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1200 Sixth Avenue
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Alaska Operations Office - Anchorage

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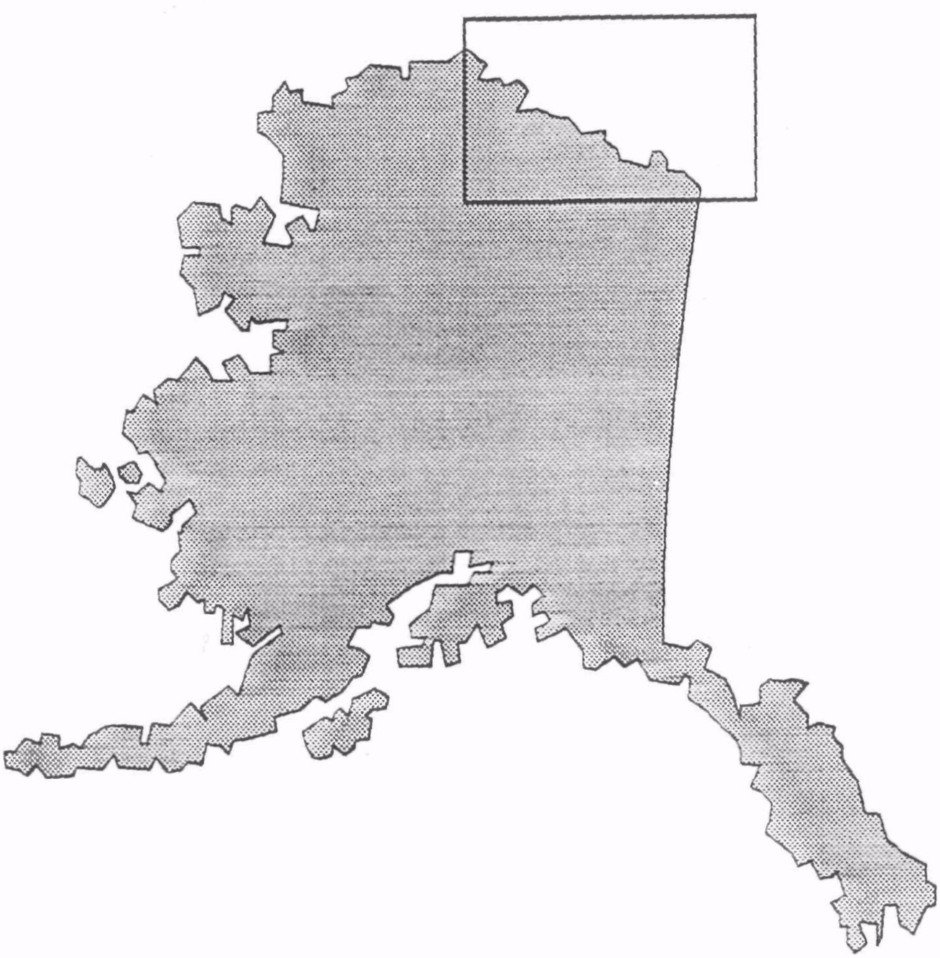
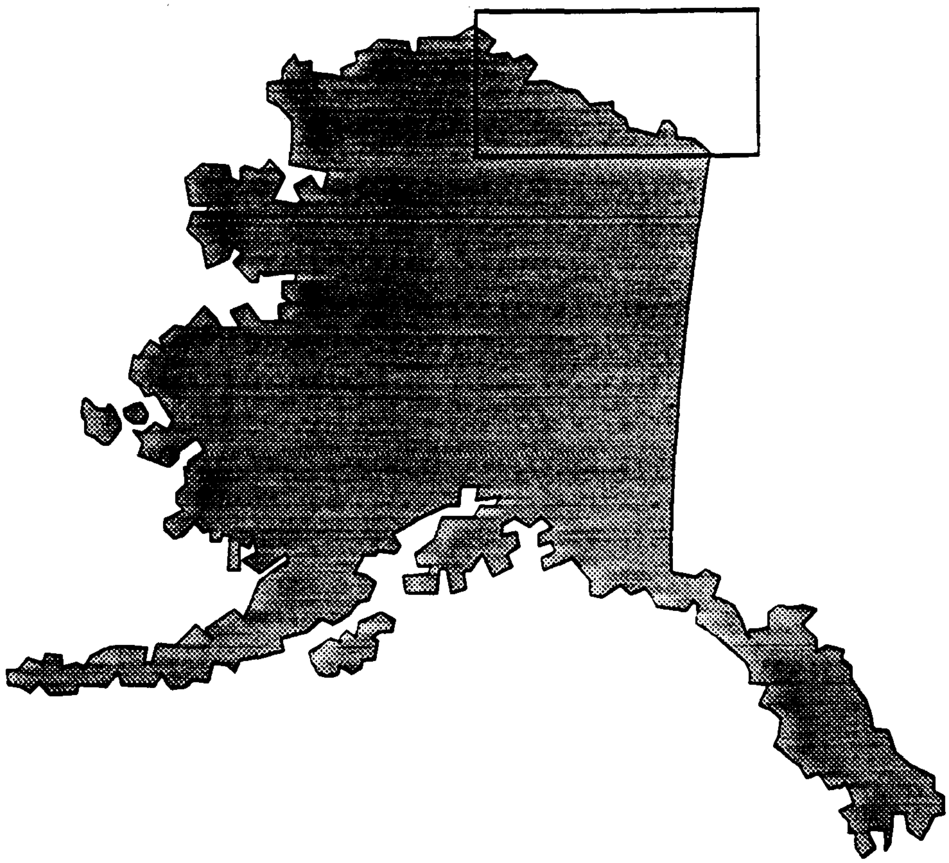
Causeways in the Alaskan Beaufort Sea





United States Environmental Protection Agency
Region 10

Causeways in the Alaskan Beaufort Sea

Prepared By:
Brian D. Ross
Fisheries Biologist
NEPA and Wetlands Review Section
Alaska Operations Office
Anchorage, Alaska

October, 1988

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Acknowledgements

Many people contributed their time, advice, and expertise to this document. Helpful comments about technical content were made by several reviewers, too numerous to list here. The efforts of each are greatly appreciated. Linda Sewright's technical editing skills were particularly helpful in making complicated topics as understandable as possible. Finally, the graphics and publishing abilities of Eric Meyerson and Christopher Moffett were nothing short of heroic, especially considering the condition of the draft document and the impossible schedule. Grateful acknowledgement is extended to all.

ABSTRACT

Prior to the construction of major gravel causeways in the central Beaufort Sea, the shallow (<2 m) nearshore environment of the Prudhoe Bay area (including a nearby lagoon system and two river deltas) was dominated in the summer by a band of brackish, relatively warm estuarine water. These estuarine conditions were generally continuous along the nearshore during both east and west winds. Conditions in this band represent the most productive feeding and rearing habitat for the Arctic anadromous fish of the region. During prevailing easterly winds, the West Dock causeway deflects the estuarine water offshore. The deflected water mixes more directly with offshore marine water and rapidly loses its estuarine character. At the same time, the deflected water is replaced by upwelled marine water which then dominates the Stump Island Lagoon-Gwydyr Bay complex. This upwelled water causes a large area to be unsuitable as feeding habitat for many anadromous fish, and severs the nearshore band of estuarine habitat. These alterations to the natural environment cause fish migration to be delayed, and fish to be isolated from unaffected habitat areas to the east and west. Upon shifts to west winds, the marine water upwelled into the lagoon system flows around the causeway into Prudhoe Bay, forcing anadromous fish rearing there to retreat toward river delta fronts for refuge. The Endicott causeway also deflects the brackish coastal plume offshore. Similar to the West Dock causeway, the Endicott causeway induces upwelling of marine water downwind from the structure. This separates Sagavanirktok River water in the nearshore from the diverted coastal water mass. In this manner, the brackish coastal water mass and the fresh river water each mix more directly with marine water. These processes bring about an overall degradation of nearshore estuarine water quality, and hence habitat value. Cumulatively, the West Dock and Endicott causeways have fundamentally altered circulation patterns and water quality across approximately 65 kilometers of the central Beaufort Sea coast. These major changes in the physical environment place populations of anadromous fish, and the commercial and subsistence fisheries that rely upon them, at substantial risk. Indicators from causeway monitoring programs show that fish are being affected by these habitat changes; and it is possible that significant population declines have already begun to occur.

EXECUTIVE SUMMARY

Overview

The nearshore zone of the Prudhoe Bay area functions biologically as a coastal estuary. The warm, brackish water conditions found across the area are more biologically productive than the fresh or marine waters. Because of this productivity, the area is critical for the anadromous fish of the central Beaufort Sea which are dependent upon estuarine conditions for feeding and rearing. However, despite the productivity of this estuarine habitat, the harshness of the Arctic environment and the short summer season cause these fish populations to be slower growing and maturing than more southern populations.

By disrupting circulation patterns and altering the balance of fresh and marine water, the existing causeways have significantly affected water quality across approximately 65 kilometers of the central Beaufort Sea. The water quality alterations have reduced the quantity and quality of estuarine habitat. These causeway-induced changes decrease the ability of anadromous fish to obtain sufficient energy for overwintering survival, growth, and reproduction. Although the risk of population-level impacts from these changes cannot presently be quantified, several indicators from environmental monitoring programs suggest there is a substantial risk of significant population-level impacts over the life of the causeways. Eventually, existing causeways could seriously disrupt the coastal fish community and harm subsistence and commercial harvests in Canada as well as in Alaska. Restoration of circulation patterns similar to the pre-causeway environment is necessary to reduce the impacts to water quality and fish habitat. In contrast, additional causeways proposed for the area would significantly increase these impacts and risks.

Introduction

Prudhoe Bay is located on the central Beaufort Sea coast approximately halfway between Point Barrow and the Alaska-Canada border. Considerable industrial activity has occurred in the general Prudhoe Bay area, as it is the hub of the largest producing oil field in the United States and the origination point for the 1,300-kilometer long Trans Alaska Pipeline System. This industrial activity has spread into nearby offshore waters as well, and three gravel causeways have been constructed in the area. Two of these - the West Dock causeway and the Endicott causeway - extend four kilometers or more from shore and have been the subject of considerable controversy both prior to and since their construction.

The primary concerns about the gravel structures are their impacts to nearshore water quality and circulation patterns, and, consequently, the quality of habitat for the anadromous fish populations of the region. These fish are an important resource for subsistence users in both Alaska and Canada. During the brief summer period when the Beaufort Sea is not frozen, the fish are generally constrained to the immediate nearshore zone where inhospitable marine conditions are displaced by warmer, brackish waters. It is across this same critical nearshore zone that the causeways have been constructed, disrupting nearshore circulation patterns and causing the estuarine habitat to be replaced by offshore marine water along many kilometers of coastline.

The impacts and risks posed by Prudhoe Bay area causeways are significant. The Alaska District, U.S. Army Corps of Engineers, has declared the impacts of the Endicott causeway unacceptable and is considering mitigation measures. This report has been prepared as a basis of support for decisions about mitigation at both the Endicott and West Dock causeways. The report summarizes the current state of knowledge about the nearshore environment and the impacts of causeways in the central Beaufort Sea.

Environmental Setting

For 1 to 8 kilometers out from shore in the Prudhoe Bay area, the Beaufort Sea is extremely shallow - less than 2 meters deep. This includes the broad Sagavanirktok River delta and the coastal lagoon system to the west. During each winter, these areas freeze completely to the bottom and cannot serve as feeding and rearing habitat for anadromous fish for about nine months. Open surface water is found only during a few weeks in the summer. Due to the extreme shallowness of the nearshore, summer water currents are determined by the wind. The direction of the current, in turn, plays a large role in determining water quality in the area.

During summer, warm, fresh water from rivers in Canada and Alaska mixes with cold offshore marine water to form a nearshore band of brackish water, the "coastal water mass." This mass of brackish water flows east or west along the Beaufort Sea shoreline depending on the direction of the prevailing winds. The Sagavanirktok River is a major local source of fresh water input to the coastal water mass, maintaining and enhancing the estuarine habitat of the Prudhoe Bay area.

Satellite images and hydrographic surveys provide evidence that prior to the construction of the causeways, the nearshore's estuarine conditions were generally continuous across the Prudhoe Bay area. Although the coastal water mass behaved somewhat differently under easterly versus westerly winds, the integrity of the estuarine band could be maintained in either case.

Biologically, this nearshore estuarine zone is the most critical feature of the summer coastal aquatic environment. Here, the harsh conditions of the Arctic Ocean - inhospitable for many organisms - are moderated by a combination of increased solar warming (due to shallowness), lower salinities, and terrestrial as well as marine nutrient sources. Productivity in this zone is higher for phytoplankton, aquatic plants, invertebrates, and fish than it is in adjacent marine or freshwater environments. The anadromous fish of the region are particularly dependent upon these more moderate and productive estuarine conditions.

Numerically dominant anadromous fish species in the Beaufort Sea include Arctic cisco, least cisco, broad whitefish, and Arctic char. These fish support subsistence fisheries in both the United States and Canada, and play an ongoing role in the native cultures of the American Arctic. Arctic cisco in particular are an international resource, with the individuals from the same population being harvested in both the Alaskan Beaufort Sea and throughout the Mackenzie River drainage in Canada. All of the anadromous fish must obtain the vast majority (90 percent or more) of their energy intake for the entire year during the very limited period of open water. The feeding and rearing period is so limited (approximately 10 weeks) that these populations naturally grow and mature more slowly than related populations and species from more temperate areas. In addition, the ability to acquire energy rapidly is so limited that these fish are unable to spawn in consecutive years. Even though food organisms may be abundant, energy is clearly a limiting factor.

Temperature and salinity are extremely important in determining the overall quality of habitat for these fish. Typical marine conditions in the Arctic are extreme - a combination of both very cold temperatures and high salinities. These conditions are energetically adverse and generally represent unsuitable habitat conditions. The amount of time that suitable temperature and salinity conditions are available for rearing is of paramount importance. A reduction in the amount of foraging time will affect the scope for growth for that year. "Mild" years, when estuarine conditions persist in the nearshore zone longer than average, can naturally result in higher productivity and greater fish growth overall. Conversely, "harsh" years reduce growth potential because lowered temperatures slow assimilation rates at the same time that higher salinities invoke additional metabolic demands. If conditions are severe, the fish will not be able to accumulate sufficient energy reserves to survive the overwintering period.

In the absence of causeways, estuarine conditions were spread throughout the broad, shallow areas of the central Beaufort Sea including Foggy Island Bay, the Sagavanirktok River delta, Prudhoe Bay, and the lagoon system to the west. In this habitat, fish could presumably feed efficiently, with high assimilation and growth rates, and with a minimum of metabolic cost. This allowed net energy gains to be maximized over the very short summer, which in turn supported normal rates of growth, reproduction, and overwintering survival.

Causeway Projects

Development of oil and gas reserves on Alaska's North Slope has resulted in the construction of two massive, solid-fill gravel causeways into the Beaufort Sea. The West Dock causeway extends approximztely 4 kilometers offshore from the northwestern corner of Prudhoe Bay. A single, 15-meter (50-foot) opening or "breach" was constructed in the West Dock causeway in an attempt to allow anadromous fish to pass the structure. The nearly 8 kilometer long Endicott causeway is located in the middle of the Sagavanirktok River delta just east of Prudhoe Bay. It includes a total of 215 meters (700 feet) of breaching that was intended to allow fish passage as well as to mitigate the water quality impacts predicted by the Environmental Impact Statement (EIS) for the project.

Additional causeways have been proposed by the petroleum industry. The Lisburne causeway would have extended over 4 kilometers into the center of Prudhoe Bay to access a proposed drilling island. This proposal was recently withdrawn in favor of directional drilling from shore. The most recent proposal with a causeway is the Niakuk project. This proposal includes construction of a 2.2 kilometer long solid-fill causeway from Heald Point, at the northeastern end of Prudhoe Bay, to a man-made drilling island.

The primary concerns about these gravel structures center on their impacts on nearshore water circulation patterns, water quality, and, consequently, the quality of estuarine habitat for fish populations in the central Beaufort Sea. During the brief summer period when the Beaufort Sea is not frozen, anadromous fish are generally restricted to the immediate nearshore zone which is warmer and less saline that the inhospitable marine water offshore. It is across this same critical nearshore zone that the causeways have been constructed.

Impacts of Prudhoe Bay Area Causeways
The basic physical impacts of constructing causeways within the estuarine nearshore zone appear, with hindsight, to be easily predictable. However, little knowledge of the nearshore processes in the central Beaufort Sea existed before construction of the first causeway began. The evolution in knowledge during several years of monitoring, however, has provided a clearer picture of the processes affected by the causeways and the ecological risks they represent.

Causeways have disrupted the nearshore environment throughout the Prudhoe Bay area by: 1) deflecting both the estuarine coastal water mass and river plumes offshore, concurrently degrading their estuarine character through the loss of thermal energy and freshwater to offshore areas; 2) causing enhanced upwelling and intrusion of marine water directly into the nearshore zone, thus regularly severing the band of estuarine conditions along the coast; and 3) both delaying breakup and accelerating freezeup in the nearshore zone. Overall, fundamental alterations in nearshore water quality and circulation patterns have occurred along as much as 65 kilometers of the Prudhoe Bay area coastline.

The coastal water mass and the Sagavanirktok River plume are deflected offshore by both the West Dock and Endicott causeways despite the breaching incorporated into each of them. Offshore deflection causes enhanced mixing with marine water and degradation of estuarine conditions. Salinity of the deflected water has been observed to increase at rates as high as 2 parts per thousand per kilometer (ppt/km) in passing around the Endicott causeway and up to another 9 ppt/km as a result of West Dock. Offshore marine water upwells in place of the deflected water. At the Endicott causeway, salinity differences of 20 ppt have been observed between the plume water on one side of the causeway and upwelled water on the other side - an impact three times greater than predicted in the EIS for the project. West Dock causes an even more dramatic intrusion of marine conditions into the nearshore zone. During east winds, West Dock can cause upwelled marine water to dominate the Stump Island/Gwydyr Bay lagoon system for over 30 kilometers to the west. Upon shifts to westerly winds, this same upwelled water flows east around the causeway, quickly filling Prudhoe Bay.

The West Dock and Endicott causeways have also affected ice dynamics in the Prudhoe Bay area. Each causeway both deflects and restricts the early season overflooding by river water, so that breakup of sea ice in the vicinity of each causeway has been delayed by up to two weeks. While breakup is delayed, freezeup near the structures has been noted to occur up to two weeks earlier than elsewhere in the area since the causeways tend to trap newly-forming ice.

The changes to circulation patterns, water quality, and ice dynamics have dramatically affected fish distribution and use of the Prudhoe Bay area. Based on data from environmental monitoring programs, it is known that when Prudhoe Bay is filled with marine water (during shifts to west winds) most anadromous fish that had been feeding in the estuarine conditions of the bay are forced to leave and take refuge in the Sagavanirktok River delta. For these fish, all of the time spent in refuge areas reduces the amount of time they spend feeding in more productive estuarine habitat. Even when such drastic water quality changes do not occur and fish are not forced to completely abandon the nearshore zone, the quality of feeding habitat in the area is still degraded as a result of offshore deflection of plume waters. Degraded habitat quality either requires a greater energy expenditure (due to higher salinities) or reduces the assimilation rate (due to lower temperatures) of food items taken. Increased influence of marine conditions causes both effects at once. Therefore, even when fish are not forced to completely abandon the feeding areas, the energetic costs of remaining in them are increased and net energy gain is decreased.

The causeways have also altered ice dynamics directly within the critical nearshore zone. Delays in breakup and acceleration of freezeup local to the causeways affect fish distribution between feeding and overwintering areas. The highest catches of anadromous fish during the early summer period of initial dispersal to feeding areas have occurred at the Niakuk Islands. Altered ice dynamics in the vicinity of the proposed Niakuk causeway would directly affect fish use of this important migration corridor. In addition, to the extent that causeway effects on ice dynamics reduce the overall time available for feeding, the potential for growth is also reduced. The limited breaching proposed for this structure is not expected to elimate these effects.

Causeway-induced effects on fish habitat carry serious ramifications in terms of decreasing the net energy intake of the anadromous fish. The most immediate consequence is to anadromous fish that do not acquire enough fat reserves to survive the next overwintering period. These animals will die before the next spring. A year in which increased overwintering mortality occurs for some percentage of a population will result in a direct and immediate decline in overall population size by the same percentage. A population could take several decades to recover in numbers even if no similar overwintering mortality events were to occur in subsequent years. Of course, if increased overwinter mortality were to recur during subsequent generations, recovery would not proceed. If such conditions occurred more than once to a single generation, the degree of the resulting population decline would be multiplied. Similar, but less immediate, impacts could also occur if conditions become severe enough to reduce growth without directly increasing overwinter mortality. One such event per generation could reduce fecundity or delay the age at which the fish reach maturity and spawn. Reduced fecundity and delayed maturity would also result in a direct decline in population size.

Monitoring programs have provided evidence that these impacts are already beginning to occur. The indicators include: 1) basic changes in the structure of the nearshore fish community to one dominated by marine and relatively salt-tolerant species, with freshwater species having all but diasppeared in the area; 2) reduction in the strength of young age-classes of Sagavanirktok River broad whitefish since 1981; 3) smaller size-at-age for a large cohort of Arctic cisco in the Prudhoe Bay area in 1985, together with evidence that they may not have survived overwintering; and 4) evidence (including stomach sampling) that food organisms are not effectively unlimited.

The proposed Niakuk causeway would exacerbate the impacts and ecological risks posed by the existing causeways. By deflecting the coastal water mass and water from the west channel of the Sagavanirktok River, the Niakuk causeway would be expected to enhance the amount of marine water upwelled in the vicinity of Prudhoe Bay. The Niakuk causeway would further restrict river overflooding into Prudhoe Bay, affecting the formation of nearshore leads used by outmigrating fish in the early summer. It would also accelerate freeze-up processes within the single most important pathway used by fish migrating to and from the Sagavanirktok River overwintering sites and refuge areas.

Taken together, causeway-induced alterations in circulation patterns, water quality, and ice dynamics - occurring as they do directly within the critical nearshore estuarine zone - now make every year more similar to a naturally harsh year. The indicators show that the anadromous fish of the central Beaufort Sea are already being affected by these conditions. This means that long-term declines in their populations are likely. Should truly harsh years be in store, catastrophic impacts to these populations - and the fisheries they support - can quickly occur. Given the lack of reliable information on population sizes and the fact that monitoring programs have not been designed to measure population sizes directly, it is possible that significant declines have already begun to occur. Restoration of pre-causeway circulation patterns, particularly restoration of more continuous estuarine conditions in the nearshore zone, is necessary in order to reduce these impacts to fish habitat and water quality. In contrast, construction of additional causeways in the area would significantly increase these impacts and risks.

INTRODUCTION

Prudhoe Bay is located on the central Beaufort Sea coast approximately halfway between Point Barrow and the Alaska-Canada border (Figure 1). Considerable industrial activity has occurred in the general Prudhoe Bay area, as it is the hub of the largest producing oil field in the United States and the origination point for the 1,300-kilometer long Trans Alaska Pipeline System. This industrial activity has spread into nearby offshore waters as well, and three gravel causeways have been constructed in the area (Figure 2). Two of these - the West Dock causeway and the Endicott causeway - extend four kilometers or more from shore and have been the subject of considerable controversy both prior to and since their construction. The primary concerns addressed in this report are the impacts of the gravel structures to water quality and circulation patterns, and, consequently, to the quality of habitat for the anadromous fish populations of the region. (Other water quality issues, such as potential effects from waste discharges associated with industrial activities supported by the causeways, are notdiscussed here.)

The region's anadromous fish are an important resource for subsistence users in both Alaska and Canada. During the brief summer feeding period when the Beaufort Sea is not frozen, the fish are generally constrained to the immediate nearshore zone where inhospitable marine conditions are displaced by warmer, brackish waters. It is across this same critical nearshore zone that the causeways have been constructed, disrupting nearshore circulation patterns and causing the warm, brackish habitat to be replaced by offshore marine water across many miles of coastline. The impacts and risks posed by Prudhoe Bay area causeways are significant. The Alaska District, U.S. Army Corps of Engineers, has declared the impacts of the Endicott causeway unacceptable and is considering mitigation measures. This report has been prepared as a basis of support for decisions about mitigation at both the Endicott and West Dock causeways. The following pages summarize the current state of knowledge about the nearshore environment and the impacts of causeways in the central Beaufort Sea.

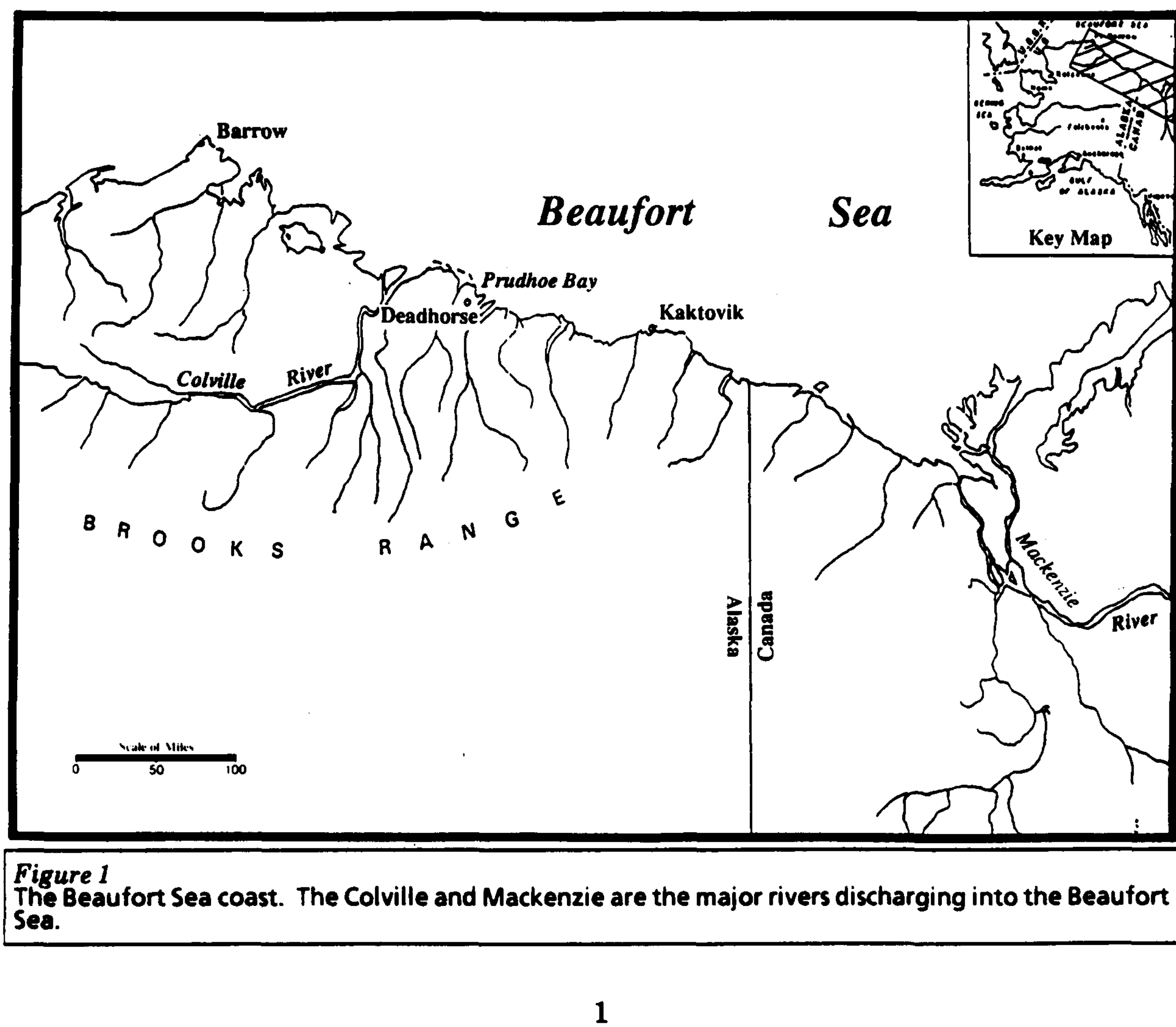

Figure 1
The Beaufort Sea coast. The Colville and Mackenzie are the major rivers discharging into the Beaufort Sea.

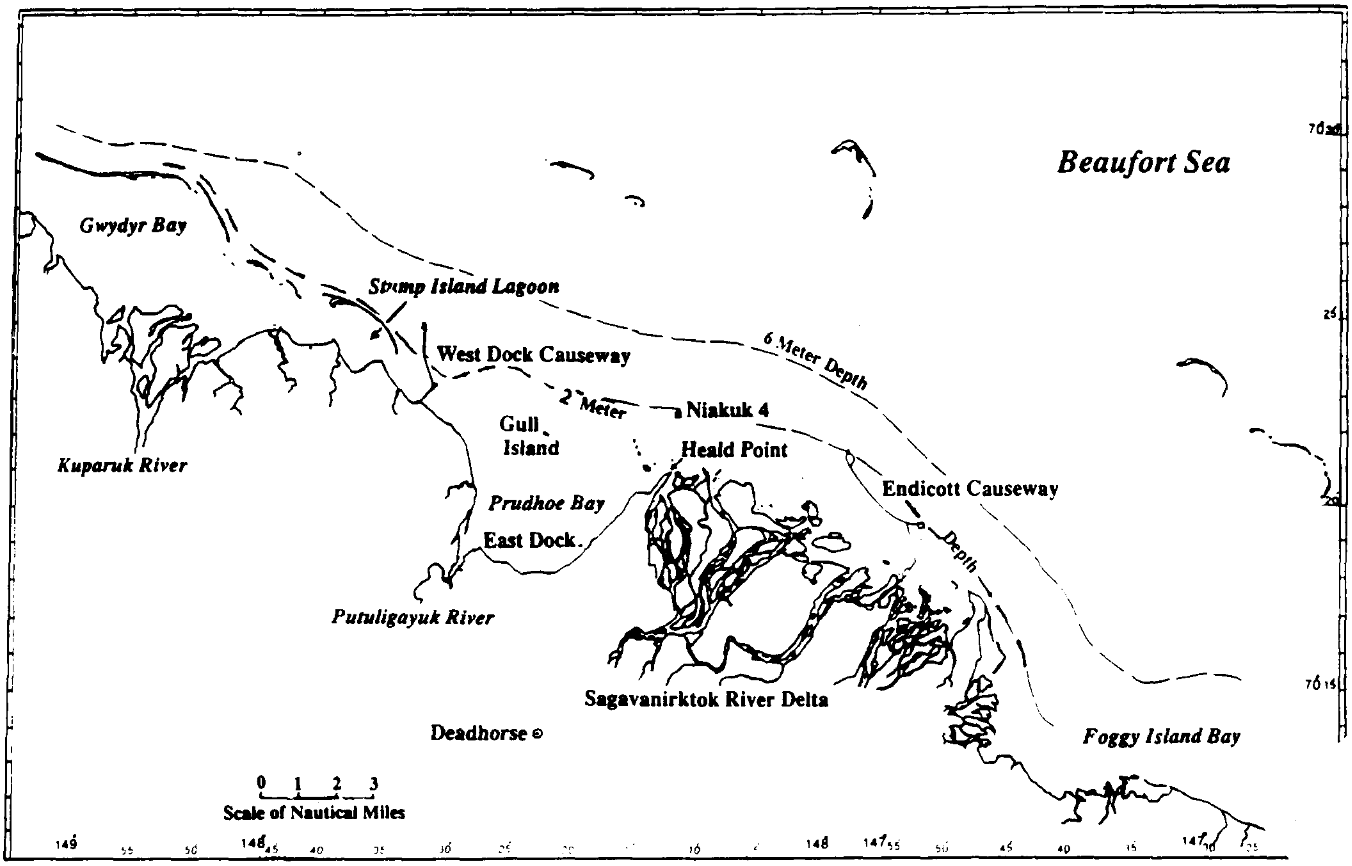

Figure 2
The Prudhoe Bay area, showing the locations of existing man-made gravel causeways.

ENVIRONMENTAL SETTING

The nearshore environment of the central Beaufort Sea is very different, both physically and biologically, from coastal zones elsewhere in the United States. A basic understanding of this special environment is necessary in order to place the impacts and risks posed by nearshore causeways into context. This section presents information about the physical processes and biological setting of the central Beaufort Sea coast in the absence of the causeways. Because pre-causeway baseline data are limited, this discussion is based largely on data gathered since construction of the West Dock causeway. Emphasis is placed on the nearshore Prudhoe Bay vicinity, defined here generally as extending from Foggy Island Bay through Gwydyr Bay and from shore to approximately the 6-meter depth (Figure 2).

PHYSICAL ENVIRONMENT

Much of the Prudhoe Bay area environment is extremely shallow: the 2-meter isobath occurs from 2 to 8 kilometers offshore in most locations (Figure 2). A shoal, where water is only approximately 1 meter deep, extends across the mouth of Prudhoe Bay from near the base of the West Dock causeway, past Gull Island, to the Heald Point area. During the winter, approximately 2 meters of ice forms along the Beaufort Sea coast. This results in most of the nearshore freezing completely to the bottom. This large area cannot serve as feeding and rearing habitat for fish until bottom-fast ice breaks up and open water is available. Ice cover here lasts about nine months, with open surface water found only during about 8 to 12 weeks in the summer.

During the summer open-water period, the direction of the current plays a large role in determining regional water quality. Due to the extreme shallowness of the nearshore area, water movements are dominated by the wind, with currents responding very rapidly to changes in wind direction or intensity. Winds from the easterly and westerly quadrants are by far the most common during the open-water season, with easterly winds generally prevailing. Therefore, water movement within the broad, shallow nearshore zone is primarily along-shore throughout the summer and generally follows bottom contours.

The two largest rivers that discharge into the Beaufort Sea are the Mackenzie, approximately 160 kilometers east of the Alaska-Canada border, and the Colville, about 70 kilometers west of Prudhoe Bay (Figure 1). These two rivers provide by far the greatest input of fresh water to the Beaufort Sea. During the summer this water, along with discharges from the Sagavanirktok (Figure 2) and several smaller rivers, mixes with cold offshore marine water to form a nearshore brackish band called the "coastal water mass" (the "coastal plume" of other authors). This band of brackish water flows east or west along the Beaufort Sea shoreline depending on the direction of the prevailing winds, as described above.

Satellite images (Stringer, 1985; Envirosphere, 1987; Envirosphere, 1988c; NOAA, 1988) and early hydrographic study (Barnes et al., 1977) provide supporting evidence that prior to construction of any causeways, the brackish coastal water mass was a generally continuous nearshore feature across the Prudhoe Bay area under both easterly (Figure 3) and westerly winds (Figure 4). Discharge from the Sagavanirktok River helped to maintain the estuarine nature of the coastal water mass as it flowed westward (under easterly winds) past Prudhoe Bay and through the Gwydyr Bay/Simpson Lagoon system. The large Colville River discharge did the same for these areas under westerly winds. Although different physical processes influenced the coastal plume under easterly versus westerly winds (as described below), the plume's integrity as a continuous mass of warm, brackish water was generally aintained.

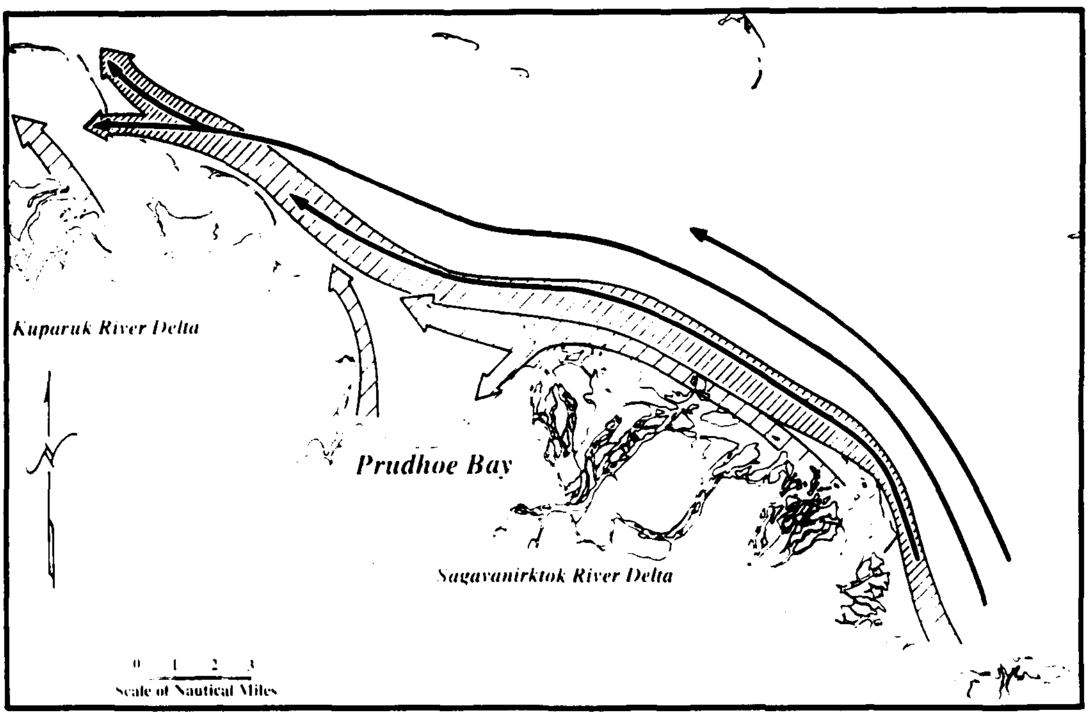

Figure 3
Generalized now of nearshore waters during sustained easterly winds, in the absence of the West Dock and Endicott causeways. Heavy solid arrows denote flow of subsurface marine water. Cross-hatched arrows denote surface flow of river and coastal water, with the density of cross-hatching proportional to salinity. Adapted fom Envirosphere, 1988b and NOAA, 1988.

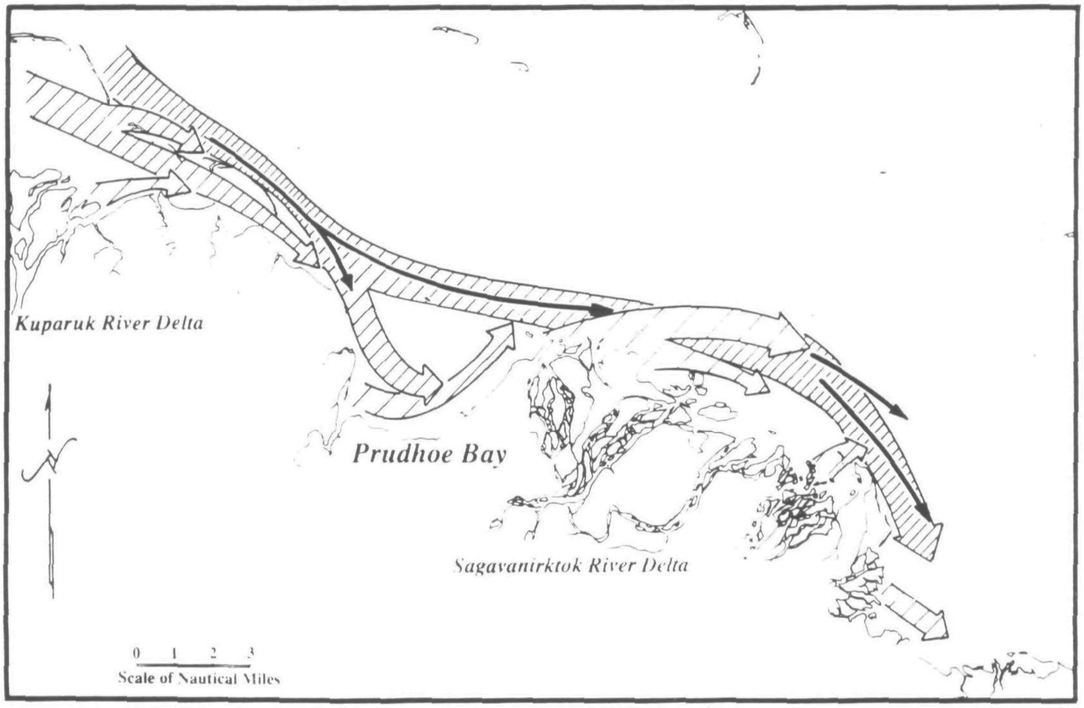

Figure 4
Generalized flow of nearshore waters during sustained westerly winds, in the absence of the West Dock and Endicott causeways. Heavy solid arrows denote flow of subsurface marine water. Cross-hatched arrows denote surface flow of river and coastal water, with the density of cross-hatching proportional to salinity. Adapted from Envirosphere, 1988b and NOAA, 1988.

East Wind, Upwelling During easterly winds, nearshore water levels are lowered due to an offshore trend in the surface current (Britch et al., 1983; NOAA, 1988). In a process called upwelling, sea level is stabilized as the surface current is replaced with deeper strata not affected by the wind. In the absence of causeways, upwelling could bring marine bottom water into nearshore locations as shallow as 2-4 meters in the Prudhoe Bay area (NOAA, 1988; Envirosphere, 1988d). A typical upwelling event during strong easterly winds, measured away from any causeway influence, is depicted in Figure 5. Two aspects of the phenomenon shown in the figure are important. First, the high salinity water that upwells to within the 3-meter depth remains overlain with brackish coastal water - it does not reach the surface. Second, because the area is extremely shallow for several kilometers offshore, the upwelled marine water does not invade very far into the nearshore zone. Hence, under normal circumstances, upwelling would not disrupt the continuity of the coastal water mass or its dominance across the broad, shallow Prudhoe Bay area.

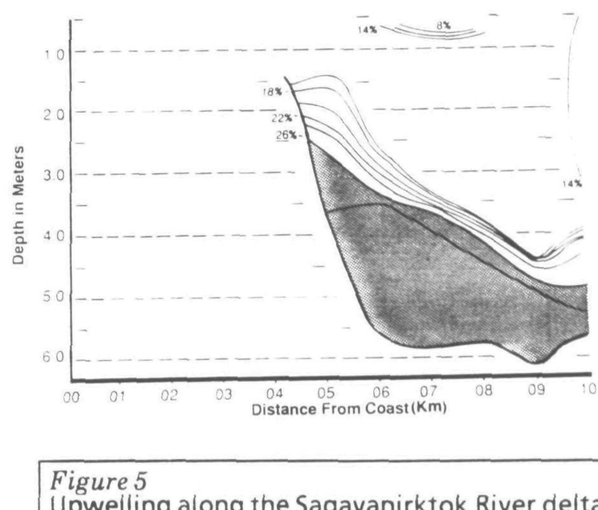

Figure 5
Upwelling along the Sagavanirktok River delta during easterly winds. In this 1982 example measured at the present location of the Endicott causeway, natural upwelling of high salinity bottom water (shaded) can be seen extending to approximately the 2.5 meter depth. Adapted from Envirosphere, 1987b.

West Wind, Intrusions During westerly winds, the surface current has a small onshore component that raises water levels. Initially, when the water level begins to rise, the entire water mass moves shoreward, generally preserving the cross-sectional characteristics that were in existence at the time the event began (Britch et al., 1983; Envirosphere, 1988d). In other words, if the water column is stratified to begin with, all of the strata will move shoreward. This is called an intrusion. For example, intrusion events can bring marine bottom water over the Gull Island shoal (Figure 2) and into Prudhoe Bay if marine water resides shallow enough on the seaward slope of the shoal before the intrusion begins. However, prior to causeway construction, the water that would move onshore during an intrusion event would be the same brackish coastal plume water generally dominant throughout the nearshore for much of the open-water period. Intrusions, in that case, would not result in any serious disruption of the continuity of nearshore brackish conditions.

Overall, nearshore Prudhoe Bay area water levels can vary by as much as 1 meter between strong easterly and westerly winds. Since so much of the area is less than two meters deep, it is not surprising that changes in wind-driven current and water levels significantly influence the nearshore zone. The change in water level comes about fairly rapidly upon shifts in wind direction (or upon a relaxation in the strength of sustained winds). Water levels generally stabilize within a day or so after easterly or westerly winds have established themeselves.

During sustained westerly winds "downwelling" also occurs . Marine water that may have upwelled into nearshore areas as shallow as 2-4 meters during east winds is forced further offshore. However, this phenomenon generally takes place farther offshore (outside the 2 or 3 meter depth contour) and after water levels have equilibrated.

Ice Dynamics Ice cover persists for approximately nine months along the Beaufort Sea coast (NOAA, 1988). During the winter, the nearshore Beaufort Sea freezes to the bottom to depths of about 2 meters; this is the same general area occupied by the coastal water mass during the summer. The timing and dynamics of breakup and freeze-up can influence the overall productivity of the nearshore environment during the brief summer season. A harsh year - one in which breakup is late and freezeup early - could significantly limit overall biological productivity. Conversely, an unusually long open-water period during the summer would allow for much higher productivity.

In the Arctic, rivers thaw and flow prior to the breakup of sea ice. Fresh river water thus initially flows over the top of the sea ice in the nearshore zone. The presence of this over-ice flow of fresh, warmer water speeds the breakup of nearshore sea ice by flowing into and opening up cracks and holes. The nearshore area thus usually has the first open water, and leads in the sea ice form there first. These leads are corridors for early dispersal of anadromous fish from overwintering sites to feeding and rearing areas. Prior to construction of the West Dock and Endicott causeways, overflooding from the Sagavanirktok, Putuligayuk, and Kuparuk rivers was unrestricted. Warm breakup flows covered the entire Prudhoe Bay area coastline (Figure 6).

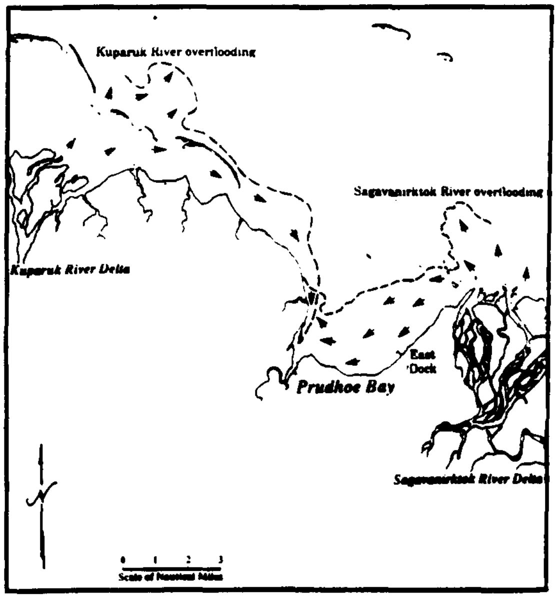

Figure 6
Estimated pre-causeway distribution of flood waters from the Kuparuk and Sagavanirktok rivers, based on LANDSAT image from May 30, 1985. Adapted from NOAA, 1988.

BIOLOGICAL ENVIRONMENT

During the summer in the central Beaufort Sea, estuarine conditions dominated the broad, shallow areas around Prudhoe Bay and the lagoon system to the west in the absence of causeways (see Physical Environment, above). These conditions created a large expanse over which primary productivity, and in turn the productivity of invertebrates (predominantly mobile crustaceans - principal prey for the anadromous fish), were presumably high (Envirosphere, 1988b). This nearshore estuarine habitat supported a fish food resource much greater than exists in North Slope rivers and streams. In this environment, fish could feed fairly rapidly, with high assimilation and growth rates and a minimum of metabolic costs. This allowed net energy gain to be maximized over the very short summer - critical for overwintering survival, year-to-year growth, and eventual reproduction (Smith, 1982).

Odum (1971) notes it to be "self-evident that different (estuarine) circulation patterns and gradients will greatly influence the distribution of individual species" and describes natural arctic ecosystems as a special class of physically stressed estuarine ecosystems. This section describes the biological setting of the Prudhoe Bay area and what is known of ecological relationships in this special estuarine environment.

Anadromous Fish Anadromous fish are those that spawn in fresh water and migrate to rear in marine or estuarine areas. Migration is undertaken for the purposes of feeding, because food is generally more available in marine and estuarine areas than in fresh water (Congleton et al., 1981 in Macdonald et al., 1988; Gross et al., 1988). However, the energetic expenditures associated with this migration in the extreme conditions of the Arctic make the advantages of this life history pattern marginal for most species (Wohlschag, 1957). In contrast to anadromous fish elsewhere that utilize estuaries for a relatively short but critical period before moving into the marine environment, Arctic marine waters are inhospitable for anadromous fish (Macdonald et al., 1988). Therefore, anadromous species in the Beaufort Sea depend heavily on estuarine habitat for feeding and rearing, because this habitat represents the most productive, least severe of the environmental conditions available to them.

The dominant anadromous fish species in the Beaufort Sea include Arctic cisco (Coregonus autumnalis), least cisco (Coregonus sardinella), broad whitefish (Coregonus nasus), and Arctic char (Salvelinus alpinus) (Figure 7). These fish must obtain the vast majority of their entire year's energy intake (90 percent or more) during the very limited period of open water. The feeding and rearing period, as well as the availability of suitable habitat conditions during this period, is so limited (approximately 10 weeks) that these populations naturally grow and mature more slowly than related populations and species from more temperate areas (Craig and Haldorson, 1981; Dutil, 1986). In addition, the ability to acquire energy rapidly is so limited that these fish are unable to spawn in consecutive years (Dutil, 1986; NMFS, 1987).

A variety of other fish species are also found in this area at times. In particular, Arctic cod (Boreogadus saida) and fourhorn sculpin (Myoxocephalus quadricornis) are routinely caught by post-causeway environmental monitoring programs. Arctic cod, a marine species, is often extremely abundant in association with the higher salinity water.

The Arctic anadromous fish are an important subsistence resource for native villages on the Beaufort Sea coast (Jacobson and Wentworth, 1982) and throughout the Mackenzie River drainage in Canada (NMFS, 1987). The only commercial fishing operation in the Alaskan Beaufort Sea is located in the Colville River delta. This operation targets on these same anadromous fish. Fish, and fishing, also play important roles in the culture of the peoples native to the North Slope (Jacobson and Wentworth, 1982). The importance of anadromous fish increases when other subsistence resources, such as caribou, are less available.

Fish Distribution in the Prudhoe Bay Area Prior to construction of the West Dock causeway, least cisco migrated into the Prudhoe Bay vicinity from the Colville River and were the most numerous anadromous fish species in Prudhoe Bay sampling (Furniss, 1974; Doxey, 1977). Least cisco were more abundant in the nearshore zone than Arctic cod and fourhorn sculpin (marine species) and much more abundant in the Prudhoe Bay vicinity than the anadromous Arctic cisco. Arctic cisco numbers were higher in the Colville River area, and these fish apparently by-passed Prudhoe Bay to a large extent during their migrations between the Colville and Mackenzie rivers. Broad whitefish, anadromous but less tolerant of marine conditions than either least or Arctic cisco, were nonetheless regularly present in river plumes within the nearshore zone in the Prudhoe Bay area. Freshwater species (including humpback whitefish and round whitefish) also appear to have been fairly regular members of this nearshore fish community prior to the final extension of the West Dock causeway.

Overall, the nearshore biological community of the Prudhoe Bay area was characterized by the presence of freshwater species and species relatively intolerant of high salinity, low temperature (marine) conditions; marine species and Arctic cisco were only minor components of the community.

The dominant anadromous fish species share some similar habitat requirements and distribution, but have important differences as well. Similarities include distribution in the estuarine water of the shallow nearshore zone, with feeding principally on near-bottom (epibenthic) invertebrates including mysids, amphipods, and copepods. In addition, they all must return to suitable, non-marine habitat to overwinter.

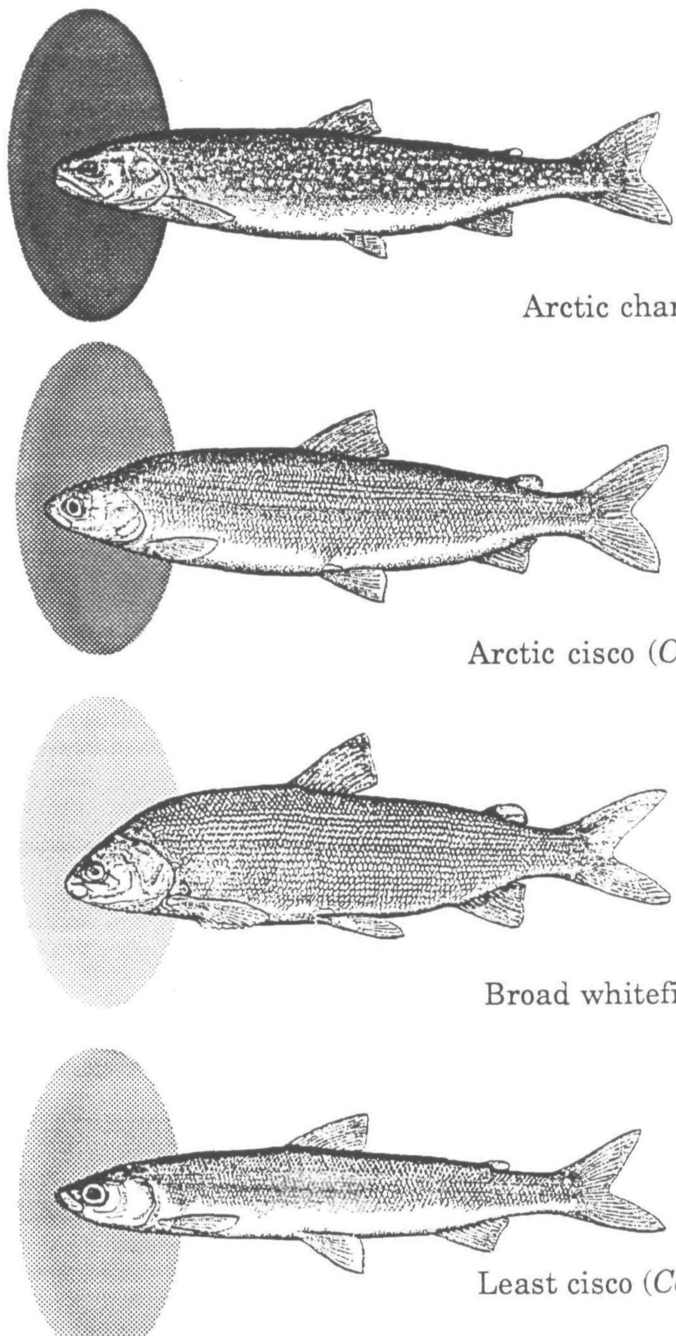

Figure 7
Anadromous fish species of primary concern in the central Beaufort Sea. Fish are shown in decreasing order according to their relative importance. Shading indicates the relative tolerance of the fish to high salinity and cold temperatures with tolerance increasing with the darkness of the shading. Fish figures adapted from McPhail and Lindsey, 1970. Figure courtesy of C. Johnson, National Marine Fisheries Service, Anchorage, Alaska.

Differences exist among the anadromous species in terms of how they use specific salinity and temperature ranges within the overall estuarine zone. The fish may tolerate a broader range of conditions than they normally use for feeding, but they must optimize multiple environmental variables in order to maximize their energy gains. Broad whitefish utilize fresher-water areas, and have a relatively localized distribution directly associated with river deltas. For this reason, they feed more exclusively on terrestrial- and riverine-derived food sources such as insect larvae. Arctic char often feed in and can tolerate higher salinities (Roberts, 1971), but may move into freshwater (if whitefish are not present) for digestion (Johnson, 1981). Because of this and physical differences that allow Arctic char to feed more efficiently on other fish (Svardson, 1976), they use different areas and have somewhat different feeding habits.

Least cisco and Arctic cisco are intermediate in their use of the nearshore habitat. Each of these species can generally tolerate somewhat higher salinities than broad whitefish, but they do not range as far from the immediate nearshore areas for feeding and rearing as Arctic char. Figure 8 shows a representation of fish use within the nearshore environment.

Another difference among species is their distribution and dispersal from spawning and overwintering areas. Least cisco in the Prudhoe Bay area are near the eastern end of their summer distribution; they spawn and overwinter in the Colville River. This is in contrast to Arctic cisco, that migrate as juveniles from spawning grounds in the Mackenzie River to rear near the Colville River. [1/] Arctic cisco also overwinter primarily in the Colville. Arctic char are represented by discrete spawning populations from several river systems along the North Slope, although summer feeding distributions intermingle.

Other differences in use of the nearshore environment occur within species (for instance, by size or age). For example, tolerance to higher salinities and lower temperatures tends to increase with age, especially for least and Arctic cisco. Because of such differences, all shallow brackish areas within the coastal zone cannot be assumed to uniformly serve as "habitat" for all species or size-classes of anadromous fish at all times.

<u>*Habitat Requirements of Beaufort Sea Anadromous Fish*</u> Temperature and salinity are very important habitat parameters for Beaufort Sea anadromous fish (Craig and Haldorson, 1981;

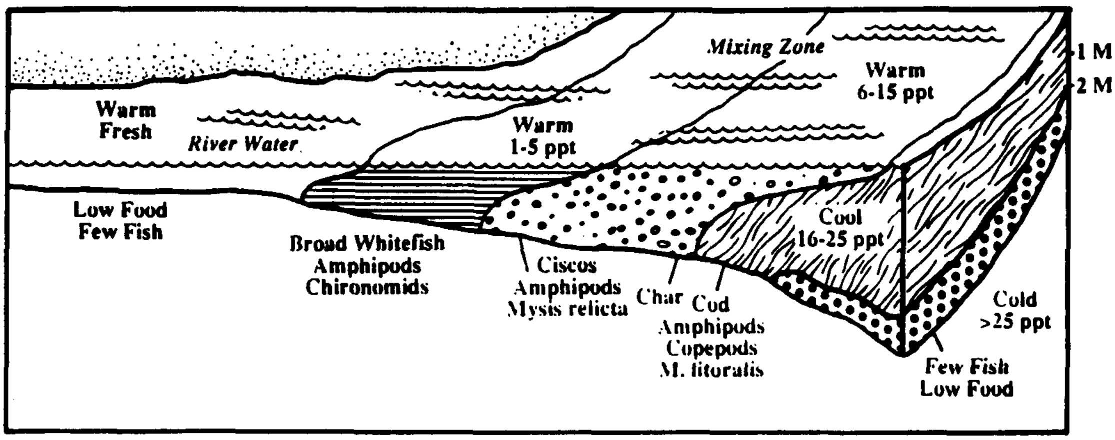

Figure 8
General use of nearshore estuarine habitat by fish in the central Beaufort Sea. Adapted from Envirosphere, 1987.

1/ It is often assumed that the Alaskan population of Arctic cisco merely represents a passively distributing portion of the overall Mackenzie River population, with the numbers in Alaskan waters being proportional to the percentage of Mackenzie River water that is blown to the west in a given year (Fechhelm and Fissel, 1988). Other data suggest this may not be the case (Envirosphere, 1988b; Envirosphere, 1988d). It is clear from the perspectives of management and risk that the Alaskan Beaufort Sea Arctic cisco must be considered a discrete stock that undergoes an active, directed migration (although almost certainly wind-aided). If this is true, effects to these fish would not be quickly reversible if the causeways were removed. These Arctic cisco may represent a genetically discrete stock originating in particular drainages of the Mackenzie, which would imply a potential for long-term causeway effects to result in detrimental impacts to the gene pool, to community structure, and to subsistence and commercial harvests in Canada as well as Alaska.

Envirosphere, 1987; Envirosphere, 1988b; Envirosphere, 1988d) and much is known about their effects. Temperature and salinity conditions have direct metabolic consequences; however, each affects fish in different ways. Basically, temperature affects the rate of energy utilization while salinity affects its distribution within the fish. For example, warm temperatures allow faster assimilation of food, leading to a greater amount of feeding and greater growth over time. Very cold temperatures make these cold-blooded organisms lethargic to the point that feeding and growth rates slow dramatically, independent of food availability (Brett, 1964; Brett, 1971; Brett, 1976). In contrast, very high or very low salinities require that a large percentage of the fish's energy be expended to regulate blood chemistry (Smith, 1982). The normal marine condition in the Arctic is extreme - a combination of both very cold temperatures and high salinity - and thus it generally represents the least suitable habitat conditions for anadromous fish.

Temperature in the Beaufort Sea is of particular importance to anadromous fish. The period during which relatively warm water dominates the nearshore zone is even more limited than the period of open water. As the summer progresses, river discharges decline and solar warming decreases (NOAA, 1988). Consequently, the quality of feeding habitat for anadromous fish often diminishes as the season progresses. Although prey abundance remains high late in the season (Envirosphere, 1987), cold marine conditions reduce the energetic value of utilizing this prey. Mild years - for example, when winds tend to hold warm, fresh river water in the nearshore zone longer than during harsher than average years - can naturally result in higher productivity and greater fish growth overall. Conversely, harsh years reduce growth potential because lowered temperatures slow assimilation rates. (As described earlier, westerly winds tend to hold fresh river water onshore, promoting more efficient mixing with the coastal water mass. These conditions result in both higher average temperatures and lower salinities in the nearshore zone.)

Although fish are affected by overall conditions, at any given moment fish respond primarily to local and immediate habitat quality. It is counter productive for fish to remain in an energetically negative environment. This is true at any time - not just late in the season when the entire region becomes more marine. Harsh years as described above limit the overall amount and quality of suitable feeding habitat available across the region, but fish must still attempt to utilize the most suitable habitat remaining available. At some point the fish simply retreat from unsuitable conditions (for example, when marine water quickly invades the nearshore habitat). Observations that cold marine water directly inhibits the movement of anadromous fish in the area have been made during the mid-summer rearing period as well as late in the season (Envirosphere, 1988b; Envirosphere, 1988d). It is clear that site-specific conditions at a given time, as opposed to average regional or seasonal conditions, are of most immediate importance to the fish.

Parameters other than temperature and salinity surely have a role in determining habitat quality for central Beaufort Sea anadromous fish , but little is known about them. For example, little is known about how to specifically define individual niches, or what constitutes optimal feeding habitat for the different anadromous fish species. Such parameters as distance from spawning or overwintering areas, water depth, wave height, turbidity, wind direction or strength, predator-prey interactions, and competition all probably have some importance. Other important ecological issues under speculation are how "optimal" habitat for different sizes or species of fish may be affected by interaction of the parameters listed above and whether any of the fish adopt behavioral strategies to maximize growth and survival within a given set of conditions. Overall, specific definition of niches for individual species is lacking and without such information the ability to make precise predictions about the effects of nearshore industrial developments on each species will continue to be limited. Future study may provide useful information. However, existing information is sufficient for identifying the more obvious impacts and risks of Beaufort Sea causeways.

CAUSEWAY PROJECTS

Two major causeways have been constructed in the Prudhoe Bay area; each is a massive solid fill gravel structure. The impacts of these causeways on water quality and fish habitat have become a major environmental concern. Studies to document the impacts of the causeways have been required by the permits authorizing causeway construction. This section briefly describes the causeways and the monitoring programs that have been undertaken to determine their impacts.

The West Dock Causeway This was the first major causeway to be built in the Prudhoe Bay area. The 13,000-foot (4,000+ meter) long causeway is located at the northwestern corner of Prudhoe Bay, on the eastern end of the Gwydyr Bay/Stump Island lagoon complex (see Figure 2). Construction occurred in three phases. The original structure was built in 1975 as access to a dockhead some 4,000 feet offshore. The second 4,000+ foot leg was completed the following year under an emergency permit from the U.S. Army Corps of Engineers because supply barges had become frozen into the sea ice. An additional dockhead that continues to support shipping activities was built onto the end of the second leg. The final 4,000-foot section of the causeway was built in 1980 to provide access to a seawater intake and treatment plant for waterflood of the Prudhoe Bay oilfield (COE, 1980). (The West Dock causeway is sometimes referred to as the "Waterflood" causeway for this reason.) A 50-foot (15-meter) bridged opening ("breach") was constructed at the shoreward end of the final leg of the causeway in an attempt to provide for fish movement between Prudhoe Bay and the Gwydyr Bay/Stump Island Lagoon system. Overall, the construction of the West Dock causeway required over 1,500,000 cubic yards of gravel. The West Dock causeway is operated by ARCO Alaska, Inc., on behalf of the Prudhoe Bay Unit owner companies.

The Endicott Causeway The Endicott causeway was constructed in 1985 to provide access to two man-made gravel oil production islands. This causeway extends over 22,000 feet (7,000 meters) into the Beaufort Sea from the middle of the Sagavanirktok River delta just east of Prudhoe Bay (see Figure 2). The Endicott causeway is actually made up of two causeways: a 15,000+ foot (4,700-meter) inter-island causeway, and a 10,000+ foot (3,150-meter) causeway to shore. Two breaches, with a combined length of 700 feet (220 meters), were built into this shoreward causeway in an attempt to ameliorate impacts to water quality and fish habitat predicted in the Environmental Impact Statement (EIS) for the project (COE, 1984). Over 2,700,000 cubic yards of gravel were used to construct this causeway. The Endicott causeway is operated by Standard Alaska Production Company for the "Duck Island Unit" owner companies.

Other Causeways In addition to the West Dock and Endicott causeways, a small 1,100-foot (350-meter) solid-fill gravel causeway known as East Dock has been built on the eastern shore of Prudhoe Bay (Figure 2, Figure 9). East Dock was built in the early 1970s for shipping related to oil exploration activities in the Prudhoe Bay area.

Other major causeways have been proposed in the Prudhoe Bay area as well (Figure 9). The Lisburne causeway, proposed by ARCO Alaska, Inc. in 1984, would have extended over 13,000 feet (4,200 meters) into the middle of Prudhoe Bay from the western shore. It would have provided access to an offshore drilling island for production from a portion of the Lisburne oilfield. (Five related drilling pads are all onshore and have been permitted and constructed separately). This

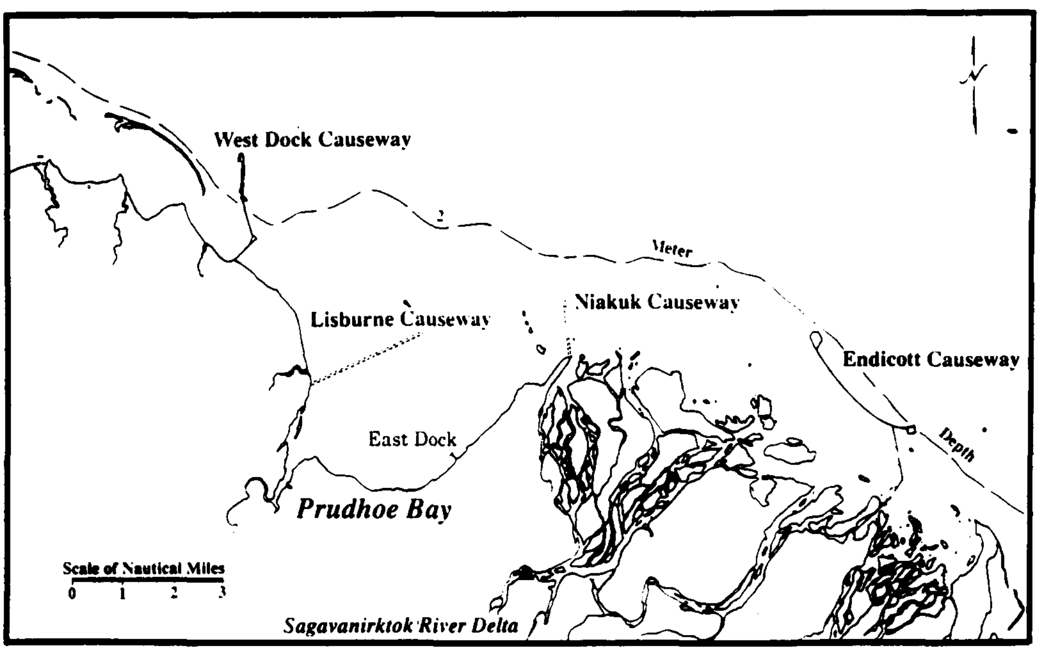

Figure 9
Location of proposed causeways in relation to existing causeways in the Prudhoe Bay area. The Niakuk causeway was proposed in 1988; the Lisburne causeway proposal has been withdrawn. Modified from SAPC, 1988.

proposal was withdrawn by the developers in 1987 in favor of directional drilling from the existing onshore sites.

Another causeway was proposed by Standard Alaska Production Company in 1987. If constructed, the Niakuk causeway would be nearly 7,000 feet (2,200 meters) long, extending north from Heald Point (at the northeast corner of Prudhoe Bay) to a man-made oil production island. Additional solid-fill gravel causeways have been contemplated by industry and may be proposed for the Prudhoe Bay area in the future. EISs for federal oil and gas lease sales have also discussed causeways relating to nearer-shore outer continental shelf development (DOI, 1982; DOI, 1984). In addition, the final legislative EIS for management of the coastal plain of the Arctic National Wildlife Refuge (ANWR), approximately 160 kilometers to the east of Prudhoe Bay, assumes that causeways may be needed to support port development there (DOI, 1987).

Causeway Monitoring Programs In 1972, Barnes et al. (1977) conducted nearshore oceanographic surveys across the central Beaufort Sea coast; however, other environmental data predating construction of the first portion of the West Dock causeway are extremely limited. Just prior to and following construction of its second leg in 1976, the West Dock causeway was the subject of several studies required by the Corps of Engineers (Furniss, 1975; Bendock et al., 1979; WCC, 1979; Moulton et al., 1980). In addition, after the Waterflood extension was built in 1980, fisheries and oceanographic monitoring continued for four years (WCC, 1982; Envirosphere, 1983; Envirosphere, 1984; Envirosphere, 1986). The draft synthesis report for these four years of monitoring was completed in 1988 (Envirosphere, 1988b).

The lack of pre-causeway baseline data is a serious limitation to the West Dock causeway monitoring programs. Also, environmental studies conducted after that causeway's construction were poorly coordinated. Monitoring objectives and methods differed substantially among the different investigators, such that comprehensive, comparable data were not collected from year to year. Each study differed as knowledge about how to measure the effects of the causeways evolved. As a result, only the final year's monitoring at the West Dock causeway was reasonably comprehensive and relatively comparable to the approach later used at the Endicott causeway.

In contrast to West Dock causeway monitoring, the Endicott causeway monitoring program was intended to emphasize coordinated planning and the collection of an internally consistent multi-year data set. This monitoring program also suffered from limited baseline data collection, this time specific to the Sagavanirktok River delta region. However, a complete monitoring program was fielded during the first three years following construction of the causeway in early 1985 (Envirosphere, 1987; Envirosphere, 1988a; Envirosphere, 1988d; NOAA, 1988). The Corps of Engineers decided to discontinue the major fisheries and supporting oceanographic portions of the Endicott causeway monitoring program after results from the three years of study showed that impacts substantially exceeded many of the predictions made in the Endicott project EIS. Other aspects of the monitoring program are expected to continue, including a terrestrial program and oceanographic monitoring not directly related to the fisheries program.

As directed by the Corps of Engineers, the Endicott causeway monitoring program was habitat-based rather than population-based. Habitat monitoring is more effective and considerably less expensive than direct population monitoring in the Arctic. Habitat monitoring has its basis in accepted ecological principles. In particular, it is recognized that populations in low diversity physically stressed environments, or those in environments that are subject to irregular environmental perturbations, tend to be regulated by physical components of the environment such as weather, currents, temperature, etc. (Odum, 1971). Anadromous fish populations in the central Beaufort Sea exist in an environment that fits both the above descriptions well. Therefore, attention for monitoring focused on habitat changes and other indicators of potential population-level impacts, as opposed to direct measurement of population sizes through time. This approach was intended to allow indicators of environmental risk to be assessed before irreversible adverse impacts were realized, rather than after such impacts had already occurred.

IMPACTS OF CAUSEWAYS

The primary concerns about the West Dock and Endicott causeways are their impacts to the water quality and circulation patterns of the central Beaufort Sea nearshore estuarine environment. During their brief summer feeding period, anadromous fish are generally constrained to this immediate nearshore zone where inhospitable marine conditions occurred less frequently in the past. It is within this same critical nearshore zone that causeways have disrupted circulation patterns and caused estuarine habitat to be replaced by offshore marine water across many miles of coastline. The following sections discuss the fundamental impacts of these massive structures to the physical and biological environments. (Other potential impacts - e.g., related to industrial discharges or spills - are not addressed in this report.)

PHYSICAL IMPACTS

The basic physical impacts of constructing the causeways within the estuarine nearshore zone appear, with hindsight, to be easily predictable. Unfortunately, little site-specific baseline knowledge of nearshore processes in the central Beaufort Sea was collected before construction of either of the causeways had begun. The evolution in knowledge during several years of monitoring, however, has provided a clearer picture of the processes affected by the causeways.

Overall, causeways have disrupted the nearshore environment throughout the Prudhoe Bay area because of their construction perpendicular to the wind and nearshore current patterns. As will be explained, this disruption occurs under both easterly and westerly winds by: 1) deflecting both the coastal water mass and river plumes offshore, concurrently degrading their estuarine character through the loss of thermal energy and freshwater to offshore areas; 2) causing enhanced upwelling and intrusion of marine water directly into the nearshore environment, thus severing the band of estuarine conditions along the coast; and 3) both delaying breakup and accelerating freezeup in the nearshore zone.

The coastal water mass and the river plumes are deflected offshore by both the West Dock and Endicott causeways despite the breaching incorporated into each of them. Offshore deflection causes enhanced mixing with marine water and degradation of estuarine conditions. Under easterly winds, marine water upwells to replace the deflected water, and marine conditions often extend and dominate for many kilometers downstream. Today, the coastal water mass and Sagavanirktok River plume no longer are maintained in a generally continuous brackish band across the Prudhoe Bay area. Instead, nearshore water quality is more heterogenous, and marine conditions have become much more dominant. Overall, fundamental alterations in nearshore water quality and circulation patterns have occurred along as much as 65 kilometers of the Prudhoe Bay area coastline.

Offshore Deflection of Estuarine Water Masses

During easterly winds, the coastal water mass moves west along the coast until it encounters the

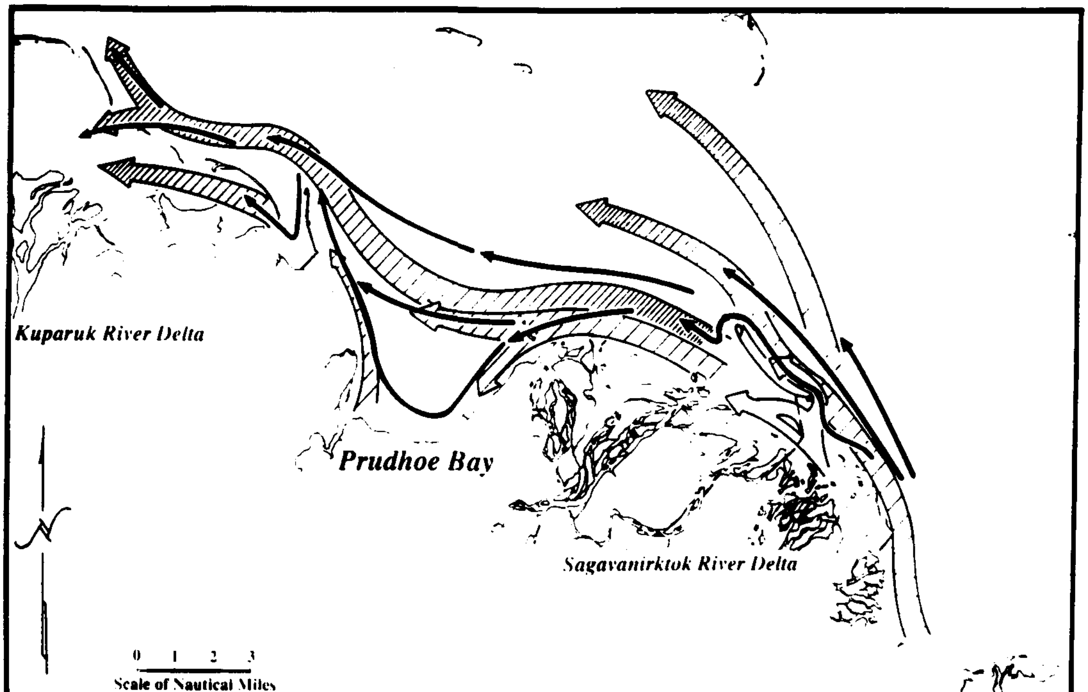

Figure 10
Generalized flow of nearshore waters during sustained easterly winds since construction of the West Dock and Endicott causeways, showing causeway-induced deflection of nearshore water masses. Heavy solid arrows denote flow of subsurface marine water. Cross-hatched arrows denote surface flow, with the density of cross-hatching proportional to salinity. Adapted from Envirosphere, 1988b and NOAA, 1988.

Endicott causeway. The nearshore 500 feet of breaching in the causeway generally does not accomodate all of the flow from the east channel of the Sagavanirktok River, and a portion of this flow is deflected to the 200-foot breach farther offshore (Envirosphere, 1988c; Envirosphere, 1988d). The second breach is not always sufficient either, so at times some of the river discharge is deflected further - around the end of the causeway. Because the existing causeway breaches are dominated by fresh Sagavanirktok River plume water, almost the entire coastal water mass is deflected offshore and around the structure (Figure 10). Depending on the precise direction of the wind, the deflected water will be held offshore (southeasterly winds), or will flow across the mouth of Prudhoe Bay, primarily just outside the Gull Island shoal (northeasterly winds). In general, a greater offshore deflection causes greater contact with offshore marine water and more rapid degradation of water quality. Increasing salinities averaging over 2 parts per thousand per kilometer (ppt/km) have been measured in the deflected water downwind from the Endicott causeway (Envirosphere, 1988a).

In the vicinity of West Dock, the deflected coastal water and the Sagavanirktok River plume often merge, but do not pass directly into the lagoon system as they did prior to construction of the causeway. The 50-foot breach in the West Dock causeway has been blocked almost continuously since its construction by gravel eroded from the causeway's sides. This breach allows virtually no water to pass. Therefore, upon encountering the causeway, coastal and Sagavanirktok River water is deflected offshore (Figure 10) outside of Stump Island Lagoon and Gwydyr Bay. Depending on the precise direction of the wind (southeasterly or northeasterly), all of the deflected water will be held offshore, or a portion may re-enter the lagoon system several kilometers to the west through various entrances between the barrier islands. After passing West Dock, the deflected water is again placed into greater contact with marine water and rapidly loses its estuarine character. Salinity of the water deflected by the West Dock causeway has been observed to increase at rates up to an additional 9 ppt/km (NOAA, 1988). Deflection of nearshore water masses also occurs during westerly winds. However, the overall physical impacts of the causeways differ during east and west winds. Upwelling during easterly winds and intrusions during the onset of westerly winds, as described below, cause much of this difference.

East Winds: Upwelling As water is deflected offshore at each causeway during easterly winds, the surface water in the lee of the structures is also blown to the west. Under pre-causeway

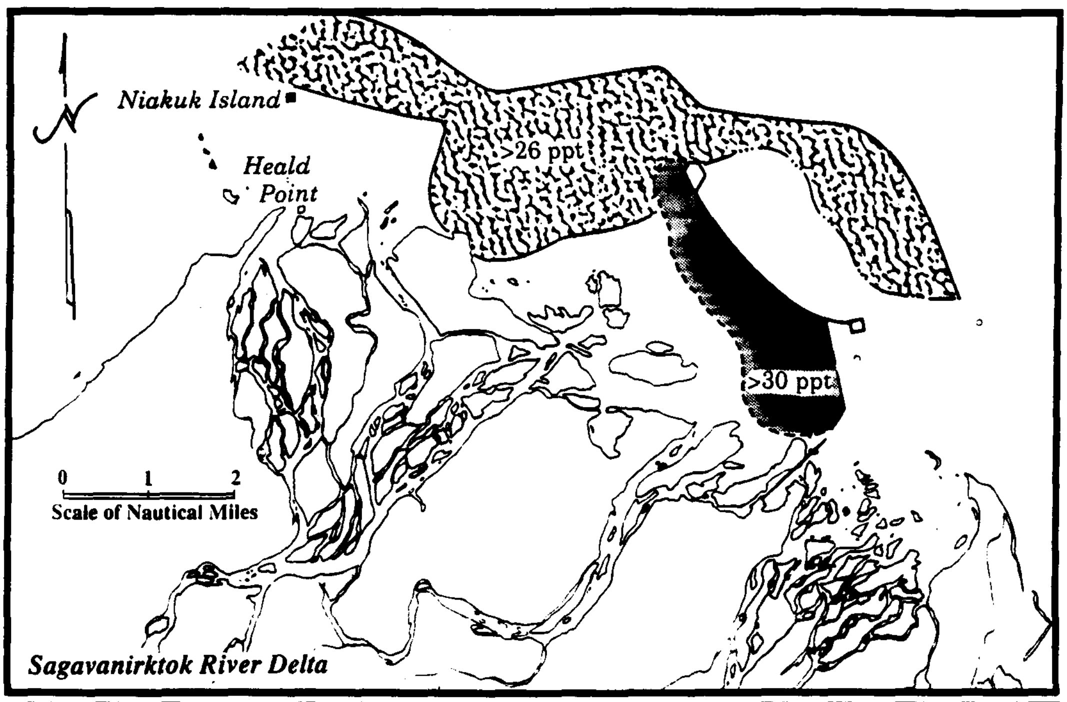

Figure 11
Salinity at 1 meter depth during sustained east winds, July 22, 1986 survey. Note that upwelled high salinity water (stippled) has been drawn into very shallow water between the Endicott causeway and Heald Point, and that even higher salinity water (shaded) has upwelled all the way in to the island-to-shore leg of the causeway, despite existing breaches. Adapted from Envirosphere, 1988d.

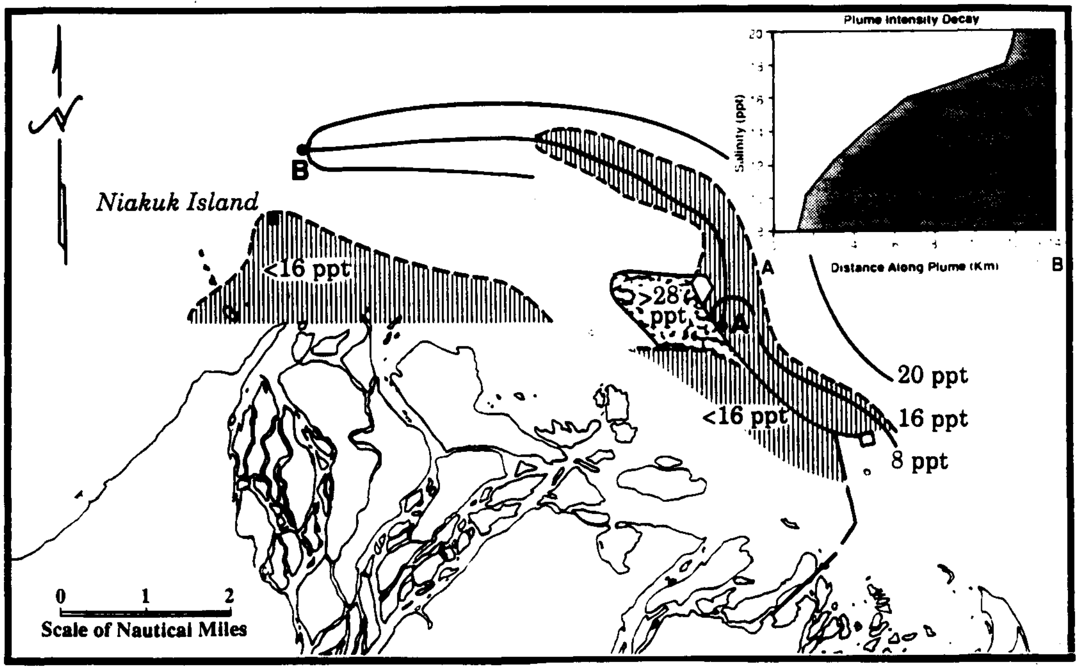

Figure 12
Detail of deflection and degradation of nearshore estuarine water at the Endicott causeway during sustained easterly winds. The A-B transect follows the center-line of the deflected water. Inset shows increasing salinity of the deflected water along the A-B transect. Adapted from Envirosphere, 1988b.

conditions, this water would be replaced by the adjacent coastal and river water; however, the causeways block this process. Subsurface marine water is drawn instead from offshore and upwells to replace the deflected water - even in very shallow areas. While natural upwelling in the region often brings marine water to the bottom in areas that are as shallow as 2-4 meters, the causeways result in upwelling to the surface in downwind areas with depths of less than 1 meter (Envirosphere, 1988d; NOAA, 1988). Given the expanse of very shallow water in the vicinity, significant additional areas now frequently experience marine conditions due to this enhanced upwelling.

The pattern of upwelling at the Endicott causeway is influenced by the structure's location between the two main channels of the Sagavanirktok River. Replacement water is partially made up of fresh discharge from the river. Some of this is fresh water that has been deflected offshore somewhat, flowing through the breaches in the causeway. The fresh water flows across the delta, past Heald Point and the Niakuk Islands at the northeast corner of Prudhoe Bay. Some enters the bay, and some crosses the bay along and outside the Gull Island shoal. While the most immediate nearshore area downwind of Endicott may thus remain primarily fresh (Figure 10), marine bottom water flowing in past the northwestern tip of the causeway upwells in the shallows between the causeway and shore (Figure 11).

The marine upwelling occurring at the Endicott causeway extends in a band to the south and west of the causeway's tip, occasionally to Heald Point. Depending on the strength of the wind, marine water also upwells to the east along the inside of the inter-island causeway as far as the west side of the island-to-shore leg of the structure (Figure 11). Both the intensity and the overall extent of the marine upwelling significantly exceeds the Endicott project EIS predictions (COE, 1984). Salinity differences of 20 ppt have been observed between the plume water on one side of the causeway and upwelled water on the other side - an impact three times greater than predicted in the EIS (Envirosphere, 1988c). The EIS also predicted significant water quality changes would occur within an area of about 11,000 acres; EPA has calculated that the area affected has actually exceeded 40,000 acres considering both east and west wind conditions.

The offshore deflection of coastal water and the marine upwelling along the delta front separate the coastal water from much of the Sagavanirktok River's fresh discharge for several kilometers. Prior to the Endicott causeway, the river discharge mixed directly with the coastal water (see Figure 3), helping to maintain the estuarine conditions across the Prudhoe Bay area (NOAA, 1988). Today these water masses are separated, and each of them is in greater contact with marine water (Envirosphere, 1988a; Envirosphere, 1988d). Thus, mixing causes each to become more marine in character as it moves through the area (Figure 12).

At the West Dock causeway, surface water immediately downwind of the structure and within the lagoon system is also blown west at the same time that estuarine water is deflected offshore. Unlike the Endicott causeway system, however, there is no significant nearby source of fresh water to partially replace the deflected water. Instead, the deflected water is entirely replaced by marine water from offshore that upwells directly into Stump Island Lagoon. Consequently, the West Dock causeway causes a much more extensive invasion of marine conditions into the nearshore zone. Marine water upwelled as a result of the causeway can extend throughout Gwydyr Bay (some 20 to 35 kilometers) and routinely dominates beyond the Kuparuk River Delta (approximately 15 kilometers).

The overall impact of the West Dock and Endicott causeways during easterly winds is that the zone of estuarine water that had dominated the nearshore area between the Colville and the Sagavanirktok rivers in the pre-causeway environment is no longer continuous under even relatively low intensity east winds. In the absence of the causeways, water would not be deflected offshore and marine water would not frequently dominate the lagoon system west of Prudhoe Bay as it does today (NOAA, 1988).

<u>*West Winds: Intrusion*</u> During westerly winds, the mass of upwelled marine water dominating the lagoon system west of the West Dock causeway begins to flow east around the causeway toward Prudhoe Bay (Figure 13). As this occurs, water level rises in an intrusion event (see Physical Environment, above). The intrusion ends relatively quickly as water level equilibrates, but usually not before the more estuarine water that had occupied Prudhoe Bay is displaced by the marine water flowing in from the end of the West Dock causeway (Envirosphere, 1988c; NOAA, 1988). Distinct boundaries between receding estuarine water and incoming marine water are observed at these times. In this manner, marine conditions regularly occur in Prudhoe Bay as a result of the West Dock causeway.

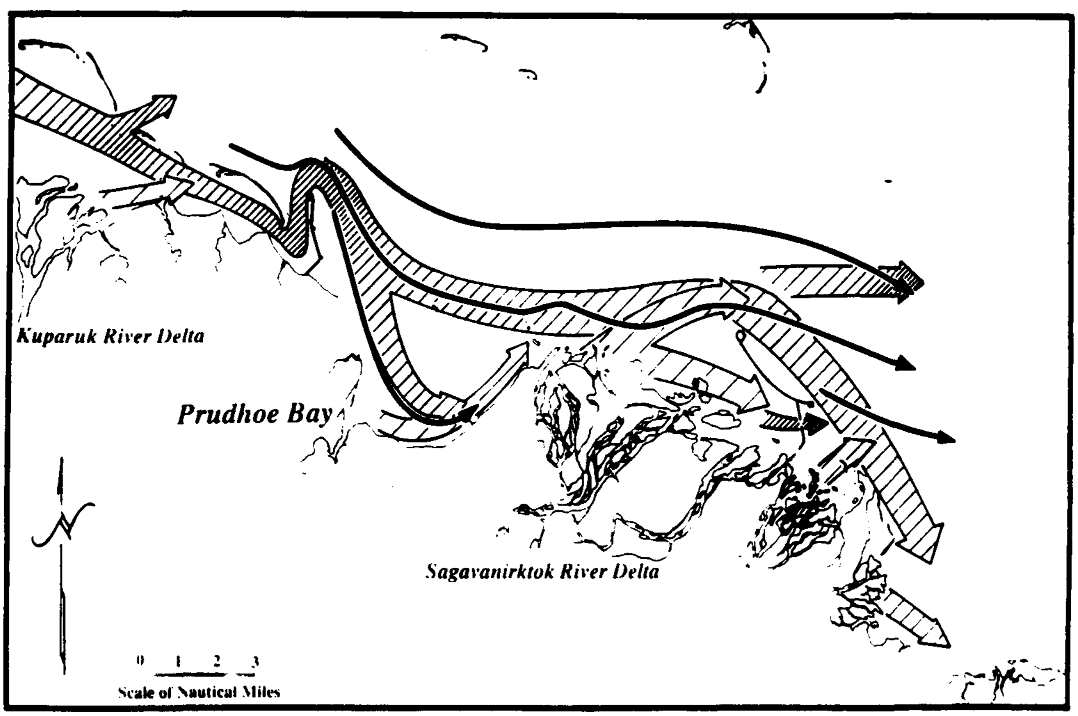

Figure 13
Generalized flow of nearshore waters during sustained westerly winds since construction of the West Dock and Endicott causeways, showing causeway-induced deflection of nearshore water masses. Heavy solid arrows denote flow of subsurface marine water. Cross-hatched arrows denote surface flow, with the density of cross-hatching proportional to salinity. Adapted from Envirosphere, 1988b and NOAA, 1988.

If west winds persist, the Colville River plume will eventually flow through the lagoon system, reaching and passing around West Dock. This was observed in 1984 and 1987. However, meteorological records for the area indicate that such conditions are unusual (Envirosphere, 1988d). Unfortunately, even when they do occur, the Colville River plume is able to do little to flush marine conditions from Prudhoe Bay, since most of the plume's flow during westerly winds (after the active intrusion ceases) occurs outside the Gull Island shoal as a result of bathymetric steering (NOAA, 1988). The first major marine intrusion event of the season can thus adversely affect Prudhoe Bay water quality for the remainder of the open water period (Envirosphere, 1988b; Envirosphere, 1988d; NOAA, 1988).

After passing Prudhoe Bay, coastal water (and at times Colville River plume water) is also deflected offshore by the Endicott causeway (Figure 13). As also occurs during easterly winds, the 700 feet of breaching in the structure is inadequate to accommodate more than a small fraction of this water. Some degradation of the estuarine conditions of the deflected water occurs during westerly winds as well. At these times, west channel Sagavanirktok River water is forced to mix both with marine water previously upwelled by the Endicott causeway and with offshore marine water as the plume is deflected around the causeway. Water from the east channel of the river also mixes with previously upwelled marine water rather than with fresh water from the west channel. In addition, being in the protected lee of the causeway during westerly winds, east channel water flows further from shore out over marine waters, rather than flowing southeast into southern Foggy Island Bay.

Fragmentation of Water Masses A net effect of the causeways, considering both east wind and west wind impacts, is that nearshore water masses frequently become separated from like masses along the coast. This water mass fragmentation would not occur naturally under the same meteorological conditions, except perhaps during unusually harsh years (e.g., low river discharges, cold temperatures). The large expanse of upwelled marine water within the Simpson Lagoon system, for instance, now routinely isolates the estuarine conditions of the Prudhoe Bay area from similar estuarine conditions maintained farther to the west by the Colville River. As a result, each of these areas is less accessible to feeding or migrating anadromous fish (see Biological Impacts, below). This east-west fragmentation of conditions within the nearshore zone, while dominant during easterly winds, also persists during westerly winds. During the first days of westerly winds, the upwelled marine water continues to fragment the nearshore water masses, but the location of the discontinuity is simply moved to the other side of the West Dock causeway (i.e., into Prudhoe Bay).

The Endicott causeway also fragments water masses because of its location within the Sagavanirktok River delta. Because this structure causes marine water to upwell between the fresh river discharge and the deflected brackish coastal water, a north-south fragmentation of nearshore water masses occurs. This fragmentation results in enhanced mixing between marine and coastal water, direct mixing between fresh river water and upwelled marine water in the nearshore zone, and a general degradation of habitat quality for the area's anadromous fish populations (see Biological Impacts, below).

Each of the other causeways that have been proposed for the Prudhoe Bay area would exacerbate the water quality impacts described above. The Lisburne causeway would have made marine waters even more difficult to flush from Prudhoe Bay. The Niakuk causeway would likely enhance the amount of marine water upwelled near Prudhoe Bay during easterly winds and would add to the offshore deflection of coastal plume water under westerly winds. The Niakuk causeway could significantly increase the rate of intrusion of marine water into Prudhoe Bay, as well as make resulting marine conditions more difficult to flush from the bay. Overall, the Niakuk and Endicott causeways together would be more problematic than either of them individually.

Ice Dynamics The West Dock and Endicott causeways have affected ice dynamics in the Prudhoe Bay area by deflecting and restricting the early season overflooding of river water, thereby altering the natural patterns of sea ice breakup (Figure 14). The breakup of sea ice in the vicinity of each causeway has been delayed by up to two weeks (Envirosphere, 1988b; Envirosphere, 1988d; NOAA, 1988). Freeze up, however, is locally accelerated by the structures. Depending on wind direction, ice builds up behind the causeways and can solidify more quickly there, causing freezeup to occur up to two weeks earlier than elsewhere in the area (Envirosphere, 1988d; NOAA, 1988).

These alterations in breakup and freezeup patterns occur primarily within about 5 km of the causeways (NOAA, 1988). However, this effect is directly within the nearshore zone used by anadromous fish. Alteration of ice dynamics within this important ecological zone represents a risk to these fish (see Biological Impacts, below).

The proposed Niakuk causeway would also alter

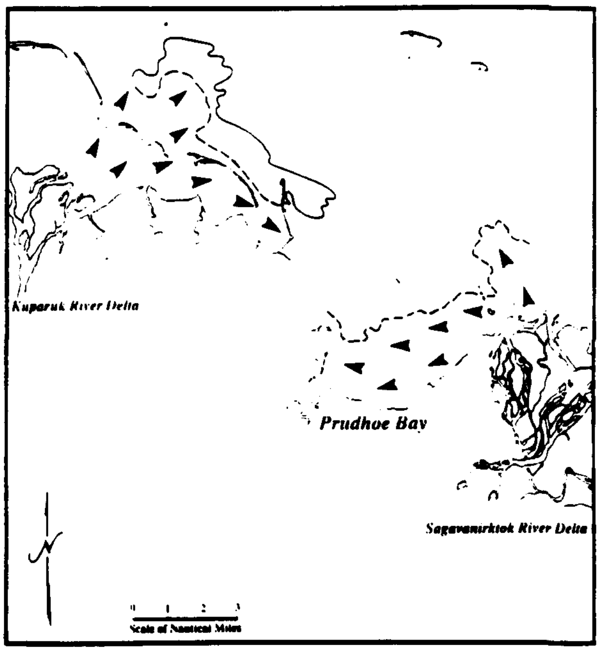

Figure 14
Distribution of flood waters from the Kuparuk and Sagavanirktok rivers, from LANDSAT image of May 30, 1985. The West Dock causeway can be seen to restrict overflooding to western Prudhoe Bay. Adapted from NOAA, 1988.

ice dynamics. The proposed structure extending from Heald Point would further restrict river overflooding into Prudhoe Bay and breakup of sea ice within the bay. It would also accelerate freezeup in the nearshore zone and within the west channel of the Sagavanirktok River. The limited breaching proposed for this structure is not expected to be capable of eliminating these effects.

BIOLOGICAL IMPACTS

Important feeding and rearing habitat for anadromous fish in the Prudhoe Bay area has been significantly altered due to the presence of the West Dock and Endicott causeways. Marine water dominates or modifies conditions across many kilometers of the coast, and both the quality and quantity of suitable feeding and rearing habitat have been substantially reduced. In addition, oceanographic changes associated with the causeways have fragmented fish habitat both near Prudhoe Bay and along the coast as a whole, affecting fish migration and distributions. Causeway-induced habitat impacts and alterations in ice dynamics occur directly within the critical nearshore zone, and are now making every year more similar to a "harsh" year as described earlier.

Serious risks to the fish populations are posed by these habitat impacts. Habitat alterations can lead to overutilization of accessible areas and underutilization of inaccessible areas. This change in utilization can translate into reductions in feeding and therefore growth for these populations that are already energetically limited. Taken together, these changes can greatly impact the populations and the overall coastal fish community, even in the absence of catastrophic or worst-case events or years.

<u>Causeway Effects on Population Sizes</u> Little or no reliable information exists about population sizes for the nearshore fish species of the central Beaufort Sea. Thus little direct evidence of declines in population sizes can be cited. However, some may question why this should remain the situation after several years of causeway monitoring. First, it is important to recall that causeway monitoring, by design, has largely been habitat-based (see Causeway Monitoring Programs, above). It is therefore possible that population declines have already begun to occur that are simply going unmeasured. (It would take a very large decline indeed to be obvious, given the habitat focus of the monitoring to date. Once very large population declines occur, it is usually too late to easily reverse them.) Second, and perhaps more important, is that reasonably comprehensive monitoring has actually been conducted only for four years, or about one-half the generation time for the affected fish species. Since these fish take 8 to 12 years to mature, it would take at least that long for the populations to decline obviously in the absense of acute, catastrophic effects. While long-term declines may be more probable than catastrophic effects, the latter can also occur under the appropriate set of conditions. This cannot be discounted given the intended life of the causeways.

<u>Causeway Effects on Habitat Quality and Quantity</u> The alteration of coastal and Sagavanirktok River plume water quality that results from offshore deflection of these water masses at the West Dock and Endicott causeways also represents a degradation of habitat quality for anadromous fish. These fish are highly dependent on estuarine conditions in the nearshore waters (see Biological Environment, above). As described earlier, the causeways have displaced much of this habitat offshore where its quality is rapidly degraded and replaced it with unsuitable marine water.

In addition to the degradation of fish habitat, the West Dock and Endicott causeways have reduced the total amount of suitable habitat available. This is true in terms of both the area occupied by suitable habitat under a given set of conditions and in terms of the overall time during which suitable habitat is available.

During both easterly and westerly winds, unsuitable marine conditions dominate large areas that once provided generally continuous estuarine habitat. For example, it is estimated that during prevailing easterly winds the Endicott causeway results in the loss of at least 60 percent of the shallow (< 2 meters) estuarine habitat that would otherwise exist in the western Sagavanirktok River delta (Envirosphere, 1988d). Similarly, the West Dock and Endicott causeways combined are estimated to cause the loss of approximately 50 percent of the anadromous fish habitat of the overall Endicott monitoring program study area (from Foggy Island Bay west through Gwydyr Bay (Envirosphere, 1988d). This is consistent with EPA's calculations, based on oceanographic survey data, that up to 365 square kilometers of the nearshore zone that had provided estuarine habitat prior to construction of the causeways have been affected.

Marine conditions, together with altered ice dynamics within the zone used by fish during migrations between overwintering areas and summer rearing areas, also reduce the total amount of time during which suitable habitat is available. These reductions in habitat quality and quantity have resulted in altered fish use of the Prudhoe Bay area, probable decreased feeding efficiency, and decreased potential for overwinter survival, growth, and reproduction.

Changes in Fish Use of the Prudhoe Bay Area The increased fragmentation of water masses that results from the Endicott and West Dock causeways translates to increased fragmentation of anadromous fish habitat. West Dock in particular creates a discontinuity in the nearshore fish habitat by enhancing upwelling of marine water during east winds (the most common winds during the summer). Eastward-moving fish from the Colville River area have been observed to retreat back to the west upon encountering marine water upwelled in the lagoon system west of the West Dock causeway (Moulton et al, 1986; Envirosphere, 1987). Fish within Prudhoe Bay are similarly blocked from moving west by this expanse of inhospitable marine water. This isolation of fish on either side of the causeway can affect return migrations to overwintering areas as well as distributions to and between rearing areas (Envirosphere, 1988b; Envirosphere, 1988d). Overcrowding on one side of the causeway will result in a reduction in feeding efficiency. Similarly, if preferred overwintering sites are made inaccessible at the critical time, the fish will not reach a suitable site or may be forced to use less suitable areas. As described earlier, the Colville River delta is the primary overwintering area for most of these fish. Delays in the return migration to the Colville River have in fact been observed at West Dock during east winds (Envirosphere, 1988b). The extent to which such delays have forced fish to attempt overwintering in unsuitable areas is unknown. However, in the winter of 1985/1986 a large number of Arctic cisco attempted to overwinter in an apparently unsuitable area of the Sagavanirktok River, and died when oxygen levels dropped (Schmidt et al, 1987; Envirosphere, 1987).

Changes in fish distribution and use of Prudhoe Bay occur during west winds, as well. The marine water previously upwelled west of West Dock flows back around the causeway when the wind shifts to westerly, and marine water fills Prudhoe Bay from the west to the east (see Physical Impacts, above). This drives the anadromous fish that had been feeding in the bay, especially Arctic and least cisco, toward the fresh water of the Sagavanirktok River delta where they can find refuge from the marine conditions (Envirosphere, 1988b; Envirosphere, 1988d). However, all of the time spent in refuge areas is time not spent feeding in more productive estuarine habitat; growth potential for these fish will therefore be reduced in proportion to time spent in refuge.

At the same time, the fresher water nearest the delta is the usual habitat of the broad whitefish. It is unknown at this time whether the increased use of the delta by other species results in overcrowding or overutilization of the broad whitefish habitat. However, sampling from 1982 through 1987 suggests a reduction in the strength of younger age-classes corresponding to post-causeway years of altered environmental conditions (Envirosphere, 1988d).

Changes to Community Structure The composition of the nearshore fish community of the Prudhoe Bay area has changed dramatically since construction of the West Dock and Endicott causeways. Where least cisco once dominated and freshwater species such as round and humpback whitefish were regularly found (see Biological Environment, above), these species now comprise a relatively small portion of the fish sampled. Instead, marine species - primarily Arctic cod - have become dominant overall. At the same time, Arctic cisco have become the dominant anadromous fish in Prudhoe Bay. In general, the nearshore fish community is now characterized mainly by a combination of marine species and anadromous species more tolerant of higher salinities, while fresher-water species have all but disappeared.

These changes are consistent with the dramatic causeway-induced changes in the physical conditions of the nearshore environment described earlier. In particular, they are consistent with a basic alteration in the balance of fresh and marine waters that had previously defined the estuarine character of the nearshore zone. Odum (1971), in a discussion of estuarine ecology, states that it "is self-evident that different circulation patterns and gradients will greatly influence the distribution of individual species, but so long as there are adapted populations the overall productivity need not be greatly affected by these differences." The nearshore environment of the Prudhoe Bay area now clearly experiences different circulation patterns and gradients as a result of the West Dock and Endicott causeways, and the distribution of individual species has certainly been affected. It is also possible that overall productivity has not substantially changed. However, that productivity has shifted from anadromous and freshwater fish to dominance by marine species - especially Arctic cod.

Bioenergetics To the extent that fish use and habitat of the Prudhoe Bay area have been altered by the causeways, several biological impacts are probable. All of these impacts are directly or indirectly related to bioenergetics: the ability of fish to aquire and store sufficient energy for survival, growth, and reproduction. If sufficient energy is not acquired and stored during each brief summer feeding period, the populations will decline.[2/] The West Dock and Endicott causeways have seriously increased the probability that this will occur. This discussion presents some of the bioenergetic impacts and risks that anadromous fish now face as a result of causeways in the Prudhoe Bay area.

Implications of Temperature and Salinity Changes Causeway-induced temperature and salinity conditions are within the overall range that naturally occurs across the region. This statement would always be true - regardless of the degree of causeway-induced impacts - because causeways neither create nor destroy heat or salt. However, not all water quality conditions within the range found across the region are suitable for use by anadromous fish. For example, nearshore conditions range from liquid to solid but, of course, solid ice does not serve as habitat for anadromous fish. Even during the open water period, some "natural" conditions in the region are often outside the range of physiological tolerance for some fish species. Exposure to conditions within but near limits of tolerance may allow fish to survive, but will exact high metabolic costs (Brett, 1971; Smith, 1982). Even minor deviations (e.g., 2-5°C) from "optimal" conditions can have significant effects on growth and reproductive potential (Magnuson et al., 1979). Whether in Arctic or temperate regions, a fish's potential for achieving an overall net energy gain that is sufficient for overwintering, growth, and reproduction will be directly reduced by both the degree and persistence of extreme conditions (Brett, 1976).

Arctic anadromous fish are not immune to these consequences. Growth rates of broad whitefish in the Prudhoe Bay area appear to be greater, on average, during west wind years when warmer temperatures and/or lower salinities have been more predominant throughout the summer feeding period (Envirosphere, 1988d). This indicates that water quality conditions integrated over the entire region and over the entire summer can affect the overall health and condition of Arctic anadromous fish populations. This is to be expected because west winds keep warm, fresh water nearshore, therefore resulting in generally higher temperatures and lower salinities. In contrast, east winds promote stratification, upwelling, and increased marine influence on the nearshore zone throughout the region.

However, as described earlier, fish do not respond directly to average or regional conditions; they must attempt to achieve the best compromise

2/ Some investigators suggest that overwintering habitat is the only true limitation to the size of Arctic anadromous fish populations. This would be due to physical limitations such as water quality (including dissolved oxygen) and space (Schmidt et al., 1987). Physical factors would be expected to often become limiting in marginal overwintering areas (for example, if higher numbers of fish are forced to attempt overwintering in less dependable sites due to causeways blocking or delaying migration to preferred Colville River sites). In fact, a water quality-related fish kill has been observed in a marginal area of the Sagavanirktok River (Envirosphere, 1988d). However, dependable, regularly used (e.g., Colville River delta) overwintering areas, by definition, should be physically capable of supporting the populations in most years and should not routinely limit the populations directly. (For example, it would be expected that severe dissolved oxygen depletion would affect all the fish in a given overwintering pool - not just a few.) However, in especially harsh years, overwintering may be directly limiting.

It is important to keep in mind that successful overwintering must occur not just in any one year, but in all years if survival to reproduction is to occur for populations to be maintained. If energetic constraints significantly disrupt this continuum at any point, the populations will decline and can even crash. Thus, even if causeways were to significantly impact fish energetics only irregularly, these events would be capable of severely affecting the population over the long term.

between several aspects of their immediate surroundings. Salinity, temperature, and prey availability are perhaps the most important of these. Monitoring programs have observed that many Arctic anadromous fish avoid marine conditions in the Prudhoe Bay area (Envirosphere, 1987; Envirosphere, 1988d). This is a direct indication that these fish, in fact, do not utilize all the conditions that naturally occur within the region.

The changes in fish distribution and use of the Prudhoe Bay area are examples of immediate behavioral responses to adverse conditions. Such behavioral responses are not without cost, however. As stated earlier, time spent in refuge areas is time not spent feeding in more suitable estuarine habitat. A reduction in the amount of time foraging will affect the scope for growth for that year. Just as east-wind-dominated years can naturally limit growth by degrading conditions on a regional scale, the more local effects of causeways within the critical nearshore habitat zone reduce the time spent feeding in high quality habitat and also affect scope for growth.

Even when drastic water quality changes do not occur and fish are not forced to take refuge, the quality of feeding habitat in the Prudhoe Bay area is often degraded by the presence of the causeways. This occurs because the brackish coastal water is deflected at each causeway, resulting in increased mixing with marine water and an overall decrease in temperature and increase in salinity. Therefore, even though fish are not always forced to completely abandon the feeding area, the energetic costs of remaining there are greater and less net energy gain is possible.

The frequency of such episodes will vary from year to year, as will the degree of degradation of feeding habitat quality. However, since energy is already a direct limitation, fish will be affected to some extent each year. Reduced health and condition (fat reserves) of individuals translates into population impacts if overwintering mortality increases, age of maturity is delayed, or fecundity is reduced.

Food Availability It has been estimated that the abundance of food organisms used by the anadromous fish greatly overshadows what the fish could possibly consume (Craig and Haldorson, 1981; Moulton et al., 1986). However, abundance is not the same as availability. Only those organisms that are available to the fish can possibly become food; and abundant food in one area is not available if surrounding water quality conditions deny the fish access to it. Beyond this, not all food organisms within a given patch of accessible habitat are necessarily available to all species and size-classes of fish. An abundance of food types preferred by one fish does not mean that other fish in the area can use them. The fact that Arctic populations of anadromous fish grow and mature more slowly and cannot spawn in consecutive years clearly indicates that energy is a limiting factor for them (abundance of food notwithstanding). Important supporting evidence has come from fish stomach sampling. Each year of monitoring has found a significant percentage of empty stomachs (Envirosphere, 1987; Envirosphere, 1988d; Envirosphere, 1988e). Given that food organisms, overall, are highly abundant, empty stomachs are a strong indication that food intake is not always high and that food is not effectively unlimited.

In addition to such natural energetic limitations, evidence has been collected through causeway monitoring programs indicating that the causeways have further limited the energy available to anadromous fish. For example, 1985 sampling found that for an abundant year-class of Arctic cisco, the size of individual fish in the Prudhoe Bay area was significantly smaller than that of individuals of the same year class captured outside the area. A smaller size-at-age can result from differential feeding success. The size difference did not reappear in the 1986 sampling, and it is unknown whether these smaller fish were too weak to survive the winter and thus disappeared from the population. However, a large mortality did occur during the winter of 1985-1986 in the Sagavanirktok River (Envirosphere, 1987c). The apparent downward trend to the Sagavanirktok River broad whitefish population may also be a result of a reduction in food availability, either due to a reduction in available habitat or due to competition from other displaced anadromous fish. The dramatic shift in the make-up of the overall nearshore fish community also indicates that feeding opportunities for fresher-water species have been reduced. However, lack of monitoring emphasis on these species limits the ability to determine whether they have suffered population declines.

Consequences of Reduced Energy Intake There are serious ramifications to causeways further limiting the net energy intake potential for the anadromous fish populations. In the immediate sense, fish are at risk of not acquiring enough fat reserves to survive the subsequent overwintering period. A year in which this occurs for some percentage of any population will result in a direct and immediate decline in overall population size by the same percentage. If such a decline is sufficient to overshadow any compensatory mechanisms that may exist, the affected population could take several decades to recover even if no further increase in overwintering mortality were to occur in subsequent years (EPA, 1985).

Significant but less immediate impacts could also occur if conditions in a given year are not so severe that overwintering mortality occurs, but are still severe enough to reduce growth. Only one such year per generation might be necessary to delay the age at which the affected fish reach maturity and spawn. Delayed maturity for a substantial proportion of any of the fish populations also can result in a direct decline in population size; however, it would not become evident until several years later when the affected age-class matures. Again, the population could require several decades to recover even if there were no further effects to other age-classes. Of course, if such conditions were to recur during subsequent generations, recovery would not proceed at all; and if such conditions occurred more than once to a single generation, the intensity of the impact would be multiplied. The same types of effects could result from a reduction in fecundity as well (which also can result from reduced net energy intake and reduced size) even if maturation is not delayed.

Taken together, causeway-induced alterations in circulation patterns, water quality, and ice dynamics - occurring as they do directly within the critical nearshore zone - now make every year more similar to a naturally harsh year. This means that long-term declines in the populations of central Beaufort Sea anadromous fish are likely. Should truly harsh years be in store, catastrophic impacts to these populations - and the fisheries they support - may quickly occur. Given the lack of reliable information on population sizes and the fact that monitoring programs have not been designed to measure population sizes directly, it is possible that significant declines have already begun to occur.

RESEARCH NEEDS

After several years of fairly intensive field investigation, much remains to be learned about the nearshore environment of the Prudhoe Bay area. Research opportunities exist in terms of both oceanographic and fisheries issues.

Now that a reasonable basic understanding exists of the physical processes that dominate in the nearshore zone, it should be possible to accurately model them mathematically. Three-dimensional computer-based circulation modeling has been recommended for adequately describing and predicting impacts of existing and proposed nearshore structures (NOAA, 1988). To be useful, such modeling should be capable of sufficient resolution to simulate local oceanographic processes and interactions, and should possess a sufficient number of internal test points to allow evaluation of a variety of scenarios. In addition, an appropriate model would need extensive calibration and verification using field-collected data prior to implementation. Computer modeling has been applied to Prudhoe Bay area causeway issues in the past; however, it has been highly controversial. True state-of-the-art modeling, thoroughly reviewed and approved by appropriate governmental agencies, should be capable of accurately simulating Prudhoe Bay area conditions. Such a model would prove an important tool for decision-making, but could take several years to fully develop.

In addition to modeling, oceanographic field surveys of the nearshore zone outside the boundaries of the Endicott monitoring program study area are needed. Some study related to offshore oil and gas leasing programs is ongoing, but the level of intensity is far short of what is desirable for site-specific decision-making. In general, much more information about nearshore oceanographic processes and hydrographic conditions across the entire Beaufort Sea coast is needed.

A substantial amount of research remains to be conducted on Beaufort Sea fish and fish populations - much of it basic in nature. Some stock identification work is ongoing, but further work would be important. In particular, an enhanced international effort to identify spawning areas for Arctic cisco in the Mackenzie River basin, and to determine whether discrete spawning populations exist, is needed. Distribution and abundance information for the fresher-water species that appear to have basically disappeared from Prudhoe Bay sampling is important to acquire, and reliable population-level data for all nearshore species would certainly be useful. The latter may continue to be difficult to effectively gather, given the importance of tagging to the effort and the extreme sensitivity of some species to the tagging methods so far employed.

Laboratory study of basic physiological responses of the different fish species (and life history stages) is basic information that is particularly lacking. Some studies have been performed and others are ongoing, but investigation into these areas is in its infancy for Beaufort Sea anadromous fish. Too often, such studies are directed at specific, narrow questions and at the same time the data they generate are interpreted too broadly. It is important that basic physiological and behavioral studies continue, but extreme caution should be exercised in any attempts to directly interpret field observations with limited laboratory data.

The single most important type of data needed, however, is adequate site-specific environmental baseline data concerning any new projects proposed for the Beaufort Sea's nearshore zone. This cannot be over-emphasized. The lack of adequate baseline data has been the most serious limitation to decision-making for Prudhoe Bay area causeways to date, affecting initial permitting decisions, the design of the monitoring programs, the effectiveness of the monitoring, and ultimately decisions about mitigation. Effective and timely decisions can only be made where a basic understanding of the affected environment exists. By conducting several years of intensive monitoring, a basic site-specific understanding of the nearshore Prudhoe Bay environment is now available. Ensuring that it also exists for future construction proposals throughout the nearshore zone of the Beaufort Sea is the best way to ensure that unnecessary and irreparable impacts to the aquatic environment can be avoided.

CONCLUSION

The nearshore estuarine conditions of the Prudhoe Bay area are critical feeding and rearing habitat for many central Beaufort Sea anadromous fish. The West Dock and Endicott causeways have significantly altered the balance of fresh and marine waters throughout this area, fundamentally altering water quality and circulation patterns along as much as 65 kilometers of coastline. The Arctic fish populations affected by these oceanographic changes are already naturally limited by their environment to the extent that they are slower growing and maturing than more southern populations. Causeway-induced habitat changes further limit the ability of these fish to obtain sufficient energy for overwintering survival, growth, and reproduction.

The causeway monitoring programs have been designed around the premise - basic to ecological study worldwide - that suitable habitat is a necessary prerequisite to healthy populations. In addition, such an approach allows mitigation decisions to be made before population-level impacts have already become irreversible, whereas simple monitoring of population sizes generally does not. As a result, post-causeway monitoring programs have not directly measured population sizes for the anadromous fish species of the Prudhoe Bay area and little or no reliable information about population sizes exists. Therefore, claims about there being a lack of evidence for population-level impacts are misleading. It is possible that significant declines are already occurring for some species, and that this is simply going unmeasured. In fact, monitoring programs have identified a variety of indicators showing that this may be the case.

These indicators include: 1) basic changes in the structure of the nearshore fish community to one dominated by marine and relatively salt-tolerant species, with freshwater species having all but diasppeared; 2) reduction in the strength of young age-classes of Sagavanirktok River broad whitefish since 1981; 3) smaller size-at-age for a large cohort of Arctic cisco in the Prudhoe Bay area in 1985, together with evidence that they may not have survived overwintering; and 4) evidence (including stomach sampling) that food organisms are not effectively unlimited.

In effect, the West Dock and Endicott causeways make each year similar to a naturally harsh year, wherein disruption of fish habitat decreases the potential for survival, growth, and eventual reproduction. The probability of population-level impacts is not presently quantifiable, but is believed to be substantial given the variability in weather and oceanographic conditions that can be expected over the life of the causeways. Ultimately, the individual anadromous fish, their central Beaufort Sea populations, and the overall nearshore fish community are at risk.

Eventually, the causeways could seriously harm subsistence and commercial harvests in the Arctic. These fish are also an international resource, supporting subsistence users in both the United States and Canada, and playing an ongoing role in the native cultures of the American Arctic. Restoration of natural nearshore circulation and water quality would be required in order to reduce the risks faced by central Beaufort Sea anadromous fish. In contrast, construction of additional causeways in the area would significantly increase the existing impacts and risks.

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