)	*American Golden Plover (*Pluvialis dominica*)
†Western Sandpiper (*Calidris mauri*)	†Bar-Tailed Godwit (*Limosa lapponica*)
†Rock Sandpiper (*Calidris ptilocnemis*)	*Whimbrel (*Numenius phaeopus*)
†Dunlin (*Calidris alpina pacifica*)	*Red Knot (*Calidris canutus*)
†Bristle-thighed Curlew (*Numenius tahitiensis*)	‡Sharp-tailed Sandpiper (*Calidris acuminata*)

SOURCE: Gill and Handel 1981.

‡ Breeds in northeastern Siberia. A large but unknown segment of the annual juvenile population moves to coastal western Alaska each September.

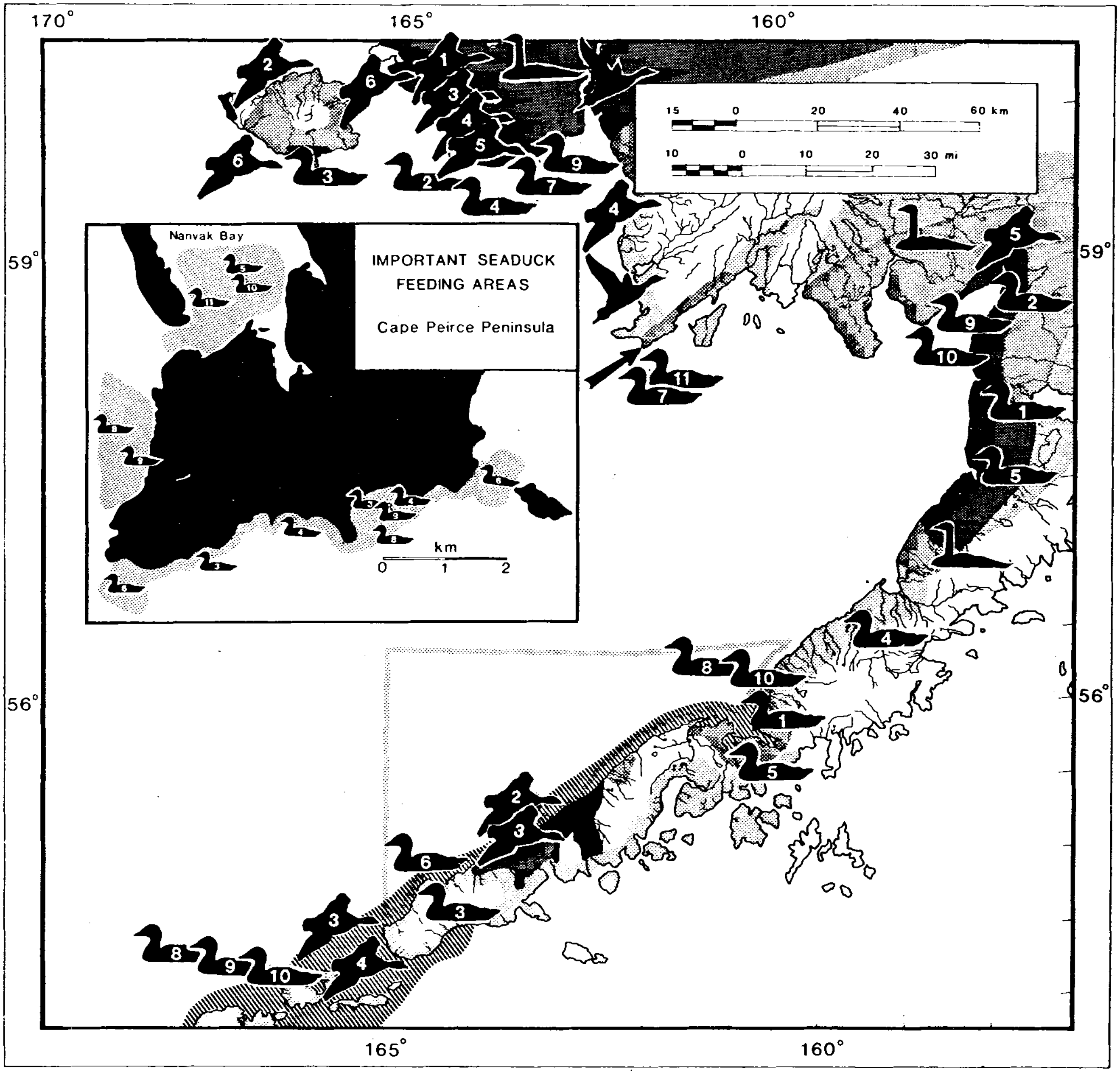


FIGURE 3.17—Use of North Aleutian Shelf littoral areas by major waterfowl species (Science Applications, Inc. 1981).

Waterfowl Nesting and Molting Area

- Low density
- Medium density
- High density
- Very high density
- Winter area

Swans

Whistling Swan

Geese

1 Cackling Canada Goose
2 Lesser Canada Goose
3 Black Brant
4 Emperor Goose
5 White-fronted Goose
6 Snow Goose

Dabbling Ducks

Pintail

Diving and Sea Ducks

1 Greater Scaup
2 Oldsquaw
3 Harlequin Duck
4 Steller's Eider
5 Common Eider
6 King Eider
7 Spectacled Eider
8 White-winged Scoter
9 Surf Scoter
10 Black Scoter
11 Red-breasted Merganser

nesting fowl in the area), and Black Scoter (720,000 birds) (Gill *et al.* 1981; King and Dau 1981). Densities of birds in excess of 1,000/km^2 have been reported for Nelson Lagoon (Gill *et al.* 1981), and abundances of 100-800 birds/km^2 are not uncommon in September and October (Arneson 1981; Strauch and Hunt 1982).

The abundance of waterfowl is greatest in these lagoons from August through October. Steller's Eiders in Nelson Lagoon molt and are flightless for 2 months, in August and September. In general, most species have departed by late October. However, some species (Steller's Eider, scoters, and Emperor Goose) may overwinter on the north side of the peninsula, an event that depends on the extent of ice cover in any year. Severe winters, as in 1976, result in movement of birds into the Gulf of Alaska. The lowest abundance of waterfowl in lagoons like Izembek occurs in June and July, before flocks return for feeding and staging.

All waterfowl use the protected waters as staging areas where some species molt but where all species feed and build fat reserves prior to southern migrations or winter residence elsewhere in Alaska. Many species are carnivorous. The Steller's Eider has been well studied with respect to feeding habits and energy utilization (Petersen 1980, 1981). Steller's Eider primarily feeds on mussels (*Mytilus edulis*) and amphipods (*Anisogammarus pugettensis*) and displays a marked seasonal shift in utilization of each. Mussels constitute more of the birds' diet in late summer and early fall, a shift attributed to the need for higher caloric content to meet greater energy requirements after molting (Petersen 1981). (Mussels contain 1.52 kcal/g whole wet weight, and amphipods 0.47 kcal/g wet weight.) Significantly, all mussels eaten are young of the year (0+ age class), which highlights the species' great dependence on a single food item.

Several dominant species of waterfowl such as Black Brant, Emperor Goose, and Pintail are herbivorous, feeding on eelgrass and other aquatic vegetation (McRoy 1968; King and Dau 1981). The dependence of geese and ducks on Izembek Lagoon is largely tied to the massive stands of eelgrass, and the partitioning and preferences for this resource are intricate (J. Sarvis and R. Jones, pers. commun.). For example, Pintails feed on the seeds of eelgrass while Black Brant feed on specific successional stages of the plant. Together, bird species consume about 15% of the annual eelgrass standing crop of Izembek Lagoon (McRoy 1968).

3.5.7 Mammals

Gray whales have been reported in Nelson Lagoon from late April until late November (NMFS, unpubl. data, 1976-79). They are apparently most numerous in August and September. Twenty-six whales were observed at one time near the village of Nelson Lagoon on 19 August 1976. Gray whales seen in the vicinity of the lagoon in April and May and in November and December are probably in migration.

Mud trails seen behind moving gray whales suggest that feeding is the primary activity in Nelson Lagoon. An invertebrate collected in the vicinity of a feeding whale in October 1977 was identified as *Crangon alaskensis*, a decapod sand shrimp. This shrimp is very abundant during the summer in Alaska Peninsula lagoons. Copulation, nursing, and other social behaviors of gray whales have also been observed in Nelson Lagoon (A. Taber, pers. commun., 1980).

Gray whale use of the lagoon has varied annually from 1976 to 1979. In 1976 and 1977, as many as 30 whales were observed using the lagoon at one time during the summer. It is unknown whether individuals are summer residents, or many different whales use the lagoon. In 1978 and 1979, the number of individuals in the lagoon was apparently fewer than 30. Fluctuating abundance of prey could be responsible for shifts in lagoon use by the whales.

Major haulout areas for harbor seals are located near each of the major bays and lagoons (Everitt and Braham 1980). McConnaughey and McRoy (1979a, 1979b) report the harbor seal as a dominant lagoonal animal in Izembek Lagoon. Available information on seal abundance consists mainly of estimates of numbers at haulout sites; seasonal patterns of use have not been described. The animals are resident to the area and pupping is presumed to occur at haulouts. Seals are usually more coastally distributed but may take refuge in bays and lagoons during storms or in search of prey.

Sea otters have been observed in Izembek Lagoon and Port Moller. Whether the animals were seeking shelter or food is not clear, although they do haul out near Cape Glazenap. Few animals were observed beyond the Port Moller region in 1982 surveys (R. Cimberg, pers. commun., April 1983). Otters tend to be more abundant in Port Moller in late summer and early fall. As winter advances, otters move to the west and possibly south of the peninsula. Sea otters were abundant in nearshore coastal waters immediately north of Bechevin Bay and it has been hypothesized that a certain portion of the North Aleutian Shelf population may move south through False Pass during winter and return in spring. Pupping areas have not been delineated.

3.6 OTHER HABITATS

Three additional regions of special habitats and populations were discussed in light of possible disturbances from OCS offshore oil and gas development in the North Aleutian Shelf. These include Amak Island, Unimak Pass, and the Krenitzin Islands/Sandman Reefs. All are close to the proposed lease area or to possible transportation corridors. Habitat descriptions provided here are not meant to be comprehensive and only those wildlife resources especially vulnerable to the proposed action are described.

3.6.1 Amak Island

Amak Island is a rocky island of volcanic origin located in Bristol Bay northwest of Izembek Lagoon. The shoreline consists of stretches of beach boulder broken by steep to vertical cliffs. *Fucus* sp. and *Alaria* sp. are abundant coastal vegetation (O'Clair *et al.* 1981). Mussels are sparsely represented near shore, where dominant invertebrates include small forms of polychaetes, gastropods, pelecypods, amphipods, and isopods. The decorator crab (*Pugettia gracilis*) is abundant in nearshore waters surrounding the island. The Sea Lion Rocks are located directly to the north of Amak Island. This island consists largely of rocky cliffs and bedrock slopes. Coastal vegetation is dominated by rockweed (*Fucus* sp.) and other floral species commonly associated with this type of beach habitat.

A small seabird colony of almost 2,500 birds is located on Sea Lion Rocks and is dominated by murres (about 2,300 birds). One of the larger North Aleutian Shelf seabird colonies (over 11,000 birds) is situated on Amak Island. Cormorants (1,500 birds), Black-legged Kittiwakes (3,600 birds), and murres (6,500 birds) are dominant breeding species at the Amak Island colony.

Amak Island and Sea Lion Rocks are currently the largest haulout area in Bristol Bay for Steller sea lions, who begin arriving at the islands by early March and occupy haulouts through mid-October. They are most abundant April through August. Almost 4,500 animals were observed in August 1981 and peak numbers may occur during that month. Counts made from 1960 to 1981 indicate that average numbers decline from about 3,500 sea lions in June to a little more than 2,000 in October (Frost *et al.* 1983).

Sea Lion Rocks is the only large breeding rookery (2,000 sea lions) along the north coast of the Alaska Peninsula (Frost *et al.* 1983); nearby Amak Island is used exclusively for hauling out, not as a rookery (Braham *et al.* 1977).

3.6.2 Unimak Pass

The role of Unimak Pass as a major migration passage for bird and mammal populations entering and leaving the Bering Sea underscores this region's importance to the continued well-being of many species.

Strauch and Hunt (1982) have described the high densities and large aggregations of seabirds in and near Unimak Pass. Sooty and Short-tailed shearwaters are particularly abundant in Unimak Pass where a mean population estimate of 1.1 million shearwaters has been recorded in the fall (U.S. Fish and Wildlife Service, unpubl. data). The mean density of all marine birds (Northern Fulmars, shearwaters, storm-petrels, Glaucous-winged Gulls, kittiwakes, murres, Tufted Puffins, other alcids) in the summer is 224 birds/km^2, corresponding to an estimated population of 720,000 birds (Strauch and Hunt 1982). Unimak Pass was identified as one of the major areas where spilled oil could severely reduce certain North American bird populations.

Unimak Pass is also the major migration corridor for marine mammals into and out of the Bering Sea (Braham *et al.* 1982). Humpback, fin, and gray whales, and northern fur seals regularly use Unimak Pass (Figs. 3.10 and 3.11). Virtually the entire eastern Pacific population of gray whales travels through the pass on northerly and southerly migrations (Braham 1977; Hall *et al.* 1977; Rugh and Braham 1979; Hessing 1983). Fin and humpback whales move through Unimak Pass and other Aleutian passes. Fur seals move through the pass in large numbers en route to the Pribilof Islands and later in the fall in departure from the southeastern Bering Sea.

3.6.3 Krenitzin Islands and Sandman Reefs

Several dominant species of breeding seabirds are concentrated at major nesting colonies on the Krenitzin Islands and Sandman Reefs. The majority of breeding seabirds on the south coast of the Alaska Peninsula are alcids, a feature that may heighten the overall sensitivity of these colonies to small oil spills. Alcids are colonial nesters which aggregate in high densities. Estimated breeding populations in this region are larger than those of the North Aleutian Shelf proper (Table 3.21). Cliffs and steep slopes afford preferred nesting habitat which may range from bare rock ledges for murres to tunnels for puffins (Sowls *et al.* 1978). Such habitat is inaccessible to large numbers of predators. Bailey and Faust (1980) correlated the presence or absence of seabird colonies on the Sandman Reefs with foxes and described the substantial impact these predators can have on unprotected populations.

Eggs of alcids, petrels, and gulls are present in nests on the Krenitzin Islands from mid-May through July (Strauch and Hunt 1982). Chicks are most abundant from early July into late August although some do not fledge until late September. The critical reproductive period is May through September. This period is often prefaced by a couple of months of feeding by adults. After fledging by September, adults and juveniles often remain abundant on the islands through November. Their major activity appears to be feeding and establishing the energy stores required for long distance migration.

The extent of ice cover in the southeastern

TABLE 3.21—Estimated breeding populations of seabirds adjacent to the North Aleutian Shelf.

Species	Krenitzin Islands	Unimak Pass	Sandman Reefs False Pass
Northern Fulmar	4	0	0
Fork-tailed Storm-Petrel	250,000+	0	200,000+
Leach's Storm-Petrel	138,000+	X*	146,000
Cormorants	11,800	2,700	15,000
Glaucous-winged Gull	24,000	850	31,440
Black-legged Kittiwake	2,000	X	6,750
Red-legged Kittiwake	2,300	0	0
All murres	107,400	310	20,650
Pigeon Guillemot	11,800	120	772
Ancient Murrelet	27,500	0	10,000
Cassin's Auklet	8,600	0	228,000
Parakeet Auklet	600	0	400
Crested Auklet	0	0	0
Least Auklet	0	0	0
Whiskered Auklet	14,000	0	0
Horned Puffin	12,000	100	172,210
Tufted Puffin	1,227,000+	530,000	194,950
Total:	1,837,004+	534,080	1,025,992+

SOURCES: Sowls *et al.* (1978), Bailey and Faust (1980), and Strauch and Hunt (1982).

* X = present.

Bering Sea dictates the magnitude of waterfowl and shorebird movement from the North Aleutian Shelf to the south side of the Alaska Peninsula in late fall. From August to May (through winter) about 28,000 geese including Black Brant reside in the bays between Pavlof Bay and False Pass, as do about 45,000 sea ducks (J. Sarvis, personal communication at the meeting).

Sea lion surveys delineating major haulouts and pupping and breeding rookeries in the Gulf of Alaska have identified several such sites in the vicinity of Cold Bay (Calkins and Pitcher 1979) (Table 3.22). Sea lions use these islands for haulouts throughout the year, although the composition of animals prior to May can vary from a single age class and sex to both sexes and all age groups (Calkins and Pitcher 1978). Beginning near the first of May the haulout status shifts to rookery areas. Pupping and breeding occur from late May to early July.

Sea otters are abundant along the south side of the Alaska Peninsula in areas of irregular shoreline and extensive shoaling. These otters have not been studied and population estimates are not available. Sea otters are present year round around False Pass and may be more abundant during winter months when animals from the coastal North Aleutian Shelf move south. Although otters are known to occur around the Krenitzin Islands, their use of and abundance in coastal habitats west of False Pass is not well documented. Other areas affording excellent sea otter habitat include the Shumagin Islands and Pavlof and Sanak islands (Calkins *et al.* 1975).

TABLE 3.22—Sea lion populations at major haulouts and pupping and breeding rookeries in the vicinity of Cold Bay.

Location	Adults	Pups (Live)	Pups (Dead)
Castle Rock	541	0	0
Atkins Rock	2,943	2,750	107
Chernabura Island	2,758	486	0
Pinnacle Rock	3,692	615	0
Clubbing Rock	2,663	725	0
Sanak Island	1,320	30	1
Total:	13,917	4,606	108

SOURCE: Calkins and Pitcher 1979.

NOTE: Population estimates from observations in June and July of 1978.

3.7 EFFECTS OF EXPOSURE TO OIL

The immediate effects of heavy oiling of the coastal zone are obvious: widespread death of plants and animals. In the longer term, the effects are more variable and subtle, and depend on the behavior and persistence of the spilled oil. Oil behaves differently in different coastal environments, depending on the porosity of the sediments and the wave-erosion activity of the area. In high-energy environments (rocky shores), the stranded oil coats the rocks and hardens into a tough, tarry "skin." The oil is gradually removed by wave erosion, at a rate which declines as weathering progresses. As much as 50% of the oil may be lost within the first 1.5 to 2 years, although pools of oil are likely to collect in hollows among the rocks, where it is protected by a skin of weathered oil and may remain essentially unchanged. On cobble and sandy beaches the oil may sink deeply into the sediments as controlled by tidal pumping and sediment grain size. Wave erosion is less effective in this environment and slow microbial degradation assumes a more important role in the removal of the oil. However, because the oil is mobile in these porous systems, some of it may be gradually returned to the overlying water where it is subject to dissipation and may also exert chronic toxic effects on the biota of the system. In muddy sediments penetration is minimal, and only the upper few centimeters are affected, but because these are low-energy environments (marshes) the stranded oil may persist for decades (Vandermeulen 1982).

3.7.1 Microbial Organisms and Communities

Recent reevaluations of marine microbial organisms and communities have indicated that bacteria have the potential to form a large active biomass component of the food chain. Bacteria are extremely efficient organisms in accumulating, assimilating, and mineralizing dissolved, dilute organic matter, the greatest proportion of organic matter in aquatic habitats. Although assimilation efficiencies greater than 50% have been reported using defined substrates at naturally occurring concentrations and natural bacterial populations, cell yields vary with carbon source and nutrient conditions (Stouthamer 1979). Bacteria, however, are able to utilize an almost infinite variety of carbon sources under widely differing physical and chemical conditions. The result is that bacterial biomass may be equal to that of the faunal crop, at least in nutrient-rich nearshore waters (Fuhrman and Azam 1980).

The pelagic component of the marine bacterial flora, while playing a major role in marine heterotrophic activity, also forms the major food source for protozoans and other water column bacterial predators. Burbanck (1942) found that the type of bacterial species consumed can affect the growth rate of many ciliates. Burbanck and Eisen (1960) observed that a ciliate predator would only grow on paramecia fed specific strains of bacteria. Fenchel (1968) reported that while some ciliated protozoans are omnivorous, most show specificity regarding the kinds of bacteria consumed. Factors which would result in changes in the composition of the bacterial population could affect the growth of water column bacterial predators.

Detrital particles observed by epifluorescent and scanning electron microscopy have a sparse (2–15 bacterial cells per 100 μm^2 of surface) complex attached bacterial flora of relatively constant composition (Fenchel and Jorgensen 1977). The adhesion and growth of bacteria on detrital particles may result in the eventual solubilization of the particle via bacterial enzymatic activity. More importantly, the nutrient-rich bacterial cells improve the nutritional quality of the detrital particles (Morita 1980). Many detrital feeders use this bacterial flora, and to a lesser extent the detritus particle, as a food source. The importance of this aspect of the marine bacterial population in the ocean's food web, however, is still a controversial matter since 90% of the heterotrophic activity of sea water has been found to be associated with organisms that pass through 1-μm filters (Azam and Hodson 1977); that is, associated with particles the size of free-swimming bacterial cells.

The benthic microbial population provides a food source for organisms living in and on the sediments. Tietjen (1980) reported that the daily dry weight consumption of benthic microflora ranges between 0.1 and 10 μg/animal with the selection of food being related to cell size and shape, animal buccal morphology, and chemical differences in cells, all of which indicate that the benthic meiofauna are not indiscriminate feeders. In addition, the benthic microflora carry out the mineralization of organic matter, the cycling of nitrogen and phosphate (key elements in the nutrition of bacteria, which are often present in marine environments in growth rate-limiting concentrations), and the conversion of sulfur compounds (Fenchel 1980). All are bacterially mediated reactions indirectly involved, but absolutely required, in the maintenance of the ocean's food web.

Marine microorganisms also carry out other processes indirectly affecting the food chain. For example, some produce enzymes for the hydrolysis of insoluble plant materials (lignin, cellulose) found in detrital particles, making them available as energy sources for higher forms; some have the ability to fix atmospheric nitrogen; and some produce growth factors (ectocrine compounds) required for the growth of, but not produced by, other organisms. These functions result in a complex interdependence of bacterial and invertebrate communities in marine sediments (Siebers 1982).

The chemical composition and morphology of bacteria vary from species to species and with the nutritional conditions of the environment in which they are grown. Therefore, the nutritional value of the bacterial components of detritus as well as the free-living bacteria will depend on the type of bacteria and the nature of the substrate(s) which sustained their growth. The introduction of any foreign material—petroleum, for example—into the marine environment could produce changes in the chemical or morphological composition of the bacterial population which could affect their role in the food chain.

The effect of petroleum on marine microorganisms depends on a number of factors; e.g., the oil spilled, the conditions of the spill, and the impacted area's previous history of exposure to hydrocarbons. In general, exposure to oil is reflected as (1) change in the numbers and types of microorganisms present and (2) change in microbe-related activities. The magnitude and type of response will depend on whether the area has been previously exposed to petroleum or petroleum by-products. Chronic low-level exposure will select for and maintain a bacterial population that is relatively insensitive to the toxic effects of oil. A catastrophic spill in this environment will produce rapid and dramatic increases in the number of hydrocarbon-degrading bacteria, as was seen after the *Amoco Cadiz* spill (Atlas and Bronner 1981). The effect of a catastrophic spill in a pristine environment will be much different. Those microorganisms that are sensitive to the new hydrocarbons will be killed, while those with the genetic potential to utilize some of the new hydrocarbons as a carbon and energy source will increase in number, mass, or both. There also will be a component of the microbial population which will not be affected by the incursion of oil. It is very possible that a relatively large spill in pristine waters will not produce any notable change in the microbial community because of the small percentage of hydrocarbon utilizers in these waters. Atlas (1982:29) states:

> In unpolluted ecosystems, hydrocarbon utilizers generally constitute less than 0.1% of the microbial community; in oil-polluted ecosystems, they can constitute up to 100% of the viable microorganisms. The degree of elevation above unpolluted compared reference sites appears to quantitatively reflect the degree or extent of exposure of that ecosystem to hydrocarbon contaminants.

The microbial communities in the sediments and the water column of the southern Bering Sea contain very few hydrocarbon-degrading microorganisms as compared to communities in the Beaufort Sea and Cook Inlet (Table 3.23). This situation reflects the lack of previous exposure of the southern Bering Sea microbial communities to petroleum. As a result, the response of these communities to the release of petroleum would be extemely small. The Baffin Island Oil Spill experiment, which was conducted in a similar high latitude pristine area, resulted in no noticeable change in any of the microbial parameters examined (Bunch *et al.* 1983; Eimhjellen *et al.* 1983).

Studies on the effects of oil on the species composition of marine heterotrophic bacterial populations are hampered by the inadequacy of existing taxonomic techniques. However, there are reports of increased species diversity in oiled salt marshes (Crow *et al.* 1975; Hood *et al.* 1975) and significant shifts in the generic composition of pelagic and intertidal beach samples upon enrichment with crude oil (Westlake and Cook 1980). These reports may be contrasted with that of Hollaway *et al.* (1980) who found no difference in the taxonomic or physiological makeup of bacterial populations recovered from an active oil field site and control sites in the Gulf of Mexico.

The chemical composition of the microbial cell depends in part on the growth substrate. For example, a hexadecane-utilizing *Acinetobacter* sp. contained hexadecane inclusion bodies and intracellular cytoplasmic membranes when grown on n-alkane hydrocarbons, but not when grown on non-hydrocarbon

TABLE 3.23—Enumeration of microbial populations including hydrocarbon utilizers.

Location and Sampling Date	Total Number		Hydrocarbon Utilizers	
	Water	Sediment	Water	Sediment
South Bering Sea August 1980	2.6×10^5	1.9×10^9	0.1	30.0×10^2
South Bering Sea January 1981	9.3×10^5	2.95×10^9	2.2	24.7×10^2
Beaufort Sea Summer 1978	6.7×10^5	1.6×10^9	26.0	2.5×10^4
Cook Inlet April 1977	4.2×10^5	2.6×10^9	37.0	6.6×10^3

SOURCE: Atlas 1982.

sources (Kennedy and Finnerty 1975).

Studies on the effect of petroleum on marine heterotrophic activity have been concerned with (1) uptake and mineralization of low molecular weight compounds, including glucose, glutamate, and acetate; (2) the hydrolysis of complex insoluble structural materials, such as cellulose and chitin, and storage compounds such as starch; (3) nitrogen fixation; and (4) denitrification rates. The results of these studies are conflicting and confusing, because the type and magnitude of the effect of oil on these processes depend on the composition and concentration of the oil used and the previous exposure history of the experimental microbial populations (Griffiths and Morita 1980). In general, a catastrophic spill in a pristine environment such as the North Aleutian Shelf would result in a significant decrease in all of these processes (Table 3.24), due to major shifts in the structure of the population by the strong selective stimulation of the spilled oil. Alternatively, in regions receiving chronic input of petroleum hydrocarbons, there would be less of an effect (Griffiths and Morita 1981; Winfry and Ward 1981).

As a result of the study of major oil spills over the past decade, one of the areas to receive increasing attention is the effect of petroleum on sediment activities. A normal marine sediment consists of a thin oxidized layer, where microbial mineralization of organic matter takes place, on top of an anaerobic zone where hydrogen sulfide and methane production occur (Vanderborght *et al.* 1977). The oxidized zone plays a major role in the microbes' potential contribution to the marine food web. Infaunal species present in sediments mix the oxidized and anaerobic layers and prey on the bacterial biomass produced as a result of the microbial mineralization processes. Griffiths and Morita (1981) report that oiled sediments from lower Cook Inlet lost this oxidized layer, resulting in a decrease in mineralization and loss of infaunal species. An increase in methane production and a smell of hydrogen sulfide was also observed. These observations all indicate marked changes in the microbial activities in these sediments (Table 3.24) and probably in the microbial populations.

In summary, the introduction of petroleum into the marine environment has a marked effect on the numbers, types, and activities of marine microorganisms. There is no direct evidence for a deleterious effect of petroleum on the role of microbes in the marine food web. However, changes in the composition and types

TABLE 3.24—Changes in the mean microbial activity of sediment samples exposed to crude oil for 18 months.

Variable	Control Sediment	Oiled Sediment	Percent Difference*	$P \leq$
Acetate uptake	38	24	−37	0.05
Glucose uptake	113	65	−42	0.05
Glutamate uptake	1,223	728	−40	0.05
Acetate, percent respired	31	37	+10	NS
Glucose, percent respired	22	40	+45	0.001
Glutamate, percent respired	47	54	+17	0.05
Denitrification	170	45	−73	0.01
CO_2 production	15	26	+73	NS
Phosphatase activity	0.38	0.24	−37	0.001
Arylsulfatase activity	0.70	0.42	−41	0.001
Methane production	2.2	6.3	+186	0.01
Hydrogen ion concentration	3.4	6.2	+82	0.05
Redox potential (bottom)	−207	−447	−116	0.001
Direct counts (number)	5.82	5.13	−12	NS

SOURCE: Griffiths and Morita 1980.

* Relative to the control mean.

of bacteria in areas impacted by oil could affect the feeding habits of bacteriovorous species, and changes in activity patterns, particularly of benthic microbes, could produce effects on mineralization of organic matter and related processes. Effects on pelagic microbial flora will in most sites be short term because of the relatively rapid interchange of waters. However, the impaction of sediments with petroleum, as would occur in marshlands and bays, and as seen in the *Amoco Cadiz* and the *Metula* spills, could result in long-term effects on the role of microbes in the food chain, at least in proximity to the spill.

3.7.2 Sea Grass

There is little information in the literature concerning eelgrass (*Zostera marina*) and hydrocarbon contamination. However, *Z. marina* is one of a group of rooted marine vascular plants, the sea grasses, with similar ecologies. Information on these other sea grasses, such as *Spartina alterniflora, Thalassia testruderium,* and *Ruppia martina,* is relevant to *Z. marina*.

The toxicity of oil to salt marsh flora and fauna and the length of recovery of oiled marsh ecosystems vary with several factors, the most important being the type of oil spilled. Recovery of the marsh grass *S. alterniflora* from No. 2 fuel oil spills is relatively slow, on the order of 4 to 5 or more years (Krebs and Burns 1977; Hampson and Moul 1978; Burns and Teal 1979). This slow recovery is assumed to be caused by a relatively high toxicity, and by the oil's ready penetration of the sediments, killing roots and rhizomes. Crude oil and No. 6 fuel oil are generally considered to be less toxic to marsh grasses than is No. 2 fuel oil (Stebbings 1970; Baker 1971; Thomas 1973; Hershner and Moore 1977). Indeed, No. 6 fuel oil has been reported to increase the net production, density, and flowering of a *S. alterniflora* marsh 1 year after oiling (Hershner and Moore 1977). In contrast, a delayed mortality in a *S. alternifora* marsh was observed by Thomas (1978) a year after the tanker *Arrow* spilled Bunker C oil in Nova Scotia. The possibility that heavier oils may be more toxic than previously believed is supported by an experimental spill of crude oil in a Virginia marsh, in which *S. alterniflora* had not fully recovered 2 years after the initial oiling (Bender *et al.* 1977).

The circumstances of the oiling are next in importance in determining the effects of oil on salt marsh vegetation. Long-term, chronic, subacute hydrocarbon pollution has been clearly identified as the cause of significant damage to marsh vegetation (Baker 1970). The species affected included *Salicornia* sp., *Suaeda maritima, Aster tripotum,* and *Spartina anglica*. Moderate single-incident pollution has been reported to cause minor, short-term changes in temperate salt marsh vegetation, with few, if any, lasting effects (Baker 1973). Preliminary studies conducted by McRoy and Williams (1977) on *Zostera* are in agreement. Exposure of *Zostera* to hydrocarbons in laboratory experiments inhibited productivity up to 2.2 times that of unexposed plants. If the exposure time was short, one tidal cycle, and if the plants were allowed a recovery period in clean seawater, the inhibition was not as severe.

The time of oiling, whether in the growing season or the nongrowing season, seems to be irrelevant; Baker (1970) presented evidence that the oiling of *Spartina* outside the growing season is not lethal but it is probable that the seasonal effect in this case was confounded with the type of oil, as these results are not supported by others. In general, heavy oiling of *Spartina* in any season is lethal (Holt *et al.* 1978).

Disruption of sea grass beds can have serious deleterious effects on the coastal environment. The effects of the massive disruption of eelgrass beds by wasting disease in the 1930's persisted for 30 years (Rasmussen 1977). Despite the high productivity of the sea grasses, return to a normal state after disruption is slow because it involves ecosystem development. The microbial aspects of detrital processes must build up nutrient levels in the sediment sufficient to support the grass bed and ecosystem.

Lastly, *Zostera* growing in oiled sediments has been found to accumulate significant levels of hydrocarbons (Vandermeulen and Gordon 1976), thereby raising the question of possible transfer of these compounds through the food chain.

3.7.3 Crabs and Shrimps

Different phylogenetic and habitat groups of animals have definite patterns of sensitivity to oil (Rice *et al.* 1983). In general, sensitivity to short-term exposures increases from lower invertebrates to higher invertebrates to fish. The variation in sensitivities among these groups is large, and there are many exceptions. The most distinctive sensitivity pattern is the correlation between sensitivity and habitat (Table 3.25). Pelagic animals are most mobile, have the most uniform environment of the three habitat groups, and are the most sensitive to stress (LC_{50}'s range from 1 to 5 ppm). Intertidal animals, which inhabit a highly variable and stressful habitat, have little or no mobility but are well adapted to withstand natural stresses (LC_{50}'s are usually >8 ppm). Benthic species are moderately tolerant of stress (LC_{50}'s range from 3 to 8 ppm).

Within each species the sensitivity to oil is usually different for each life stage. Larval stages, because of greater surface-to-volume ratios and higher metabolic rates, are usually more sensitive than the adults. The sensitivity of eggs seems to vary in parallel with the permeability of the egg membrane and the lipid content of the egg. For coonstripe shrimp (*Pandalus hypsinotus*) exposed to the water-soluble fraction of Cook Inlet crude oil, Rice *et al.* (1983) report 96-hour LC_{50}'s of 1.4 ppm for adults, 1.0 ppm for stage I-III larvae, and greater than 1.4 ppm for eggs.

Typical concentration ranges producing lethal and sublethal effects in adult and larval marine organisms are given in Table 3.26. Crustaceans, because of the molt cycle, are among the more sensitive marine organisms; concentrations of 1-4 ppm are lethal to a large fraction of both adult and larval crabs and shrimps. In general, shrimps are twice as sensitive as crabs and the larvae of both shrimps and crabs are 2-3 times more sensitive than the adults. Ninety-six-hour LC_{50}'s for four species of adult shrimps and juvenile king crabs were between 1.9 and 4.3 ppm. The LC_{50}'s for the stage I larvae of the same species were between 0.95 and 1.8 ppm. Moreover, EC_{50}'s, observed as "failure to swim," were between 0.2 and 0.7 ppm for these organisms and the effect was apparent in 10-20 minutes (Rice *et al.* 1983). Even though planktonic crustacean larvae that have stopped swimming may live up to 10 days in the laboratory, "failure to swim" in the open ocean probably results in almost immediate death.

TABLE 3.25—Ranges of sensitivities of different fish and shellfish habitat groups to the water-soluble fraction of Cook Inlet crude oil.

	96-hour LC_{50}'s (ppm)		
	Pelagic	Benthic	Intertidal
Fish	1-3	4- >5	>12
Crabs and Shrimps	1-5	3-5	8- >10
Molluscs	--	4- >8	8

SOURCE: Rice *et al.* 1979.

The relative insensitivity of crustacean eggs to hydrocarbons (Rice *et al.* 1983) would seem to have environmental implications, but as the eggs are carried by the female throughout development and so cannot survive without the adult, the LC_{50} for crustacean eggs is effectively the same as that of adults. Exposure to hydrocarbons has been reported to have a significant effect on the number of live young produced per brood in several species of crustaceans (Berdugo *et al.* 1977; Tatem 1977; Geiger and Buikema 1982). For example, gravid female grass shrimp (*Palaemonetes pugio*) exposed to 1.4 ppm for 72 hours released 9 larvae each, 1 week later, as compared to 45 larvae released by each of the control shrimp (Tatem 1977).

Growth has been reported to be markedly reduced by exposure to hydrocarbons. Reduction in growth rates would seem to entail clear ecological consequences and probably reflects the cumulative impact of interacting physiological, biochemical, and behavioral dysfunctions. In crustaceans, reduced growth may be the result of interference with chemosensory food-finding mechanisms (Olla *et al.* 1981), altered physiology and increased energy expenditure (Johns and Pechenik 1980; Rice *et al.* 1983), decreased feeding (Edwards 1978; Samain *et al.* 1980), interference with molting (Katz 1973; Cucci and Epifanio 1979), or some combination of these. The effects on crustacean growth and development seem to be reversible, however, if the concentrations are low. Both Tatem (1977) and Laughlin *et al.* (1978) reported that there was no significant size difference between the experimentals and the controls of crabs exposed continuously from hatching to 6 months of age

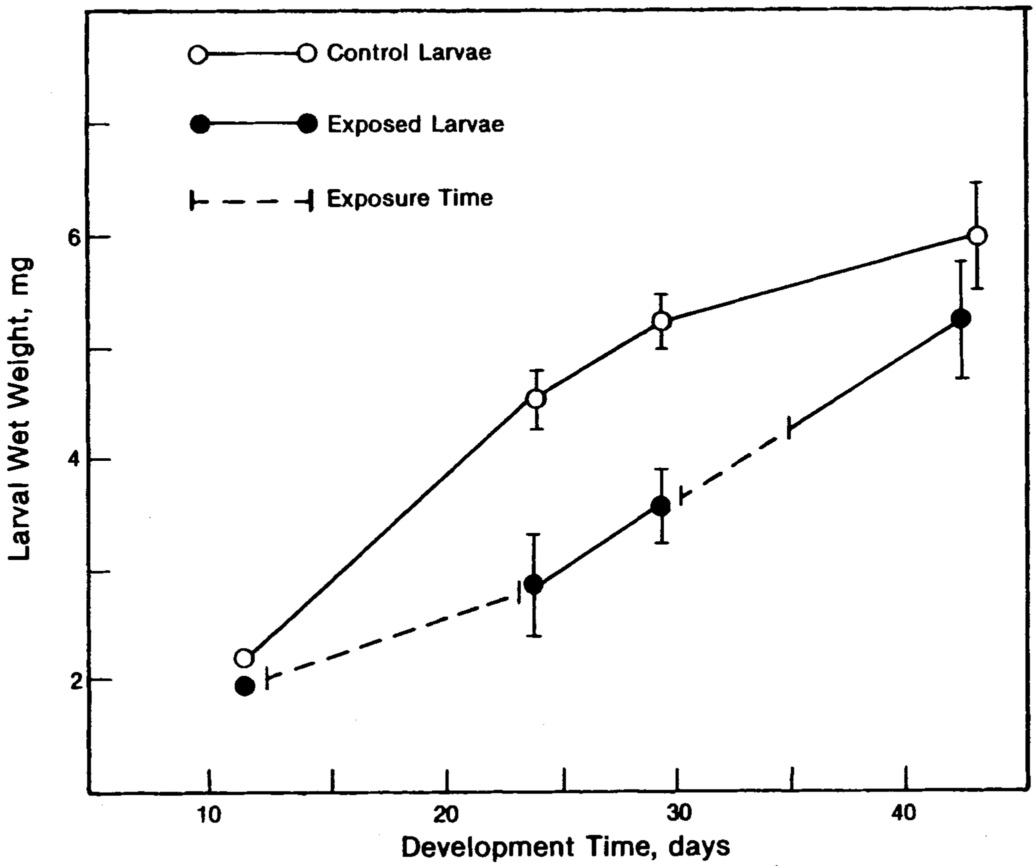


FIGURE 3.18—Effects of exposure to a dilute WSF of No. 2 fuel oil (0.5-0.8 ppm total hydrocarbons) on the growth of grass shrimp (*Palaemonetes pugio*) larvae. Larvae were exposed to the WSF only during periods indicated by the dashed lines. Each value represents the mean wet weight of 10-12 larvae. Vertical lines represent standard errors of the mean. (Adapted from Tatem 1977.)

and grass shrimp exposed intermittently until day 14 (Fig. 3.18). These results may be explained by the observation that the sensitivity to oil decreases as the larvae grow to juvenile and adult stages; i.e., younger larvae (stage I) are more sensitive to petroleum hydrocarbons than older larvae.

TABLE 3.26—Generalized sensitivities (minimum) of marine organisms to the seawater-soluble fractions of petroleum.

Concentration (ppm)	Effect	Life Stage
1-100	Lethal	Adults
0.1-1.0	Lethal	Larvae, some eggs
0.01-1.0	Sublethal	Adults and larvae

SOURCE: Moore and Dwyer 1974.

3.7.4 Birds

The direct effect of oil on a bird is to cause matting of the feathers and derangement of the feather barbules (Hartung 1967), which in turn lead to the breakdown of waterproofing and insulation and allow the birds' feathers to absorb water. A lightly oiled mallard may increase its body weight by 7-10% (Holmes and Cronshaw 1977). A more heavily oiled bird may absorb sufficient water to sink. Any increase in body weight makes flying, swimming, and diving much more energy-consuming and less efficient. At the same time, the loss of insulation results in an increase in metabolic activity at a time when the bird is less able to collect the food needed to meet the increased energy re-

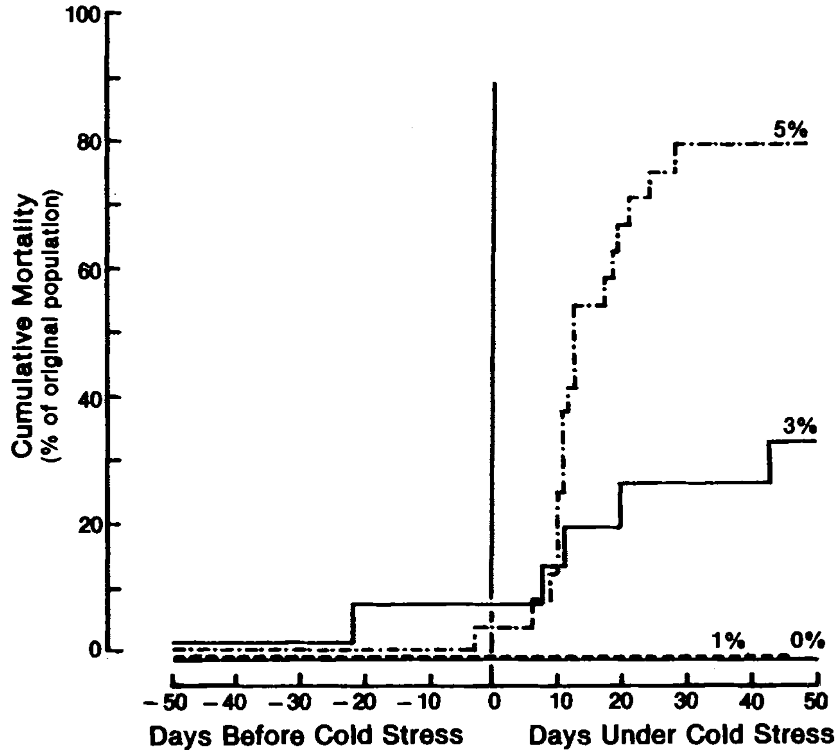


FIGURE 3.19—Cumulative mortalities before and during cold stress among groups of seawater-adapted Mallards given food contaminated with different concentrations of crude oils. (Adapted from Holmes *et al.* 1979.)

quirements. The result is usually death. The amount of oiling required to cause death depends on the condition of the bird and the ambient temperature. In a moderate environment a lightly oiled bird has a good chance of preening the oil off its feathers; Birkhead *et al.* (1973) reported that oiled murres, razorbills, and gulls cleaned themselves in about 2 weeks. Birds in cold climates are more sensitive to oiling than birds in warmer climates, and all birds are most vulnerable after prolonged stormy weather when feeding has been limited and energy reserves are low (Natural Environment Research Council 1971).

Birds may ingest oil by preening it off of their feathers, or by feeding on oiled prey or in oiled areas. Once ingested, oil apparently causes only minor physiological stress, of which adrenal hypertrophy is a symptom, but this makes the birds less able to cope with future stresses. Mallards have been demonstrated to do well on daily doses of crude oil but to die off very rapidly when subjected to an additional stress such as an abrupt drop in air temperature (Fig. 3.19) or an increase in the salinity of their drinking water (Holmes *et al.* 1979). These data have strong implications for those species, such as Black Brant, which in the fall migrate directly from Izembek Lagoon to northern California.

The effects of oil on reproduction may have the most severe and long-lasting repercussions on bird populations. The ingestion of oil by adult birds has been demonstrated to temporarily disrupt egg formation and laying. Mallards dosed orally with 2 g of lubricating oil stopped laying completely for 2 weeks (Hartung 1965). Other species laid fewer eggs and the hatching success of those eggs which were laid was reduced (Grau *et al.* 1977; Ainley *et al.* 1981). The application of oil to the surface of the incubating egg has been demonstrated to cause the death of the embryo 2–3 days after the oil is supplied. Covering only 5% of the total egg surface with mineral oil causes a significant decline in the hatchability of mallard eggs (Albers 1977). Under natural conditions, such small quantities could easily be transferred to the eggs from the feathers of the incubating parent. Birkhead *et al.* (1973) observed a wild, oiled Great Black-backed Gull which managed to clean itself, but the eggs it was incubating failed to hatch.

The ingestion of oil by young birds has been claimed to reduce their rate of growth and increase the time to fledging. For example, young guillemots given a single 0.2-ml dose of crude oil were significantly lighter (20%) than the control birds at the normal times of fledging 20 days later (Miller *et al.* 1978). This amount of oil could very possibly be fed to the young bird by the parent. Storm-petrels have been reported to deliver small amounts of petroleum hydrocarbons to their chicks with each foraging load (Boersma 1981).

Finally, natural history will influence the severity of the impact of spilled oil on bird populations. The birds most vulnerable to direct oiling are those which are gregarious, spend most of their time on the water, and dive rather than fly up when disturbed. Alcids, especially murres and puffins, and diving ducks (eiders, for example), scoters, and Oldsquaws are all especially vulnerable. In contrast, the large gulls spend much of their time on shore, which reduces their chances of coming into contact with spilled oil; the damage to most shorebirds would be indirect, through the effects of oil on their feeding habitat (King and Sanger 1979; McKnight and Knoder 1979; Quammen 1982). Also, most seabird groups are characterized by a very low breeding rate (Table 3.27). Petrels lay only a single egg each year and are unable to replace it. Alcids also lay a single egg but are capable of replacing it and successfully rearing chicks from replacement provided that relaying takes place early enough. Gulls in general, and sea ducks, have larger clutches and a greater capability of replacing lost clutches. Low breeding rates and high adult survival rates (Table 3.27) will exacerbate the problems of hydrocarbon exposure.

3.7.5 Marine Mammals

Over the past 10 years, reports by the media and some scientific review articles have implicated oil fouling as the cause of death of seals, sea otters, and both small and large whales. The most noteworthy incident is that of the 1969 blowout in the Santa Barbara Channel. Accounts of the incident speculated that gray whales had died as a result of the spill. *Time* magazine reported the presence of a stranded dolphin with an oil-clogged blowhole and lung hemorrhage. Similar accounts involved northern elephant seals (*Mirounga angustirostris*), California sea lions (*Zalophus californianus*), and the northern fur seal. However, critical assessments of the spill did not conclusively link the marine mammal deaths with the presence of oil (Simpson and Gilmartin 1970; Brownell and Le Boeuf 1971; Le Boeuf 1971). In spills that have occurred since then, oil has continued to be implicated in the death of marine mammals but

TABLE 3.27—Age at first breeding, clutch size, and adult mean annual survival in certain seabirds.

Group and Species	Age at First Breeding (years)	Normal Clutch Size	Mean Annual Survival Rate of Adults (%)
Alcids			
Guillemot	3-7	1	94
Razorbill	4-5	1	91
Petrels and Shearwaters			
Fulmar	9.2	1	97
Manx Shearwater	5-6	1	80-95
Gulls			
Herring Gull	5.25	2-6	91-96
Kittiwake	3-5	1-3	81-86
Ducks			
Eider	2-3	4-5	93
Common Scoter	2-3	7-9	77

SOURCE: Dunnet 1982.

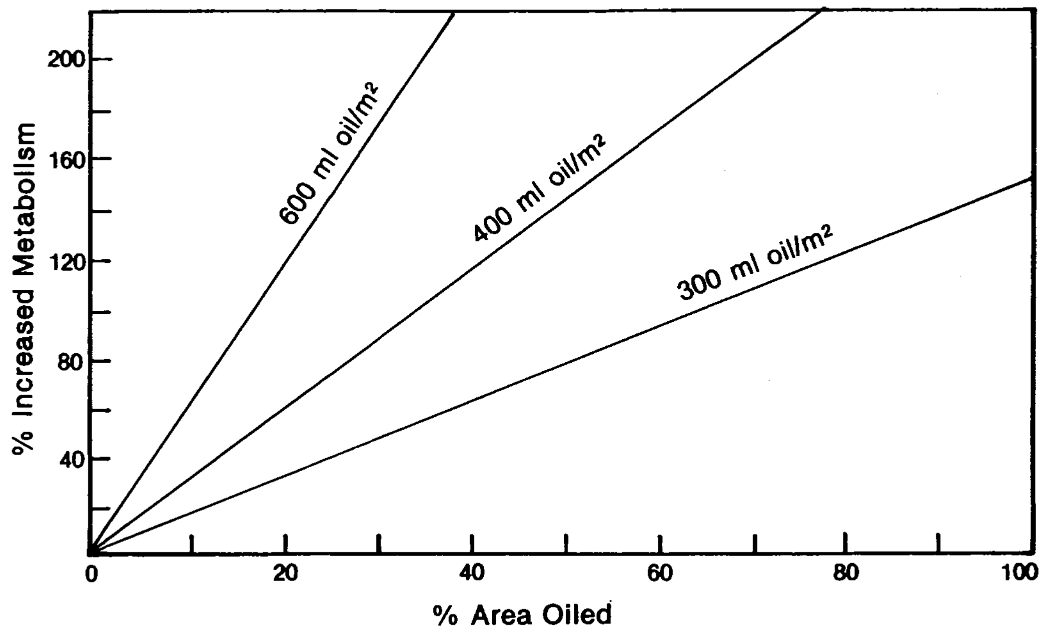


FIGURE 3.20—Predicted increases in the resting metabolism of sea otters as a function of percent body surface oiled for three densities of oil contamination. (Adapted from Costa and Kooyman 1981.)

a causal relationship has not been established.

Recently, oiling experiments have indicated that after contact with or ingestion of oil, some marine mammals exhibit problems of thermoregulation, irritation, and metabolism. Sea otters and fur seals rely for insulation on a well-groomed, mostly waterproof fur coat which traps a layer of warmed, stagnant air against their skin. Oil mats the fur and causes loss of waterproofing and buoyancy, resulting in greater heat flow across the body surface and loss of heat from the body core. The loss of heat from the body core is compensated for by an increase in basal metabolism. The increase in metabolism varies directly with the amount of body surface covered and with the amount of oil (Costa and Kooyman 1981) (Fig. 3.20). Field studies conducted in Prince William Sound with sea otters oiled over less than 10% of their body surface indicated that the animals would survive and clean themselves. When 13–25% of the body surface of otters maintained in the laboratory was oiled, the metabolic rate increased up to 41% and those animals that did not die were in obvious distress (Costa and Kooyman 1981). In a real spill, oiling of 25% of the body surface may be a conservative figure, indicating the possibility of a major impact on the sea otter population.

Alternatively, bare-skinned whales, dolphins, porpoises, and walrus are probably the least sensitive to oil contact, in terms of thermoregulation. Their primary barrier to heat loss is a thick skin, a layer of subcutaneous fat or blubber, or both. The thermal conductance of flensed blubber is similar to that of asbestos (Scholander *et al.* 1950). Oil cannot damage these animals' body insulation.

Polar bears, phocid seals, sea lions, and all other hair-bearing marine mammals keep warm both by body coverings (guard hairs, woolly underfur) and subcutaneous blubber. Their sensitivity to direct oiling is highly variable, depending on the fur's significance to total insulation. Usually the insulative value of the fur is relatively small, but this differs greatly between species or changes with age, general health, and season.

For all marine mammals, oiling is expected to be most stressful to pups and lactating females. Because of the pups' higher surface-to-volume ratio, any decrease in the thermal insulation of their coat would be greater than that of the adults, given equal percentage of oiled surface. Lactating females are expected to be highly sensitive because of the increased energy requirements of nursing. Along the North Aleutian Shelf, the extensive use of the nearshore by adult male sea otters makes this population also extremely vulnerable.

Exposure to oil may irritate the sensitive mucous membranes of the animals' eyes and respiratory tracts. Ringed seals kept in holding tanks with a 1-cm layer of Norman Wells crude oil showed signs of blinking, squinting, severe conjunctivitis, and swollen nictitating membranes within minutes (Geraci and Smith 1976). Three hours after the seals were placed in clean seawater, the condition began to clear up and was no longer apparent after 20 hours. Inhalation of highly concentrated petroleum vapors can lead to inflammation and damage to the mucous membranes of the airways. However, the concentrations of these vapors in the air above an oil slick are so low (Payne *et al.* 1984) and exist for such short periods of time that mammalian population vulnerability is expected to be negligible.

The direct ingestion of oil, either a single dose or a few small doses, probably does no irreversible harm. Geraci and Smith (1976) fed adult ringed seals 5 ml/day of Norman Wells crude oil for 5 days and a single dose of 75 ml to seal pups with little or no effect. However, long-term exposure, either as the result of cleaning oiled fur or consuming contaminated prey organisms, may result in a range of effects from decreased reproductive success (Gilmartin *et al.* 1976; Helle *et al.* 1976; Van Bree 1977) to death (Oritsland *et al.* 1981).

The consequences of an oil spill will depend in part on the degree and duration of an animal's exposure to it. Whether or not marine mammals are capable of detecting oil and avoiding it is moot. Mortalities reported from accidental spills indicate that in some cases pinnipeds and sea otters do not avoid oil, whereas a cetacean has yet to be found coated with oil. This may be because cetacean skin is smooth and cannot accumulate oil, or it may be that cetaceans are able to detect and avoid oil. Geraci and St. Aubin (1982) reported that bottlenose dolphins (*Tursiops truncatus*) can detect and will avoid a surface slick of mineral oil. Under experimental conditions, the avoidance behavior was clear and consistent. At sea this response might be modified by social interactions, feeding, agonistic behavior, migration, or human activity. Observations of gray whales migrating through surface slicks from naturally occurring oil seeps off the California coast are inconclusive. Typically the whales swam through the oil, modifying their swimming speed but without a consistent pattern. However, while they were in oiled waters, they spent significantly less time on the surface: 55 seconds per blow sequence as compared to 91 seconds in clear water.

3.8 IMPACTS RELATED TO OCS OIL AND GAS DEVELOPMENT

Several sources of pollution from planned offshore oil and gas development in the North Aleutian Shelf are predictable. Paramount among these is the threat of a catastrophic oil spill. Other coastal impacts related to offshore oil and gas development involve increased human presence in the remote communities and wildlife-rich areas of the Alaska Peninsula.

3.8.1 Hypothetical Oil Spills

The potential impacts of three hypothetical oil spills on coastal habitats and species of the North Aleutian Shelf were specifically identified by meeting coordinators for discussion. Two of the scenarios involve pipeline ruptures on the north side of the Alaska Peninsula near Amak Island (55°25′ N., 162°57′ W.) and in the vicinity of Port Moller (56°35′ N., 160°46′ W.). Both are assumed to occur at depths of approximately 50 m in late June during a high spring tide series. A total of 10,000 bbl of oil (1,280 t) are released over a 5-day period. In the third scenario the oil spill is larger and occurs south of the peninsula, west of Deer Island and south of Cold Bay in proximity to the Sandman Reefs (54°49′ N., 162°40′ W.). This hypothetical situation assumes an instantaneous release of 200,000 bbl (about 25,600 t) from a grounded tanker in late June. Other spills, such as an accident within Izembek Lagoon, were also discussed, as were potential habitat disruptions from sources other than oil pollution.

Amak Island

Oil released at Amak Island in June would most likely move to the northeast parallel with the shore. The chances of oil moving directly onshore are remote. However, if directed toward shore by prevailing winds, oil would reach the surf zone within 44 hours and about 20% of the original volume would traverse the mouth of Izembek Lagoon and cover less than 1 km². The most probable trajectory of oil would result in a triangular area of surface contamination 8 km wide by 20 km long 5 days after the spill began. Although 20–40% of the oil mass might volatilize during this time, concentrations of hydrocarbons in the contaminated plume beneath this slick would range from 0.2 ppm at the boundaries to 1.0 ppm at the origin, and would be mixed uniformly to the bottom in these shallow waters. The lower lethal limit of water-soluble fractions of the spilled oil is assumed as about 0.2 ppm.

Oil transported offshore and essentially dissipated before reaching the shore would cause little impact to most animal species in the area. Seabirds in the immediate vicinity of direct oiling would be most heavily impacted by the spill. Shearwaters are the dominant seabird in the lease area and, as surface feeders, would probably contact oil during foraging. However, although numbers killed could be large, shearwater numbers along the North Aleutian Shelf relative to the total population size are such that population-level impacts are unlikely. Nesting alcids foraging in the spill plume could be more significantly impacted than shearwaters because Amak Island provides substantial nesting habitat (relative to other local colonies) for several species (Sowls *et al.* 1978). Adult seabirds might die from direct oiling and subsequent loss of thermoregulatory capabilities. Eggs might be contaminated by oiled adults returning to their nests. However, in the perspective of total nesting populations elsewhere in the southeastern Bering Sea, the impact to breeding seabird species caused by this spill would be slight.

Sea otters are the most susceptible species in the vicinity and could sustain high mortalities. Populations are large offshore of Izembek Lagoon (Schneider 1981), and groups of several hundred may form rafts at sea or haul out on sandbars in the channels to the lagoon (D. Costa, pers. commun.). Both adults and pups swimming in contaminated waters would be directly oiled and killed by thermoregulatory impairment and uptake of hydrocarbons. To the extent that oil is accumulated in sediments and bioaccumulated by fish and invertebrates, the potential for chronic exposure of otters through food webs exists, although the consequences—whether lethal or benign—are not known. Substantial reduction in the otter population near Izembek Lagoon within weeks of a spill and oiling of coastal waters is likely. In a year of severe cold and abnormally extensive ice cover, the range and numbers of sea otters could be significantly decreased by the synergistic impact of these two events (Schneider 1981).

Other mammals such as harbor seals and sea lions would not be as severely affected, although exposure is likely on sandy peninsula beaches or rocky areas of Amak Island and Sea Lion Rocks. Because these animals are protected by blubber layers, oiling does not pose a serious threat to temperature regulation; however, pups of pinnipeds are sensitive to oiling until blubber insulation is formed (Braham *et al.* 1982).

Coastally occurring gray whales between Amak Island and Izembek Lagoon in the spring and summer would possibly encounter one of the hypothetical spill zones. Effects of oil exposure on these animals are unknown but, from observation, thought to be slight (Brahm *et al.* 1982). Whales may alter their behavior to circumvent or leave an oiled area by increasing diving times and deviating from preferred depth contours. In general, the impact of oil on this endangered species group might be slight and largely irritative in nature, but remains unknown.

Pelagic invertebrates, primarily crustaceans, would experience high mortality rates from exposures to oil concentrations near or exceeding 0.2 ppm. Acute toxicity may result in near-complete mortality of patches or swarms of zooplankton including copepods, euphausiids, and crab and shrimp larvae. Once the spill ceases, dispersion of the oil would quickly dilute hydrocarbons to sublethal concentrations, and toxicity could only continue through oil leaching from impacted sediments.

The most important commercial invertebrate in the lease area (and spill plume) is the red king crab. Its larvae occur in the water column during June (Armstrong *et al.* 1981), but because the larvae range from Amak Island to well beyond Port Moller and Port Heiden, even the loss of all larvae within the impacted zone would probably be insignificant to the overall strength of a year-class. Little effect on benthic juvenile and adult crab populations along the North Aleutian Shelf is predicted by virtue of the same argument.

A more substantial impact on king crab might occur if oil was transported to Amak Island and mixed into sublittoral rocky habitats. Very young juvenile king crab, less than 2 years old, in the Kodiak region prefer rocky, cobble habitat that affords shelter from predators (Feder and Jewett 1980; Jewett and Powell 1981). Very little habitat of this type exists along the North Aleutian Shelf (Michel *et al.* 1982) and young-of-the-year (0+) juveniles that settle on open bottom are probably vulnerable to heavy predation. Thus any habitat that offers protection to young crabs is critical to their benthic survival. The extent of use of this habitat by juveniles in comparison with other seafloor types in the lease area is not known. Heavy oiling of Amak Island's shallow sublittoral zone could destroy a substantial portion of one or two juvenile king crab year-classes that metamorphosed to that area.

Larvae of other decapods such as shrimps, hermit crabs, and Tanner crabs would be killed by lethal exposures in the spill plume with little overall affect on North Aleutian Shelf populations. Sessile invertebrates would be heavily impacted in the immediate vicinity of the spill via oiling of the benthos. It has been speculated that oil could reach densities of 4–10 g/m² (Curl and Manen 1982; C. A. Manen, communication at the meeting). A substantial portion of the epi- and infaunal community subjected to toxic exposures would be killed. Survivors could bioaccumulate hydrocarbons via sublethal exposure or through predator-prey routes. Again, the area impacted relative to the entire North Aleutian Shelf is trivial, and it is likely that any loss of invertebrates in the impacted area would not pose a threat to the lease area population as a whole. It is noteworthy that the nearshore area from Izembek Lagoon to Cape Seniavin, to a depth of 60 m, equals about 12,560 km²; the zone contaminated by a 10,000-bbl spill in this scenario is less than 160 km², or 1.3% of the coastal lease area.

Izembek Lagoon

The total quantity of oil that could reach Izembek Lagoon under the Amak Island spill scenario would not pose a major biological threat. Because roughly only 20% of the original 10,000 bbl would be transported to the lagoon, only a small portion would reach the coast and barrier islands. However, a more serious spill of longer duration or a spill within the lagoon itself (at the meeting workshop participants were informed of a Minerals Management Service scenario which assumed a pipeline would traverse Izembek Lagoon with a pipeline to Morzhovoi Bay) could be a major and long-lasting perturbation to this ecosystem. A spill within the lagoon or a more chronic discharge only 9 km off the entrance channels would likely result in a higher proportion of low molecular weight, toxic hydrocarbons reaching the lagoon rather than being dissipated by volatilization and dilution at sea. The acute toxic effects to invertebrate meiofauna and macrofauna would be pervasive throughout the lagoon due to substantial transport and mixture of oil by the large tidal exchange. Oiled sediments would cause significant mortality of regional infauna and epifauna. Degradation of these hydrocarbons could take several years and, as a consequence, a pronounced decrease in community biomass and a shift in structure would persist for as many as 5–10 years. Bacteria might be largely eliminated soon after the spill and, although recovery would include strains able to degrade oil, overall bacterial production could be depressed for several years. Even though much of the eelgrass production is transported from the lagoon, bacteria process some within the system which adds an important component of detrital food that is grazed by many invertebrates and some fish.

A late June spill scenario would pose the least immediate threat to the many bird populations that use Izembek Lagoon for feeding and staging. Numbers of birds are lowest in June and July (J. Sarvis, U.S. Fish and Wildlife Service, Cold Bay, pers. commun.), and increase to seasonal highs in August through September. Extensive oiling of the lagoon in June would still adversely affect the birds arriving one or two months later. Food supplies would be reduced and those birds remaining could be contaminated. Food availability might be lowered, thereby reducing fitness for migration by staging birds. Direct oiling of some portion of the population is likely along the fringing littoral areas of the lagoon where oil "mousse" would persist. Reduced food supplies, ingestion of oil, or avoidance of the lagoon with no suitable alternative habitat available, could result in death to major portions of the shorebird and waterfowl species that utilize this system. The inextricable dependence of birds on Izembek Lagoon is exemplified by Black Brant whose entire world population stages there from August through October. A large-scale spill event within Izembek Lagoon during these months would be catastrophic to the species.

Eelgrass is the largest source of primary production in the lagoon, is a major food for resident waterfowl, and over 400,000 t is annually exported from the lagoon to nearshore habitats. Hydrocarbon toxicity to eelgrass on a chemical level may be low, but destruction of stands in Izembek Lagoon by other causes could be great. Physical trauma to plants could result from windrows of oil mousse moved by wind and tides. An oil coating could cause thermal stress at low tides and impede gas exchange across leaf surfaces. A more insidious and chronic effect might come from microhabitat alterations in sediment chemistry caused by destruction of bacteria. The microbial community is responsible for generating a large share of inorganic nutrients used by *Zostera marina* and, in turn, eelgrass rhizome networks pump oxygen into the sediments which promotes bacterial activity. These relationships highlight an intricate interdependence between eelgrass and sediment microbes that ensures proper conditions of pH, redox potential, and aerobic zones for optimum production. The microbial community of the sediments and eelgrass epiphytes would be highly susceptible to oil toxicity and their loss could lead to widespread reduction of eelgrass stands. Recovery of eelgrass removed from small areas by natural events such as ice scour might take 5 years, but coverage of large areas could take 30 years; the rate of recovery from chemical poisoning could be slower (C. P. McRoy, pers. commun.).

Port Moller

Much of the preceding discussion concerning oil spill impact offshore of Amak Island and in Izembek Lagoon is germane to predictions of the magnitude of biological harm resulting from a 10,000-bbl spill off Port Moller. Given the greater distance of this particular spill scenario from shore (34 km) and its position northeast of the Port Moller–Nelson Lagoon complex, the overall effects of this hypothetical spill would be relatively benign to animal populations occurring there. As before, the 160-km^2 area contaminated by oil at 0.2 ppm or greater is exceedingly small, and complete mortality of pelagic and benthic animals within this zone, if realized, would not threaten North Aleutian Shelf populations.

Alternative scenarios in this area which resulted in (1) a large volume of oil reaching the estuary, or (2) an extensive oiling of the shallow nearshore benthos and loss of pelagic larvae from Cape Seniavin to Port Heiden would be serious. In the former situation, potential oil toxicity in Nelson Lagoon and Port Moller would pose some of the same threats as in Izembek Lagoon. Shorebirds (especially Dunlins, sandpipers, and godwits) and waterfowl (especially Steller's Eiders, King Eiders, and Emperor Geese) use this area extensively from June through October. The use of Nelson Lagoon by gray whales for feeding might be impeded by a spill.

An oil spill in excess of 10,000 bbl from the hypothetical Port Moller spill site would pose a serious threat to red king crab. High female abundance is typically observed off the Port Moller to Port Heiden region and larval densities are usually greatest there. A nearshore zooplankton survey in June and August 1982 caught very few king crab larvae from western Unimak Island to Izembek Lagoon, but large numbers from Port Moller to Cape Seniavin (D. Armstrong, unpubl. data). Armstrong *et al.* (1981) reviewed the potential threat of oil spills in the North Aleutian Shelf to king crab populations and drew three major conclusions. First, an extensive spill could kill a significant portion of any larval year-class, particularly if it occurred after peak hatch which would then preclude replacement of killed larvae by other cohorts hatching later, after the oil dissipated. Second, the probability of a significant year-class mortality would be higher in late July and August when crab larvae that have survived since hatching are approaching metamorphosis. Because natural mortality of larvae is very high, those remaining as fourth stage zoeae or glaucothöe are a small percentage of the original number hatched (a few percent) and, in a sense, represent the last chance for successful propagation in any year. Third, benthic female king crab carry eggs for 11 months, so there is a strong chance that developing embryos could be contaminated and stressed by exposure to oiled sediment. An extensive spill in any year could conceivably kill a significant portion of two year-classes as larvae in the water column and developing eggs on the benthos. In addition, transport and mixture of oil to the bottom via planktonic fecal pellets and turbulence could kill large numbers of juvenile crab if metamorphosis and early benthic residence occur nearshore from Port Moller to Port Heiden.

Another benthic resource that might be adversely affected by an extensive spill in this region is the surf clam (*Spisula polynyma*) population between Cape Seniavin and Port Heiden. These clams represent a potential fishery and are of untold trophic importance, especially to walrus. Reductions in *Mya arenaria* populations after an oil spill in Nova Scotia and the loss of tens of millions of bivalves following the *Amoco Cadiz* spill attest to the vulnerability of these clams and other infaunal groups. Impacts to surf clams might require many years to mitigate through natural recovery because the species is long-lived (25 years) and requires 6–8 years to reach sexual maturity.

Marine mammal populations would not, for the most part, be greatly impacted by an offshore Port Moller oil spill because local populations are relatively low. Only small numbers of sea otters range this far to the east (D. Costa and R. Cimberg, pers. commun., June 1982), and walrus and Steller's sea lions do not often occur there in great numbers. However, harbor seals are found at six major haulout areas along the North Aleutian Shelf including Port Moller (8,000), Seal Islands (3,500), and Port Heiden (10,000). These animals haul out on beaches and sandbars and could be susceptible to direct oiling. Further, harbor seals pup and molt from May through September, events that may enhance oil toxicity and increase mortality following a spill incident near Port Moller.

Cold Bay

It is estimated that 250 km² would be contaminated with concentrations approaching 1 ppm. Relatively little oil would be washed ashore in less than 30 hours; at this time remaining surface oil (75%) would be mostly of a thick mousse consistency. The impacts of this spill on animals are much more difficult to predict because so little information is available on the magnitude of regional populations in this part of the Pacific Ocean. One exception is the relatively good information available concerning bird colonies near Cold Bay.

Sea otters are abundant along the south side of the peninsula with populations ranging from 5 to 50 per island. It is reasonable to assume that many otters within the 250 km² affected would be heavily oiled and probably die. Numbers contacting the slick cannot be predicted but several thousand animals probably range in this area. Recovery of populations after an oil spill might be rapid judging from data concerning expansion of ranges along the Aleutian Islands (Schneider 1981).

Seabirds are the group most vulnerable to an oil spill in the Cold Bay region due to the presence of large nesting colonies on the Sandman Reefs. Nearly half a million birds nest in this area; dominant species include Glaucous-winged Gull, Cassin's Auklet, and Horned and Tufted puffins (Bailey and Faust 1980). Oil-induced mortalities would be greatest during summer months (e.g., direct oiling, ingestion, coating of eggs, low survival of chicks through loss of parents), and the impact of losses on seabird populations might persist for several years. Strauch and Hunt (1982) have reviewed the ramifications of oil spills on nesting birds on the Pribilof Islands in light of simulation models of recovery time as a function of percent mortality, species, and life-history stage affected (Wiens *et al.* 1979). Paramount conclusions drawn from their results are: (1) time for recovery is an exponential function of the one-time mortality rate, and (2) death of adults slows recovery time more than the death of other age-classes. If oil from a large spill is carried to the small islands around Deer Island, south to the Goose Island group or west to Amagat Island, mortality of seabirds could be exceedingly high and recovery of populations might take from 5 to 10 years.

Other Spills

Numerous other oil spill scenarios, no matter how unlikely, are possible events that could potentially affect animal populations.

Greater amounts of oil spilled in any location have the potential for causing greater harm to plant and animal life than smaller quantities, particularly near coastal beaches and estuaries. If 10,000 bbl of oil released off Izembek Lagoon have a low probability of coming ashore, some portion of a 100,000- to 500,000-bbl spill must have a higher probability of entering the lagoon in devastating quantities, or of being transported far enough alongshore that a significant portion of a larval year class of king crab is killed. A spill (tanker or pipeline) that occurs over weeks and extends 150 to 200 km along the North Aleutian Shelf from Amak Island to Cape Seniavin (*Amoco Cadiz* heavily oiled 320 km of the Brittany coast) sometime between May and September would imperil shorebirds and waterfowl, sea otters and harbor seals (perhaps on this scale migratory whales as well), pelagic and benthic developmental stages of king crab, other benthic biota, major lagoons at Izembek and Port Moller—in short, the general marine ecology of the proposed lease area.

An oil spill on the west end of Unimak Island or on one of the Krenitzin Islands bordering the pass could seriously impact regional populations of birds and mammals. A spill event of large enough magnitude (250,000 bbl) to significantly oil Unimak Pass in early spring or late fall could expose great numbers of fur seals and gray whales to hydrocarbon contaminants. The mortality to fur seals from a large spill at this time would be high. Immense flocks of shearwaters feeding in the pass could be contaminated, and nesting colonies of several hundred thousand Tufted Puffins on the nearby eastern Aleutian Islands might be decimated by heavy mortalities on foraging adults.

3.8.2 Other OCS-Related Impacts

Potential impacts to birds and mammals arising from increasing human presence and noise were discussed at the St. George Basin Synthesis Meeting (Hameedi 1982). These discussions are also germane to similar situations that can be expected with development of oil fields in the North Aleutian Shelf. Because Cold Bay may be enlarged to furnish logistics for oil development (and perhaps receive tankers to unload oil delivered by pipeline from the north), Izembek Lagoon may be the area most seriously threatened by factors other than spilled oil. Increased boat and plane traffic in and over the lagoon could routinely disturb birds during critical staging periods. Frequent low altitude aircraft flights could disrupt feeding, cause expenditure of extra energy, and possibly reduce fat deposition required for long migratory flight. The close proximity of Cold Bay to Izembek Lagoon (about 10 km) ensures greater use of this area for recreation as more people join an expanding work force. Excessive disturbance of birds by people would only add to the adverse impact of noise from boats and planes in support of offshore structures. Mammals such as sea otters and seals might avoid traditional haulout or feeding areas as rural communities grow and patterns of local land use change.

3.9 RESEARCH NEEDS

Participants of the coastal habitats workshop identified several topics that require more attention preparatory to leasing in the North Aleutian Shelf in order to adequately address the full range of possible impacts to regional habitats and biota.

Winter surveys of bird populations in the Krenitzin Islands adjacent to Unimak Pass are needed. The strategic importance of this pass as a shipping lane could result in winter oil spills with possible impacts to overwintering birds. At present there is little data on the location and extent of use of such populations.

The distribution, abundance, and population dynamics of red king crab in nearshore waters of the North Aleutian Shelf are poorly described. Despite many crab surveys in the southeastern Bering Sea, little work has been done shoreward of the 50- to 60-m isobaths. There is evidence that ovigerous females reside nearshore where eggs hatch. Questions such as how abundant and widely distributed sexually mature females are in this region remain to be answered. Larvae occur nearshore but only a few zooplankton samples support this trend. Their distribution from Port Moller to Port Heiden and farther into Bristol Bay is unstudied, and yet the majority of any year-class may be hatched there rather than to the west near Amak Island. Other topics needing to be addressed include the location of the 0+ to 2+ juvenile crabs and identification of their preferred habitat.

Nearshore benthic community structures and dependence on coastal nutrient exports pose interesting scientific hypotheses, especially in the Izembek Lagoon area. Based on the sheer magnitude of fish, crab, bird, and mammal populations that exist and feed nearshore, benthic invertebrates must be abundant and productive. The indirect impact of oil on apex consumers by disruption of food webs is difficult to assess without knowledge of abundance patterns and trophic relationships.

Increased plane and helicopter traffic could disturb birds. Information is needed on altitudes and distances of flight paths from large populations that eliminate or substantially reduce disturbance.

In addition to these research priorities, workshop participants voiced some reservations and warnings concerning oil development in the North Aleutian Shelf. Most important was the consensus that the nearshore is a special region upon which a number of animals have come to depend during at least part of their lives. Izembek Lagoon and Port Moller were considered as especially sensitive and critical habitats for many species. A proposal to lay a pipeline across Izembek Lagoon was regarded as ill-advised; that plan should be abandoned. So, too, Unimak Pass was listed as crucial to many birds and mammals for food and passage between the Bering Sea and the Gulf of Alaska.

3.10 SUMMARY

The presence of an oceanographic front along the 50-m contour of Bristol Bay influences the ecological partitioning of the North Aleutian Shelf lease area into two distinct habitat zonations. Those waters lying between 50 and 100 m have been described biologically as supporting a diverse benthic ecosystem. This ecosystem is fueled by sinking planktonic matter ineffectively cropped by the small-sized herbivores characteristic to these waters. The offshore habitat has a rich infaunal community and an abundance of demersal fish and crabs. Coastal waters also process high infaunal biomasses, especially high standing stocks of clams. Their abundance may be due in part to detrital inputs from coastal embayments and lagoons in association with sinking organic matter from an uncoupled trophic link in the overlaying pelagic regime. The bays and lagoons along the northern coast of the Alaska Peninsula constitute a major portion of the total estuarine areas in the Bering Sea and another habitat type pertinent to the North Aleutian Shelf. These areas are of special importance to staging and feeding migratory waterfowl and shorebirds and are habitats in which biological losses could be great if spilled oil were allowed to enter.

As the available data allowed, the structural and functional components of biological communities were described for each habitat. In this way the possible consequences of hypothetical oil spills on the regional biota and the overall ecology of the North Aleutian Shelf could be qualitatively evaluated. Oil spills of 2,000 bbl/day lasting 5 days and originating from launch points within the boundaries of the lease area were not perceived as a special threat to any population, although some mortalities could be expected and certain species—sea otters and red king crab—were thought to be more vulnerable than others. Only if oil were released in the offshore habitat in such quantity that significant amounts were delivered to and accumulated on the bottom would the benthic environment and species living there be affected. Such a spill would probably have to be at least an order of magnitude greater than the hypothetical scenarios discussed. Environmental consequences of spilled oil in coastal and estuarine habitats were thought to be of greatest concern due to expected increased levels of hydrocarbon concentrations in shallower waters and prolonged persistence of oil and effects in protected waters. The Krenitzin Islands and Unimak Pass were also discussed as special habitats where oiling could severely impact regional biota.

With the exception of winter, the coastal habitat of the North Aleutian Shelf is a region of intense biological activity. It is heavily utilized as a migratory corridor by endangered gray whales and Pacific salmon. The area between Unimak Pass and Port Moller is extensively foraged by seals, sea lions, walrus, and possibly gray whales. All of the sea otters that are found in Bristol Bay are distributed in this coastal zone with highest densities reported Bechevin Bay and Izembek Lagoon. The coastal zone is also the major reproductive site of Bering Sea red king crab. Capelin, herring, sand lance, and other trophically important fish species are abundant in coastal waters in spring and summer months. These species are major prey of seabirds found in the numerous small-sized colonies scattered along the Alaska Peninsula, Amak Island, and Sea Lion Rocks. Major breeding seabird species include cormorants, kittiwakes, gulls, murres, and puffins. Shorebirds, waterfowl, and gulls are also abundant on coastally exposed beaches and inshore waters. Gregarious species, especially those birds that rest and feed on the surface, or those that are divers, are most vulnerable to possible contamination from oil spills.

The eelgrass beds of Izembek Lagoon are among the richest in the world; daily eelgrass productivity ranges from 3.3 to 8.0 g C/m^2. Microbial degradation of eelgrass detritus is a major lagoonal process affecting most trophic relationships and energy transfers among lagoonal inhabitants. Eelgrass leaves support large numbers of epiphytic organisms with a total biomass perhaps approaching that of the eelgrass itself. Food webs are very short in the lagoon and in most cases consist of fewer than six intermediate species. Shrimps, crabs, juvenile fish, and an abundance of other invertebrates are dominant species. The bays and lagoons are critical habitat for many species of shorebirds and waterfowl who use them for staging in spring and fall. Nelson and Izembek lagoons are particularly important habitat for staging birds. For instance, in October, the entire world's population of Black Brant is found in Izembek Lagoon. Harbor seals and sea otters are dominant estuarine mammals, and gray whales feed within Nelson Lagoon in summer and early fall.

Unimak Pass is one of the major migration corridors for bird and mammal populations entering and leaving the Bering Sea. Large aggregations of seabirds are found in and near the pass. Sooty and Short-tailed shearwaters are particularly abundant; a mean fall population estimate of 1.1 million shearwaters has been recorded. Major portions of endangered populations of humpback, fin, and gray whales and northern fur seals are regular seasonal migrants through the pass. An oil spill in Unimak Pass could seriously impact regional populations of birds and mammals. A spill large enough to significantly oil the pass in early spring or late fall would expose great numbers of fur seals and gray whales to hydrocarbon contaminants. Mortalities of fur seals during these seasons would be high. Immense flocks of shearwaters feeding in Unimak Pass would be vulnerable to oiling. The nesting colonies of several hundred thousand Tufted Puffins on nearby Aleutian Islands might be decimated by heavy oiling of foraging adults.

Possible shore-based developments near Cold Bay and increased vessel traffic on the south side of the Alaska Peninsula are likely actions of planned offshore oil and gas development in the North Aleutian Shelf. Breeding seabirds, fall populations of shorebirds and waterfowl, and sea lions and sea otters are the most vulnerable and conspicuous coastal species. Alcids, petrels, and gulls are dominant breeding seabirds nesting at colonies on the Krenitzin Islands and Sandman Reefs. The extent of ice coverage in the Bering Sea dictates the movement of shorebirds and waterfowl to the Cold Bay region each year. Sea lions and sea otters are abundant year round in the nearshore waters south of the Alaska Peninsula.

3.11 REFERENCES CITED

ADAMS, A. E.
1979. The life history of the snow crab, *Chionoecetes opilio*: a literature review. Univ. Alaska, Fairbanks, Sea Grant Rep. 78-13, 141 p.

AINLEY, D. G, C. R. GRAU, AND S. H. MORELL.
1981. Influence of petroleum on egg formation and embryonic development in seabirds. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 13: 315–356.

ALASKA DEPARTMENT OF FISH AND GAME.
1980. Marine resources of the North Aleutian Shelf proposed lease sale area. Arctic Environmental Information and Data Center, Univ. Alaska,

Anchorage. 1 map.

ALBERS, P. H.
1977. Effects of external applications of fuel oil on hatchability of mallard eggs. *In* D. A. Wolfe (ed.), Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms, p. 158–163. Pergamon Press, New York.

ALEXANDER, V., AND R. T. COONEY.
1979. Ice edge ecosystem study: Primary productivity, nutrient cycling, and organic matter transfer. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Boulder, 165 p.

ARMSTRONG, D. A., L. S. INCZE, J. L. ARMSTRONG, D. L. WENCKER, AND B. R. DUMBAULD.
1981. Distribution and abundance of decapod crustacean larvae in the southeastern Bering Sea with emphasis on commercial species. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1981, 2: 365–597.

ARNESON, P. D.
1981. Identification, documentation, and delineation of coastal migratory bird habitat in Alaska. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 15: 1–363.

ATLAS, R. M.
1982. Assessment of potential interactions of micro-organisms and pollutants resulting from petroleum development on the outer continental shelf of Alaska. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 190 p.

ATLAS, R. M., AND A. BRONNER.
1981. Microbial hydrocarbon degradation within intertidal zones impacted by the *Amoco Cadiz* oil spillage. *In Amoco Cadiz*: fates and effects of the oil spill. Proc. of the international symposium, Centre Océanologique de Bretagne, Brest (France), November 19–22, 1979, p. 251–256. Centre National pour l'Exploitation des Océans, Paris.

AZAM, F., AND R. E. HODSON.
1977. Size distribution and activity of marine microheterotrophs. Limnol. Oceanogr. 22(3): 492–501.

BAHR, L. M., JR., J. W. DAY, JR., T. GAYLE, J. G. GOSSELINK, C.S. HOPKINSON, AND D. STELLAR.
1978. The construction of a conceptual model of the Chenier Plain coastal ecosystem in Louisiana and Texas. *In* J. B. Johnston and L. A. Barclay (eds.), Contributed papers on coastal ecological characterization studies, presented at the Fourth Biennial International Estuarine Research Conference, Mt. Pocono, Pa., 2–5 October 1977, p. 32–43. Off. Biol. Serv., U.S. Fish Wildl. Serv. FWS/OBS-77/37.

BAILEY, E., AND N. FAUST.
1980. Summer distribution and abundance of marine birds and mammals in the Sandman Reefs, Alaska. Murrelet 61: 6–19.

BAKER, J. M.
1970. Oil pollution in salt marsh communities. Mar. Pollut. Bull. 1(2): 27–28.
1971. Comparative toxicities of oils, oil fractions, and emulsifiers. *In* E. B. Cowell (ed.), The ecological effects of oil pollution on littoral communities, p. 78–87. Inst. Pet., London.
1973. Recovery of salt-marsh vegetation from successive oil spillages. Environ. Pollut. 4: 223–230.

BARNES, R. D.
1968. The crustaceans. *In* Invertebrate zoology, p. 427–523. W. B. Saunders Co., Philadelphia.

BARSDATE, R. J., M. NEBERT, AND C. P. MCROY.
1974. Lagoon contributions to sediments and water of the Bering Sea. *In* D. W. Hood and E. J. Kelley (eds.), Oceanography of the Bering Sea with emphasis on renewable resources, p. 553–576. Proc. Int. Symp. Bering Sea Study, Hakodate, Japan, 31 Jan.–4 Feb. 1972. Inst. Mar. Sci., Univ. Alaska, Fairbanks, Occas. Publ. No. 2.

BAXTER, R. E.
1975. Inshore marine resources, Bristol Bay, Alaska. Unpubl. manuscr., 171 p. Alaska Dep. Fish Game, Bethel, AK 99559.

BENDER, M. E., E. A. SHEARLS, R. P. AYRES, C. H. HERSCHNER, AND R. J. HUGGETT.
1977. Ecological effects of experimental oil spills on eastern coastal plain estuarine ecosystems. *In* Proceedings of joint conference on prevention and control of oil spills, New Orleans, La., p. 505–509. Am. Pet. Inst., Washington, D.C.

BERDUGO, V., R. P. HARRIS, AND S. C. O'HARA.
1977. The effect of petroleum hydrocarbons on reproduction of an estuarine planktonic copepod in laboratory cultures. Mar. Pollut. Bull. 8: 138–143.

BIRKHEAD, T. R., C. LLOYD, AND P. CORKHILL.
1973. Oiled seabirds successfully cleaning their plumage. Brit. Birds 66: 535–537.

BLAKE, J. A.
1975. Phylum Annelida: Class Polychaeta. *In* R. I. Smith and J. T. Carlton (eds.), Light's manual, 3rd ed., p. 151–243. Univ. Calif. Press, Berkeley.

BOERSMA, P. D.
1981. Storm-petrels as indicators of environmen-

tal conditions. Interim rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 30 p.

BRAHAM, H. W.
1977. California gray whale (*Eschrichtius robustus*) spring migration in Alaska. *In* Proc. (abstracts), Second Conf. Biol. Mar. Mammals, San Diego, Calif., 12-15 December 1977, p. 59. (Avail. from author, U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Natl. Mar. Mammal Lab., 7600 Sand Point Way NE, Seattle, WA 98115.)

BRAHAM, H. W., R. D. EVERITT, B. D. KROGMAN, D. J. RUGH, AND D. E. WITHROW.
1977. Marine mammals of the Bering Sea: a preliminary report on distribution and abundance, 1975-76. Processed rep., 90 p. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Mar. Mammal Div., Seattle.

BRAHAM, H. W., R. D. EVERITT, AND D. J. RUGH.
1980. Northern sea lion population decline on eastern Aleutian Islands. J. Wildl. Manage. 44: 25-33.

BRAHAM, H. W., G. W. OLIVER, C. FOWLER, K. FROST, F. FAY, C. COWLES, D. COSTA, K. SCHNEIDER, AND D. CALKINS.
1982. Marine mammals. *In* M. J. Hameedi (ed.), Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981, p. 55-81. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

BROOKS, J. W.
1954. Beluga. Alaska Dep. Fish., Annu. Rep. for 1954: 51-57.

BROOKS, J. W., A. S. MOSSMAN, AND H. Z. HANSEN.
1955. Beluga investigations. Alaska Dep. Fish., Annu. Rep. for 1955: 98-106.

BROWNELL, R. L., JR., AND B. J. LE BOEUF.
1971. California sea lion mortality: natural or artifact? *In* D. Straughan (ed.), Biological and oceanographical survey of the Santa Barbara Channel oil spill, 1969-1970, Vol. 1, biology and bacteriology, p. 287-305. Allan Hancock Found., U.C.L.A.

BUNCH, J. N., C. BEDARD, AND T. CARTIER.
1983. Microbiology: 1. Effects of oil on bacterial activity—a summary of 1982 study results. (BIOS) Baffin Island Oil Spill Working Rep. 82-5, 17 p.

BURBANCK, W. D.
1942. Physiology of the ciliate *Colpidium colpoda*. 1. The effect of various bacteria as food on the division rate of *Colpidium colpoda*. Physiol. Zool. 15: 342-362.

BURBANCK, W. D., AND J. D. EISEN.
1960. The inadequacy of monobacterially fed *Paramecium aurelia as* food for *Didinum nasutum*. J. Protozool. 7: 201-206.

BURNS, J. J.
1970. Remarks on the distribution and natural history of pagophilic pinnipeds in the Bering and Chukchi seas. J. Mammal. 51: 445-454.
1978. Ice seals. *In* D. Haley (ed.), Marine mammals of eastern North Pacific and Arctic waters, p. 193-205. Pacific Search Press, Seattle.

BURNS, J. J., AND S. J. HARBO.
1977. An aerial census of spotted seals, *Phoca vitulina largha*, and walruses, *Odobenus rosmarus*, in the ice front of the Bering Sea, final report. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Q. Rep., April-June, 1: 58-132.

BURNS, J. J., L. H. SHAPIRO, AND F. H. FAY.
1981. The relationships of marine mammal distributions, densities and activities to sea ice conditions. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 11: 489-670.

BURNS, K. A., AND J. M. TEAL.
1979. The West Falmouth oil spill: hydrocarbons in the salt marsh ecosystem. Estuarine Coastal Mar. Sci. 8: 349-360.

BURRELL, D. C., K. TOMMOS, A. S. NAIDU, AND C. M. HOSKIN.
1981. Some geochemical characteristics of Bering Sea sediments. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. I, p. 305-319. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

CALKINS, D., G. ANTENOLIS, AND G. OLIVER.
1981. Preliminary report of ice seal research on *Zyagino*, March-April, 1981, Joint U.S.-U.S.S.R. Environmental Scientific Exchange Program, 21 p. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Natl. Mar. Mammal Lab., Seattle.

CALKINS, D. G., AND K. W. PITCHER.
1978. Population assessment, ecology, and trophic relationships of Steller sea lions in the Gulf of Alaska. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1978, 1: 373-413.
1979. Population assessment, ecology, and trophic relationships of Steller sea lions in the Gulf of

Alaska. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1979, 1: 144-208.

CALKINS, D. G., K. W. PITCHER, AND K. SCHNEIDER.
1975. Distribution and abundance of marine mammals in the Gulf of Alaska. Unpubl. manuscr., 39 p. + 31 charts. Alaska Dep. Fish Game, 333 Raspberry Rd., Anchorage, AK 99502.

COACHMAN, L. K., AND R. L. CHARNELL.
1979. On lateral water mass interaction—a case study, Bristol Bay, Alaska. J. Phys. Oceanogr. 9(2): 278-297.

COONEY, R. T.
1981. Bering Sea zooplankton and micronekton communities with emphasis on annual production. D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 947-974. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

COONEY, R. T., AND K. O. COYLE.
1980. Trophic implications of cross-shelf copepod distributions in the southeast Bering Sea. Inst. Mar. Sci., Univ. Alaska, Fairbanks, PROBES Prog. Rep. 2: 131-166.

COONEY, R. T., AND G. GEIST.
1978. Studies of zooplankton and micronekton in the southeast Bering Sea. *In* R. T. Cooney (ed.), Environmental assessment of the southeast Bering Sea: final report, p. 238. Univ. Alaska, Fairbanks.

COSTA, D. P., AND G. L. KOOYMAN.
1981. Effects of oil contamination in the sea otter, *Enhydra lutris*. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 10: 65-107.

CROW, S. A., M. A. HOOD, AND S. P. MEYERS.
1975. Microbiological aspects of oil intrusion in southeastern Louisiana. *In* A. W. Bourquin, D. G. Ahearn, and S. P. Meyers (eds.), Impact of the use of microrganisms on the aquatic environment, p. 221-227. Natl. Environ. Res. Cent., U.S. Environ. Prot. Agency, Corvallis. EPA 600-3-75-001.

CUCCI, T. L., AND C. E. EPIFANIO.
1979. Long-term effects of water-soluble fractions of Kuwait crude oil on the larval and juvenile development of the mud crab *Eurypanopeus depressus*. Mar. Biol. 55(3): 215-220.

CURL, H. E., JR., AND C. A. MANEN.
1982. Shellfish resources. *In* M. J. Hameedi (ed.), Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981, p. 141-159. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

DAGG, H., J. VIDAL, T. E. WHITLEDGE, R. L. IVERSON, AND J. J. GOERING.
1982. The feeding, respiration, and excretion of zooplankton in the Bering Sea during a spring bloom. Deep-Sea Res. 29(1A): 45-63.

DAUBENMIRE, R.
1968. Plant communities: a textbook of plant synecology. Harper and Row, New York, 300 p.

DUNNET, G. M.
1982. Oil pollution and seabird populations, p. 413-428. *In* R. B. Clark (ed.), The long-term effects of oil pollution on marine populations, communities, and ecosystems. Philos. Trans. R. Soc. Lond. B Biol. Sci. 297.

EDWARDS, R. R. C.
1978. Effects of water-soluble fractions on metabolism, growth, and carbon budget of the shrimp *Crangon crangon*. Mar. Biol. 46(3): 259-265.

EARTH TECHNOLOGY CORPORATION.
1983. Seafloor geologic hazards on the North Aleutian Shelf, Vol. 1. Draft final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Natl. Ocean Serv., Off. Oceanogr. Mar. Serv., Ocean Assess. Div., Juneau, 8 chap. + 4 append.

EIMHJELLEN, K., O. NILSSEN, K. JOSEFSEN, T. SOMMER, E. SENDSTAD, P. SVEUM, AND T. HODDO.
1983. Microbiology: II. Biodegradation of oil—1982 study results. (BIOS) Baffin Island Oil Spill Working Rep. 82-6, 57 p.

EVERITT, R. D., AND H. W. BRAHAM.
1980. Aerial survey of Pacific harbor seals in the southeastern Bering Sea. Northwest Sci. 54(4): 281-288.

FAY, F. H.
1974. The role of ice in the ecology of marine mammals of the Bering Sea. *In* D. W. Hood and E. J. Kelly (eds.), Oceanography of the Bering Sea with emphasis on renewable resources, p. 383-399. Proc. Int. Symp. Bering Sea Study, Hakodate, Japan, 31 Jan.-4 Feb. Inst. Mar. Sci., Univ. Alaska, Fairbanks, Occas. Publ. No. 2.
1982. Ecology and biology of the Pacific walrus *Odobenus rosmarus divergens* Illiger. U.S. Fish Wildl. Serv., North Am. Fauna 74, 279 p.

FAY, F. H., AND L. F. LOWRY.
1981. Seasonal use and feeding habits of walruses in the proposed Bristol Bay clam fishery area. Final rep. to North Pacific Fishery Management Council, Contract 80-3, Anchorage, 60 p.

FEDER, H. M.
1978. Distribution, abundance, community struc-

ture, and trophic relationships of the nearshore benthos of the Kodiak Shelf, Cook Inlet, northeast Gulf of Alaska, and the Bering Sea. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1978, 4: 416-730.

FEDER, H. M., K. HAFLINGER, M. HOBERG, AND J. MCDONALD.
1981. The infaunal invertebrates of the southeastern Bering Sea. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 9: 257-670.

FEDER, H. M., AND S. C. JEWETT.
1981. Feeding interactions in the eastern Bering Sea with emphasis on the benthos. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 1229-1261. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

FENCHEL, T. M.
1968. The ecology of marine microbenthos. II. The food of marine benthic ciliates. Ophelia 5: 73-121.
1970. Studies on the decomposition of organic detritus derived from the turtle grass, *Thalassia testudinum*. Limnol. Oceanogr. 15(1): 14-20.
1972. Aspects of decomposer food chains in marine benthos. Verh. Dtsch. Zool. Ges. 65. Yahresversamml. 14: 14-22.
1977. Aspects of the decomposition of seagrasses. *In* C. P. McRoy and C. Helfferich (eds.), Seagrass ecosystems: a scientific perspective, p. 123-145. Marcel Dekker Inc., New York.
1980. Mud, microbes, and mineralization. *In* L. A. Underkofher and M. L. Wulf (eds.), Developments in industrial microbiology 21, p. 1-10. Soc. Industr. Microbiol., Arlington, Va.

FENCHEL, T. M., AND B. B. JORGENSEN.
1977. Detritus food chains of aquatic systems: the role of bacteria. Adv. Microbiol. Ecol. 1: 1-58.

FOWLER, C. W.
1982. Interactions of northern fur seals and commercial fisheries. *In* Transactions of the 47th North American wildlife and natural resources conference, p. 278-292. Wildl. Manage. Inst., Washington, D.C.

FROST, K. J., AND L. F. LOWRY.
1981. Foods and trophic relationships of cetaceans in the Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea Shelf: oceanography and resources, Vol. II, p. 825-836. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

FROST, K. J., L. F. LOWRY, AND J. J. BURNS.
1983. Distribution of marine mammals in the coastal zone of the Bering Sea during summer and autumn. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep. 20: 365-561.

FUHRMAN, J. A., AND F. AZAM.
1980. Bacterioplankton secondary production estimates for coastal waters of British Columbia, Antarctica, and California. Appl. Environ. Microbiol. 39(6): 1085-1095.

GEIGER, J. G., AND A. L. BUIKEMA, JR.
1982. Hydrocarbons depress growth and reproduction of *Daphnia pulex* (Cladocera). Can. J. Fish. Aquat. Sci. 39(6): 830-836.

GERACI, J. R., AND D. J. ST. AUBIN.
1982. Study of the effects of oil on cetaceans. U.S. Dep. Inter., Bur. Land Manage., Washington, D.C., 274 p.

GERACI, J. R., AND T. G. SMITH.
1976. Direct and indirect effects of oil on ringed seals (*Phoca hispida*) of the Beaufort Sea. J. Fish. Res. Board Can. 33(9): 1976-1984.

GILL, R. E., JR., AND C. M. HANDEL.
1981. Shorebirds of the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 719-738. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

GILL, R., JR., C. HANDEL, AND M. PETERSEN.
1979. Migration of birds in Alaska marine habitats. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 5: 245-288.

GILL, R., JR., AND P. D. JORGENSEN.
1977. Population dynamics and trophic relationships of marine birds in the Gulf of Alaska and southern Bering Sea. Appendix A. A preliminary assessment of timing and migration of shorebirds along the northcentral Alaska Peninsula. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. 1977, 4: 617-632.

GILL, R., P. D. JORGENSEN, A. R. DEGANGE, AND P. KUST, SR.
1977. Population dynamics and trophic relationships of marine birds in the Gulf of Alaska and southern Bering Sea, Part XII: avifaunal assessment of Nelson Lagoon, Port Moller, and Herendeen Bay, Alaska. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1977, 4: 594-632.

GILL, R. E., JR., M. R. PETERSEN, AND P. D. JORGENSEN.
1981. Birds of the northcentral Alaska Peninsula,

1976-1980. Arctic 34(4): 286-306.

GILL, R. E., JR., AND G. A. SANGER.
1979. Tufted puffins nesting in estuarine habitat. Auk 96: 792-794.

GILMARTIN, W. G., R. L. DELONG, A. W. SMITH, J. C. SWEENEY, B. W. DELAPPE, R. W. RISENBROUGH, L. A. GRINER, M. D. DAILEY, AND D. B. PEAKALL.
1976. Premature parturition in the California sea lion. J. Wildl. Dis. 12: 104-115.

GOERING, J. J., AND R. L. IVERSON.
1981. Phytoplankton distribution on the southeastern Bering Sea. D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 933-946. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

GOERING, J. J., AND C. P. MCROY.
1981. A synopsis of PROBES. EOS, Trans. Am. Geophys. Union 62: 730-734.

GOULD, P. J., D. J. FORSELL, AND C. J. LENSINK.
1982. Pelagic distribution and abundance of seabirds in the Gulf of Alaska and eastern Bering Sea. U.S. Dep. Inter. Fish Wildl. Serv., Anchorage, FWS/OBS-82/48, 294 p.

GRAU, C. R., T. ROUDYBUSH, J. DOBBS, AND J. WATHEN.
1977. Altered yolk structure and reduced hatchability of eggs from birds fed single doses of petroleum oils. Science 195: 779-781.

GRIFFITHS, R. P., AND R. Y. MORITA.
1981. Study of microbial activity and crude oil-microbial interactions in the waters and sediments of Cook Inlet and the Beaufort Sea. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 10: 417-784.

GUNDLACH, E. R., J. L. SADD, G. I. SCOTT, L. C. THEBEAU, AND D. J. MAIERO.
1981. Oil spill sensitivity of coastal environments and wildlife, Norton Sound and the Pribilof Islands, Alaska. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 171 p. + maps.

GUSEY, W. F.
1979. The fish and wildlife resources of the southern Bering Sea region. Environ. Affairs, Shell Oil Co., Houston, 383 p.

HAFLINGER, K. E.
1978. A numerical analysis of the distribution of the benthic infauna of the southeastern Bering Sea shelf. M.S. thesis, Univ. Alaska, Fairbanks. (Avail. *in* Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 9: 303-404.)
1981. A survey of benthic infaunal communities of the southeastern Bering Sea shelf. D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 1091-1103. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

HALL, J. D., C. S. HARRISON, J. NELSON, AND A. TABER.
1977. The migration of California gray whales into the Bering Sea. *In* Proc. (abstracts), Second Conf. Biol. Mar. Mammals, San Diego, Calif., December 12-15, 1977, p. 8. (Avail. from first author, P.O. Box 58, Kasilof, AK 99610.)

HAMEEDI, M. J. (ED.).
1982. Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 162 p.

HAMPSON, G. R., AND E. T. MOUL.
1978. No. 2 fuel oil spill in Bourne, Massachusetts: Immediate assessment of the effects on marine invertebrates and a 3-year study of growth and recovery of a salt marsh. J. Fish. Res. Board Can. 35(5): 731-744.

HARGRAVE, B. T.
1970. The utilization of benthic microflora by *Hyalella azteca* (Amphipoda). J. Anim. Ecol. 39: 427-437.

HARLIN, M.
1980. Seagrass epiphytes. *In* R. Phillips and C. P. McRoy (eds.), Handbook of seagrass biology: an ecosystem approach, p. 117-151. Garland STPM Press, New York.

HARTUNG, R.
1965. Some effects of oiling on reproduction of ducks. J. Wildl. Manage. 29: 872-874.
1967. Energy metabolism in oil-covered ducks. J. Wildl. Manage. 31: 798-804.

HAYES, M. O., AND E. R. GUNDLACH.
1979. Coastal processes field manual for oil spill assessments. RPI, Inc., Columbia, S.C., 172 p.

HAYNES, E. B.
1973. Description of prezoeae and stage I zoeae of *Chionoecetes bairdi* and *C. opilio* (Oxyrhyncha, Oregoniinae). Fish. Bull., U.S. 71(3): 769-775.
1974. Distribution and relative abundance of larvae of king crab, *Paralithodes camtschatica*, in the southeastern Bering Sea, 1969-70. Fish. Bull., U.S. 72(3): 804-812.

HEBARD, J. F.
1959. Currents in southeastern Bering Sea and possible effects upon king crab larvae. U.S. Fish Wildl. Serv. Spec. Sci. Rep. Fish. 293, 11 p.

HELLE, E., M. OLSSON, AND S. JENSEN.
1976. PCB levels correlated with pathological changes in seal uteri. Ambio. 5: 261-263.

HERSHNER, C., AND K. MOORE.
1977. Effects of the Chesapeake Bay oil spill on salt marshes of the lower bay. *In* Proceedings of the 1977 oil spill conference, p. 529-533. Am. Pet. Inst., Washington, D.C.

HESSING, P.
1983. Gray whale (*Eschrichtius robustus*) migration into the Bering Sea observed from Cape Sarichef, Unimak Island, Alaska, Spring, 1981. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep. 19: 47-74.

HIGGENS, B. E.
1978. An assessment of certain living marine resources and potential resource-use conflicts between commercial fisheries and petrolum development activities in outer Bristol Bay Basin and Bristol Bay, southeastern Bering Sea. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Juneau, 241 p.

HOLLAWAY, S. L., G. M. FAW, AND R. K. SIZEMORE.
1980. The bacterial community composition of an active oil field in the northwestern Gulf of Mexico. Mar. Pollut. Bull. 11: 153-156.

HOLMES, W. N., AND J. CRONSHAW.
1977. Biological effects of petroleum on marine birds. *In* D. C. Malins (ed.), The effects of petroleum on arctic and subarctic marine environments and organisms, Vol. II, p. 359-398. Academic Press, New York.

HOLMES, W. N., J. GORSLINE, AND J. CRONSHAW.
1979. Effects of mild cold stress on the survival of seawater-adapted mallard ducks (*Anas platyrhynchos*) maintained on food contaminated with petroleum. Environ. Res. 20: 424-444.

HOLT, S., S. RABALAIS, N. RABALAIS, S. CORNELIUS, AND J. S. HOLLAND.
1978. Effects of an oil spill on salt marshes at Harbor Island, Texas. I. Biology. *In* C. C. Bates (ed.), Proceedings of the conference on assessment of ecological impacts of oil spills, June 14-17, 1978, Keystone, Colo., p. 344-352. Am. Inst. Biol. Sci., Washington, D.C.

HOOD, M. A., W. S. BISHOP, SR., R. W. BISHOP, S. P. MEYERS, AND T. WHELAN, III.
1975. Microbial indicators of oil-rich marsh sediments. Appl. Microbiol. 30: 892-897.

HOOD, D. W., AND J. A. CALDER (EDS.).
1981. The eastern Bering Sea shelf: oceanography and resources. 2 vols. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

HUGHES, S. E., AND N. BOURNE.
1981. Stock assessment and life history of a newly discovered Alaska surf clam (*Spisula polynyma*) resource in the southeastern Bering Sea. Can. J. Fish. Aquat. Sci. 38(10): 1173-1181.

HUNT, G. L., JR., P. J. GOULD, D. J. FORSELL, AND H. PETERSON, JR.
1981a. Pelagic distribution of marine birds in the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 689-718. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

HUNT, G. L., JR., B. BURGESON, AND G. A. SANGER.
1981c. Feeding ecology of seabirds of the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 629-647. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

HUNT, G. L., JR., Z. EPPLEY, AND W. H. DRURY.
1981b. Breeding distribution and reproductive biology of marine birds in the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 649-687. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

INCZE, L., D. ARMSTRONG, AND D. WENCKER.
1982. Rates of development and growth of larvae of *Chionoecetes bairdi* and *C. opilio* in the southeastern Bering Sea. Alaska Sea Grant Symposium on Tanner Crab, May 1982 (in press).

INTERAGENCY TASK GROUP.
1978. Final environmental impact statement: consideration of a waiver of the moratorium and return of management of certain marine mammals to the state of Alaska. I. Summary and text. U.S. Dep. Commer. and U.S. Dep. Inter., Washington, D.C.

INTERNATIONAL NORTH PACIFIC FISHERIES COMMISSION.
1960. Progress report on king crab research in the eastern Bering Sea. *In* Int. North Pac. Fish. Comm. 1960 Annu. Rep. II, p. 70-75.
1963. King crab investigations in the eastern Bering Sea. *In* Int. North Pac. Fish. Comm. 1963 Annu. Rep. II, p. 88-101.
1965. King crab investigations in the eastern Bering Sea. *In* Int. North Pac. Fish. Comm. 1965 Annu. Rep. II, p. 56-64.

IVERSON, R. L., L. K. COACHMAN, R. T. COONEY, T. S. ENGLISH, J. J. GOERING, G. L. HUNT, JR., M. C. MACAULEY, C. P. MCROY, W. S. REEBURG, AND T. E. WHITLEDGE.
1979. Ecological significance of fronts in the southeastern Bering Sea. *In* R. J. Livingston (ed.), Ecological processes in coastal and marine systems, p. 437-466. Plenum Press, New York.

IVERSON, R. L., AND J. J. GOERING.
1979. Primary production and phytoplankton composition. Inst. Mar. Sci., Univ. Alaska, Fairbanks, PROBES Prog. Rep. 1: 145-161.

JEWETT, S. C., AND H. M. FEDER.
1981. Epifaunal invertebrates of the continental shelf of the eastern Bering and Chukchi seas. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 1131-1153. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

JEWETT, S. C., AND G. C. POWELL.
1981. Nearshore movement of king crab. Alaska Seas and Coast 9(3): 6-8.

JOHNS, D. M., AND J. A. PECHENIK.
1980. Influence of the water-accommodated fraction of No. 2 fuel oil on energetics of *Cancer enoratus* larvae. Mar. Biol. 55: 247-254.

KAJIMURA, H. , R. H. LANDER, M. A. PEREZ, A. E. YORK, AND M. A. BIGG.
1979. Preliminary analysis of the pelagic fur seal data collected by the United States and Canada during 1958-1974. 22nd Ann. Meet., Standing Sci. Comm. North Pac. Fur Seal Comm., Natl. Mar. Mammal Lab., Seattle, Wash.
1980. Further analysis of pelagic fur seal data collected by the United States and Canada during 1958-74. 23rd Ann. Meet. Standing Sci. Comm. North Pac. Fur Seal Comm., Natl. Mar. Mammal Lab., Seattle, Wash.

KATZ, L. M.
1973. The effects of water-soluble fractions of crude oil on larvae of the decapod crustacean *Neopanope texana* (J.). Environ. Pollut. 5: 199-240.

KENNEDY, R. S., AND W. R. FINNERTY.
1975. Microbial assimilation of hydrocarbons II. Intracytoplasmic membrane induction in *Acinetobacter* sp. Arch. Microbiol. 102: 85-90.

KENYON, K. W.
1972. Aerial surveys of marine mammals in the Bering Sea, 6-16 April 1972. Unpubl. manuscr., 79 p. U.S. Dep. Inter. Fish Wildl. Serv., Bur. Sport Fish. Wildl., Seattle, Wash.

KIKUCHI, T.
1980. Faunal relationships in temperate seagrass beds. *In* R. Phillips and C. P. McRoy (eds.), Handbook of seagrass biology: an ecosystem approach, p. 153-172. Garland STPM Press, New York.

KINDER, T. H., AND L. K. COACHMAN.
1978. The front overlying the continental slope in the eastern Bering Sea. J. Geophys. Res. 83: 4551-4559.

KINDER, T. H., AND J. D. SCHUMACHER.
1981. Hydrographic structure over the continental shelf of the southeastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. I, p. 31-52. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

KING, J. E.
1964. Seals of the world. Brit. Mus. (Nat. Hist.), London, 154 p.

KING, J. G., AND C. P. DAU.
1981. Waterfowl and their habitats in the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 739-753. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

KING, J. G., AND G. A. SANGER.
1979. Oil vulnerability index for marine-oriented birds. *In* J. C. Bartonek and D. N. Nettleship (eds.), Conservation of marine birds of northern North America, p. 227-239. U.S. Fish Wildl. Serv., Wildl. Res. Rep. 11.

KLINKHART, E.
1966. The beluga whale in Alaska. Alaska Dep. Fish Game, Fed. Aid Wildl. Restoration Proj. Rep. 7, 11 p.

KLUG, M.
1980. Detritus-decomposition relationships. *In* R. Phillips and C. P. McRoy (eds.), Handbook of seagrass biology: an ecosystem approach, p. 225-245. Garland STPM Press, New York.

KON, T.
1967. Fisheries biology of the Tanner crab, *Chionoecetes opilio*. I. On the prezoeal larva. Bull. Jpn. Soc. Sci. Fish. 33(8): 726-730.
1970. Fisheries biology of the Tanner crab. IV. The duration of the planktonic stages estimated by rearing experiments of larvae. Bull. Jpn. Soc. Sci. Fish. 36(3): 219-224. (Fish. Res. Board Can., Transl. Ser. 1603.)

KOZLOFF, P.
1981. Fur seal investigations, 1980. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., 2725 Montlake Blvd. E., Seattle, WA 98112. Proc. Rep. 81-2.

KREBS, C. T., AND K. A. BURNS.
1977. Long-term effects of an oil spill on populations of the salt marsh crab, *Uca pugnax*. Science 197: 484-487.

KROGMAN, B. A., H. W. BRAHAM, R. M. SONNTAG, AND R. G. PUNSLY.
1979. Early spring distribution, density, and abundance of the Pacific walrus (*Odobenus rosmarus*). Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 47 p.

KURATA, H.
1960. Studies on the larvae and post-larvae of *Paralithodes camtschatica.* 3. The influence of temperature and salinity on survival and growth of the larvae. Bull. Hokkaido Reg. Fish. Res. Lab. 21: 9-14. (Transl. by H. C. Kim, U.S. Bur. Comm. Fish., Auke Bay, Alaska.)

LAEVASTU, T., AND F. FAVORITE.
1981. Ecosystem dynamics in the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 611-625. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

LAEVASTU, T., AND P. LIVINGSTON.
1980. Basic inputs to PROBUB model for the eastern Bering Sea and western Gulf of Alaska. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., 2725 Montlake Blvd. E., Seattle, WA 98112. Proc. Rep. 80-3, 28 p.

LAUGHLIN, R. B., JR., L. G. L. YOUNG, AND J. M. NEFF.
1978. A long-term study of the effects of water-soluble fractions of No. 2 fuel oil on the survival, development rate, and growth of the mud crab *Rhithropanopeus harrisii. Mar. Biol. 47(1): 87§95.*

LEATHERWOOD, S., AND W. E. EVANS.
1982. Aerial surveys of endangered whales in the southern Bering Sea and western Gulf of Alaska (Shelikof Strait). Interim rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau. Hubbs-Sea World Res. Inst., San Diego, Calif., Contract NA82RAC0039, 25 p. + 3 append.

LE BOEUF, B. J.
1971. Oil contamination and elephant seal mortality: a "negative" finding. *In* D. Straughan (ed.), Biological and oceanographical survey of the Santa Barbara Channel oil spill, 1969-1970, Vol. 1, biology and bacteriology, p. 277-285. Allan Hancock Found., U.C.L.A.

LENSINK, C. J.
1961. Status report: beluga studies. Unpubl. manuscr., 20 p. Div. Biol. Res., Alaska Dep. Fish Game, Juneau.

LEVINGS, C. D., R. E. FOREMAN, AND V. J. TUNNICLIFFE.
1983. Review of the benthos of the Strait of Georgia and contiguous fjords. Can. J. Fish. Aquat. Sci. 40: 1120-1141.

LOWRY, L. F., K. J. FROST, D. G. CALKINS, G. L. SWARTZMAN, AND S. HILLS.
1982. Feeding habits, food requirements, and status of Bering Sea marine mammals. Final report, Vol. 1. North Pacific Fishery Management Council, Contract 814, Anchorage, 401 p.

MACDONALD, K. B., E. G. WOLF, AND N. L. SAVAGE.
1980. Coastal wetland studies, Cook Inlet, Alaska. Vegetation, primary production and wetland-estuary interactions. U.S. Environ. Prot. Agency, Off. Research and Development, Corvallis Environ. Res. Lab.

MACINTOSH, R. A., AND D. SOMERTON.
1981. Marine gastropods of the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 1215-1228. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

MANN, K. H.
1972. Macrophyte production and detritus food chains in coastal waters. Mem. Ist. Ital. Idrobiol. Dott Marco Marchi 29: 353-383.
1982. Ecology of coastal waters: a systems approach. Studies in Ecology, Vol. 8. Univ. California Press, 332 p.

MARUKAWA, H.
1933. Biological and fishery research on Japanese king crab *Paralithodes camtschatica* (Tilesius). (In Jpn., Engl. abstr.). J. Imp. Fish. Exp. Stn. 4(37): 1-52.

MCCONNAUGHEY, T., AND C. P. MCROY.
1979a. Food web structure and the fractionation of carbon isotopes in the Bering Sea. Mar. Biol. 53: 257-262.
1979b. ^{13}C label identifies eelgrass (*Zostera marina*) carbon in an Alaskan estuarine food web. Mar. Biol. 53: 263-269.

MCDONALD, J., H. M. FEDER, AND M. HOBERG.
1981. Bivalve mollusks of the southeastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 1155-1204. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

MCKNIGHT, D. E., AND C. E. KNODER.
1979. Resource development along coasts and on the ocean floor: potential conflicts with marine bird conservation. U.S. Fish Wildl. Serv. Res. Rep. 11: 183-194.

MCROY, C. P.
1966. The standing stock and ecology of eelgrass (*Zostera marina* L.) in Izembek Lagoon, Alaska. M.S. Thesis, Univ. Washington, Seattle, 138 p.
1968. The distribution and biography of *Zostera marina* (eelgrass) in Alaska. Pac. Sci. 22: 507-513.
1970. Standing stocks and other features of eelgrass (*Zostera marina*) populations on the coast of Alaska. J. Fish. Res. Board Can. 27(10): 1811-1821.

McRoy, C. P., and J. J. Goering.
1974. Nutrient transfer between the seagrass *Zostera marina* and its epiphytes. Nature 248: 173–174.

McRoy, C. P., J. J. Goering, and W. E. Shiels.
1972. Studies of primary production in the eastern Bering Sea. *In* A. Y. Takenouti (ed.), Biological oceanography of the northern North Pacific Ocean, p. 199–216. Idemitsu Shoten, Tokyo.

McRoy, C. P., and C. McMillan.
1977. Production, ecology and physiology of seagrass. *In* C. P. McRoy and C. Helfferich (eds.), Seagrass ecosystems: a scientific perspective, p. 53–87. Marcel Dekker Inc., New York.

McRoy, C. P., and S. L. Williams.
1977. Sublethal effects on seagrass photosynthesis, final report. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1977, 12: 636–673.

Michel, J., D. D. Domeracki, L. C. Thebeau, C. D. Getter, and M. O. Hayes.
1982. Sensitivity of coastal environments and wildlife to spilled oil of the Bristol Bay area of the Bering Sea, Alaska. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Asses., Juneau, 117 p. + 106 maps.

Miller, D. S., D. B. Peakall, and W. B. Kinter.
1978. Ingestion of crude oil: sublethal effects in herring gull chicks. Science 199: 315–317.

Moore, S. F., and F. L. Dwyer.
1974. Effects of oil on marine organisms: a critical assessment of published data. Water Res. 8(10): 819–827.

Morita, R.
1980. Microbial life in the deep sea. Can. J. Microbiol. 26: 1375–1385.

Motoda, S., and T. Minoda.
1974. Plankton of the Bering Sea. *In* D. W. Hood and E. J. Kelley (eds.), Oceanography of the Bering Sea with emphasis on renewable resources, p. 207–241. Proc. Int. Symp. Bering Sea Study, Hakodate, Japan, 31 Jan.–4 Feb. 1972. Inst. Mar. Sci., Univ. Alaska, Fairbanks, Occas. Publ. No. 2.

Natural Environment Research Council.
1971. The seabird wreck in the Irish Sea, autumn 1969. N.E.R.C. Publ. Sci. C., No. 4, London.

Newell, R.
1965. The role of detritus in the nutrition of two marine deposit feeders, the prosobranch, *Hydrobia ulvae* and the bivalves *Macoma balthica*. Proc. Zool. Soc. Lond. 144: 25–45.

Niebauer, H. J., V. Alexander, and R. T. Cooney.
1981. Primary production at the eastern Bering Sea ice edge: the physical and biological regimes. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 763–780. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

Niggol, K.
1982. Data on fish species from Bering Sea and Gulf of Alaska. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., 2725 Montlake Blvd. E., Seattle, WA 98112. NOAA Tech. Memo. NMFS F/NWC-29, 125 p.

O'Clair, C. E., J. L. Hanson, R. T. Myren, J. A. Gharrett, T. R. Merrell, Jr., and J. S. MacKinnon.
1981. Reconnaissance of intertidal communities in the eastern Bering Sea and the effects of ice-scour on community structure. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 10: 109–415.

Olla, B. L., W. H. Pearson, P. C. Sugarman, D. L. Woodruff, and J. W. Blaylock.
1981. The effects of petroleum hydrocarbons on chemoreception and behavior in the Dungeness crab *Cancer magister*. U.S. Environ. Prot. Agency, Washington, D.C. EPA-600/7-81-093.

Oritsland, N. A., F. R. Engelhardt, F. A. Juck, R. Hurst, and P. O. Watts.
1981. Effect of crude oil on polar bears. Dep. Indian Affairs and Northern Development, Canada. Publ. QS-8283-020-EEA1.

Otto, R. S.
1981. Eastern Bering Sea crab fisheries. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 1037–1066. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

Otto, R. S., R. A. MacIntosh, T. M. Armetta, and S. Wilson.
1980. King and Tanner crab research in the eastern Bering Sea, 1980. Document submitted to the annual meeting of the International North Pacific Fisheries Commission, Anchorage, Alaska, October 1980, 54 p. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., 2725 Montlake Blvd. E., Seattle, WA 98112.

Payne, J. R., B. E. Kirstein, G. D. McNabb, Jr., J. L. Lambach, R. Redding, R. E. Jordan, W. Hom, C. de Oliveira, G. S. Smith, D. M. Baxter, and R. Gaegel.
1984. Multivariate analysis of petroleum weathering in the marine environment-sub arctic. Volume 1-Technical results. U.S. Dep. Com-

mer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep. 21 (entire volume; paginated by chapter).

PEREYRA, W. T., J. E. REEVES, AND R. G. BAKKALA.
1976. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Processed rep., 619 p. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., 2725 Montlake Blvd. E., Seattle, WA 98112.

PETERSEN, M. R.
1980. Observations of wing-feather moult and summer feeding ecology of Steller's Eiders at Nelson Lagoon, Alaska. Wildfowl 31: 99-106.
1981. Populations, feeding ecology, and molt of Steller's Eiders. Condor 83: 256-262.

PIKE, G. C.
1962. Migration and feeding of the gray whale (*Eschrichtius gibbosus*). J. Fish. Res. Board Can. 19(5): 815-838.

PITCHER, K. W., AND D. G. CALKINS.
1981. Reproductive biology of the Steller sea lions in the Gulf of Alaska. J. Mammal. 62: 599-605.

PLATT, T., AND D. V. SUBBA RAO.
1975. Primary production of marine microphytes. *In* J. P. Cooper (ed.), Photosynthesis and productivity in different environments, p. 249-280. Intern. Biol. Prog., Vol. 3. Cambridge Univ. Press.

QUAMMEN, M. L.
1982. Influence of subtle substrate differences on feeding by shorebirds on intertidal mudflats. Mar. Biol. 71(3): 339-343.

RASMUSSEN, E.
1977. The wasting disease of eelgrass (*Zostera marina*) and its effects on environmental factors and fauna. *In* C. P. McRoy and C. Helfferich (eds.), Seagrass ecosystems: a scientific perspective, p. 1-51. Marcel Dekker Inc., New York.

REDBURN, D. R.
1976. Coastal ecosystems of Alaska: a preliminary review of the distribution and abundance of primary producers and consumers in the marine environment. Alaska Dep. Environ. Conservation, Div. Water Programs/Environ. Analysis Section, Juneau, 227 p.

RICE, D. W., AND A. A. WOLMAN.
1971. Life history and ecology of the gray whale, *Eschrichtius robustus*. Am. Soc. Mammal. Spec. Publ. 3, 142 p.

RICE, R. L.
1981. Feeding habits of crangonid shrimps and some aspects of sediment-detrital food systems in lower Cook Inlet, Alaska. M.S. Thesis, Univ. Alaska, 64 p.

RICE, S. D., D. A. MOLES, J. F. KARINEN, S. KORN, M. G. CARLS, C. C. BRODERSEN, J. A. GHARRETT, AND M. M. BABCOCK.
1983. A comprehensive review of all oil effects research on Alaskan fish and invertebrates conducted by Auke Bay Laboratory, 1970-1981. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Natl. Ocean Serv., Off. Oceanogr. Mar. Serv., Ocean Assess. Div., Juneau, 145 p.

RICE, S. D., D. A. MOLES, T. L. TAYLOR, J. F. KARINEN.
1979. Sensitivity of 39 Alaskan marine species to Cook Inlet crude oil and No. 2 fuel oil. *In* Proceedings of 1979 oil spill conference (prevention, behavior, control, and cleanup), p. 549-554. Am. Pet. Inst., Washington, D.C.

RUGH, D. J., AND H. W. BRAHAM.
1979. California gray whale (*Eschrichtius robustus*) fall migration through Unimak Pass, Alaska, 1977: a preliminary report. Rep. Int. Whaling Comm. 29: 315-320.

SAMAIN, J., J. MOAL, A. COUN, J. LE COZ, AND J. DANIEL.
1980. Effects of the "Amoco Cadiz" oil spill on zooplankton: a new possibility of ecophysiological survey. Helgol. Wiss. Meeresunters. 33: 225-235.

SANGER, G.
1972. Preliminary standing stock and biomass estimates of seabirds in the subarctic Pacific region. *In* A. Y. Takenouti (ed.), Biological oceanography of the northern North Pacific Ocean, p. 589-611. Idemitsu Shoten, Tokyo.

SANGER, G. A., AND P. A. BAIRD.
1977a. Ecosystem dynamics of birds and marine mammals. Part II: aspects of the feeding ecology of Bering Sea avifauna. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1977, 12: 372-417.
1977b. Population dynamics and trophic relationships of marine birds in the Gulf of Alaska and southern Bering Sea. Part XIV: the trophic relationships of marine birds in the Gulf of Alaska and the southern Bering Sea. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1977, 4: 694-756.

SATO, S.
1958. Studies on larval development and fishery biology of king crab, *Paralithodes camtschatica* (Tilesius). (In Jpn., Engl. abstr.) Bull. Hokkaido Reg. Fish. Res. Lab. 17: 1-102.

SCHEFFER, V. B.
1958. Seals, sea lions, and walruses: a review of the Pinnipedia. Stanford Univ. Press, 179 p.

SCHNEIDER, K. B.
1981. Distribution and abundance of sea otters in the eastern Bering Sea. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. II, p. 837-845. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

SCHNEIDER, K. B., AND J. FARO.
1975. Effects of sea ice on sea otters. J. Mammal. 56: 91-101.

SCHNEIDER, D., AND G. L. HUNT.
1982. Carbon flux to seabirds in waters with different mixing regimes in the southeastern Bering Sea. Mar. Biol. 67: 337-344.

SCHOLANDER, P. F., V. WALTERS, R. HOCK, AND L. SWENG.
1950. Body insulation of some arctic and tropical mammals and birds. Biol. Bull. (Woods Hole) 99: 225-236.

SCHUMACHER, J. D., T. H. KINDER, D. J. PASHINSKI, AND R. L. CHARNELL.
1979. A structural front over the continental shelf of the eastern Bering Sea. J. Phys. Oceanogr. 9: 79-87.

SCHUSTERMAN, R. J.
1981. Steller sea lion—*Eumetopias jobatus*. *In* S. H. Ridgway and R. J. Harrison (eds.), Handbook of marine mammals, Vol. 1, p. 119-142. Academic Press, New York.

SCIENCE APPLICATIONS, INC.
1981. North Aleutian Lease Area. Twenty-one resource assessment sheets prepared for OCSEAP. SAI, Boulder, Colo.

SEARS, H. S., AND S. T. ZIMMERMAN.
1977. Alaska intertidal survey atlas. Processed manuscr., 402 charts. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Auke Bay Lab., P.O. Box 155, Auke Bay, AK 99821.

SELKGREGG, L. L. (ED.).
1974. Alaska regional profiles: southwest region. Arctic Environmental Information and Data Center, Univ. Alaska, Anchorage, 313 p.

SHAUGHNESSY, P. D., AND F. H. FAY.
1977. A review of the taxonomy and nomenclature of the North Pacific harbor seal. J. Zool. (Lond.) 182: 385-419.

SIEBERS, D.
1982. Bacterial-invertebrate interactions in uptake of dissolved organic matter. Am. Zool. 22: 723-733.

SIMPSON, J. S., AND W. G. GILMARTIN.
1970. An investigation of elephant seal and sea lion mortality on San Miguel Island. BioScience 20: 289.

SONNTAG, N. C., R. R. EVERITT, D. MARMORCK, AND R. HILBORN.
1980. Report of the Bering Sea ecological processes study modeling workshop. Environmental and Social Systems Analysts Ltd., Vancouver, B.C., 96 p.

SOWLS, A. L., S. A. HATCH, AND C. J. LENSINK.
1978. Catalog of Alaskan seabird colonies. U.S. Dep. Inter. Fish Wildl. Serv. FWS/OBS-78/78.

STEBBINGS, R. E.
1970. Recovery of a salt marsh in Brittany sixteen months after heavy pollution by oil. Environ. Pollut. 1(2): 163-167.

STOUTHAMER, A. H.
1979. The search for correlation between theoretical and experimental growth yields. *In* J. R. Quayle (ed.), Microbial biochemistry, p. 1-47. International Review of Biochemistry, Vol. 21 (H. L. Kornberg and D. C. Phillips, series eds.). Univ. Park Press, Baltimore, Md.

STRAUCH, J. G., AND G. L. HUNT, JR.
1982. Marine birds. *In* M. J. Hameedi (ed.), Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981, p. 83-110. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

TATEM, H. E.
1977. Accumulation of naphthalenes by grass shrimp; effects on respiration, hatching, and larval growth. *In* D. A. Wolfe (ed.), Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms, p. 201-209. Pergamon Press, New York.

THOMAS, M. L. H.
1973. Effects of Bunker C oil on intertidal and lagoonal biota in Chedabucto Bay, Nova Scotia. J. Fish Res. Board Can. 30: 83-90.
1978. Comparison of oiled and unoiled intertidal communities in Chedabucto Bay, Nova Scotia. J. Fish. Res. Board Can. 35: 707-716.

TIETJEN, J. H.
1980. Microbial-meiofaunal interrelationships: a review. *In* D. Schlessenger (ed.), Microbiology—1980, p. 335-338. Am. Soc. Microbiol., Washington, D.C.

U.S. DEPARTMENT OF COMMERCE.
1980a. Living marine resources and commercial fisheries relative to potential oil and gas development in the North Aleutian Shelf area (tentative sale no. 75). U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Seattle, 92 p.
1980b. Living marine resources and potential

impacts of oil and gas development in the Bering-North Aleutian Shelf area (lease sale #75). NOAA/OCSEAP resource inventory for sale #75. Unpubl. manuscr., 28 p. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., P.O. Box 1808, Juneau, AK 99802.

1980c. Final environmental impact statement on the interim convention on conservation of the North Pacific fur seal. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Washington, D.C., 116 p.

1981. Tidal current tables 1982: Pacific coast of North America and Asia. U.S. Dep. Commer., NOAA, Natl. Ocean Serv., Rockville, Md.

U.S. DEPARTMENT OF THE INTERIOR.

1981. Alaska Peninsula National Wildlife Refuge. Final environmental impact statement. U.S. Dep. Inter. Fish Wildl. Serv., Washington, D.C., 339 p.

VAN BREE, P. J. H.

1977. On former and recent strandings of cetaceans on the coast of the Netherlands. J. Saeugetierk. D. Mitt. 42: 101-107.

VANDERBORGHT, J. P., R. WOLLART, AND G. BILLEN.

1977. Kinetic models of diagenesis in disturbed sediments. Part 1. Mass transfer properties and silica diagenesis. Limnol. Oceanogr. 22(5): 787-793.

VANDERMEULEN, J. H.

1982. Some conclusions regarding long-term biological effects of some major oil spills, p. 335-349. *In* R. B. Clark (ed.), The long-term effects of oil pollution on marine populations, communities, and ecosystems. Philos. Trans. R. Soc. Lond. B Biol. Sci. 297.

VANDERMEULEN, J. H., AND D. C. GORDON, JR.

1976. Re-entry of 5-year-old standard bunker C fuel oil from a low energy beach onto the water, sediments, and biota of Chedabucto Bay, Nova Scotia. J. Fish. Res. Board Can. 33: 2002-2010.

VIDAL, J., AND S. SMITH.

1982. Biomass, growth, and development of populations of herbivorous zooplankton in the southeastern Bering Sea during spring. Unpubl. manuscr. Submitted to Deep-Sea Res.

WARNER, I. M., AND P. M. SHAFFORD.

1981. Forage fish spawning surveys, southern Bering Sea. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Final Rep., Biological Studies 10: 1-64.

WEBER, D. D.

1967. Growth of the immature king crab *Paralithodes camtschatica* (Tilesius). Int. North Pac. Fish. Comm. Bull. 21: 21-47.

WESTLAKE, D. W. S., AND F. D. COOK.

1980. Petroleum biodegradation potential of northern Puget Sound and Strait of Juan de Fuca. U.S. Environ. Prot. Agency, Washington, D.C., EPA-600/7-80-133.

WIENS, J. A., G. FORD, D. HEINEMANN, AND C. FIEBER.

1979. Simulation modeling of marine bird population energetics, food consumption, and sensitivity to perturbation. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1978, 1: 217-270.

WINFREY, M. R., AND D. M. WARD.

1981. Effect of the *AMOCO CADIZ* oil spill on predominant anaerobic microbial processes in intertidal sediments. *In Amoco Cadiz*: fates and effects of the oil spill. Proceedings of the international symposium, Centre Océanologigue de Bretagne, Brest (France), November 19-22, 1979, p. 257-267. Centre National pour l'Exploitation des Océans, Paris.

WHITLEDGE, T. E., R. T. COONEY, R. IVERSON, AND J. WALSH.

1980. Some aspects of the pelagic springtime ecosystem over the southeastern Bering Sea shelf. Inst. Mar. Sci., Univ. Alaska, Fairbanks, PROBES Prog. Rep. 2: 631-668.

ZIEMAN, J., AND R. WETZEL.

1980. Productivity in seagrasses: methods and rates. *In* R. Phillips and C. P. McRoy (eds.), Handbook of seagrass biology: an ecosystem perspective, p. 87-116. Garland STPM Press, New York.

ZIMMERMAN, S. T., AND T. R. MERRELL.

1976. Baseline/reconnaissance characterization, littoral biota, Gulf of Alaska and Bering Sea. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Q. Rep., July-September 2: 252-267.

ZIMUSHKO, V. V., AND S. A. LENSKAYA.

1970. Feeding of the gray whale (*Eschrichtius robustus* Erx.) at foraging grounds. Ekologia, Akad. Nauk SSSR, 1(3): 26-35. (Transl. by Consultants Bur., Div. of Plenum Publ. Corp., 227 West 17th St., New York, NY 10011.)

4

Fishery Resources

Fredrik V. Thorsteinson and Lyman K. Thorsteinson

Workshop Chairman: F. V. Thorsteinson. Participants: T. Boyd, F. Jamsen, S. Langdon, M. J. Pelto, S. D. Rice, D. Rogers, R. R. Straty, L. K. Thorsteinson, R. Wolotira, and H. Yuen.

4.1 INTRODUCTION

The Bering Sea supports more than 300 species of finfish representing at least 43 families, of which 8 are of commercial interest. Sockeye salmon runs into Bristol Bay are world renowned, and together with the red king and Tanner crab harvests, regional domestic catches have been valued at more than $400 million annually in recent years. Although little foreign fishing is conducted in the North Aleutian Shelf lease area, the region contains major portions of these target species seasonally as most undergo extensive migrations. Many of the coastal streams draining into the lease area are the spawning grounds for salmon originating along the north side of the Alaska Peninsula. Villagers from Sand Point to Port Heiden depend heavily on these stocks for portions of their annual incomes and subsistence needs. Including these local stocks, approximately 88% of all salmon entering streams around the Bering Sea pass through North Aleutian Shelf waters on their spawning migration.

In a workshop held during the St. George Basin Synthesis Meeting, 28–30 April 1981, the distributions, abundance, and life histories of many finfish were described (Thorsteinson and Thorsteinson 1982). Species considered included yellowfin sole, rock sole, flathead sole, Greenland turbot, Pacific halibut, Pacific cod, Pacific herring, sablefish, and walleye pollock. These fish, with the possible exceptions of sablefish and turbot, occupy the waters of the North Aleutian Shelf seasonally as adults or during early developmental stages. Because of this, the North Aleutian Shelf fisheries workshop concentrated mainly on the salmon of Bristol Bay and the north side of the Alaska Peninsula, and the potential impacts of OCS development on these stocks.

4.2 PACIFIC SALMON

Pacific salmon, *Oncorhynchus* spp., are managed on the basis that runs of a given species returning to various river systems or principal tributaries constitute individual stocks. Stocks are mixed in the open ocean and remain so as they begin return migration from the ocean. Segregation occurs when they approach the vicinity of natal streams. Because of reproductive isolation, each stock has its own requirements for spawning, incubation of eggs, and rearing. Salmon passing through the North Aleutian Shelf lease area are a complex mixture of stocks of five species of salmon bound for streams and rivers located on the north sides of Unimak Island and the Alaska Peninsula, around Bristol Bay, and further north along the Bering Sea coast. They are present in North Aleutian Shelf waters from May through at least October as seaward-migrating juveniles or returning adults; relatively small numbers of immature salmon of all species remain in the area year round.

Adult salmon that migrate through the area are exploited in a number of localities (Fig. 4.1, Table 4.1). With the exception of the fishery on the south side of Unimak Island, all are terminal fisheries targeted on segregated stocks in bays

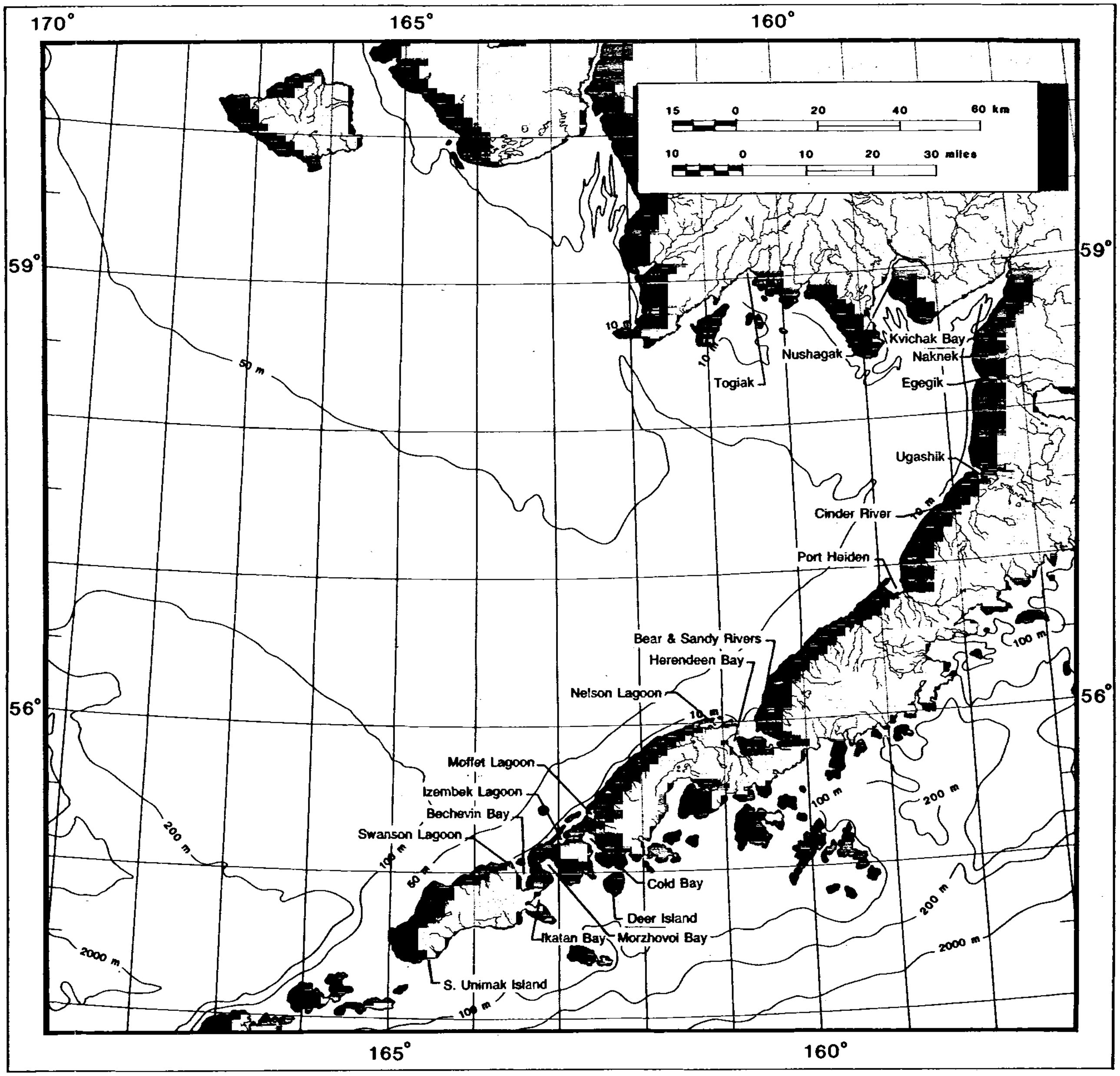


FIGURE 4.1—Location of fisheries on salmon migrating through the North Aleutian Shelf.

or at river mouths. The Bristol Bay area with its five major river systems (Ugashik, Egegik, Kvichak-Naknek, Nushagak, and Togiak) is by far the most important contributor; although all five species utilize these systems, sockeye salmon is the most important (Tables 4.1–4.3). The Kvichak and Naknek rivers are the major producers of sockeye salmon; the Nushagak, second in sockeye production, also has important runs of king, chum, and, in even-numbered years, pink salmon.

Salmon runs fluctuate widely in magnitude from year to year. The total catch of all species in Bristol Bay varied from 1.5 million in 1973 to 28.2 million in 1981. Total runs for these same years are estimated at 2.4 and 34.4 million, respectively. The largest sockeye salmon run on record occurred in 1980, when the total run into Bristol Bay systems was an estimated 62.3 million fish; the 1980 catch of 23.7 million does not reflect total run size, as a fishermen's strike reduced fishing time.

The 1981 total catch of all salmon species from runs that migrate through North Aleutian Shelf waters amounted to 32.8 million fish with an estimated ex-vessel value of $99.5 million: 27.7 million salmon taken in Bristol Bay and 5.1 million in fisheries from south Unimak Island to Cinder River, valued at $84 million and $15.1 million, respectively. Of all the salmon stocks that pass through the lease area, those of Bristol Bay are overwhelmingly important numerically and in value.

All salmon species have similar life histories but they differ in fecundity, food habits, growth rate, migration patterns, freshwater and ocean age, age and size at maturity, and time and location of spawning. Salmon eggs are deposited in gravel beds of rivers, streams, or lakes. Alevins hatch from the eggs during the winter and remain in the gravel until spring, when their yolk sacs are absorbed and they emerge from the gravel as fry. Pink and chum salmon fry proceed immediately to sea after emergence; fry of other species reside in fresh water for a few weeks or one or more years. Young salmon, after leaving rivers along the Bering Sea coast, migrate seaward across the continental shelf to ocean waters of the central and western Bering Sea and the North Pacific Ocean, where they spend most of their marine life. Depending on species, salmon usually spend from 1 to 4 years at sea.

The biology of Pacific salmon, as it pertains to the North Aleutian Shelf, can be conveniently divided into three phases: seaward migration of juveniles, immatures, and the return adult spawning migration. In this report, discussion of these facets of their life history focuses on description of abundance and seasonality so that some judgment of consequences, based on salmon presence or absence, might be made in the event of an environmental perturbation.

4.2.1 Seaward Migration

Of the five species of Pacific salmon inhabiting the Bering Sea, only sockeye salmon have been studied sufficiently to describe in some detail their seaward migration. Information on the seaward migration of the other species of salmon from Bristol Bay and salmon from streams draining the north side of the Alaska Peninsula is fragmentary and obtained incidentally from the sockeye studies (Straty 1974; Straty and Jaenicke 1980; Straty 1982) or from casual observations by area fishery managers. Research fishing in North Aleutian Shelf waters has not been conducted beyond late September, so there is little direct evidence as to how long salmon remain abundant there. Juvenile salmon are within this area during September and October and probably even later. Juveniles are abundant in the area from mid-May through at least September. Chinook salmon are the first species to enter the area, followed in order by sockeye, chum, pink, and coho salmon.

Juvenile Sockeye Salmon

Juvenile sockeye salmon originating in the various rivers of Bristol Bay and those along the north side of the Alaska Peninsula enter the Bering Sea at different times during late spring and early summer. The seasonal timing of the migration is species and stock specific and varies according to annual differences in environmental conditions, such as the time of ice breakup on lakes, streams, and rivers and the warming of these waters. Young sockeye leave Bristol Bay streams from mid-May to August with the peak migration occurring about 1 June under average conditions. Emigrations from the north side of the Alaska Peninsula probably occur through the same time period but peak at a somewhat later date, as the rivers are shorter and closer to the ocean feeding grounds. Virtually nothing is known of the distribution and migration routes of juvenile sockeye salmon originating in rivers northwest of Bristol Bay (Kuskokwim Bay, Norton Sound, and Kotzebue Sound). The extent to which salmon from these rivers and north slope Alaska Peninsula rivers may intermingle with Bristol Bay emigrants is not known, but intermingling must occur to some degree in coastal waters and, more certainly, in pelagic waters of the open ocean.

Because juvenile sockeye salmon enter the sea at different times, individual Bristol Bay river stocks are somewhat segregated during the first weeks of seaward migration. Differences in age and size at the time of entry into salt water also contribute to initial separation. The 2-year-old sockeye precede the 1-year-olds, and owing to their larger size probably migrate seaward at a more rapid rate. The result of these differences is that juvenile sockeye salmon are distributed throughout most of the area encompassing the seaward migration route (Fig. 4.2) from late May through late July. From late May to early August, when usual environmental conditions prevail, the greatest biomass of juvenile sockeye is present along the coast of Bristol Bay to the northeast of Port Heiden (Straty 1974). Early migrants are more abundant farther seaward. After early August the greatest biomass of juvenile sockeye salmon is to the west or seaward of Port Heiden.

From late May to late September the young fish travel in a belt between the coast and 48 km offshore. Feed is less abundant in inner Bristol Bay than farther seaward and the juvenile sockeye move fairly rapidly to the vicinity of Port Heiden where prey items become more abundant. Preferred prey items (euphausiids, copepods, cladocerans, and sand lance) are more abundant offshore and juvenile sockeye tend to seek these waters. Food type, size, and abundance probably determine how long young fish may reside in a given geographic region dur-

TABLE 4.1—Fisheries on salmon migrating through the North Aleutian Shelf, village participants, and gear employed; 1981 catch, periods taken, and peak weeks.

	South Unimak Island	Urilia and Bechevin Bays	Izembek and Moffet Bays	Nelson Lagoon	Herendeen Bay
Village Participants	Sand Point King Cove False Pass	False Pass	False Pass King Cove	Nelson Lagoon	Nelson Lagoon
Gear Employed	Purse seine Drift Gillnet Set Gillnet	Hand seine	Drift gillnet Hand seine	Drift gillnet Set gillnet	Hand seine
Chinook Salmon					
1981 Catch	4,550	6	7	10,981	3
Period taken	31 May-4 July	--	--	7 June-1 Aug.	--
Peak week	21-27 June	--	--	21-27 June	--
Sockeye Salmon					
1981 Catch	1,483,374	20,442	30,943	374,722	967
Period taken	31 May-4 July	15 June-8 Aug.	5 July-8 Aug.	7 June-29 Aug.	5-18 July
Peak week	14-20 June	21-27 June; 26 July-1 Aug.	2-8 Aug.	5-11 July	5-11 July
Chum Salmon					
1981 Catch	533,452	60,266	296,440	62,764	114,198
Period taken	31 May-4 July	21 June-5 Sept.	5 July-15 Sept.	21 June-29 Aug.	28 June-25 July
Peak week	21-27 June	28 June-4 July	2-8 Aug.	26 July-1 Aug.	12-18 July
Pink Salmon					
1981 Catch	333,644	9,063	0	13	7
Period taken	7 June-4 July	15-22 Aug.	--	--	--
Peak week	21-27 June	9-15 Aug.	--	--	--
Coho Salmon					
1981 Catch	738	151	0	133,477	0
Period taken	21 June-18 July	6-12 Sept.	--	26 July-19 Sept.	--
Peak week	5-11 July	6-12 Sept.	--	30 Aug.-5 Sept.	--

SOURCE: Henry Yuen, Alaska Department of Fish and Game, Anchorage. Data provided for Fisheries Workshop of the North Aleutian Shelf Synthesis Meeting.

ing seaward migration. Straty (1982; communication at the meeting) estimates rates of travel for juvenile sockeye and coho salmon (length, 100 mm; sea temperature, 6°C; active migration, 10 h/d) at 11.5 and 14.3 km/d, respectively. Presumably pink, chum, and chinook salmon would travel at slightly lesser or greater rates depending on comparative size under the same conditions; however, there are no data to ascertain this. During research fishing in Bristol Bay, seaward-migrating sockeye salmon were found to be most abundant in the upper 2 m of the water column (Straty 1974). They were most abundant in the top 1 m at night and at a depth of 2 m during the day. A few were taken to a depth of 5 m in daytime sets of variable-mesh gill nets.

Straty (1981) summarized numerous studies focusing on the apparent responses of salmon to certain environmental conditions (notably sea temperature) and their variability. The seasonal distribution and abundance of juvenile sockeye can undergo considerable variation. For example, in 1971, a year characterized by anomalously cold sea temperatures from spring through fall (Fig. 4.3), juvenile sockeye were virtually absent in outer Bristol Bay seaward of Port Heiden in early July, whereas they were abun-

TABLE 4.1—*Continued.*

	Moller Bay, Bear and Sandy Rivers	Three Hills-Ilnik	Port Heiden	Cinder River	Bristol Bay*
Village Participants	False Pass Sand Point King Cove	Sand Point Nelson Lagoon	Port Heiden	Port Heiden	Bristol Bay villages Port Heiden Nonresident
Gear Employed	Drift Gillnet	Drift Gillnet Set Gillnet	Drift gillnet Set Gillnet	Drift gillnet Set gillnet	Drift Gillnet
Chinook Salmon					
Catch	1,195	23	6,085	0	238,065
Period taken	7 June-8 Aug.	--	24 May-27 June	--	
Peak week	5-11 July	--	7-13 June	--	
Sockeye Salmon					
Catch	1,345,569	68,893	3,874	24	25,713,242
Period taken	7 June-5 Sept.	28 June-5 Aug.	31 May-25 July	16-22 Aug.	
Peak week	5-11 July	5-11 July	28 June-4 July	16-11 Aug.	
Chum Salmon					
Catch	166,985	7,148	227	0	1,475,307
Period taken	7 June-5 Sept.	28 June-5 Aug.	7-25 June	--	
Peak week	5-11 July	5-11 July	28 June-4 July	--	
Pink Salmon					
Catch	1,654	480	0	0	7,528
Period taken	5 July-5 Sept.	5 July-15 Aug.	--	--	
Peak week	9-15 Aug.	9-15 Aug.	--	--	
Coho Salmon					
Catch	4,721	4	3,845	12,899	313,167
Period taken	12 July-5 Sept.	--	30 Aug.-12 Sept.	9 Aug.-12 Sept.	
Peak week	23-29 Aug.	--	30 Aug.-5 Sept.	23-29 Aug.	

*Pink salmon runs dominant in even-numbered years.

dant in this area in 1967, a year with warm temperatures during June. Seawater temperature differences can be expected to result in variations in the time juveniles reach the North Aleutian Shelf and the length of time they remain in this region. The influence of anomalous sea temperatures on the rate of seaward migration is apparent in Figure 4.4.

In addition to restricting the seasonal distributions of young salmon, sea temperatures may also influence the width of the seaward migration route (Straty 1974). Coastal waters on the southeastern side of Bristol Bay are generally warmer than adjacent waters offshore (i.e., isotherms parallel the coast). Thus, during their seaward migration through this area, juvenile salmon are afforded a range of temperatures that may best suit their immediate thermal requirements. Juveniles appear to avoid the colder offshore waters, particularly in years when anomalous cold sea temperatures prevail as in 1971 (Straty 1974). In 1971 juvenile sockeye were captured during research fishing by the National Marine Fisheries Service (NMFS) only at locations nearest the coast and in the shallowest waters that could be fished (U.S. Department of Commerce 1966–72). Such occurrences could determine the extent to which juvenile salmon travel further offshore during continued seaward migration.

Juvenile Chum, Pink, Chinook, and Coho Salmon

The following summary of the available information concerning seaward migrations of juvenile chum, pink, chinook, and coho salmon through the North Aleutian Shelf lease area is drawn largely from the report prepared by Straty (1982) for the synthesis meeting.

In Bristol Bay juvenile chum and pink salmon have been captured during research fishing at various times between early summer and early fall in the area encompassing the seaward migration route of juvenile sockeye salmon.

TABLE 4.2—Bristol Bay salmon catch by district and species, 1981.

	Sockeye	Chinook	Chum	Pink*	Coho
Togiak					
Catch	620,811	24,348	236,407	6,722	29,554
Period taken	8 June–15 Aug.	1 June–29 Aug.	8 June–29 Aug.	15 June–29 Aug.	26 July–29 Aug.
Peak period	12–18 July	29 June–4 July	6–11 July	6–11 July	24–29 Aug.
Nushagak					
Catch	7,713,416	194,869	772,869	338	225,409
Period taken	8 June–15 Aug.	18 May–5 Sept.	8 June–22 Aug.	16 June–29 Aug.	16 July–5 Sept.
Peak period	1–6 July	6–12 June	19–25 June	NA	6–12 Aug.
Kvichak-Naknek					
Catch	10,948,744	10,378	345,955	177	785
Period taken	8 June–14 Aug.	1 June–8 Aug.	15 June–14 Aug.	NA	14 July–14 Aug.
Peak period	1–6 July	4–11 July	4–11 July	NA	27 July–2 Aug.
Egegik					
Catch	4,480,710	5,834	87,452	262	30,602
Period taken	1 June–8 Aug.	1 June–8 Aug.	8 June–8 Aug.	NA	17 July–29 Aug.
Peak period	30 June–6 July	18–25 June	29 June–6 July	NA	8–15 Aug.
Ugashik					
Catch	1,949,531	3,636	32,624	29	29,817
Period taken	15 June–25 Aug.	25 May–25 July	15 June–25 July	NA	27 July–12 Sept.
Peak period	8–14 July	17–24 June	7–13 July	NA	28 Aug.–3 Sept.

SOURCE: Henry Yuen, Alaska Department of Fish and Game, Anchorage. Data provided for Fisheries Workshop of the North Aleutian Shelf Synthesis Meeting.

*Pink salmon runs dominant in even-numbered years.

Small numbers of chum salmon were captured by purse seine in the coastal waters of Bristol Bay as early as mid-June in 1967; however, juveniles did not become abundant in these waters until after mid-July in 1967 and 1969. Juvenile chum salmon remained abundant along the southwestern coast of Bristol Bay seaward of longitude 159° W. through August and until at least mid-September in 1969 and 1970 (U.S. Department of Commerce 1966–72).

Juvenile pink salmon have not been captured in Bristol Bay in the area encompassing the seaward migration route of the juvenile sockeye salmon until after late June. They have been captured primarily in the coastal areas of inner Bristol Bay, east of longitude 159° W., where they increased in abundance from late June through mid-August of 1969. Presumably Bristol Bay juvenile pink salmon did not reach the coastal areas of outer Bristol Bay (the North Aleutian Shelf) until late August and September. In 1969 a few were captured near Port Moller at 56°12′ N., 161°00′ W. on 25 August. These were the only juvenile pink salmon captured seaward of 159° W. during the various years of intensive research fishing in the area by NMFS (U.S. Department of Commerce 1966–72). Juvenile pink salmon probably do not become abundant in North Aleutian Shelf waters until sometime in September or October.

Juvenile chinook and coho salmon have also been captured with juvenile sockeye salmon during research fishing in Bristol Bay. The distribution of juvenile chinook and coho salmon is similar to that of other salmon: they are most abundant along the southeastern coast. Only a few juvenile chinook salmon were captured in Bristol Bay during research fishing by NMFS in 1966, 1967, 1969, and 1970. These fish were caught in early June 1966 in the inner bay. None have been captured in the continental shelf area of Bristol Bay beyond June. Between June and August a few were taken during research fishing farther west in the Bering Sea (Hartt and Dell 1976).

The absence of juvenile chinook salmon in

TABLE 4.3—Mean salmon catch for major salmon-producing districts on the Alaska Peninsula and Bristol Bay, 1977-81.

District	Chinook	Sockeye	Coho	Pink	Chum	Total
North Side of Alaska Peninsula						
Izembek and Moffet Bays	7	18,920	0	440	139,860	159,227
Nelson Lagoon	6,040	256,780	133,477	13	33,920	430,230
Port Moller	540	19,180	118	9	47,620	67,467
Bear and Sandy Rivers	1,100	843,140	4,538	1,604	76,200	926,582
Ilnik	40	128,940	0	337	9,160	138,477
Port Heiden	6,640	13,900	3,845	0	720	25,105
South Side of Unimak Island (Kenmore Head to Scotch Cap)	?	1,065,000	?	?	248,000	?
Bristol Bay						
Ugashik	5,205	673,892	10,314	290	18,958	708,659
Egegik	4,351	2,467,242	13,255	6,997	65,124	2,556,969
Kvichak-Naknek	6,653	9,762,448	3,198	500,796	250,545	10,523,640
Nushagak	123,683	3,851,076	122,854	3,329,877	717,131	8,144,621
Togiak	31,827	475,744	78,290	63,597	262,108	911,566

SOURCE: Henry Yuen, Alaska Department of Fish and Game, Anchorage. Data provided for Fisheries Workshop of the North Aleutian Shelf Synthesis Meeting.

NOTE: All data 5-year mean from 1977 to 1981 except the following which are 1981: all Alaska Peninsula coho and most Alaska Peninsula pink salmon except Izembek-Moffet (1977-81); Bristol Bay pink salmon are 1978 and 1980 only. Salmon bound for rivers farther to the northwest have been excluded as their numbers and occurrence in North Aleutian Shelf waters are less well known.

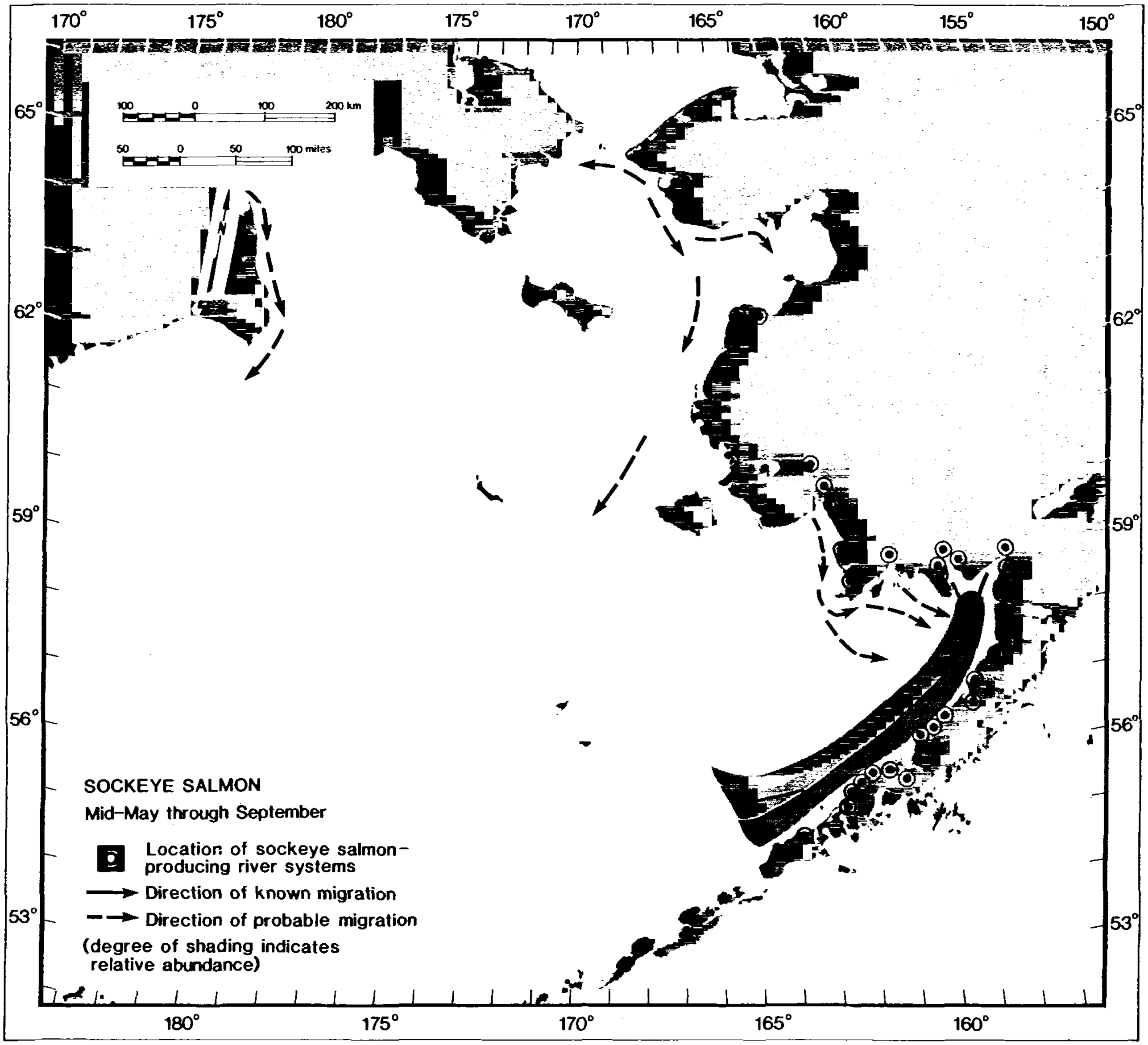


FIGURE 4.2—Distribution of sockeye salmon during seaward migration, mid-May through September (Straty 1981).

Bristol Bay after early June indicates that either the majority of the chinook had left the bay before that intensive research fishing began or that for some unexplained reason they were missed by fishing gear. In the Salcha River drainage of the Yukon River, most chinook salmon migrate downstream between the second half of May and early June (Trasky 1974). Chinook salmon from the Bristol Bay river systems probably also migrate seaward during May and early June. The absence of juvenile chinook in the shelf area of Bristol Bay beyond June also implies that these fish migrate seaward much faster than the other salmon species, which enter the bay later in the spring and summer than the juvenile chinook salmon and remain in the shelf area at least through mid-September. It is also likely that juvenile chinook salmon may move offshore out of the coastal waters earlier than the other species. Juvenile chinook salmon are undoubtedly the first salmon species to enter North Aleutian Shelf waters each year during seaward migration, most probably in mid- to late June.

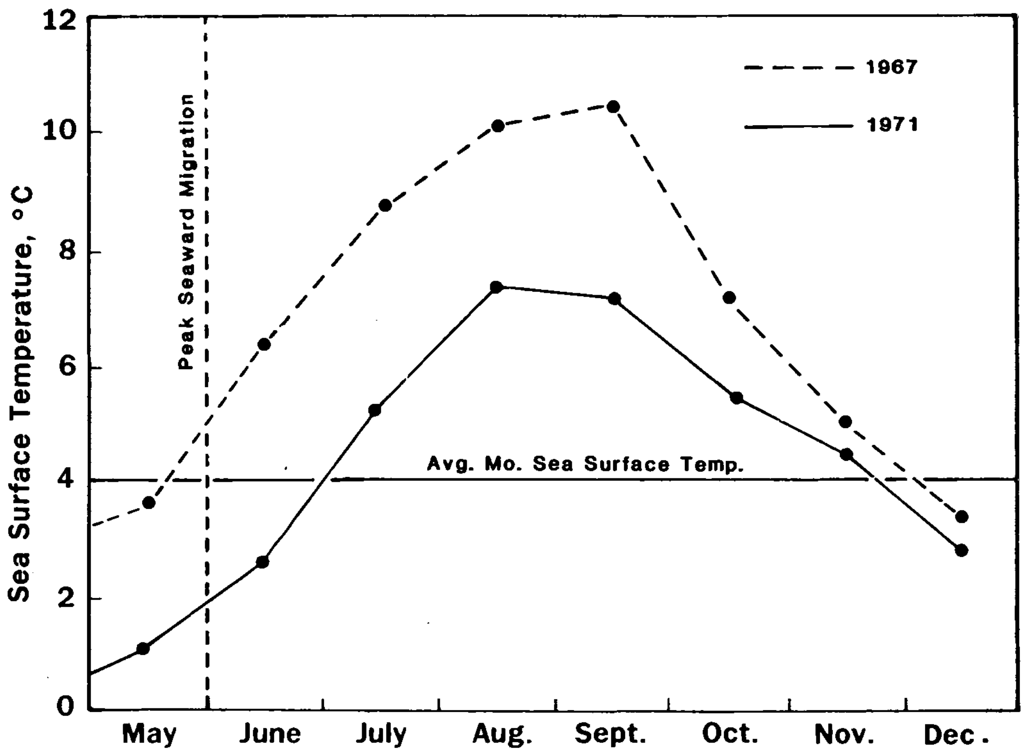


FIGURE 4.3—Average monthly sea surface temperatures in Bristol Bay 160 km northwest of Port Moller, May-December 1967 and 1971. Vertical line represents time of peak seaward migration of sockeye salmon (Straty and Jaenicke 1980).

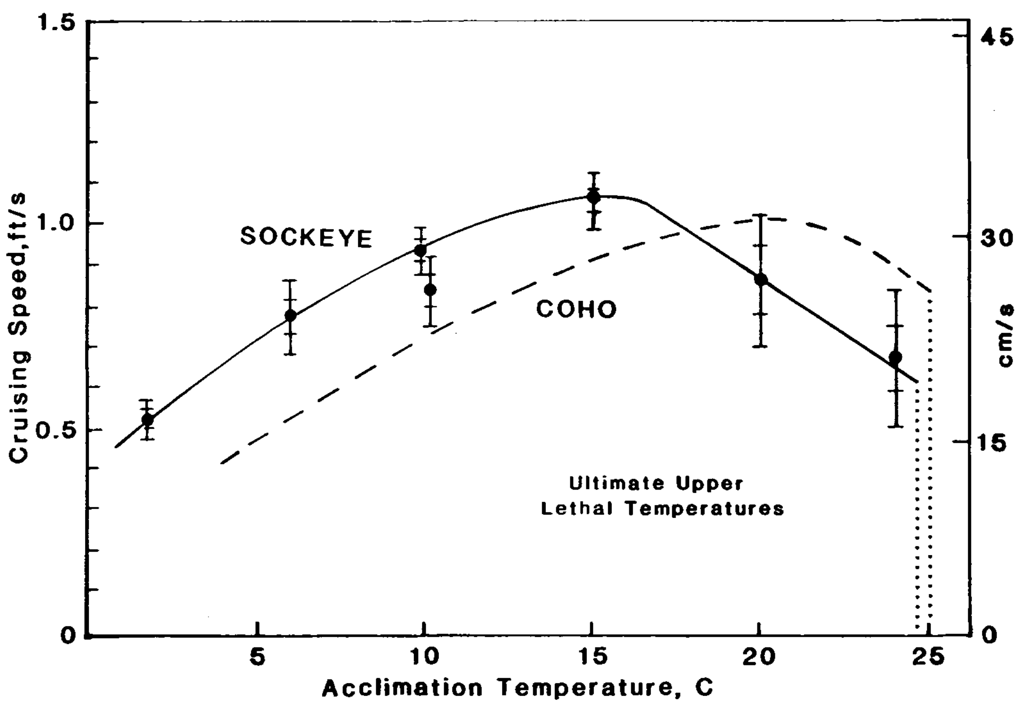


FIGURE 4.4—Variations in cruising speed for temperature-acclimated underyearling sockeye salmon and coho salmon adjusted in each case to common mean lengths of 6.9 cm and 5.4 cm, respectively. The samples were cultured under similar conditions and are of comparable age, 4-6 months from hatching (Brett *et al.* 1958).

According to the time of their appearance and the magnitude of their numbers as indicated by fish catches made in the coastal waters of Bristol Bay, juvenile coho salmon are the last species of Pacific salmon to enter the Bay. Although they have been captured along the southeastern coast of Bristol Bay as early as mid-June, research fishing indicates that they are not abundant until late June or early July (U.S. Department of Commerce 1966–72); they remain abundant throughout July and August. Some juvenile coho salmon were still present in the coastal waters of Bristol Bay in mid-September of 1970. They most probably become increasingly abundant seaward of 159° W. after this time and, like the juveniles of other salmon species, move further offshore during continued seaward migration.

4.2.2 Immature Salmon

The exceedingly sparse information available on immature salmon (1 year or more from spawning age) occupying the North Aleutian Shelf comes from the 1977–79 catches of foreign trawlers operating in the western part of this region between longitudes 164° and 165° W. and latitudes 53°30′ and 58° N. Immature salmon taken by trawl are generally assumed to have been captured at or near the bottom rather than in midwater during the trawl's transit to and from the bottom (Straty 1982). Immatures were taken throughout the year and occurred in greater numbers during the fall and winter months of 1977 and 1979 and in the spring and summer months of 1978. Their relative abundance in the area is not known. Chinook salmon composed 88–93% of the immature salmon caught during these 3 years; chum salmon composed 6–10%; and coho, sockeye, and pink salmon made up the remainder. Age data are available only for chinook salmon: 2% had spent 1 year at sea; 77%, 2 years; 19%, 3 years; and 2%, 4–6 years.

4.2.3 Spawning Migration

The time of the spawning migration, from departure of sexually maturing fish from the high seas of the North Pacific Ocean and Bering Sea until arrival at the mouths of their home river systems, is species and stock specific. Maturing salmon are most abundant in the southeastern Bering Sea shelf region, which includes Bristol Bay and the North Aleutian Shelf, from mid-May to early September. Results of research fishing with variable-mesh gill nets indicate that maturing salmon migrating through this region are most abundant in the upper 5 m of the water column (Hokkaido University 1965, 1968).

Maturing chinook salmon enter this region earliest; later, in order, come sockeye, summer chum, pink, fall chum, and coho salmon. The length of time a given salmon stock is present and its distribution in this region during spawning depend upon the geographic location of the stock's natal river system, the size or ocean age of fish composing the population, and environmental conditions that influence the rate and direction of migration.

Straty (1981) estimated migration rates from the shelf edge (200-m isobath) to the mouth of the Kvichak River, a distance of 1,259 km, during the last 30 days of the spawning migration to be 45 km/d for sockeye and chum; 56 km/d for chum and coho; and 60 km/d for chinook. Salmon migrate along the southeastern Bering Sea coast in a belt extending to 162 km offshore. The center of abundance varies from 50 to 100 km from the shore.

Sockeye, chum, and pink salmon have been captured in varying numbers during U.S. and Japanese research fishing and tagging studies at many places throughout the Bering Sea during spawning migration. However, fewer chinook and coho salmon have been caught, because they are less abundant and research fishing has not taken place when they were at their peak abundance. Research fishing and tagging experiments have taken place mainly between mid-June and late July, when sockeye and chum salmon are most abundant on the southeastern Bering Sea shelf; chinook salmon begin entering this area in mid- to late May, coho in mid- to late July. Consequently, the distribution and direction of movement of chinook and coho salmon are not as well understood as those of sockeye, chum, and pink salmon.

The distribution, migration, and relative abundance of five species of Pacific salmon on the entire Bering Sea have been described by Straty (1981), who plotted the locations of capture of each species on a chart of this region for

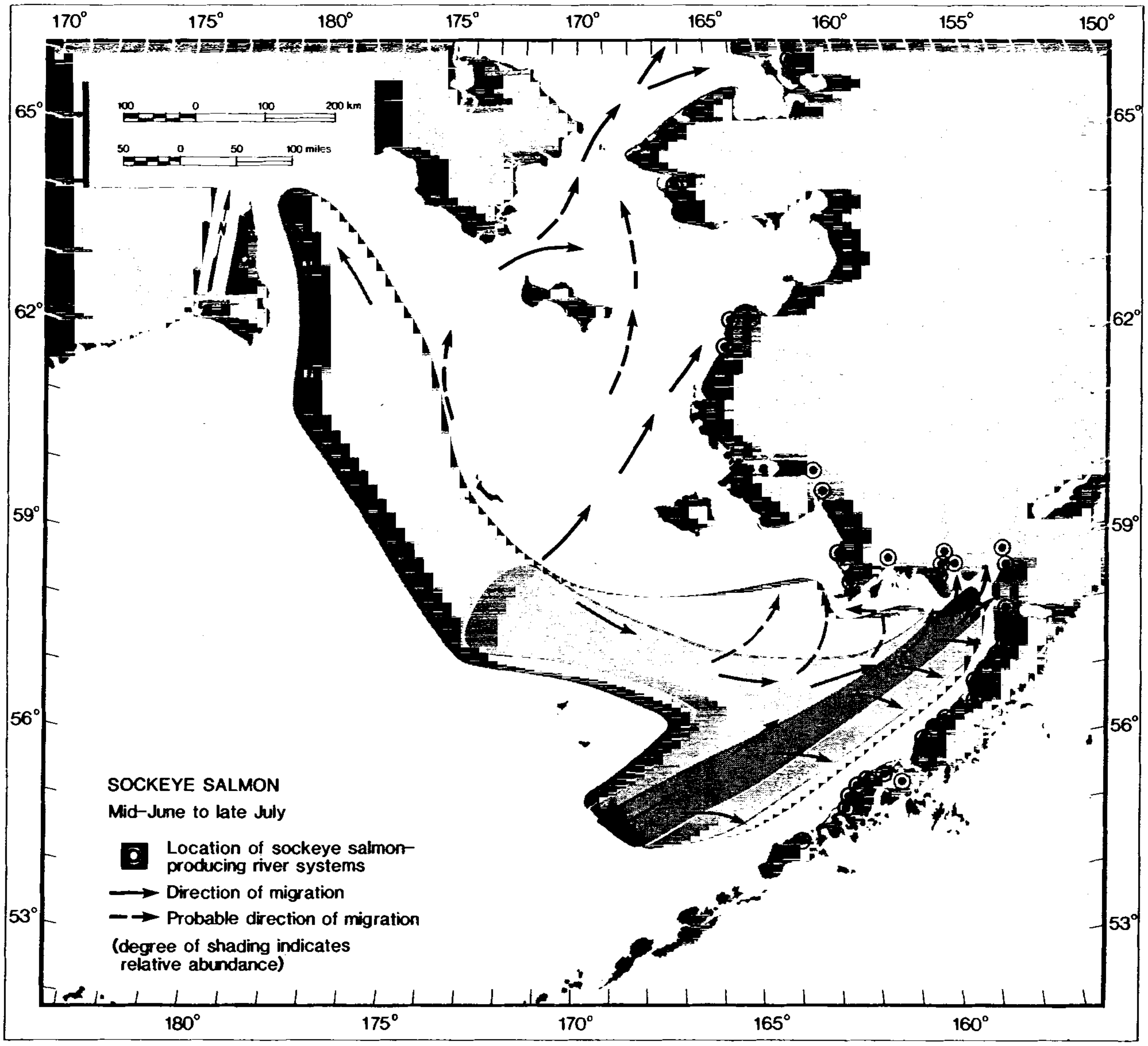


FIGURE 4.5—Distribution of sockeye salmon during spawning migration (Straty 1981).

all years for which data were available. For sockeye, chum, and pink salmon, certain areas of the shelf consistently yielded larger catches or larger catches per unit effort than other areas. For chinook and coho salmon, comparable data were available only for Bristol Bay, where these species have been captured most frequently. Direction of migration of each species was derived from the published results of tagging experiments and studies of direction of movement. The probable direction of migration was based on the geographic location or proximity of the home river system of the species and the verified direction of movement of other salmon species captured in the same area.

Sockeye Salmon

Sockeye salmon are the most abundant species in the spawning migrations through the southeastern Bering Sea. They concentrate offshore in two bands, north and south of the Pribilof Islands, which traverse all of Bristol Bay (Fig. 4.5). These fish are primarily bound for rivers located around Bristol Bay, the north side of the Alaska Peninsula, and Kuskokwim Bay.

As the spawning migration proceeds toward

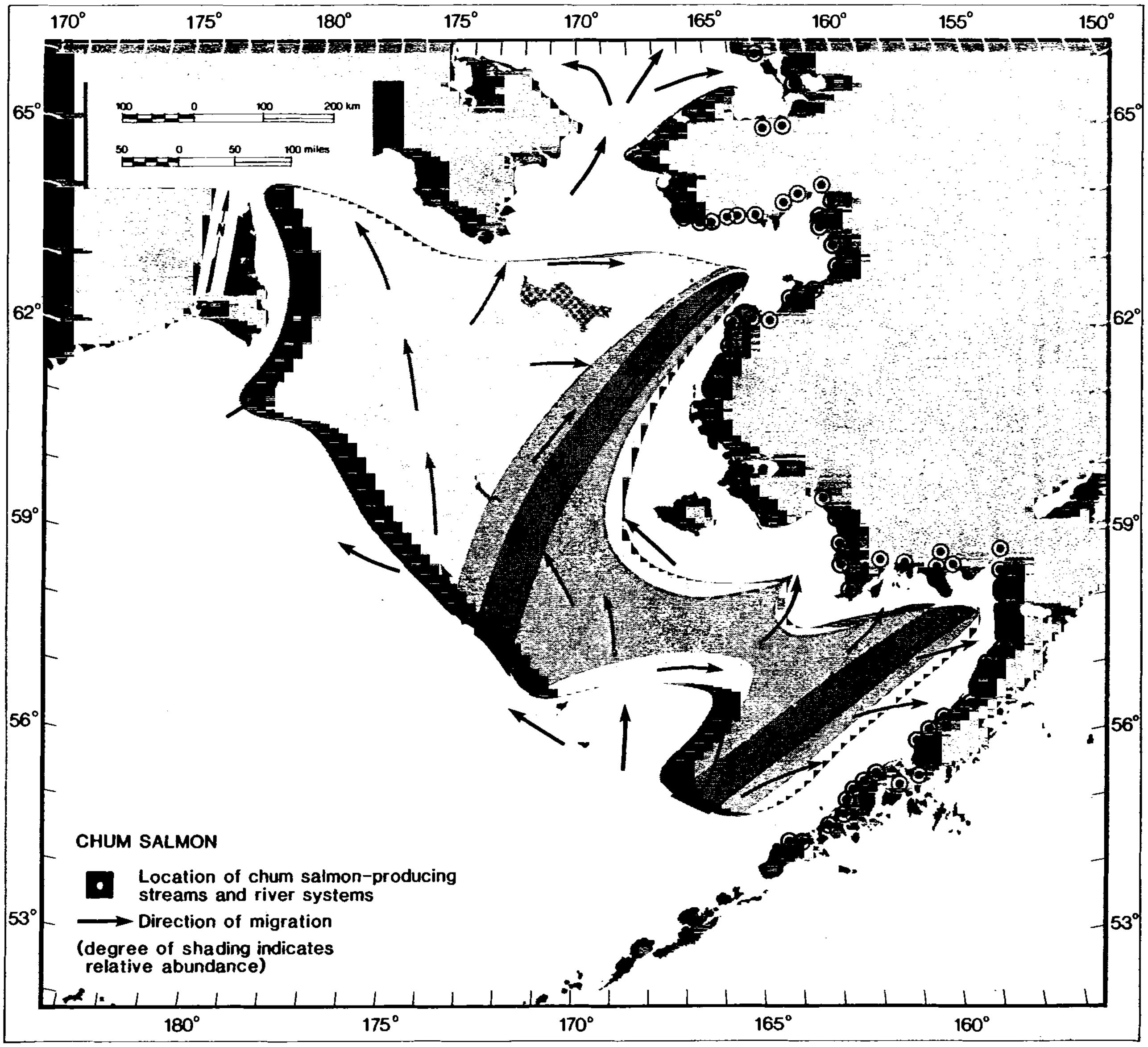


FIGURE 4.6—Distribution of chum salmon during spawning migration, mid-June to early August (Straty 1981).

the head of Bristol Bay the stocks progressively segregate according to the location of the mouths of their river systems (Straty 1975). Sockeye bound for rivers on the north side of Bristol Bay (i.e., rivers draining into Nushagak and Togiak bays) are apparently more abundant in the northern than in the southern portion of this distribution, sockeye bound for the north side of the Alaska Peninsula are probably more abundant in the southern portion, while those bound for the head of Bristol Bay are probably most abundant in the middle of the distribution.

Chum Salmon

Chum salmon are more widely distributed throughout the Bering Sea during the spawning migration than are sockeye salmon, probably because chum salmon spawn in many streams in Norton and Kotzebue sounds (Fig. 4.6). Like sockeye, chum salmon are heavily concentrated in bands north and south of the Pribilof Islands. The southern band traverses Bristol Bay and includes chum salmon bound primarily for the rivers of Bristol and Kuskokwim bays and the north side of the Alaska Peninsula. Like sockeye

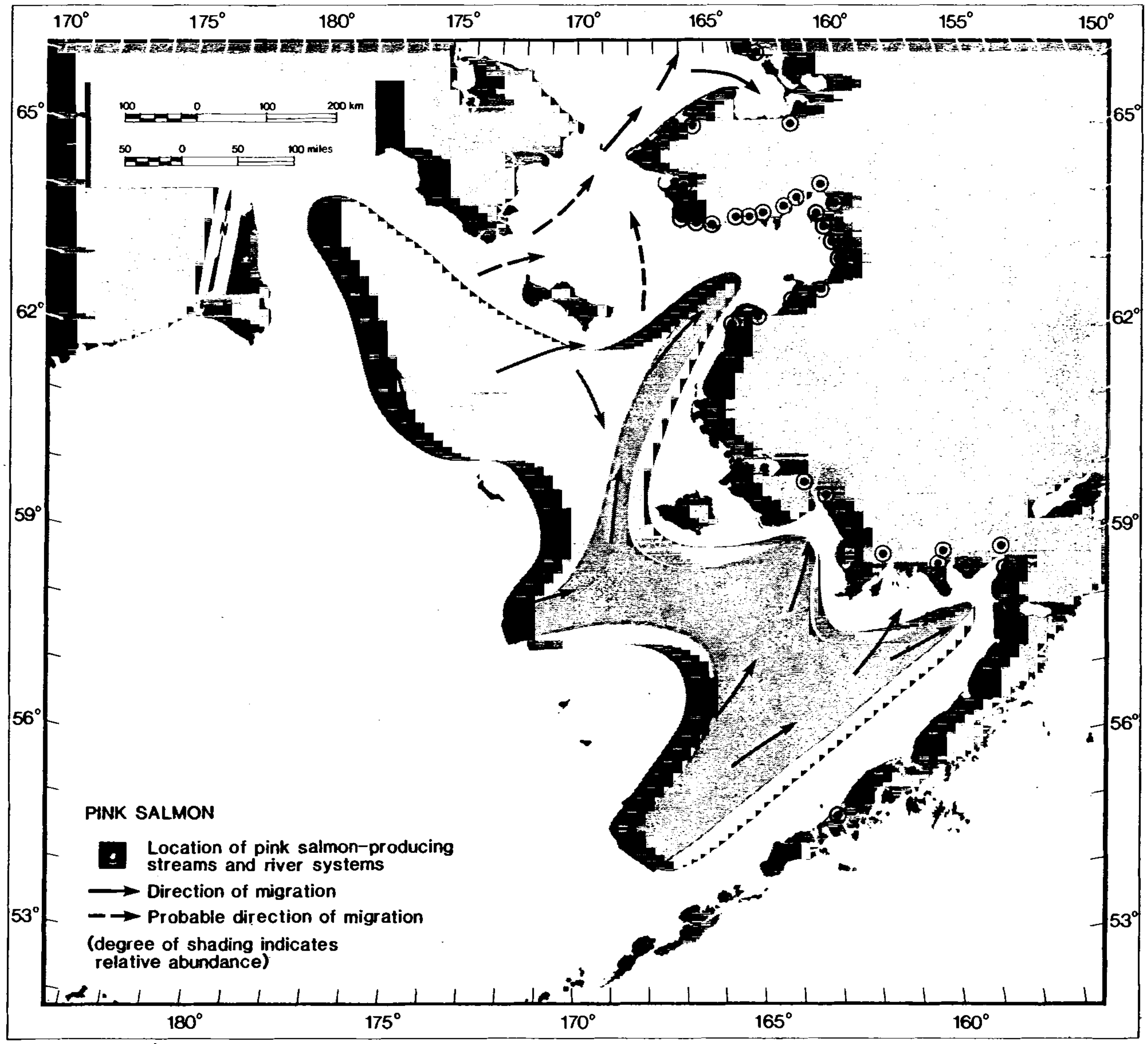


FIGURE 4.7—Distribution of pink salmon during spawning migration, mid-June to mid-August (Straty 1981).

salmon, chum salmon stocks probably begin to segregate according to the location of the mouths of their home river systems while in outer Bristol Bay.

Pink Salmon

Pink salmon have been captured throughout the offshore areas of the Bering Sea during spawning migration. As with sockeye and chum salmon, the heaviest concentrations of pink salmon traversing the Bering Sea during spawning migration occur north and south of the Pribilof Islands (Fig. 4.7). This distribution is apparently related to the size of pink salmon populations migrating to specific streams or river systems and the geographic location of these systems. Pink salmon migrating south of the Pribilof Islands through Bristol Bay are primarily bound for rivers entering Kuskokwim and Bristol bays and a few streams along the north side of the Alaska Peninsula.

Chinook Salmon

Maturing chinook salmon have been captured throughout the Bering Sea during spawning migration, but little information is available to

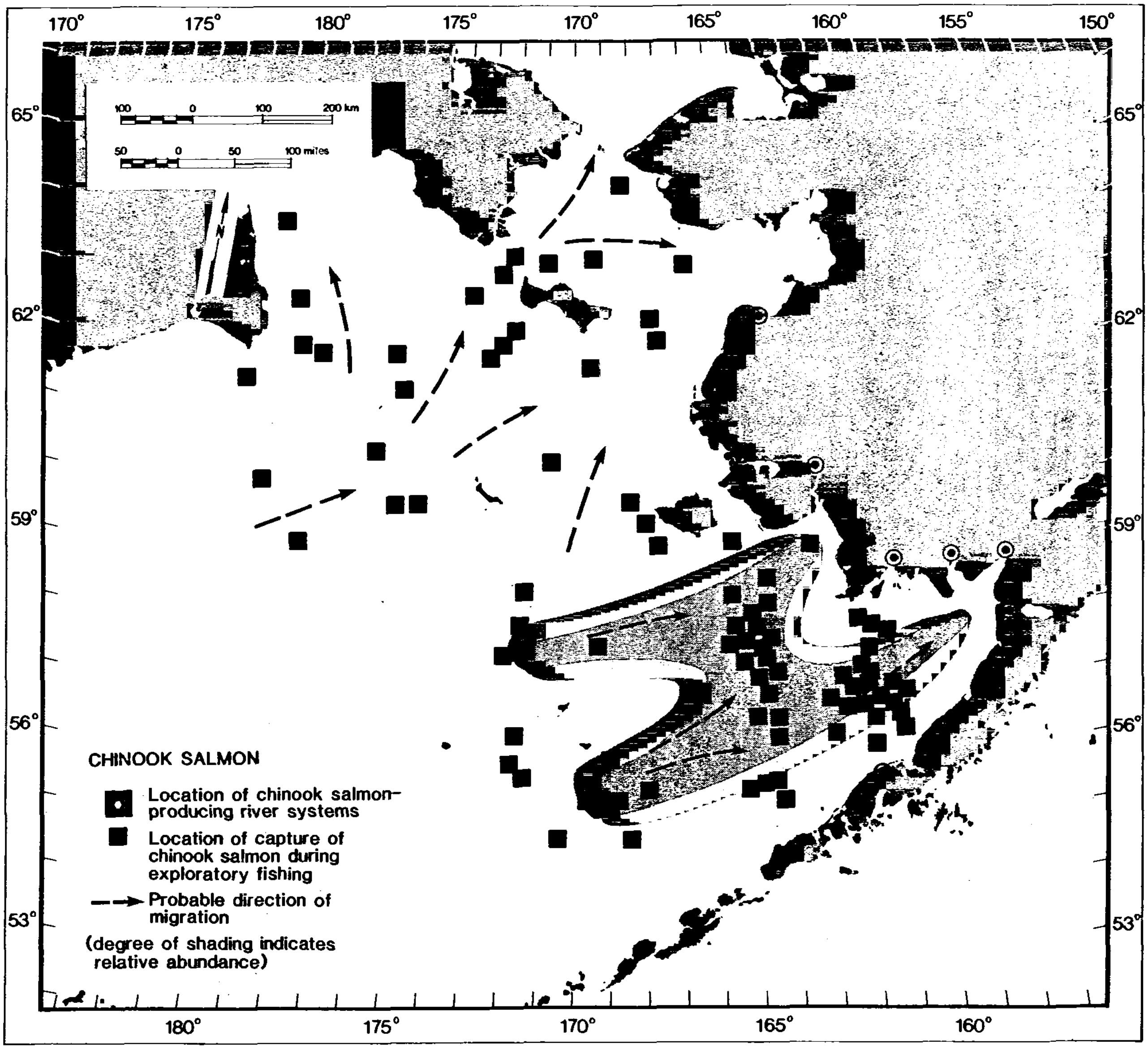


FIGURE 4.8—Distribution of chinook salmon during spawning migration, early June to mid-July (Straty 1981).

verify the direction of migration. If chinook salmon respond similarly to the same environmental cues as sockeye, chum, and pink salmon, they can be expected to follow similar migration routes. Based on this assumption, Straty (1981) determined the probable directions of migration of chinook salmon captured at various areas (Fig. 4.8).

Chinook salmon were captured most frequently in Bristol Bay where research fishing concentrated on sockeye salmon, and were generally more abundant than sockeye farther offshore from the north side of the eastern Aleutian Islands and the Alaska Peninsula. This offshore distribution is probably related to the destinations of spawning populations migrating to specific river systems in Bristol Bay and the Kuskokwim and Yukon rivers.

Coho Salmon

Coho salmon have been captured at relatively few locations during research fishing in the southeastern Bering Sea (Fig. 4.9). This is due to a lack of exploratory fishing from late July to late August when they would be most abundant on the shelf. Coho salmon have been taken

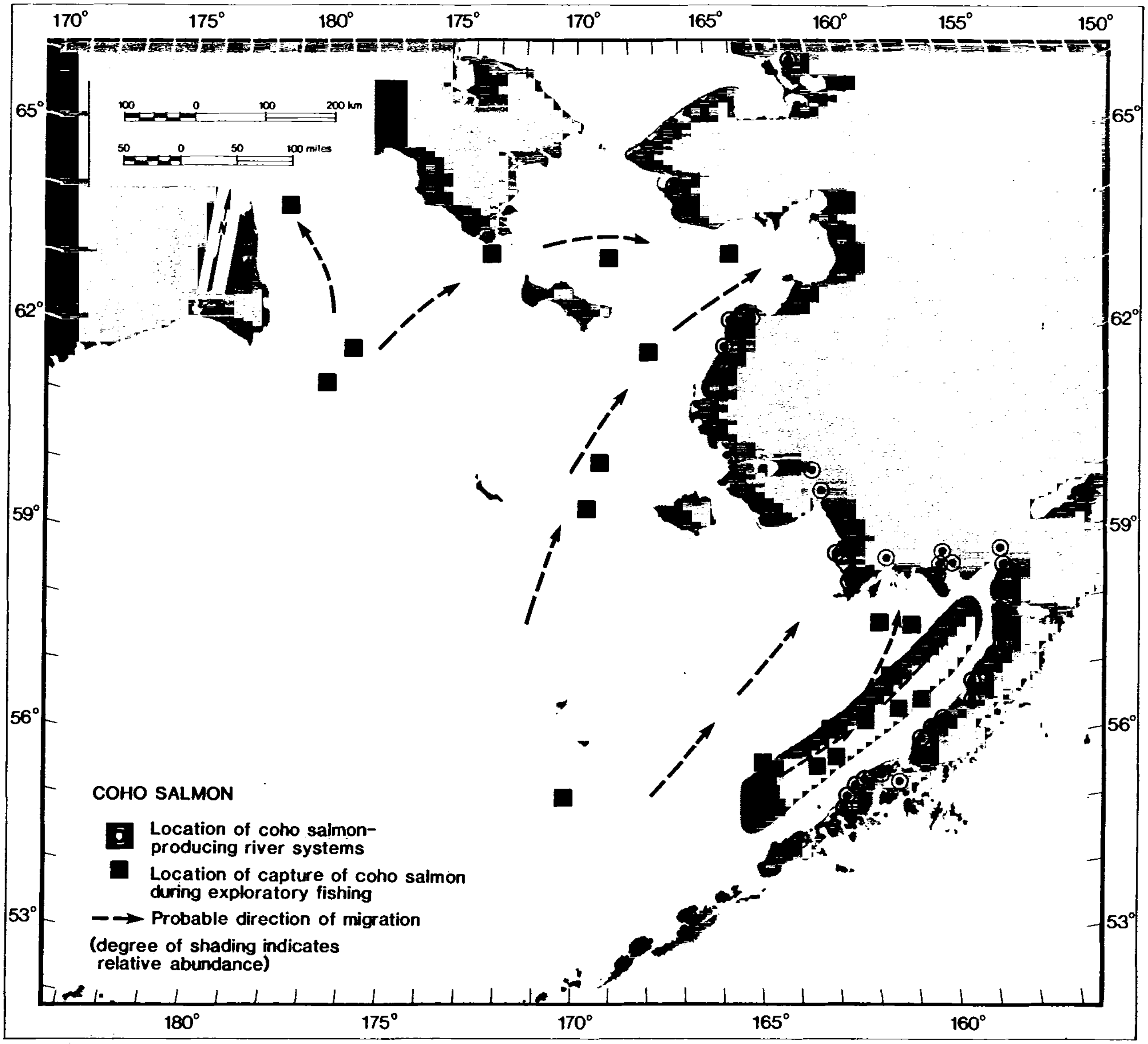


FIGURE 4.9—Distribution of coho salmon during spawning migration, early July to early September (Straty 1981).

incidentally in research fishing for sockeye salmon.

4.3 CRAB AND OTHER FINFISH RESOURCES

Besides salmon, the crab and groundfish resources located in the North Aleutian Shelf lease area are extremely valuable renewable resources. Not only is the area an important reproductive and nursery site for many species, it contains major portions of the entire catch areas for red king crab and Tanner crabs from the Bering Sea and is also the site for a developing Pacific cod fishery and a joint venture fishery for yellowfin sole.

The natural histories and commercial significance of the principal species in the southeastern Bering Sea have been extensively reviewed by Pereyra *et al.* (1976a) and updated in considerable detail in the proceedings of the St. George Basin Synthesis Meeting (Curl and Manen 1982; Thorsteinson and Thorsteinson 1982); this information is summarized for North

TABLE 4.4—Spawning periods, locations, and major concentrations of selected finfish and shellfish, North Aleutian Shelf area.

Species	Spawning Period		Spawning Location in the North Aleutian Shelf	Major Concentration Areas Within the NAS	Fishing Information for NAS			
					Nation	Season	Catch Examples	
							Year	Catch
King Crab	*Larval release*	*Molting/mating*	Yes	Females, yes	USA	15 Sept.- ?	1980	12,400 t
	Mar.-Apr.	Apr.-May/ Apr.-May	Perhaps throughout	Males, yes Juveniles, yes		(Jan. 1)	1978	16,727 t
Tanner Crab								
C. bairdi	Apr.-May	Apr.-May/ Apr.-May	Yes	Female, yes Male, yes Juveniles, yes	USA	15 Feb.-May	1981	6,439 t (~50% of total)
C. opilio	Feb.-Mar.	June-July/ Mar.-Apr.	No	Females, no Males, yes (w. Gulf) Juveniles, no	USA USA	15 Feb.-June	1981	2,016 t (8% of total)
	Spawning							
Pollock	Feb.-June		No or minor	No, relative to shelf edge	USA	Mar.-June	1980	~500 t
					Japan-ROK	Mar.-Dec.	1980	~47,000 t
					USSR, ROK, Poland, & W. Germany		1980	~620 t
Pacific Halibut	Nov.-Feb.		No	Juveniles, yes Adults, no		No		
Pacific Herring	Late Apr.-June		Yes—Port Moller	?		No		
Yellowfin Sole	July-Sept.		No or minor	Small juveniles near shore year round	USA	May-Sept.	1980	8,638 t (from NAS)
				Spring (adults)—yes Winter (adults)—yes Summer (adults)—no Fall (adults)—no	Japan-ROK	Year round, but mostly summer-fall	1980	77,636 t (from NAS)
Pacific Cod	Jan.-May		No or minor in deeper waters	No—relative to shelf edge,	USA	Mar.-June	1980	8,363 t
				occasionally near	Japan-ROK	Mar.-Dec.	1980	1,757 t

Aleutian Shelf species in Table 4.4. Commercially valuable species occurring in or near the North Aleutian Shelf include:

Red king crab	*Paralithodes camtschatica*
Tanner crabs	*Chionoecetes bairdi, C. opilio*
Walleye pollock	*Theragra chalcogramma*
Pacific cod	*Gadus macrocephalus*
Yellowfin sole	*Limanda aspera*
Pacific halibut	*Hippoglossus stenolepis*
Pacific herring	*Clupea harengus pallasi*
Rock sole	*Lepidopsetta bilineata*
Flathead sole	*Hippoglossoides elassodon*
Alaska plaice	*Pleuronectes quadrituberculatus*
Butter sole	*Isopsetta isolepis*
Other flounders	

Historically, foreign fleets have dominated all crab and groundfish catches in the Bering Sea. Red king crab were initially harvested by the United States, the USSR, and Japan. However, since 1974 this resource has been harvested entirely by the domestic fleet. Japan and the USSR began directed fisheries on Bering Sea Tanner crabs in the mid-1960's when negotiations with the United States led to reductions in their king crab quotas in this region. The United States entered this fishery in 1968 but until 1974 the domestic Tanner crab harvest was incidental to king crab fisheries. The USSR discontinued fishing for Tanner crabs in 1971 and Japan followed suit in 1980, although many continue to be taken as by-catch in deepwater trawls.

Foreign groundfish fisheries are conducted year round on the continental shelf to the west and northwest of the North Aleutian Shelf. Since much of the lease area has been identified as a crab pot sanctuary and a Winter Halibut Savings Area (Fig. 4.10), very little trawl effort has occurred there. In 1978 and 1979 only 4% and 2%, respectively, of all Japanese effort by stern trawl, pair trawl, Danish seine, and longlines occurred within the lease area. Japan remains the principal groundfish harvester in the Bering Sea, although small but increasingly important joint ventures between U.S. fishermen and foreign processors are developing. In the first year of a joint venture with the USSR, five American catcher boats caught 8,638 t of food-grade yellowfin sole, 1,421 t of Pacific cod, and 3,118 t of fish-meal-grade product valued at approximately $1.6 million between early June and mid-September (Fisher 1980). At present a small number of U.S. trawlers are capturing Pacific cod in the North Aleutian Shelf and delivering to Akutan Island during the off season for king crab.

4.3.1 Crabs

The crab resources of the eastern Bering Sea have contributed 10 to 20% of the total world harvest of crabs during the past decade. By 1978 crab harvests from this region represented over 50% of the landed value of crabs in the entire United States. In recent years ex-vessel values have been in excess of $150 million annually.

Red King Crab

The red king crab population is the most extensive and important shellfish resource in the southeastern Bering Sea. The population is cyclic on 7- to 14-year intervals; abundance varies from natural and man-made causes, but is primarily influenced by environmental conditions. Only male crabs with a carapace wider than 16.5 cm are harvested. At present the abundance of male king crabs is following a downward trend which began in 1981 and is attributed to three factors: (1) below average recruitment which continued in 1981 and will apparently continue in the near future, (2) apparent increased predation on larvae and pre-recruit juveniles by Pacific cod, and (3) possible increased losses of pre-recruit juveniles due to capture and release in the 1980 fishery in areas where both harvestable males and pre-recruit crabs occur together.

The decline in harvestable males was most notably apparent in the reduced commercial catch from 1980 to 1981. In 1980, 21 million crabs (12,400 t) were captured compared to the 1981 harvest of 4.8 million crabs (2,862 t). Despite this decline, the 1981 catch was the eighth largest in the history of the fishery, which has ranged from 3,636 t in 1958 to the record catch in 1980. Harvests are by stationary pots fished individually, up to 500 per boat. The red king crab fishery has undergone tremendous growth in the past decade with 51 boats fishing in 1971, 194 in 1975, and 236 in 1980 and 1981.

Despite the reduced population size of male king crabs, the reproductive potential of the stock does not appear to be adversely affected.

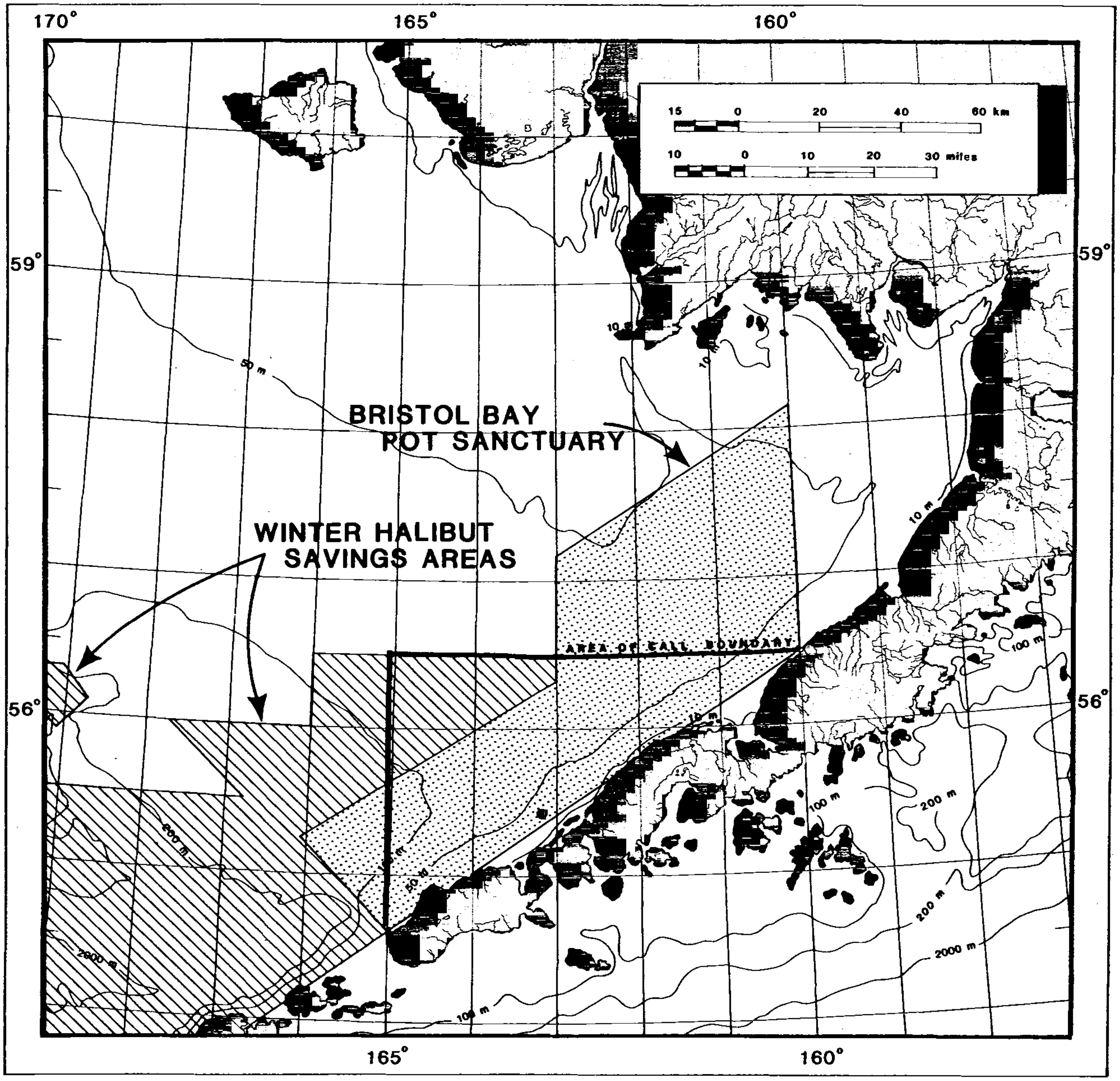


FIGURE 4.10—Locations of Winter Halibut Savings Areas and the Bristol Bay Pot Sanctuary. (Adapted from U.S. Department of Commerce 1980.)

In 1981 the number of females present and the proportion carrying full, viable egg clutches were essentially the same as in 1980. In 1980 roughly three to four times as many males were present.

The North Aleutian Shelf lies to the south of areas of highest abundance of harvestable male king crabs (Curl and Manen 1982). In 1980 only 21% of the total red king crab catch came from the lease area. The proportion of total catch from the area has been higher though, with 42% of the total coming from this region in 1978.

Red king crab have been identified as one of the species most vulnerable to detrimental impacts from offshore development in the southeastern Bering Sea. Male crabs are generally more abundant in the deeper waters to the north and west of the North Aleutian Shelf but move to the shallower waters in or nearby the proposed lease area in spring to mate. Although females migrate to greater depths during winter months, their migrations are not as extensive as the males', and in spring they are found in greatest densities in the coastal waters north of the Alaska Peninsula.

Eggs are carried for 11 months by gravid females and are hatched beginning in April in nearshore waters. The timing of the hatch is temperature dependent in response to warming temperatures. Although it has been postulated that the hatch is relatively synchronous, occurring within a 3-week period, recently gathered information from the North Aleutian Shelf suggests spawning over a protracted period of 3 months (D. Armstrong, pers. commun.). Sonntag *et al.* (1980) described an entire year class hatch during April, May, and June as proportions of 20%, 60%, and 20%, respectively. High larval densities are those in excess of 800 to 1,000/1,000 m^3 and may be as great as 1,500/1,000 m^3. High abundance during May extends from Unimak Island to Port Moller (Armstrong *et al.* 1981).

Upon hatching larvae are planktonic; pelagic larvae are present in the upper 60 m of the water column with greatest densities found in the upper 30 m. Larvae are more vertically dispersed at night. The availability of appropriate food items is critical to the survival of larvae, and if they do not feed within 2 days, they will succumb. Larvae molt through four zoeal stages, spend about a month as megalopae, then metamorphose to first instars from mid-July to August. At this time they take up a benthic existence and resemble miniature adults in appearance. Young of year molt from 8 to 11 times in the first year. High-frequency molting could make them susceptible to nearshore oil perturbations since ecdysis is the time of greatest sensitivity to toxicant stress (Armstrong *et al.* 1976). Little has been reported on the distribution of juveniles until their third year; it is speculated that they may bury themselves in rocky-pebbly habitats in their early years (W. Pearson, pers. commun., June 1982, *Miller Freeman* cruise). Pre-recruit crabs, age 3 +, may be solitary or podding in the inshore waters of the North Aleutian Shelf and farther east in Bristol Bay. In June 1982 these age groups were most abundant 50–70 m off Port Moller. King crab mature sexually at 5 to 6 years. At this age, podding behavior ceases and younger crabs join the adults in their seasonal migrations for food and reproduction. Fecundity increases with size, the largest females producing up to 400,000 eggs. Male king crab enter the commercial fishery at about 8 years of age.

Tanner Crabs

The two species of Tanner crab found in the southeastern Bering Sea are substantially different in habitat preference and consequently occur in different regions. *Chionoecetes opilio* is a colder water species and has a worldwide distribution associated with sea ice cover. The release of larvae in the spring occurs in conjunction with the spring melt of ice and phytoplankton blooms along the ice edge. The distribution of *C. opilio* extends from the waters east and northwest of Unimak Island to and beyond the Pribilof Islands. *Chionoecetes bairdi* is a warmer-water species and more widely distributed, occurring throughout the Bering Sea south of latitude 58° N. and along the shelf edge northward to around 60° N. The species are found together in the southeastern portion of the North Aleutian Shelf and are captured during April, May, and June.

From 1967 to 1979 Tanner crab catches in the southeastern Bering Sea fluctuated between 136,364 t and 50,000 t. Catches declined to 41,818 t in 1980, and 37,273 t in 1981. Prior to 1977 *C. bairdi* was the preferred species because they are larger (2.5 lb) than *C. opilio* (1.5 lb) and more robust. However, a substantial decline in the number of harvestable male *C. bairdi* led to an increasing dependence on *C. opilio* to sustain harvests. Harvests of the two species were roughly equal in 1979 and 1980, and in 1981 *C. opilio* composed about 65% of the total Tanner crab harvest in the Bering Sea. Nearly one-half of the 1981 harvest of *C. bairdi* came from the North Aleutian Shelf. Overall Tanner crab harvests in the area in 1981 composed 25% of the total from the Bering Sea. Only a very small fraction—2,000 t, or about 8%—of the total *C. opilio* harvest came from the lease area.

Like the king crab, Tanner crab populations are cyclic with current harvests heavily dependent upon recruit year classes. A series of weak year classes were initially recruited into the Bering Sea fishery in 1979. Current stock conditions are stable and slowly improving as better than average recruitment is anticipated in about

1982 (R. Wolotira, communication at the meeting). Bering Sea populations of Tanner crabs do not appear to undergo extensive seasonal migrations, and, as a result, recruitment of *C. opilio* in the southern edge of their distribution and in the North Aleutian Shelf occurs in cold-weather years when ice coverage is farther to the south than usual.

Females of both *C. bairdi* and *C. opilio* are very fecund: *C. opilio* average 36,273 eggs (range, 5,500–150,000) and *C. bairdi* 169,000 eggs (up to 318,000 have been reported). Reproduction occurs in the spring as early as February, and eggs are carried for 11 months by females. Roughly 20% of *C. bairdi* eggs are lost through various natural agents before they are hatched (Armstrong *et al.* 1981).

Tanner crab larvae molt through two pelagic stages of approximately 1 month each, and a planktonic megalopa stage that may last for 6 months. Stage 1 *C. opilio* zoeae are present in the water column in early April in densities as high as 10,000–100,000 larvae/1,000 m^3. Megalopae of both species are present by mid-July. Larval occurrence is highest in the upper 60 m; some migration to slightly greater depths (90 m) at night has been described. The collection of *C. bairdi* megalopae in salmon stomach contents from fish captured in the Gulf of Alaska during winter months suggests these larvae may overwinter in the plankton in the Bering Sea. In the North Aleutian Shelf lease area, the megalopa of each species molts to the first benthic crab stage shortly after it descends to the bottom. During the first year of life, juveniles molt two or three times. Collections of larvae and juveniles from the North Aleutian Shelf indicate a much higher abundance of *C. bairdi* than *C. opilio* in this lease area, although larvae of both species would be expected from April through October.

Tanner crabs mature within 5 to 6 years and carapace widths at maturity and recruitment into the fishery ensure that most males will have at least one reproductive season before they are legally harvestable.

4.3.2 Other Finfish

The relative lack of foreign fishing activities in the North Aleutian Shelf compared with the St. George Basin to the east is largely the result of closures and restrictions imposed by the United States to protect domestic gear and resources. Foreign trawling is prohibited year round in the Bristol Bay Pot Sanctuary, which overlaps with the North Aleutian Shelf to a large degree, and from 1 December to 31 May in the Winter Halibut Savings Areas (Fig. 4.10). Foreign fishing by longline or trawl gear is prohibited year round in the Fisheries Conservation Zone between 5.6 and 22.2 km from the baseline used to measure the territorial sea (U.S. Department of Commerce 1980). As a result, foreign fishing is restricted to the northwest corner of the North Aleutian Shelf 1 June–30 November, but generally takes place during June, July, and August.

Historically, about 5% of the total foreign catch from the Bering Sea has been taken from North Aleutian Shelf waters. In 1978 this catch was about 24,000 t and was composed of walleye pollock, Pacific Ocean perch (*Sebastes alutus*), sablefish (*Anoplopoma fimbria*), Atka mackerel (*Pleurogrammus monopterygius*), Pacific herring, "turbot" (*Hippoglossoides robustus* and *Atherestes stomias*), rock sole, flathead sole, Alaska plaice, Greenland halibut (*Reinhardtius hippoglossoides*), other flounders, squid, and other species (U.S. Department of Commerce 1980). Prior to 1976, foreign trawl fisheries caught primarily yellowfin sole in this lease area, but pollock have since become the major species. The following discussions are limited to the species of greatest commercial interest.

Walleye Pollock

Pollock are the most extensive fishery resource in the Bering Sea. Following a decline in stock size due to overharvesting by foreign fleets in the early 1970's, the resource has slowly increased to a standing stock biomass of about 7.5 million t in 1979. In the early 1970's, through 1974, harvests averaged 1.8 million t per year and have recently averaged around 1 million t. Current populations are stable but still smaller than those of a decade ago. The maximum sustainable yield (MSY) is estimated at 1.5 million t, and the allowable biological catch (ABC) at 0.86–1.2 million t. (The ABC is defined as the maximum harvest that can be taken without eliminating the rebuilding of a stock that is below levels sufficient to maintain

MSY.) Although a joint venture fishery for pollock has been developed recently in Shelikof Strait-Gulf of Alaska, these stocks are not currently harvested by U.S. fishermen in the Bering Sea.

All life stages of pollock are found in North Aleutian Shelf waters. The form having the highest abundance is juveniles with lesser numbers of eggs, larvae, and adults. Spawning concentrations are greatest in the deeper waters (100–200 m) to the west of the area.

Pacific Cod

In recent years the biomass of Pacific cod has significantly increased and is currently estimated at 0.81–0.86 million t as a result of an extremely strong year class in 1977 (and perhaps 1978). Analysis of 1968–76 catch information suggested a MSY of 58,636 t; however, the 1977 year class bolstered this substantially and the current ABC is closer to 168,182 t. Although much of the foreign catch is taken from waters north and west of the North Aleutian Shelf, several U.S. draggers are working the nearshore (30 m) and deeper waters of the area for Pacific cod. Adult fish are abundant throughout the North Aleutian Shelf from Cape Sarichef to Cape Seniavin and appear to be heavily preying on 3- and 4-year-old red king crab (L. Thorsteinson, pers. commun., June 1982, *Miller Freeman* cruise). Predation by cod may be at least partially responsible for the reductions in year class strength evidenced in the 1981 fishery. The shallow waters of the North Aleutian Shelf were not thought to be of great importance to Pacific cod; however, recent OCSEAP research catches (June 1982, *Miller Freeman* cruise) suggest the contrary. Juveniles and adults are the most abundant life stages found in North Aleutian Shelf waters.

Yellowfin Sole

Yellowfin sole is the species most commonly associated with the North Aleutian Shelf. In the spring, dense concentrations have been found along the southern edge of the lease area from Unimak Pass to Port Moller. Later in the year the fish are distributed over the proposed lease area and waters adjacent to it. In the early 1960's this species was heavily exploited by Japanese fleets and catches yielded as many as 454,500 t annually. After such heavy fishing pressure, the yellowfin sole population declined and has only recently begun to improve. The current ABC is about 215,000 t; however, in 1980 only about 40% of the ABC was taken, and today the species continues to be underutilized even though joint venture fisheries are developing. U.S. harvests via joint ventures in 1980 were 9,636 t, or about 11% of the total catch of yellowfin sole from the Bering Sea.

Very young juveniles (2 years old or less) are found in the shallow nearshore regions of the North Aleutian Shelf. Older sole are found in high densities in the more offshore regions of the area. In the spring, adults migrate through this area en route to spawning grounds near Nunivak Island in Bristol Bay.

Pacific Halibut

Halibut stocks in the eastern Bering Sea continue to be low relative to population sizes present in the region prior to extensive foreign and domestic fisheries in the early 1960's. The entire North Aleutian Shelf lease area falls within the region identified by the International Pacific Halibut Commission (IPHC) as a Halibut Nursery Area. No commercial halibut fishing is allowed within this area due to the substantial numbers of juvenile halibut found there. Annual IPHC surveys have found these immature fish to be distributed along the south shore of the southeastern Bering Sea from Unimak Island into Bristol Bay. This portion of the halibut stock remains in the nearshore waters year round, whereas adults migrate onto the shelf in the lease area from deeper waters during summer months.

Pacific Herring

Very little information is available describing the magnitude of Pacific herring stocks associated with the North Aleutian Shelf. Spawning by this species occurs inside of Port Moller in late April through June, but no studies have been conducted to quantify the stock present. Although they are not well studied, this stock is believed to be much smaller than stocks spawning along the northern shore of Bristol Bay and in Norton Sound.

Although relatively small numbers of Pacific herring rely on the nearshore waters of the

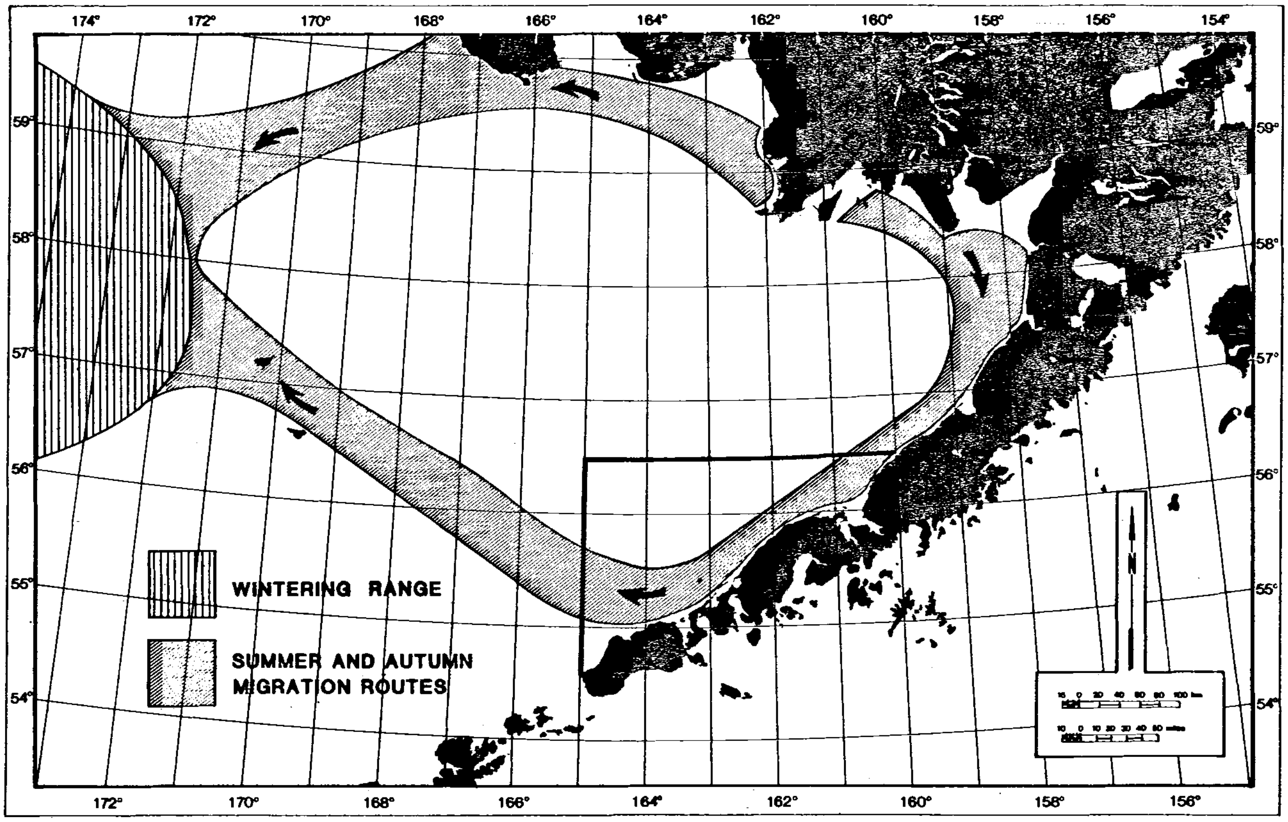


FIGURE 4.11—Bering Sea herring summer and fall migration routes in relation to proposed St. George Basin and North Aleutian Shelf lease areas.

North Aleutian Shelf for spawning, initial growth, and development, the region is of importance to other stocks as a migratory corridor (Fig. 4.11). Pacific herring overwinter at depth in the central Bering Sea northwest of the Pribilof Islands. Those adults en route to spawning areas in inner Bristol Bay move through the lease area during spring, probably near the end of March. After spawning, the adults move back through the lease area in summer months upon feeding migrations. Little is known about the distribution of larval and juvenile herring; it is assumed that they too move through the lease area, feeding and growing while en route to overwintering habitat.

4.4 FISHERY RESOURCES SOUTH OF THE ALASKA PENINSULA

A number of commercially important flatfish, roundfish, rockfish, and shellfish may be seasonally present in the general vicinity of Deer Island (Table 4.5); however, their relative abundance at the site is unknown. While details of fish migrations and distributions are not as yet well defined for this area, they most likely tend to display the same patterns seen in areas where studies have been made.

Flatfish are more widely dispersed in the spring and summer and move offshore during winter to spawn (Hughes 1974). Roundfish (cod, pollock, sablefish) appear similar in their patterns of movement. Cod are winter spawners, while pollock probably spawn in the spring. There are few data on the seasonal movements of sablefish in the area. Hughes (1974) states that they generally move to deep waters in the fall where they remain throughout the winter.

Because of their importance in southwest Alaska Peninsula and south Unimak Island fisheries, a considerable body of information exists for Pacific salmon that spawn in local streams or that migrate through the area. During June, migrating salmon bound for Bristol Bay systems and rivers further to the northwest (principally sockeye, chum, and pink salmon) are caught in Ikatan Bay and along the south shore of Unimak Island (Thorsteinson and Merrell 1964). Catches generally peak in the third week of June and then fall off sharply. Pink and chum salmon are the main species that spawn in streams of Cold Bay, Morzhovoi Bay, and Deer Island. Smaller runs of sockeye and coho salmon also occur in Morzhovoi Bay, in Thin Point Lagoon at the western entrance to Cold Bay, and in Cold Bay. Chinook salmon are not known to spawn in streams located along the southwestern shore of the Alaska Peninsula. The local salmon runs appear along the coast in early July and enter streams to spawn from mid-July through August or early September. Seaward-bound salmon leave the streams from late April to early June with the peak migration occurring from early to mid-May. The juveniles probably remain in coastal waters until early autumn.

TABLE 4.5—Commercially important fish and shellfish occurring in the vicinity of the hypothetical oil spill off Deer Island.

Common Name	Scientific Name
Sockeye salmon	*Oncorhynchus nerka*
Chum salmon	*O. keta*
Pink salmon	*O. gorbuscha*
Coho salmon	*O. kisutch*
Chinook salmon	*O. tshawytscha*
Walleye pollock	*Theragra chalcogramma*
Pacific cod	*Gadus macrocephalus*
Sablefish	*Anoplopoma fimbria*
Arrowtooth flounder	*Atheresthes stomias*
Rock sole	*Lepidopsetta bilineata*
Flathead sole	*Hippoglossoides elassodon*
Pacific halibut	*Hippoglossus stenolepis*
Pacific Ocean perch	*Sebastes alutus*
Red king crab	*Paralithodes camtschatica*
Tanner crab	*Chionoecetes bairdi*
Dungeness crab	*Cancer magister*
Pink shrimp	*Pandalus borealis*
Coonstripe shrimp	*P. hypsinotus*
Humpy shrimp	*P. goniurus*
Spot shrimp	*P. platyceros*
Sidestripe shrimp	*Pandalopsis dispar*

Shellfish inhabiting the general vicinity of the hypothetical spill are red king, Dungeness, and Tanner (most commonly *C. bairdi*) crabs, and pandalid shrimp. Red king crab move to inshore waters in a spring molting and breeding migration and to offshore waters in a late summer and autumn feeding migration. Females carry eggs for 11 months before larval release. Fecundity increases with size, the largest females carrying 400,000 eggs (Weber and Miyahara 1962). Larvae settle on inshore shallow substrates and after several molts, juveniles are distributed from intertidal depths to 200 m (Rietze 1975).

Tanner crabs have been taken in fishery surveys in waters 38–250 m deep (Hughes 1974) but seem to prefer depths of 50–130 m in summer and fall (Arctic Environmental Information and Data Center [AEIDC] 1974). Spawning occurs from January to May; females carry, on the average, 30,000–80,000 eggs for about 11 months before larval release. There are no data on larval distribution in this area; distribution of juveniles is only characterized as "widespread" (North Pacific Fishery Management Council 1978).

The Dungeness crab is the predominant crab of Alaska bays and estuaries and is found primarily from the intertidal zone to a depth of 90 m. The shallower portion of its depth range is occupied during springtime breeding. Spawning occurs in early spring and summer; females produce as many as 1.5 million eggs which they carry from 7 to 10 months. Adults move offshore to depths as great as 200 m in autumn and remain there through the winter. Juvenile Dungeness crab inhabit intertidal and subtidal waters, often in association with algal shelter (Hoopes 1973; AEIDC 1974). At all depths Dungeness crab seem to prefer sandy or sand-mud substrates.

Five species of pandalid shrimp occur in the south Alaska Peninsula–Unimak Island area. All have similar life cycles. Spawning occurs in shallow bays and around island groups during August and September (Ivanov 1969) with 900 to 3,000 eggs produced per female. Females carry eggs about 6 months; larvae occupy the nearshore environment during their entire 2½-month life stage; and juveniles are found in water less than 40 m deep in winter and at greater depths in summer (AEIDC 1974). Initially these shrimp develop as males and mature in 2 years. They breed as males during their third or fourth year, then transform into females and breed until age 6 (AEIDC 1974; Pereyra *et al.* 1976b). They display diurnal movements, rising in the water column at night to feed.

4.5 EFFECTS OF OIL ON FISH AND SHELLFISH

Within the last few years much information has been published concerning the fate and effects of petroleum hydrocarbons in the marine environment (reviewed by American Institute of Biological Sciences 1976; Malins 1977; Wolfe 1977; Neff 1979; Olla *et al.* 1980; Malins and Hodgins 1981; Rice 1981; Energy Resources Co. Inc. 1982; Hameedi 1982; Malins et al. 1982). As a result of the commercial value of fish populations and their ecological role in marine ecosystems, the potential impacts of spilled oil have stimulated many studies to identify the effects of oil on fish. Researchers have developed many different approaches to oil toxicity studies and much confusion exists regarding the comparability of experimental results. The validity of comparing the sensitivities of various organisms as reflected by acute bioassays is envisioned as a pervasive problem of oil effects studies. It has been questioned because of differences in (1) methods of mixing oil into water, (2) methods of exposing fish to contaminated water, and (3) analytical methods of quantifying the variety and concentrations of the various hydrocarbons. Results of toxicity studies *within* a laboratory are usually comparable; however, caution is advised when comparisons with outside studies are made. This situation is further complicated by problems associated with applying laboratory data to natural spill conditions. Irrespective of these considerations, the laboratory studies do show that fish exposed to petroleum in water, sediment, and in their food take up hydrocarbons and store them in various tissues and body fluids with varying effects. Although the literature documents that oil can affect fish in a variety of ways, the effects of actual oil spills on fish populations are difficult and expensive to measure; and once measured they are seldom unequivocal because oil-induced perturbations are often masked by other factors, including normal variations in population numbers, fishing, and the synergistic or antagonistic effects of other pollutants providing too many uncontrolled variables (Rice 1981).

After an oil spill, a number of physical and chemical properties affect the hydrocarbon exposure and ability of a fish to respond effectively to the pollutant (Olla *et al.* 1980). These include the size, shape, and duration of the spill as well as the amount of oil incorporated into the water column and bottom sediments. Oil weathering processes are greatly influenced by wave height, wind velocity, tidal phase, temperature, salinity, amount of sunlight, and other factors (*see* Chapter 2). Field measurements have shown that after a large-scale spill, total dispersed and dissolved hydrocarbons that are in the order of hundreds of parts per million near the source are quickly diluted and dispersed to the parts per billion range downstream of the spill site. Hydrocarbon concentrations in the contaminated sediments beneath the oil slick may range as high as surface densities of 12 g/m², which translate to concentrations in the order of thousands of parts per million depending on the mixing of oil with interstitial waters and sediments.

The LD_{50}'s of marine organisms determined in toxicity tests serve as general indicators of their minimum sensitivities to the watersoluble fraction (WSF) of petroleum hydrocarbons in seawater. According to Rice (1981):

> Refined oils are generally more toxic than the WSF of crude oils as they more readily mix in seawater and possess a higher concentration of aromatic hydrocarbons than crudes. As the molecular size of aromatic oil components increases, so does their toxicity to both fish and invertebrates. In general, as the aromatic [compounds] get larger, by either increased ring numbers or methyl substitution, they become more toxic, less soluble in water, and less available in the WSF.

It is generally agreed that the portions of fish or shellfish life histories most vulnerable or sensitive to contaminant exposure or environmental stress are those associated with gonadal development, early embryos, and larval stages (Rosenthal and Alderdice 1976). Larvae are especially vulnerable when the yolk sac has been fully absorbed and they must actively search for prey. Eggs and larvae have been the focus of many studies on fish and invertebrate species because both groups usually have at least one planktonic life stage. At this time the eggs or larvae are largely free-floating, relatively immobile, and unable to protect themselves from changes in their surroundings such as environmental perturbations and predation. A synthesis of existing bioassay results indicates the relative sensitivities for various ecological groups to the WSF of petroleum hydrocarbons given in Table 4.6.

Most fish and many of the shellfish present in the southeastern Bering Sea undergo seasonal migrations, and have differing ontogenies and habitat requirements. Therefore, a species' vulnerability is determined not only by the physical and chemical processes affecting the oil but by the time, size, and location of the spill. Additionally, the amount of natural or ecological stress an animal is under will play an important but poorly understood role in how it reacts behaviorally or physiologically to petroleum in seawater. Once exposed to spilled oil the organisms may suffer death by asphyxiation, contact poisoning, or exposure to the WSF of oil at some time or distance from the spill (Curl and Manen 1982). The toxicity of the WSF may result from dissolution of fatty acids, which causes alteration of cell membrane permeability and loss of ability to regulate salt balance (Rice 1981).

TABLE 4.6—Concentrations (ppm) of the water-soluble fraction of petroleum hydrocarbons lethal to life stages of major fish and shellfish ecological groups.

Ecological Group	Eggs	Larvae	Juveniles	Adults
Shellfish				
Shrimp	0.01-1	0.01	0.1-1	0.1-1
Crab	?	>0.1-2	1-4	1-4
Finfish				
Flatfish	0.1-1	0.1-1	>5	>5
Semidemersal	0.1-1	0.1-1	1-3	1-3
Pelagic	0.1-1	0.1-1	1-3	1-3

SOURCE: Thorsteinson and Thorsteinson 1982.

Because the eggs and larvae of many species float near the surface of the open ocean, they are particularly susceptible to damage from an open-ocean spill. Generally, bioassay results indicate greater sensitivity with earlier life stage; the earlier in its development an embryo is exposed to oil hydrocarbons, the more severely it is damaged. As it nears hatching it gains resistance to oil, after which sensitivity increases again until the critical period during which the yolk sac is absorbed and it must seek food (Rice 1981). A typical response of fish or crustacean larvae to oil in concentrations greater than 0.01 ppm includes a brief increase in activity followed by reduced activity, sporadic twitching, narcosis, and ultimately death. Short exposures to low concentrations are enough to kill many larval finfish and shellfish. Larval crustaceans cease swimming, becoming moribund after 10-minute exposures. Juvenile and adult finfish and shellfish would not be killed by short-term, low-level exposures of less than 1 ppm, but could suffer a myriad of sublethal effects if exposures lasted more than 2 weeks. On the other hand, post-larval animals unable to avoid doses greater than 1 ppm might experience large-scale losses if exposures lasted longer than 18 hours in the case of most finfish, and 1-4 days for most crustaceans.

Marine fish and shellfish may also experience lethal exposures to petroleum hydrocarbons through uptake from contaminated bottom sediments. Although the effects and magnitude of oil contamination via this pathway are largely unknown, flatfish, crabs, and other benthic organisms would be most vulnerable to impact from oiled sediments. Unless a massive spill occurred in relatively shallow waters, the amount of bottom sediment impacted would be small, with correspondingly low concentrations of contaminants spread over broad regions. Under these conditions, most organisms might experience sublethal impact, such as changes in growth and metabolism, but lasting effects only if exposures and uptake were long term.

If animals can detect sublethal concentrations, they may avoid contaminated areas or rely on other behavioral adaptions to reduce exposures. If they remain in contaminated waters, they may initially survive exposure but may face reduced longevity or viability from sublethal exposure in the long term. Sublethal amounts of hydrocarbons may be accumulated and sometimes concentrated in tissues and fluids from surrounding water and food (Malins 1980).

Once hydrocarbons are accumulated in fish and shellfish, they are metabolized or excreted. Metabolite research is still in its infancy, but the data from initial studies suggest that metabolite generation may result in the formation of potentially harmful carcinogenic or mutagenic compounds. According to Rice (1981):

> If oil concentrations from a spill are not high enough to cause direct mortalities to fish, they could adversely affect fish by causing abnormal amounts of energy consumption, damage in cells, tissues, or organs, and ultimately limit a fish population in a given area. Obviously, such effects are more subtle than direct mortalities and more difficult to detect and, once detected, nearly impossible to assign a direct relationship between oil exposure and the effect. Laboratory experiments with controlled variables indicate that oil can be taken into fish tissue, can be metabolized to some extent, and can affect metabolism, growth, reproduction, etc. In a few cases, some effects on fish exposed to oil in the field have been observed, but the effect of oil exposure on fish populations remains undocumented.

Laboratory experiments and field studies have demonstrated that hydrocarbons and their metabolites manifest themselves in a wide variety of sublethal effects, including changes in behavior, physiology, histology, and pathology (Table 4.7). Most work has been conducted on juvenile and adult animals; although concentrations less than 0.1 ppm may be lethal to eggs and larvae, it is more likely that they will prove to be more subtly affected.

The rate and quantity of petroleum uptake will depend on the size of the molecules of a compound in question, as well as the exposure concentration (Rice 1981). High-molecular-weight compounds can reach greater concentrations in tissues than low-molecular-weight compounds, but are less available in WSF's. Most hydrocarbons are metabolized in the liver by mixed function oxidases. In fish this enzyme activity increases dramatically after exposure, whereas in invertebrates, although the enzyme response is similar, it is of lesser degree (Rice 1981). The rate of hydrocarbon elimination var-

TABLE 4.7—Examples of sublethal effects demonstrated by laboratory studies of hydrocarbons and their metabolites.

Behavioral Changes*
Avoidance
Disruption of chemoreception
Mediate food finding
Courtship
Spawning
Symbiotic and parasitic relationships
Predator avoidance
Disruption in taxes (through swimming activity)
Phototactic
Geotactic
Disruption of predator-prey interaction
Decreased consumption
Lowered aggressiveness
Disruption in learning
Physiological Changes
Decreased heart rate
Decreased and increased respiratory rate
Increased coughing
Interference with reproduction and early development
Alterations in embryonic activity
Premature or delayed hatching
Malformed larvae
Decreased survival of larvae
Changes in blood parameters indicating pollutant stress
Increased blood glucose and cortisol
Decreased energy reserves
Reduced glycogen storage
Histological Changes
Damage to: liver
gill
gut
vertebrae
eye lens
stomach
brain
olfactory organs
Pathological Changes
Increased vulnerability to disease
Increased fin erosion
Decreased number of external bacterial flora species
Decreased rate of tissue regeneration

* From Olla *et al.* 1980.

ies by species, the tissues where hydrocarbons are concentrated, and other factors. Although laboratory studies suggest that depuration usually occurs within 200 hours after the contaminated organism is placed in clear water, the storage of petroleum hydrocarbons in lipid-rich tissues may taint an animal's flesh by producing changes in appearance, texture, odor, or taste (Rice 1981). In the case of commercially valuable fish or shellfish, a real or perceived taint may severely reduce a species' marketability.

Impairment of a fishery from oil pollution could be caused by fish kills; failures of spawning and recruitment; or changes in habitat, behavior, or migration patterns that make fish unavailable (Rice 1981). Other losses can be attributed to tainting of catch, loss of fishing time, or fouled gear. Fishermen may reduce their activities after a spill so as not to foul their gear with oil and harbors may be closed during cleanup operations (Allen *et al.* 1976; Straughan 1972). Other sources of fishing and oil industry problems may include (1) at-sea conflicts between fishing and petroleum development activities, including those resulting from obstructions caused by platforms, rigs, and the network of collected pipeline between platforms; (2) competition for offshore facilities and space; and (3) interference with traditional lifestyles and subsistence use of fisheries resources.

4.6 HYPOTHETICAL OIL SPILLS NORTH OF THE ALASKA PENINSULA

The biological consequences of two hypothetical oil spills in North Aleutian Shelf waters were considered in the fisheries workshop. One spill site was located at 55°25′ N., 162°57′ W. in the Amak Island region, 9 km offshore from the Kudiakof Islands in 33 m of water. The other was off Cape Seniavin at 56°35′ N., 160°46′ W. The scenario for both sites was a pipeline rupture releasing 2,000 bbl a day for 5 days. In each case, discussions addressed a summer spill, beginning 22 June; specific dates for a winter spill were not considered. However, this did not preclude discussions of impacts associated with hypothetical spills during the various seasons.

Amak Island and Cape Seniavin are separated by approximately 185 km. As a result of this closeness the physical features of pollutant transport and weathering would be much the same at both sites for hypothetical summer spills. The pollutant transport workshop (*see* Chapter 2) description of the contaminated zone from 10,000 bbl spilled over 5 days was as follows: (1) a plume extends 20 km to the east from the origin and covers 80 km^2; (2) bottom-to-surface mix of total hydrocarbons in the plume ranges from 1 ppm, covering 3.2 km^2, in the vicinity of the source to 0.2 ppm at the outer edge, 20 km downstream; and (3) spill conditions persist 6–7 days after the spill begins on 22 June. The slick from the spill would move to the east in the same direction as the plume and would appear as a series of ribbons on the surface. Under winter conditions the rupture would result in similar plume characteristics and movements, the only difference being in slick movement to the west-southwest instead of east.

The toxicities of oil and oil components to many fish and shellfish resources are well documented in laboratory studies, but extensive fish kills after oil spills are generally not. Concentrations ranging from 1 to 4 ppm generally are considered potentially lethal for the fish and shellfish occurring in the Bering Sea. Toxicity can further be generalized by habitat and life stage. Concentrations of oil in seawater from 1 to 3 ppm are considered toxic to most pelagic fish, with flatfish being somewhat more tolerant. Eggs and larvae are thought to be the most sensitive to spilled oil and are often more vulnerable because of their lack of mobility and inability to avoid contamination. Sublethal effects can occur after exposures to hydrocarbon concentrations of less than 1 ppm (Malins *et al.* 1982). They are not as well understood as lethal toxicities but may be more important because any energy drain on an individual fish can lead to reduced growth, reduced reproductive success, and reduced fish populations.

4.6.1 Juvenile Salmon

Seasonal vulnerability scores (1–10; 10 being most vulnerable) were developed for juvenile salmon in the North Aleutian Shelf and at the Amak Island and Cape Seniavin spill sites from abundance estimates provided at the meeting (Fig. 4.12). Juvenile fish begin appearing in the

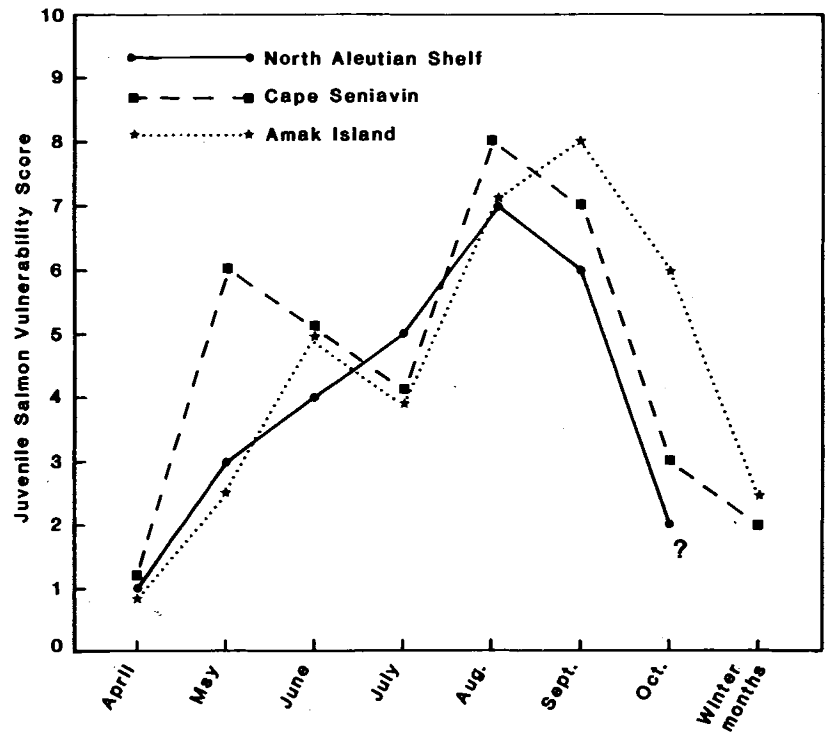


FIGURE 4.12—Seasonal vulnerability of Pacific salmon in the North Aleutian Shelf and at two hypothetical spill sites.

lease area in April, are most abundant throughout the area in August and September, and rapidly decrease in number by October. The winter distributions of these small fish in the Bering Sea are largely unknown, although incidental catches of immature chinook and other salmon in foreign trawls just west of the lease area indicate their presence (to an unknown extent) throughout the year. The bimodal patterns of salmon abundance (reflected in vulnerability scores) at each spill site reflect (1) local and regional patterns of juvenile emigration from around Bristol Bay, and (2) minor differences in seasonal vulnerabilities due to the distance between the spill sites and rates of salmon movement.

In general, a spill at Cape Seniavin would be most detrimental to ocean-going salmon (all species considered) in May and again between late July and early September with greatest salmon abundance in the first part of August. Because Amak Island is more than 175 km to the west of Cape Seniavin and the Amak Island spill site probably lies inshore of the major migratory pathway of early ocean-going species (chinook and sockeye), the potential impacts to salmon would be somewhat less in early summer at Amak Island, where they would be at greatest risk in early June. Likewise, salmon numbers would be lowest in July at Cape Seniavin, becoming more abundant later in the summer between August and mid-September.

The seasonal vulnerabilities for each species of juvenile Pacific salmon traveling through or originating from the North Aleutian Shelf, and relative to each spill site, are derived from monthly abundance estimates (Fig. 4.13). These estimates may not be completely reliable, however, as much has been drawn from investigations dealing with the rates and patterns of juvenile sockeye movement from Bristol Bay. Current uncertainties regarding juvenile salmon distribution and abundance in North Aleutian Shelf waters are indicated in Figure 4.13. Yearly variations in salmon presence and abundance (as much as 6 weeks) associated with temperature influences on growth and movement, as well as prey availability, have been noted above.

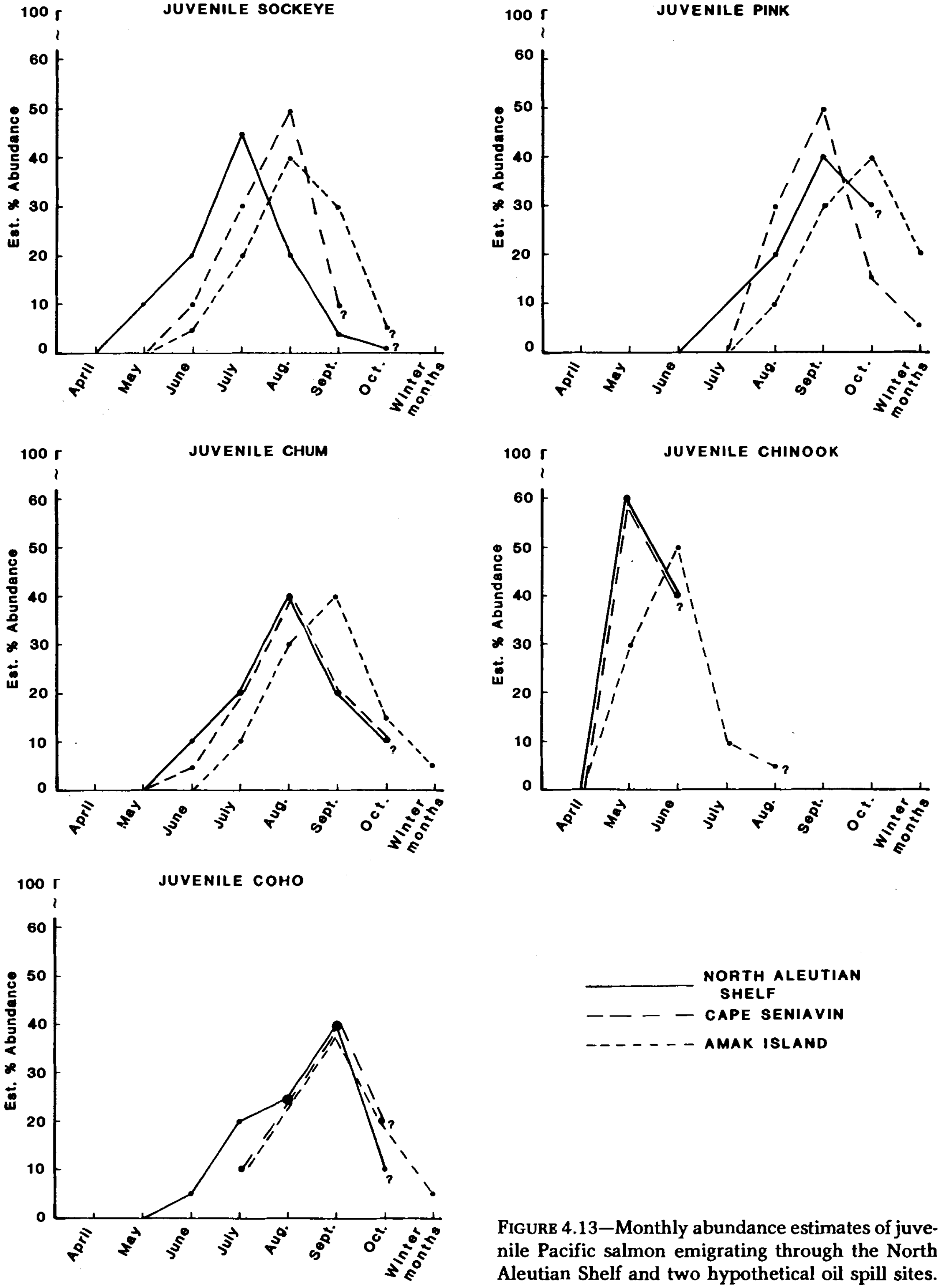


FIGURE 4.13—Monthly abundance estimates of juvenile Pacific salmon emigrating through the North Aleutian Shelf and two hypothetical oil spill sites.

As can be seen from the abundance estimates and the summary of vulnerable periods at each site for juveniles of each salmon species (Table 4.8), potential impact to chum salmon would be approximately equal in magnitude at both the Cape Seniavin and the Amak Island spill sites, although the maximum relative vulnerabilities differ by 1 month; 1 August vs. 1 September, respectively. Impacts to juvenile coho would be similar at both sites if a spill were to occur during summer months.

Under the 22 June spill scenarios, at each site the juvenile salmon as a whole appear to be less vulnerable than during the preceding or following periods. In early June, chinook salmon are the most abundant salmon species at Cape Seniavin. In May and June, fewer juvenile chinook salmon are found in the vicinity of Amak Island than Cape Seniavin, probably reflecting an offshore movement in the vicinity of Port Moller. By the middle of June most chinook salmon have moved through the proposed lease area and juvenile sockeye numbers are building. The abundance of sockeye and other species does not peak until late in the summer. Therefore, given the hypothetical spill date and the yearly variations in salmon abundance, it is likely that juvenile chinook and sockeye salmon would be most impacted by a spill on 22 June. A spill at either site would be the most detrimental to all species from August to mid-September.

It is not possible to specify how many juvenile salmon would enter the contaminated spill zone, or how long they would be exposed to oiled seawater. Assuming that juvenile salmon travel at a rate of 3.7 to 4.3 km/d, they could be exposed for as long as 3-4 days. If they were unable to avoid such areas, fish experiencing doses greater than 1 ppm would probably be killed. Lower concentrations may not kill fish but may reduce their longevity via a multitude of potential changes in behavioral, physiological, and other sublethal responses, depending on hydrocarbon uptake and disposition. The subsequent fate of such fish is not known but it may ultimately be death.

Although some juvenile losses are expected, the long-term effects of a 10,000-bbl spill would cause no lasting harm to the salmon populations of Bristol Bay. This is due to the vast number of migrants in the region, their somewhat staggered stock- and species-specific migrations, and the relatively small area of the spill plume. In addition, the WSF's of petroleum hydrocarbons associated with this size of spill are neither highly concentrated nor persistent. Any oil-induced deaths would be indistinguishable from deaths due to natural causes (unless observed in the field immediately after the spill), as evidenced by the wide natural fluctuations in returning adults each year.

4.6.2 Adult Salmon

Adult salmon bound for the north side of the Alaska Peninsula and Bristol Bay river systems enter the Bering Sea through Unimak Pass and other Aleutian passes to the west. As with juveniles, most investigations concerning returning migratory behavior have focused on sockeye salmon. If adult salmon respond to the same environmental cues, other species may follow the same migratory path. The sockeye salmon migratory band extends as far as 162 km offshore, with the center of abundance 50-100 km from shore. At both spill sites the peak abundance of chinook and sockeye salmon occurs during

TABLE 4.8—Periods of greatest juvenile salmon abundance across the North Aleutian Shelf lease area and at two hypothetical spill sites.

Juvenile Salmon	North Aleutian Shelf	Cape Seniavin	Amak Island
Sockeye	15 June-15 July	15 July-15 Aug.*	15 Aug.-7 Sept.
Pink	15 Aug.-1 Oct.	15 Aug.-15 Sept.*	1 Sept.-15 Oct.
Chum	15 July-15 Aug.	15 July-15 Aug.*	1 Aug.-15 Sept.*
Chinook	21 Apr.-1 June	21 Apr.-1 June*	15 May-15 June
Coho	1 Aug.-15 Sept.	1 Aug.-15 Sept.*	1 Aug.-15 Sept.*

* Denotes times and spill locations of greatest comparative impact.

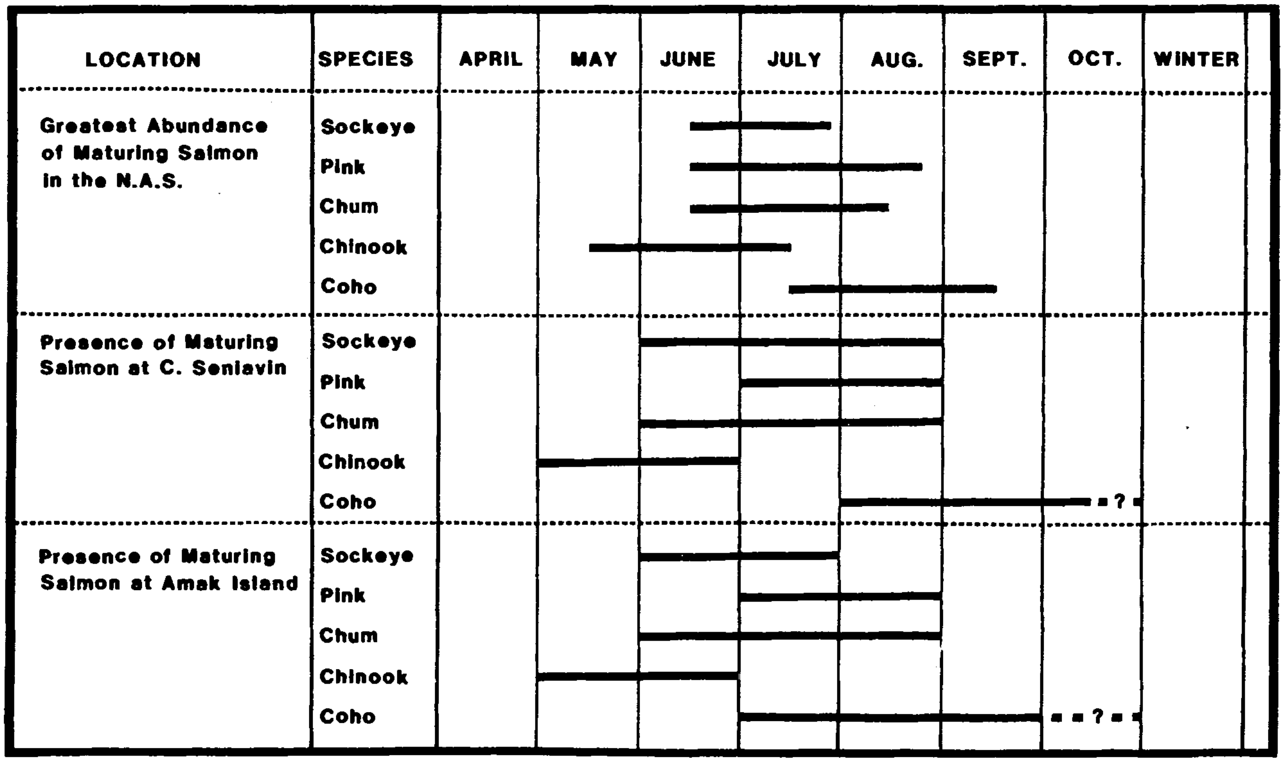


FIGURE 4.14—Chronology of occurrence of maturing Pacific salmon in the North Aleutian Shelf and at two hypothetical spill sites.

June, and of chum and pink salmon during July–August; coho salmon are at peak abundance at Amak Island during July–September, and at Cape Seniavin during August–October (Fig. 4.14).

The impacts of a 10,000-bbl spill on 22 June to adult salmon would be similar at both Amak Island and Cape Seniavin. Chinook and sockeye would be the most abundant species present with minor variations in their numbers at either site associated with timings of local runs. Considering the small size of the spill plume, and a salmon's rate of movement and motivation to spawn, a fish would probably migrate through the widest area of contamination within 12–24 hours. Depending on the length of exposure, fish entering the 1-ppm sector of the spill could be killed. As was the case with juveniles, even if large numbers were killed, such losses would be undetectable in total run size due to the large fluctuations in survival from fry and smolts to returning adults. Even substantial losses from a spill of much larger proportions—perhaps 200,000–300,000 fish—would not be detected in that year's catch nor would such losses be harmful to total Bristol Bay salmon runs that vary from 3 to 60 million returns annually. Local stocks returning to natal streams along the Alaska Peninsula could suffer greatest impact from a spill at a time when they were massing after having separated into individual spawning units.

Concern was expressed about the possible loss of market associated with a real or perceived tainting of salmon flesh if a spill were to occur. Even in a relatively short period, adults could accumulate oil through feeding, swallowing, or through uptake in their gills. If some of the tainted fish (detectable by odor, taste, or both) were processed, there could be be major economic repercussions for both fishermen and processors. Undoubtedly an oil spill in Bristol Bay would be widely publicized and, whether or not tainting of the flesh were proved to occur, the market for canned salmon might suffer. In this situation the size of an oil spill or number of fish exposed to hydrocarbons would be of little consequence.

4.6.3 Crabs

Of all the finfish and shellfish species in the Bering Sea, none is thought to be more vulnerable to substantial impact from development of North Aleutian Shelf leases than the red king crab. Resource surveys have revealed that the waters in or nearby the lease area contain some of the highest densities of egg-carrying females in the entire Bering Sea and that this is a region of extremely high larval density in spring and summer. The larvae are relatively immobile and are especially sensitive to very low concentrations of hydrocarbons in seawater; they can be rendered moribund after exposures of only 10 minutes. In this state they are extremely vulnerable to increased predation and susceptible to physiological and histological changes, depending on hydrocarbon exposure. Exposures to WSF concentrations of 0.1–1 ppm for 12–24 hours are lethal to larval crustaceans.

The distribution of red king crab larvae in relation to the North Aleutian Shelf lease area (Fig. 4.15) indicates greatest larval abundance in the Port Moller region. Larval densities east of Cape Seniavin have not been surveyed but are suspected to be high due to larval drift from regions of large hatch, such as Port Moller, and local input from spawning females. Although the period of peak hatch may occur during the latter parts of April and early May, larval release is spread over several months, significantly reducing the magnitude of potential loss from a single spill event. Losses as high as 3–5% of the larval red king crab population were hypothesized if 10,000 bbl of oil were released off Port Moller, or some other area of high larval abundance, in late April.

A spill in late June could be more damaging to king crab than one in April. By then, pelagic larvae have already suffered substantial natural losses before taking up a benthic existence. The presence of floc on the sea floor and its postulated higher hydrocarbon concentration may be more harmful to the population by causing large kill-offs of juveniles congregated in limited suitable habitat, or it could affect their growth rates and survivability through disruptions in predator-prey relationships. Impacts to juveniles in the North Aleutian Shelf are hard to predict because, at present, the distribution, habitat, and energy requirements of young crabs in Bristol Bay are poorly understood.

The effects of oiled seawater and sediments on crab reproduction were also discussed at the workshop, and in greater detail by Armstrong *et al.* (1981). The impacts include (1) curtailed feeding by adults due to high hydrocarbon concentrations, resulting in energy requirements not being fully met and reduced production of gametes; (2) hydrocarbons being deposited in gametes with unknown effect on egg and sperm viability; and (3) sediment hydrocarbons absorbed by lipid-rich developing embryos on females, resulting in weak year-class strength due to poor hatch. It has also been speculated that sublethal concentrations of oiled seawater may impact crab reproduction by interfering with the extrusion of testoterone needed to attract males by breeding females. Similarly, oil may block the male chemoreceptors needed to detect the female attractant. In all cases, a spill incident would have to be a massive event (possibly an order of magnitude greater than discussed) to damage the entire Bristol Bay population of red king crab; otherwise effects would be localized and small scale.

Tanner crab populations, especially spawning populations, are more widely dispersed in the Bering Sea than the red king crab. Larval *C. opilio* are more frequently encountered in plankton samples to the north and west of the North Aleutian Shelf, whereas larval *C. bairdi* are distributed throughout the southern Bering Sea (Fig. 4.15). Like other decapod crustaceans, the eggs and larvae of Tanner crabs are very sensitive to concentrations of oil (as low as 0.2 ppm) and if exposed to contaminated waters or sediments, they would suffer the same spectrum of impacts as red king crab. Because *C. opilio* are not present in the Cape Seniavin and Amak Island areas, they would not be impacted by OCS development or oil spills there. There could be extensive losses among larvae of *C. bairdi*, but fewer among the juveniles and adults because they are most abundant at greater depths than the hypothetical pipeline ruptures. A winter spill, when larvae would not be as abundant (maybe not present), would be of far less consequence than a summer spill. For either

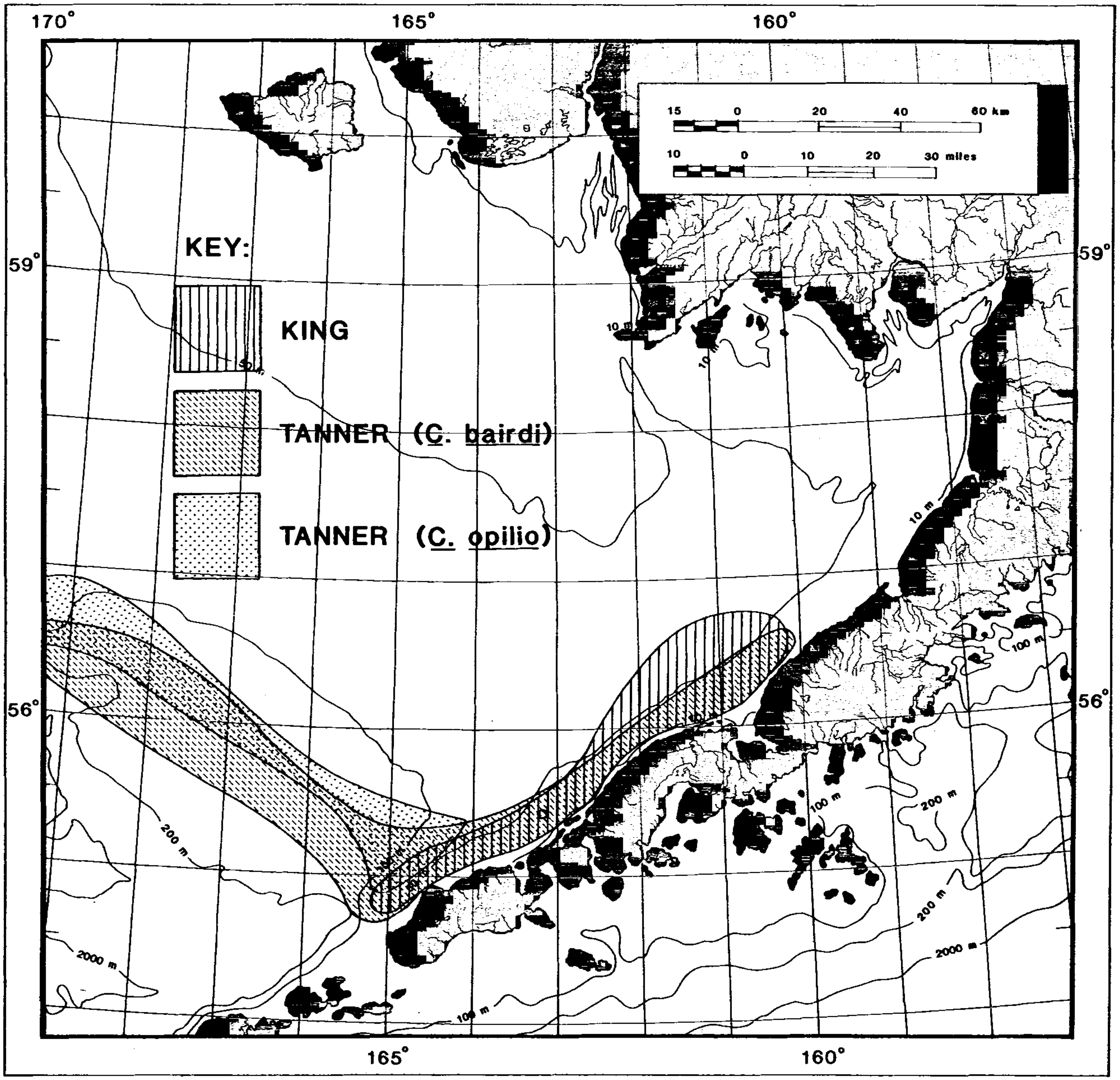


FIGURE 4.15—Distribution of larval king and Tanner crabs in the southeastern Bering Sea, March–mid-August. (Adapted from Armstrong *et al.* 1981.)

species, because of the widespread distribution and seasonality of pelagic larval occurrence compared to the small zone of contamination expected from a 10,000-bbl spill, any losses associated with the spill would be insignificant and undetectable in terms of causing long-lasting changes in total *C. bairdi* numbers.

4.6.4 Other Fish Resources

The relative vulnerabilities of other fishery resources of the North Aleutian Shelf were also considered at the workshop. Pollock, yellowfin sole, Pacific cod, Pacific halibut, Pacific herring, and other commercially important finfish occupy the waters of the lease area seasonally as adults or during early life stages. Like Tanner crabs, they are widely dispersed in the southeastern Bering Sea. Losses associated with a spill anywhere in the North Aleutian Shelf would be localized and vary with time of year (Figs. 4.16–

4.18). The hypothetical spills discussed at the meeting would be on such a small scale that neither resource nor fishery would be significantly damaged. Such losses would be transient and masked by natural deaths and normal population fluctuations.

This is not to say that Bering Sea fishery resources could not be impacted by an oil spill catastrophe in the North Aleutian Shelf lease area. This region has received only cursory study, especially near shore, but appears to contain the major nursery grounds for several species of flatfish including yellowfin sole, halibut, and other flounders (Thorsteinson and Thorsteinson 1982). A spill event impacting a far greater proportion of the lease area (i.e., a spill an order of magnitude larger than those prescribed in the scenarios at the synthesis meeting) could conceivably destroy significant fractions of Bering Sea groundfish stocks and cripple their year-class strengths for several years in succession. Pacific halibut would be the species at greatest risk from a mishap of this magnitude. Pacific herring are known to spawn in Port Moller and nowhere else along the North Aleutian Shelf coast. Although this stock would not be harmed under the spill conditions described for Amak Island and Cape Seniavin, a 10,000-bbl spill closer to Port Moller and during late May could seriously harm these species.

4.7 HYPOTHETICAL OIL SPILL SOUTH OF THE ALASKA PENINSULA

In addition to the hypothetical spills north of the Alaska Peninsula, a 200,000-bbl spill simulating a tanker accident was posed for the vicinity of Deer Island off Cold Bay. As in the other scenarios, the date for the tanker spill was 22 June.

The physical properties and dimensions of the Deer Island spill provided by the pollutant transport workshop (Chapter 2) include (1) an impacted cylindrical volume with a diameter of 18 km; (2) concentrations under the slick from surface to bottom as high as 4 ppm, decreasing to 1 ppm at outer boundaries and persisting for at least 4–5 days; and (3) a general westward movement of the spill with low probabilities of oil reaching the beaches. There was a low probability that oil would hit selected landfalls within 50–70 hours after the spill.

Although several commercially important species occur in the vicinity of the hypothetical Deer Island spill, it is impossible to assess its impact on a species-by-species basis because their actual presence in the spill zone cannot be reliably described. However, given the dimensions and properties of the spill (surface area of approximately 250 km^2 with bottom-to-surface concentrations of total hydrocarbons as high as 4 ppm, decreasing to 1 ppm at the outer boundaries and persisting 4 or 5 days) and the lethal concentrations for various life stages of shellfish and finfish given earlier in this chapter, massive, if not total, mortalities would be expected for all species entrapped in the spill zone.

4.8 INFORMATION NEEDS RELEVANT TO NORTH ALEUTIAN SHELF DEVELOPMENT

Several research topics, most having Pacific salmon as their subject, were suggested by participants at the North Aleutian Shelf Synthesis Meeting.

Few conclusive studies have examined the avoidance of petroleum hydrocarbons by juvenile and mature salmon. Observations of juvenile coho salmon in a Y maze (Maynard and Weber 1981) suggest that immature salmon may or may not be attracted to various hydrocarbon concentrations and that their movement into contaminated areas is influenced by preferences in lighting conditions and other environmental stimuli. Adult chinook and coho salmon tested *in situ* (Weber *et al.* 1981) at the peak of their upstream migration substantially avoided hydrocarbon mixtures greater than 3 ppm; the researchers opined that similar exposures in the open ocean could potentially delay the time of return to streams. In each case it was concluded that avoidance by salmon depends on an individual fish's motivation to remain in or move to a particular habitat.

More definitive studies examining the oil avoidance capabilities of both juvenile and adult salmon are needed. Other questions that remain unanswered are: How will juveniles be impacted by ingesting contaminated food items? How will prey be impacted by a spill? The food habits of juvenile pink, chum, coho, and chi-

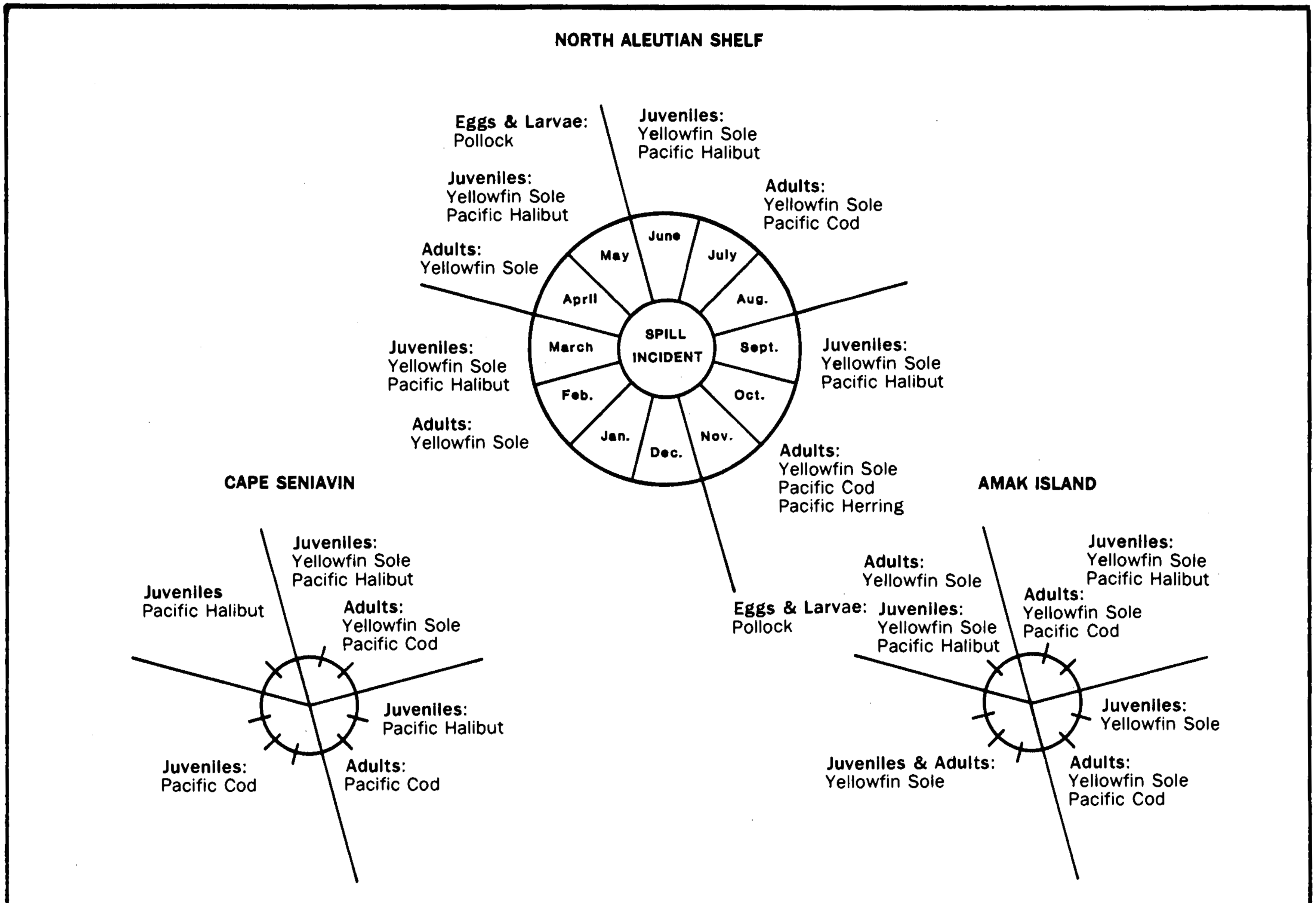


FIGURE 4.16—Seasonal vulnerabilities of life stages of major commercial species exhibiting *high* impact potential from oil releases in the North Aleutian Shelf and at two hypothetical spill sites.

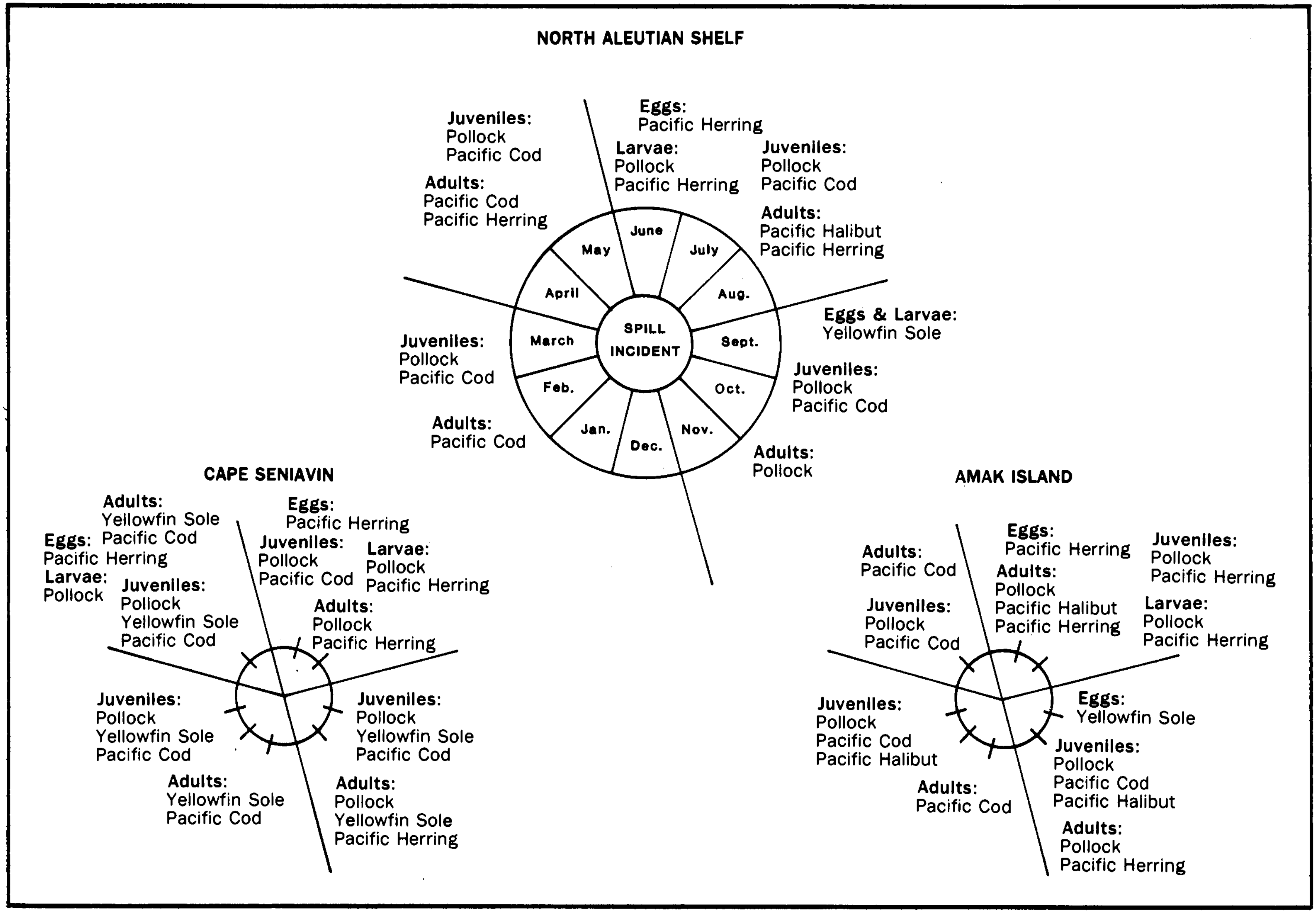


FIGURE 4.17—Seasonal vulnerabilities of life stages of major commercial species exhibiting *moderate* impact potential from oil releases in the North Aleutian Shelf and at two hypothetical spill sites.

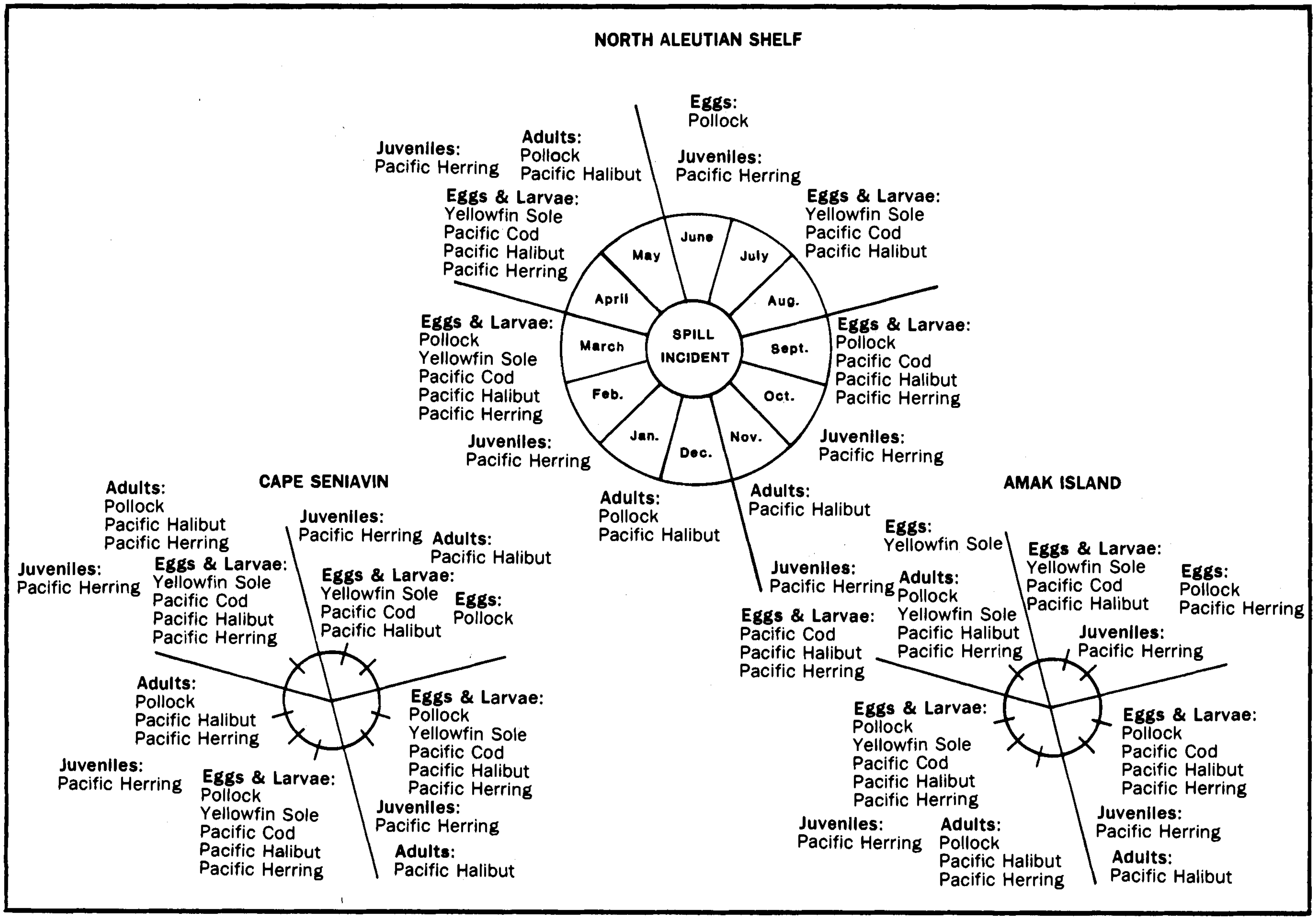


FIGURE 4.18—Seasonal vulnerabilities of life stages of major commercial species exhibiting *low* impact potential from oil releases in the North Aleutian Shelf and at two hypothetical spill sites.

nook salmon from Bristol Bay may be different from the relatively well-studied sockeye salmon from this region. Workshop participants recommended that research on adult salmon include the effects of ingested oil on fish behavior, mortality, and tainting of flesh (with potential loss of market for canned salmon industry).

Suggested research on juvenile (under 2 years) king crab included distributional characteristics inshore of the North Aleutian Shelf. During the summer of 1982, after the synthesis meeting, OCSEAP initiated a study on the feeding ecology of juvenile king and Tanner crabs in the lease area, and NMFS conducted a nearshore survey in the vicinity of Port Moller and Port Heiden to study the distribution and abundance of young king crab. Pacific cod predation on juvenile king crab was also recommended for study.

Regarding herring, information is needed on definition of Port Moller spawning stock. In addition, more information is required on the abundance and spawning of capelin and other forage species in North Aleutian Shelf waters.

4.9 SUMMARY

The North Aleutian Shelf lease area is centrally located in one of the world's richest commercial fishing grounds—the southeastern Bering Sea. As such it is an area positioned between the multinational groundfish fisheries to the west and extremely lucrative domestic salmon fisheries to the east in Bristol Bay. The lease area itself is a region of significant red king crab and salmon catches for local and Pacific Northwest fisheries. More importantly, the North Aleutian Shelf provides migratory, foraging, and nursery habitat for many commercial species that are abundant seasonally or reside within the nearshore waters of the lease area prior to their recruitment in fisheries conducted elsewhere in the southeastern Bering Sea.

Pacific salmon, both seaward-bound juveniles and returning adults, are abundant in the area from May to September. Emigrating juveniles are more coastally distributed in a migratory band extending approximately 60 km from the shore. Returning adults remain farther offshore, intermingling with salmon bound for anadromous waterways from all around Bristol Bay. Upon approaching natal rivers and streams within the lease area, these fish segregate into individual spawning stocks and move inshore. At this time they are most vulnerable to local fishing efforts and potentially spilled oil. Although spilled oil could necessitate areal closures to fisheries operating in somewhat abbreviated seasons, biological losses resulting from relatively small and short-lived discharges would have negligible impact on the Bristol Bay salmon resources.

Perhaps the most vulnerable species of economic value found in the North Aleutian Shelf is the red king crab. These crab, especially the young and mature females, are abundant in lease area waters throughout the year. Juvenile crab are distributed nearer shore and somewhat to the northeast of adult females. The lease area contains the major reproductive site for this species in the entire Bering Sea. Adult males move into shallower waters for brief periods each spring to spawn. After fertilization, eggs are carried for 11 months by females before hatching. Once hatched, larvae are distributed pelagically and move to the northeast with prevailing currents for 3 to 4 months before taking up a benthic existence. While free-floating the larvae are largely contained in a narrow envelope in upper water layers extending from the 20- to 70-m contours. Larvae are extremely sensitive to water-soluble fractions of spilled oil and it is during this period that widespread hydrocarbon contamination between Amak Island and Cape Seniavin could severely impact the strength of a given year class.

Other species of commercial interest are frequent visitors or residents of the North Aleutian Shelf. Many are migrants whereas others seek refuge in nearshore waters during early life phases, sometimes as juveniles for several years. Most notable are those species such as the pollock, Pacific cod, yellowfin sole, and other flounders that are harvested in huge quantities by foreign fisheries operating in the U.S. Fisheries Conservation Zone of the Bering Sea. Yellowfin sole use the region extensively upon foraging migrations in spring and summer months, and also for passage to major spawning grounds off Cape Newenham in June. These fish are currently exploited by U.S. fishermen participating in developing joint venture fisheries. Pacific herring are also of domestic interest in Bristol Bay. Although most schools of herring move through the lease area to spawning areas located farther in Bristol Bay, intertidal spawning does occur in Port Moller.

The fishery resources of the southeastern Bering Sea and Bristol Bay are world reknowned, not only for the magnitude of catches, but for the extreme economic value they represent. Salmon and red king crab fisheries in this region are among the nation's most valuable. Although there is a widespread public perception of impending environmental degradation and resultant loss to harvestable populations coinciding with possible oil spills, this does not appear to be justified for relatively small oil spills such as those discussed at the meeting. Because most species are widely dispersed in the Bering Sea and because stocks exhibit high annual variability in year class strengths, even the largest estimated oil-induced mortalities from spills occurring under open-water conditions would probably be undetectable in regional fisheries.

4.10 REFERENCES CITED

ALLEN, D. W., R. B. ALLEN, R. E. BLACK, J. M. FRIEDMAN, L. G. MALLON, R. W. MORSE, S. B. PETERSON, AND L. J. SMITH.
1976. Effects on commercial fishing of petroleum development off the northeastern United States. Marine Policy and Ocean Management Program, Woods Hole Oceanographic Institution, Mass., 80 p.

AMERICAN INSTITUTE OF BIOLOGICAL SCIENCES.
1976. Sources, effects, and sinks of hydrocarbons in the aquatic environment. Proceedings of the symposium, American University, August 9-11, 1976. AIBS, Washington, D.C., 578 p.

ARCTIC ENVIRONMENTAL INFORMATION AND DATA CENTER.
1974. The western Gulf of Alaska: a summary of available knowledge. AEIDC, Univ. Alaska, Anchorage, 599 p.

Armstrong, D. A., D. V. Buchanan, M. H. Mallon, R. S. Caldwell, and R. E. Milleman.
1976. Toxicity of the insecticide methoxychlor to the Dungeness crab, *Cancer magister*. Mar. Biol. 38(3): 239-252.

ARMSTRONG, D. A., L. S. INCZE, J. L. ARMSTRONG, D. L. WENCKER, AND B. R. DUMBAULD.
1981. Distribution and abundance of decapod crustacean larvae in the southeastern Bering Sea with emphasis on commercial species. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Annu. Rep. March 1981, 2: 365-597.

BRETT, J. R., M. HOLLANDS, AND D. F. ALDERDICE.
1958. The effect of temperature on the cruising speed of young sockeye and coho salmon. J. Fish. Res. Board Can. 15(6): 587-605.

CURL, H. E., JR., AND C. A. MANEN.
1982. Shellfish Resources. *In* M. J. Hameedi (ed.), Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981, p. 141-159. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

ENERGY RESOURCES CO. INC.
1982. Ixtoc oil spill assessment final report. Prepared for U.S. Dep. Inter., Bur. Land Manage., Contract AA851-CT0-71. Cambridge, Mass., 327 p.

FISHER, R. B.
1980. The joint venture fishery for yellowfin sole: the Bering Sea, summer 1980—a case study in fishery development. Alaska Fisheries Development Foundation and North Pacific Fishery Management Council, Anchorage, 89 p.

HAMEEDI, M. J. (ED.).
1982. Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 162 p.

HARTT, A. C., AND M. B. DELL.
1976. Life history of juvenile Pacific salmon and steelhead trout during their first summer in the open sea. Unpubl. manuscr. Fish. Res. Inst., Univ. Washington, Seattle.

HOKKAIDO UNIVERSITY, FACULTY OF FISHERIES.
1965. The *Oshoro Maru* cruise 9 to the northern North Pacific, Bering, and Chukchi seas in June-August 1964. Data Rec. Oceanogr. Obs. Explor. Fish. (Hokkaido) (1965): 219-330.
1968. The *Oshoro Maru* cruise 24 to the northern North Pacific and Bering seas in June-August 1967. Data Rec. Oceanogr. Obs. Explor. Fish. (Hokkaido) (1968): 291-420.

HOOPES, D. T.
1973. Alaska's fishery resources—the Dungeness crab. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Fishery Facts-6, 14 p.

HUGHES, S. E.
1974. Groundfish and crab resources in the Gulf of Alaska—based on International Pacific Halibut Commission trawl surveys, May 1961-

March 1963. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Seattle, Data Rep. 96, 87 p.

IVANOV, B. G.
1969. The biology and distribution of the northern shrimp, *Pandalus borealis* Kr., in the Bering Sea and the Gulf of Alaska. FAO Fish. Rep. 57(3): 800-810.

MALINS, D. C. (ED.).
1977. Effects of petroleum on arctic and subarctic marine environments and organisms. Academic Press, New York, 2 vols.

MALINS, D. C.
1980. Toxicity of oil in marine habitats. Unpubl. manuscr., 17 p. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Seattle.

MALINS, D. C., AND H. O. HODGINS.
1981. Petroleum and marine fishes: a review of uptake, disposition, and effects. Environ. Sci. Technol. 15(11): 1273-1280.

MALINS, D. C., H. O. HODGINS, U. VARANASI, S.-L. CHAN, B. B. MCCAIN, D. D. WEBER, AND D. W. BROWN.
1982. Sublethal effects of petroleum hydrocarbons and trace metals, including biotransformations, as reflected by morphological, chemical, physiological, pathological, and behavioral indices. Final rep. to OCSEAP, U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau, 268 p.

MAYNARD, D. J., AND D. D. WEBER.
1981. Avoidance reactions of juvenile coho salmon (*Oncorhynchus kisutch*) to monocyclic aromatics. Can. J. Fish. Aquat. Sci. 38(7): 772-778.

NEFF, J. M.
1979. Polycyclic aromatic hydrocarbons in the aquatic environment: sources, fates, and biological effects. Applied Science Publishers Ltd., Backing, England, 262 p.

NORTH PACIFIC FISHERY MANAGEMENT COUNCIL.
1978. Fishery management plan for the commercial Tanner crab fishery off the coast of Alaska. Unpubl. rep., 197 p. North Pacific Fishery Management Council, P.O. Box 3136DT, Anchorage, AK 99510.

OLLA, B. L., W. H. PEARSON, AND A. L. STUDHOLME.
1980. Applicability of behavioral measures in environmental stress assessment. Rapp. P.-V. Réun. Cons. Int. Explor. Mer 179: 162-173.

PEREYRA, W. T., J. E. REEVES, AND R. G. BAKKALA.
1976a. Demersal fish and shellfish resources of the eastern Bering Sea in the baseline year 1975. Processed rep., 619 p. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., 2725 Montlake Blvd. E., Seattle, WA 98112.

PEREYRA, W. T., G. HIRSCHHORN, AND L. L. RONHOLT.
1976b. Baseline studies of demersal resources of the northern Gulf of Alaska shelf and slope. U.S. Dep. Commer., NOAA, OCSEAP Environmental Assessment of the Alaskan Continental Shelf, Q. Rep., October-December 1976, 2: 234-270.

RICE, S. D.
1981. Review: Effects of oil on fish. Unpubl. manuscr., 34 p. Prepared for National Academy of Sciences Workshop on Petroleum in the Environment, November 1981. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Auke Bay Lab., P.O. Box 155, Auke Bay, AK 99821.

RIETZE, H. L.
1975. An assessment of marine fish and mammals in the western Gulf of Alaska and potential resource-use conflicts resulting from offshore oil and gas development. Unpubl. rep., 49 p. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Juneau.

ROSENTHAL, H., AND D. F. ALDERDICE.
1976. Sublethal effects of environmental stressors, natural and pollutional, on marine fish eggs and larvae. J. Fish. Res. Board Can. 33(9): 2047-2065.

SONNTAG, N. C., R. R. EVERITT, D. MARMOREK, AND R. HILBORN.
1980. Report of the Bering Sea ecological processes study modeling workshop. Environmental and Social Systems Analysts Ltd., Vancouver, B.C., 96 p.

STRATY, R. R.
1974. Ecology and behavior of juvenile sockeye salmon (*Oncorhynchus nerka*) in Bristol Bay and the eastern Bering Sea. *In* D. W. Hood and E. J. Kelley (eds.), Oceanography of the Bering Sea with emphasis on renewable resources, p. 285-320. Proc. Int. Symp. Bering Sea Study, Hakodate, Japan, 31 Jan.-4 Feb. 1972. Inst. Mar. Sci., Univ. Alaska, Fairbanks, Occas. Publ. 2.

1975. Migratory routes of adult sockeye salmon, *Oncorhynchus nerka*, in the eastern Bering Sea and Bristol Bay. U.S. Dep. Commer., NOAA Tech. Rep. NMFS SSRF-690, 32 p.

1981. Trans-shelf movement of Pacific salmon. *In* D. W. Hood and J. A. Calder (eds.), The eastern Bering Sea shelf: oceanography and resources, Vol. I, p. 575-595. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

1982. Origin, timing, and distribution of Pacific salmon (*Oncorhynchus* spp.) in the coastal and offshore waters of Bristol Bay and the eastern

Bering Sea. Unpubl. rep., 44 p. Prepared for North Aleutian Shelf Synthesis Meeting, 9-11 March 1982, Anchorage. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Auke Bay Lab., P.O. Box 155, Auke Bay, AK 99821.

STRATY, R. R., AND H. W. JAENICKE.
1980. Estuarine influence of salinity, temperature, and food on the behavior, growth, and dynamics of Bristol Bay sockeye salmon. *In* W. J. McNeil and D. C. Himsworth (eds.), Salmonid ecosystems of the North Pacific Ocean, p. 247-265. Oregon State Univ. Press, Corvallis.

STRAUGHAN, D.
1972. Biological effects of oil pollution in the Santa Barbara Channel. *In* M. Ruivo (ed.), Marine pollution and sea life, p. 355-359. FAO, Fishing News Ltd., Surrey, England.

THORSTEINSON, F. V., AND T. R. MERRELL.
1964. Salmon tagging experiments along the south shore of Unimak Island and the southwestern shore of the Alaska Peninsula. U.S. Fish Wildl. Serv. Spec. Sci. Rep. Fish. 486, 15 p.

THORSTEINSON, F. V., AND L. K. THORSTEINSON.
1982. Finfish resources. *In* M. J. Hameedi (ed.), Proceedings of a synthesis meeting: the St. George Basin environment and possible consequences of planned offshore oil and gas development; Anchorage, Alaska, April 28-30, 1981, p. 111-139. U.S. Dep. Commer., NOAA, Off. Mar. Pollut. Assess., Juneau.

TRASKY, L. L..
1974. Yukon River anadromous fish investigations. Completion rep. for July 1, 1973 to June 30, 1974, Proj. AFC-47, Anadromous Fish Conservation Act. U.S. Dep. Commer., NOAA, Washington, D.C.

U.S. DEPARTMENT OF COMMERCE.
1966-72. Fishing statistics from research investigations in the Bering Sea. Unpubl. data. U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent. Auke Bay Lab., P.O. Box 155, Auke Bay, AK 99821.
1980. Living marine resources and commercial fisheries relative to potential oil and gas development in the North Aleutian Shelf area (tentative sale no. 75). U.S. Dep. Commer., NOAA, Natl. Mar. Fish. Serv., Northwest and Alaska Fish. Cent., Seattle, 92 p.

WEBER, D. D., D. J. MAYNARD, W. D. GRONLUND, AND V. KONCHIN.
1981. Avoidance reactions of migrating adult salmon to petroleum hydrocarbons. Can. J. Fish. Aquat. Sci. 38(7): 779-781.

WEBER, D. D., AND T. MIYAHARA.
1962. Growth of the adult male king crab *Paralithodes camtschatica* (Tilesius). U.S. Fish Wildl. Serv., Fish. Bull. 62(200): 53-75.

WOLFE, D. A. (ED.).
1977. Fate and effects of petroleum hydrocarbons in marine ecosystems and organisms. Pergamon Press, New York, 478 p.

Synthesis Meeting Participants

Al A. Allen
Alaskan Beaufort Sea Oil Spill
Response Body
201 Danner Avenue, Suite 170
Anchorage, AK 99502

George Allen
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Rick Austin
Alaska Department of Natural
Resources
Division of Resource and
Development
Pouch 7-005
Anchorage, AK 99510

Edward Baker
U.S. Department of Commerce
NOAA/ERL/PMEL
3711 15th Avenue, N.E.
Seattle, WA 98105

David Benton
Friends of the Earth
1069 W. 6th Avenue
Anchorage, AK 99501

Chris Bowden
Alaska Department of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Tom Boyd
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Debbie Clauson
Alaska Department of Fish & Game
Habitat Division
333 Raspberry Road
Anchorage, AK 99502

Joel D. Cline
U.S. Department of Commerce
NOAA/ERL/PMEL
3711 15th Avenue, N.E.
Seattle, WA 98105

Dan Domeracki
Research Planning Institute, Inc.
925 Gervais Street
Columbia, SC 29201

Paul Dubsky
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Howard Feder
University of Alaska
Institute of Marine Science
Fairbanks, AK 99701

Kathy Frost
Alaska Department of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Lee Gefvert
ANO695
ARCO Exploration Company
P.O. Box 360
Anchorage, AK 99510

Charles Getler
Research Planning Institute, Inc.
925 Gervais Street
Columbia, SC 29201

Judith Gottlieb
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Patrick Gould
U.S. Fish and Wildlife Service
1011 E. Tudor Road
Anchorage, AK 99507

Bill Gusey
Shell Oil Company
P.O. Box 4320
Houston, TX 77210

David Hale
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

M. Jawed Hameedi
U.S. Department of Commerce
NOAA/NOS/OCSEAP
P.O. Box 1808
Juneau, AK 99802

John Heiderman
Exxon Production Research
P.O. Box 2189
Houston, TX 77001

Joel Hubbard
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Fred Jamsen
Alaska Department of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Laurie Jarvela
U.S. Department of Commerce
NOAA/NOS/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Steve Jewett
Institute of Marine Science
University of Alaska
Fairbanks, AK 99701

Ancel Johnson
U.S. Fish and Wildlife Service
P.O. Box 67
San Simeon, CA 93452

Bill Jones
Operations Engineer
Sohio Company
Pouch 6-612
Anchorage, AK 99502

Bob Jones
SRA Box 5203
Eagle River, AK 99577

Don Keene
ARCO Alaska, Inc.
711 W. 8th Avenue
Anchorage, AK 99510

Bruce Kirstein
Science Applications, Inc.
476 Prospect
Box 1454
La Jolla, CA 92038

Robert LaBelle
U.S. Department of the Interior
U.S. Geological Survey
Environmental Affairs Office
Environmental Modeling Group
Reston, VA 22090

Steve Langdon
University of Alaska
3321 Providence Drive
Anchorage, AK 99504

Jan L. Leendertse
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

David Liu
The Rand Corporation
1700 Main Street
Santa Monica, CA 90406

Carol-Ann Manen
U.S. Department of Commerce
NOAA/NOS/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Karen McGuiness
Alaska Department of Natural Resources
Division of Resource and Development
Pouch 7-005
Anchorage, AK 99510

Peter McRoy
University of Alaska
Institute of Marine Science
Fairbanks, AK 99701

Chuck Meecham
Alaska Department of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Byron Morris
U.S. Department of Commerce
NOAA/NMFS/EAD
701 C Street
Box 43
Anchorage, AK 99513

Larry Moulton
Alaska Department of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Dick Mylius
Alaska Department of Natural Resources
Division of Resource and Development
Pouch 7-005
Anchorage, AK 99510

Mike Nelson
P.O. Box 199
Dillingham, AK 99576

Thomas Newbury
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

James Payne
Science Applications, Inc.
476 Prospect
Box 1454
La Jolla, CA 92038

Mauri J. Pelto
U.S. Department of Commerce
NOAA/NOS/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Greg Peters
Bristol Bay CRSA Board
P.O. Box 189
Dillingham, AK 99576

Richard Prentki
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99502

Jim Ray
Shell Oil Company
P.O. Box 4320
Houston, TX 77210

Stanley D. Rice
U.S. Department of Commerce
NOAA/NMFS/NWAFC
Auke Bay Biological Laboratory
P.O. Box 155
Auke Bay, AK 99821

Scott Robertson
ARCO Oil and Gas Company
P.O. Box 360
Anchorage, AK 99510

Dan Rogers
Fisheries Research Institute
University of Washington
Seattle, WA 98195

Dave Rugh
U.S. Department of Commerce
NOAA/NMFS/PMEL
7600 Sand Point Way, N.E.
Bldg. 32
Seattle, WA 98115

Gerald A. Sanger
U.S. Fish and Wildlife Service
1011 E. Tudor Road
Anchorage, AK 99507

John Sarvis
Izembek National Wildlife Refuge
Pouch Z
Cold Bay, AK 99571

James D. Schumacher
U.S. Department of Commerce
NOAA/ERL/PMEL
3711 15th Avenue, N.E.
Seattle, WA 98105

David Simpson
Alaska Department of Natural Resources
323 East 4th Avenue
Anchorage, AK 99501

Rod Smith
U.S. Department of the Interior
Minerals Management Service
800 A Street
Anchorage, AK 99501

Richard R. Straty
U.S. Department of Commerce
NOAA/NMFS/NWAFC
Auke Bay Biological Laboratory
P.O. Box 155
Auke Bay, AK 99821

Fredrik V. Thorsteinson
P.O. Box 287
Auke Bay, AK 99821

Lyman K. Thorsteinson
U.S. Department of Commerce
NOAA/NOS/OCSEAP
P.O. Box 1808
Juneau, AK 99802

Jeff Tobolski
14225 Jefferson Way
Alderwood Manor, WA 98036

Lance Trasky
Alaska Department of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Tom Warren
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Robert Weinhold
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

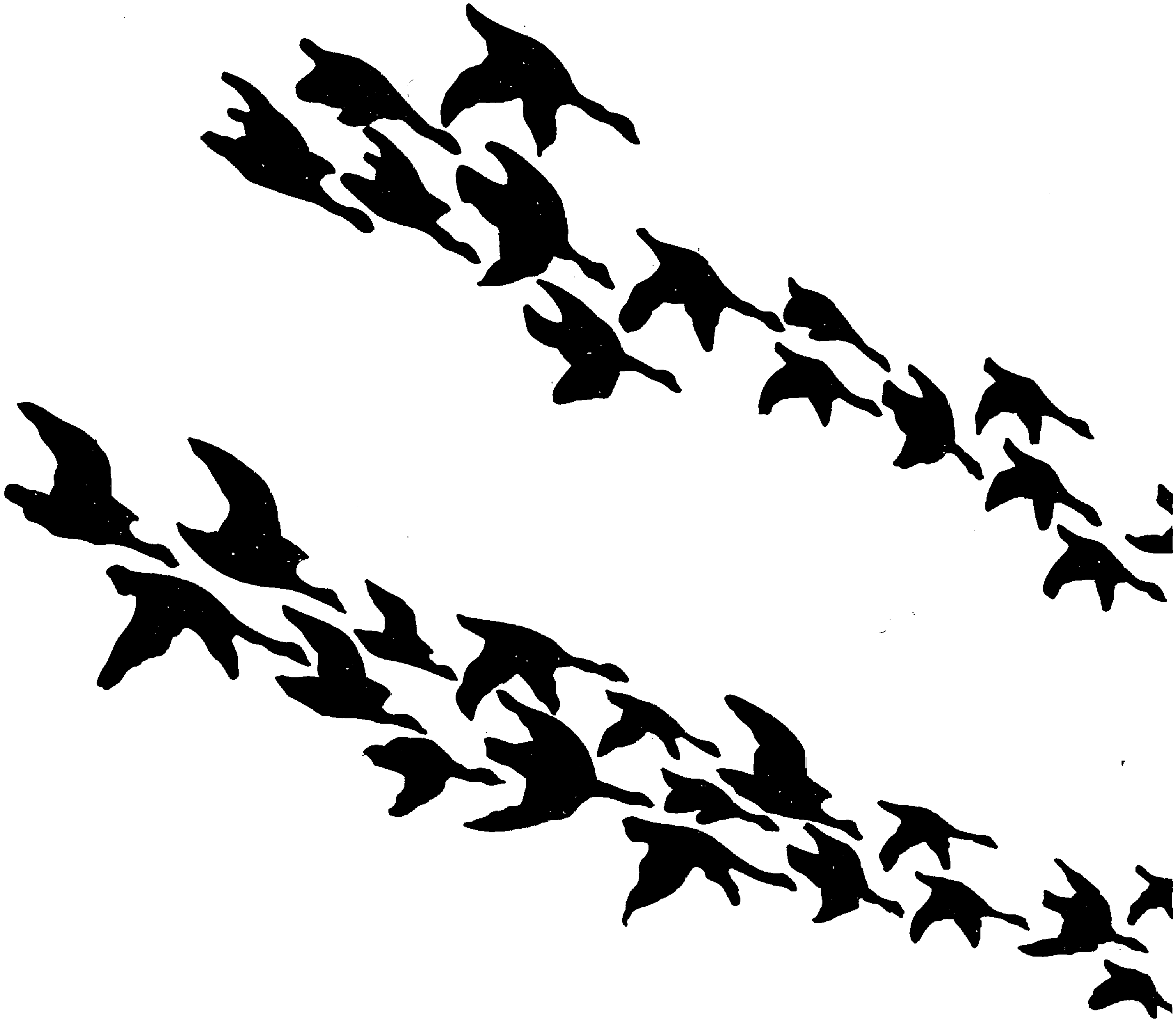
Curt Wilson
U.S. Fish and Wildlife Service
1011 East Tudor Road
Anchorage, AK 99503

Robert Wolotira
U.S. Department of Commerce
NOAA/NMFS/NWAFC
P.O. Box 11638
Kodiak, AK 99815

Esther Wunnicke
U.S. Department of the Interior
Bureau of Land Management
Alaska OCS Office
P.O. Box 1159
Anchorage, AK 99510

Henry Yuen
Alaska Department of Fish & Game
333 Raspberry Road
Anchorage, AK 99502

Steven T. Zimmerman
U.S. Department of Commerce
NOAA/NOS/OCSEAP
P.O. Box 1808
Juneau, AK 99802



U. S. DEPARTMENT OF COMMERCE
NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION

OMPA Alaska Office, RD/MPF24
Post Office Box 1808
Juneau, Alaska 99802

POSTAGE AND FEES PAID
U.S. DEPARTMENT OF COMMERCE
COM-210

U.S.MAIL

CLASS OF POSTAL SERVICE

OFFICIAL BUSINESS
PENALTY FOR PRIVATE USE, $300

NOAA FORM 61-32A (11-77)
See NDM 61-50 for Class of Postal Service