PHYSICAL PROCESSES AND CRITICAL BIOLOGICAL AREAS IN THE VICINITY OF A PROPOSED PETROLEUM TRANSFER FACILITY

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ABSTRACT

The Northern Tier Pipeline Company proposes to locate a major crude oil transfer facility along the Strait of Juan de Fuca at or west of Port Angeles, Washington. The facility would receive tankers carrying primarily Alaska North Slope crude oil and transport this crude to Midwest refineries via a 1500-mile long pipeline. A portion of the pipeline would pass through the eastern end of the Strait. Most of the critical marine biological areas in the vicinity of the proposed facility are located in the nearshore habitats to the east of the transfer facility site. These areas are highly important to migratory and breeding marine birds, marine mammals, nearshore fishes, and benthic invertebrates. Nearshore currents along the south shore and local winds in the vicinity of the site are frequently from the west, resulting in a probable eastward transport of any oil spills that may occur during the operation of the facility. Thus, though the critical areas are not immediately adjacent to the proposed facility site, they could be affected by oil spilled at the site being transported eastward. Also, the underwater portion of the proposed pipeline passes directly through or very near some critical biological areas. This paper describes and interrelates the major physical processes that would influence the fate of spilled oil and the major biological communities that exist within the influence of the proposed facility.

INTRODUCTION

Increased U.S. energy demands have resulted in ever-increasing volumes of tanker-delivered crude oil arriving at coastal ports. As the volume of crude transported to the United States increases, the likelihood of biological impacts resulting from leaks and spills will also increase. In the Puget Sound area of the northwestern United States (figure 1), crude oil is currently transported through the Strait of Juan de Fuca to four major U.S. refineries. The combined capacity of these refineries is about 300,000 barrels per day. Additional amounts of crude and products are transported to and from other refineries and storage facilities in Canada and Washington.

Tanker transport of crude through the Strait will likely increase as the demand for products increases in the northwestern and midwestern parts of the United States. Also, as the flow of Alaskan North Slope crude through the Alyeska Pipeline increases in the 1980's, all or some portion of that supply will be transhipped and/or refined in the northern Puget Sound/Strait of Juan de Fuca area. Several engineering proposals have been made by petroleum and/or common carrier pipeline companies to receive large volumes of primarily Alaska crude, and either refine it locally, transport it via a new pipeline to the Midwest for refining, or a combination of the two options.

The proposal given tentative approval by the federal government is that of Northern Tier Pipeline Company (NTPC). The proposed petroleum transfer system would involve construction of tanker docking facilities at or west of Port Angeles, nearby onshore storage tanks, and an underwater pipe across the eastern Strait (figure 1). A 1500-mile long pipeline would then carry crude to Midwest refineries. An initial throughput volume of 700,000 barrels per day is planned, eventually increasing to a maximum of about 933,000 barrels per day. Tanker traffic would average about 300 port calls per year initially, eventually increasing to 395. The pipeline system could be expanded to include a spur line to refineries in northern Puget Sound, in which case most or all tanker calls in Puget Sound could be routed to the NTPC docks.¹

A 5-year multidisciplinary research project, titled "An Environmental Assessment of Northern Puget Sound and the Strait of Juan de Fuca," was initiated in 1975 to provide information usable in solving environmental questions pertaining to the increased transport, transfer, or refining of petroleum in the Puget Sound area. The Project was funded by the U.S. Environmental Protection Agency (EPA) and administered by the U.S. National Oceanic and Atmospheric Administration (NOAA). It was not intended to address potential environmental impacts of any specific engineering project. Data were collected by academic, private, and government researchers.

The objective of this paper is to provide a general overview or synthesis of some of the major results of the project and discuss application of the data

Figure 1. Study area and proposed pipeline route.

to the possible marine environmental implications of the NTPC project. The physical/chemical processes that would likely influence the fate of spilled oil and the critical biological communities that could be affected will be emphasized.

PROJECT DESCRIPTION

Since the data used in this report were collected by a variety of researchers using widely differing techniques, only brief descriptions of each research project are presented below for the sake of brevity. Details are available in the technical reports (see References) which resulted from the individual studies. Research projects were implemented which involved physical transport processes, oil spill trajectory modelling, chemical changes of spilled oil, and characterization and distribution of critical marine biological communities. Some projects were nearing completion as of this writing, thus only partial results were available for the respective topics being studied.

The physical oceanography of the Strait was studied over a three-year period. Results available thus far were summarized by Cannon² and Holbrook et al.³ A mathematical oil spill trajectory model was developed for the Strait.^{4,5} Surface drifter experiments were conducted once each in the western Strait,⁶ in the eastern Strait,⁷ and in the vicinity of Port Angeles.⁸ Ebbesmeyer⁹ prepared a synthesis of available oceanographic data for Port Angeles harbor and vicinity.

Existing levels of petroleum hydrocarbons were determined.¹⁰ Feely and Lamb¹¹ determined the distribution of suspended matter and Baker et al.¹² measured the adsorptive capacity of riverine sediments with regard to Prudhoe Bay crude. The

characteristics and rates of microbial degradation of crude oil were determined experimentally.¹³

Manuwal et al.¹⁴ examined the distribution, density, and species composition of marine bird populations and their probable vulnerability to spilled oil. The behavior and distribution of marine mammals were determined.^{15,16} Simenstad et al.¹⁷ developed an overview of the marine food webs that support these animals and their prey. The composition, abundance, standing crop, and feeding habits of nearshore fishes were studied.^{18,19} Epibenthic zooplankton samples were collected once at many of the fish collecting sites.²⁰ Nyblade^{21,22} and Webber²³ characterized the intertidal and shallow subtidal benthic communities.

RESULTS

Oceanographic Processes in the Strait of Juan de Fuca: The net estuarine flow in the Strait of Juan de Fuca is westward toward the Pacific Ocean at the surface and eastward near the bottom. The surface currents in the main channel average 20 to 40 cm/sec and the bottom currents average 5 to 15 cm/sec, varying with season, depth, and location.²

Circulation in the Strait is caused by estuarine flow, tides, and winds. Due to the influence of freshwater runoff, the near-surface water is normally 2-3‰ less saline than the bottom water and forms a longitudinal sea-surface slope directed westward. More saline Pacific Ocean water enters the Strait near the bottom. Diurnal and semidiurnal tides dominate the flow regime over time periods of 4-6 hours, resulting in strong currents (100 to 150 cm/sec) in the main channel of the Strait. Tidal currents exceed 200 cm/sec in

constricted passages.

Winds and storm systems have a major influence on currents, particularly at the surface. In the winter, coastal winds are mostly from the southwest, while those in the western Strait are from the east and those in the eastern Strait are from the south-southwest. In the summer coastal winds are generally from the northwest, those in the Strait mainly from the west.² In the immediate vicinity of Port Angeles, winds are almost invariably from the west. The highest wind speeds at Port Angeles are in July, corresponding with westerly winds throughout the Strait; the weakest are in February and October. South-southeast winds have been recorded in January.⁹

The importance of winds in the transport of surface-water and surface-borne materials was documented with several surface drifter experiments. Drifters launched near Pillar Point in the western Strait in July 1977 predominantly moved south under the influence of a flooding tide and westerly winds.⁶ Strong westerly winds very quickly transported drift cards released in the eastern Strait eastward onshore on Whidbey Island. Cards released in the central and eastern Strait were found along the western Strait and outer coast when easterly winds prevailed.²⁴ During a period of weak and heterogeneous winds, drifters launched in the eastern Strait moved in many directions. Many accumulated over several days near Dungeness Spit.⁷ Iterative trial runs of the oil spill trajectory model predicted westward tracks of simulated oil spills initiated north of Freshwater Bay during easterly winds and eastward trajectories during westerly winds. Easterly trajectories "grounded" on Whidbey Island and in the San Juan Islands.²

While the net surface currents in the Strait are normally westward, an analysis of near-surface current meter data collected in 1976 and 1977 revealed numerous reversal events. During these events, surface currents averaged 25 to 55 cm/sec eastbound and accounted for 35% of the observational period. They appeared to be associated with coastal storms with high southwesterly winds. These strong winds raised the sea level sufficiently offshore to reverse the net westward estuarine surface flow. The result was a net eastward flow into the Strait lasting for 3 to 10 days.² Seven reversals associated with strong south-southwesterly coastal winds were also recorded in the eastern Strait during the winter of 1977-1978. Although these reversals occur more frequently in winter they can occur at any time. A reversal which propagated up-Strait to Dungeness Spit was observed in August 1978. This was confirmed by current meters,³ CODAR observations,²⁵ and surface drifters.²⁶ Satellite infrared photographs (figure 2) of a September 1979 reversal showed a tongue of relatively warm Pacific Ocean water extending eastward into the Strait as far as Protection Island. The temperature differential between warmer ocean water and Strait surface water was about 6-9°C (James Holbrook, U.S. NOAA, personal communication).

Figure 2. Characterization of LANDSAT infrared photograph of the Strait of Juan de Fuca. Dark area = warm Pacific Ocean water; dark hatching = mixing zone; light hatching = cool inland water.

Oceanographic Processes in Port Angeles Harbor and Vicinity:

The shape of both Ediz Hook and Dungeness Spit strongly suggests that accretion of these features has resulted from historical littoral transport of beach materials from sources to the west. Historical oceanographic data and hydraulic model experiments indicate that tidally-induced eddies form in Port Angeles harbor accompanied by weak (~ 1 cm/sec) net eastward flow. Distribution patterns of suspended materials and biological responses to pulp mill effluents indicate a net eastward flow along the shore between Port Angeles and Dungeness Spit.⁹ The majority of the drift sheets and cards recovered following release in Port Angeles harbor were found ashore east of the harbor. Some cards were found as far east as Whidbey and Fidalgo Islands. Winds were westerly during these experiments, as is typical of prevailing winds throughout the year.⁸

Drift cards and sheets released in Port Angeles harbor and dye injections in the eastern Strait hydraulic model (figure 3) clearly show a tendency of surface waters to be transported out of Port Angeles harbor eastward beyond the tip of

Figure 3. Characterization of streak photograph of southeastern Strait of Juan de Fuca hydraulic model on flooding tide (after Ebbesmeyer et al., 1979). Inset shows tidal phase of photograph.

Dungeness Spit. Dye injections also show that a large clockwise tidal eddy forms southeast of Dungeness Spit on flood tides, affecting the entire area bounded by Dungeness Spit, Jamestown and Miller and Quimper Peninsulas. A less-structured counter-clockwise eddy forms during some ebb tides.⁹

Processes Influencing Chemical Fate of Oil: Very low concentrations of petroleum hydrocarbons were found associated with suspended matter,¹² intertidal sediments, and mussel tissue.¹⁰ Individual aromatic hydrocarbons rarely exceeded 10 ng/g dry weight of sediments collected in maritime harbors or near refineries and were either nondetectable or less than 1 ng/g dry weight in areas distant from cities, harbors, or refineries.

In laboratory conditions simulating those of the study area, microbial degradation of crude oil failed to take place after 28 days. With elevated (above ambient) nutrient levels and temperatures about one-third of the oil was degraded by microorganisms, one-third weathered by physical/chemical processes, and one-third remained as a residue.¹³

Suspended sediment particles that enter the region's marine waters from rivers are highly efficient in sorbing oil, accommodating and coprecipitating up to their own weight in oil under controlled laboratory conditions. During an oil spill, this process would only become significant in areas where suspended sediments were concentrated. The lowest suspended sediment concentrations encountered by Baker et al.¹² were in the open water of the Strait. Though no measurements were made near-shore, suspended sediment concentrations would likely be higher there.

Distribution of Critical Biological Communities:

Densities of marine birds were determined by numerous censuses along the shoreline of the Strait. Densities were, then, projected mathematically to the areas represented by standardized subregions (figure 4). Projected total counts were greatest, by far, in the Jamestown area (subregion 0307), especially during the fall and winter when gulls, ducks, geese, and other diving birds were very abundant. Projected totals were also relatively high at Cape Flattery (0203) in summer, Vancouver Island (0202) in fall, and southern Lopez Island (0316) in fall. Protection Island was identified as the most important site for breeding birds, especially for Rhinoceros Auklets (figure 5). Pelagic Cormorants, Black Oystercatchers, Glaucous-winged Gulls, Pigeon Guillemots, and Tufted Puffins also breed on Protection Island. Of the 30,000 breeding pairs of birds counted in the Strait and northern Puget Sound in 1978, about 23,000 were found in the eastern Strait region, including over 19,000 found at Protection Island. The species of ducks, geese, alcids, and other diving birds found in the Jamestown/Protection Island area are known to be highly susceptible to the effects of spilled oil.¹⁴ Second-year (1979) data, not yet published, are very similar to those of 1978.

Figure 4. Projected total counts per region per season for marine birds in the shoreline habitats of the Strait of Juan de Fuca surveyed in 1978 (from Manuwal et al., 1979). Open water counts are excluded. (*No observations made.)

The eastern portion of the Strait was observed to have the majority of the harbor seals (*Phoca vitulina*) censused in the study area (figure 6). Highest counts were made for standard regions 1, 2, 5, 8, and 15. Regions 5 (Smith-Minor Islands) and 8 (Protection Island) were the smallest delineated by the authors, yet average counts there were among the highest encountered. Smith-Minor Islands, Dungeness Refuge, and Protection Island were among the most important sites for pupping.^{15,16}

Northern sea lions (*Eumatopias jubatus*) and California sea lions (*Zalophus californianus*) were very abundant (>300 individuals) at Race Rocks on Vancouver Island in the winter. Killer whales (*Orcinus orca*) frequently travel through the eastern Strait, Admiralty Inlet, and passages through the San Juan Islands in at least four identifiable pods, comprising together a total of about 80 animals.¹⁵

Though marine birds and mammals could be adversely affected directly by oil port construction and oil spills, they also could be threatened by loss of or reduction in prey. Simenstad et al.¹⁷ estimated that 68% of the marine bird species in the study area use fish or benthic invertebrates as principal prey; the remainder are planktivorous, herbivorous, omnivorous, or scavengers. They found that 54% of the bird species feed primarily in the protected shallow sublittoral, salt marsh, and mud-flat habitats; the remainder feed in open neritic water, on exposed sand or rock beaches, or universally. Manuwal et al.¹⁴ found loons, grebes, cormorants, ducks, geese, shorebirds, gulls, and

Figure 5. Summary of Strait of Juan de Fuca breeding pairs of marine birds (from Manuwal et al., 1979). *Breeding colonies known to exist, but not quantified.

alcids most abundant in the Strait, particularly in the sublittoral zones and protected embayments. Simenstad et al.¹⁷ showed that these species feed primarily upon benthic invertebrates (bivalves, crustaceans, and polychaete annelids), fish eggs, baitfish (herring, sand lance, smelt), cottids (sculpins), embiotocids (perch), eelgrass, and marsh plants. They also found that in shallow nearshore areas the harbor seals (*Phoca vitulina*) feed primarily upon demersal fishes and benthic invertebrates, including pleuronectids (flatfish), scorpaenids (rockfish), embiotocids (perch), cottids (sculpin), gadids (cod), shrimp, and octopus. A minor amount of baitfish and salmonids are also consumed.

Species richness, biomass, and total abundance of nearshore demersal fishes were often greatest in beach seine samples collected in protected habitats, particularly at Beckett Point in the mouth of Discovery Bay. Fish catches at exposed sampling sites usually were low. However, infrequent capture of schooling smelt or herring occasionally resulted in high-biomass, high-density data for these sites. Beckett Point beach seine catches were consistently high and included pleuronectids, scorpaenids, embiotocids, cottids, gadids, and a large variety of epibenthic macroinvertebrates.

Fish densities at Jamestown were also among the highest of the sites sampled.¹⁹

Demersal species, such as the cottids and pleuronectids caught in beach seines, are highly dependent upon epibenthic organisms, mostly small crustaceans such as harpacticoid copepods and gammarid amphipods, for food. These organisms are, in turn, dependent upon a detrital food base, and thus, are most concentrated in or upon nearshore sediments where algal, eelgrass, and saltmarsh debris accumulate.¹⁹ Along the Strait these detrital-based food webs appear to be most important in protected embayments where eelgrass beds exist or which act as accumulation zones for detrital particles.¹⁷ For example, at Beckett Point demersal fish species richness was highest and, as will be shown below, benthic infaunal and epifaunal communities there were highly productive.

Epibenthic zooplankton collected once at six sites along the Strait were most dense and provided greatest biomass in eelgrass beds in the protected areas of Port Williams and Beckett Point, exceeding all other sampling sites by at least an order of magnitude in both categories (figure 7). The majority of the taxa were amphipods, polychaetes, gastropods, isopods, and copepods in order of decreasing importance. Gammarid amphipod species richness was greatest in eelgrass at Port Williams,

Figure 6. Average combined counts of adult and pup harbor seals (calculated from monthly aerial censuses) for 15 regions surveyed in 1977-78 and 1978-79 (from Everitt et al., 1979, 1980).

where 21 species were found; and lowest at Twin Rivers and Kydaka Beach, where 5 species were found. Simenstad et al.²⁰ concluded that the eelgrass habitats of the Strait, such as those found at Port Williams and Beckett Point, are highly productive in terms of prey species of nearshore demersal fishes, in many cases, much more productive than other temperate marine nearshore areas for which similar data exist.

Analyses of intertidal and shallow subtidal benthic samples collected by Nyblade^{21,22} along the Strait showed that exposed rock, exposed cobble, and protected mixed mud habitats were generally highest in species richness, biomass, and density. These parameters were consistently lowest in exposed sand and gravel habitats. Organism abundance in intertidal and subtidal samples was often the highest among the sites sampled at Jamestown and Beckett Point, though biomass was low since many of the organisms found there were relatively small bi-valves, annelids, and crustaceans. Since many of the organisms found at exposed rock and cobble sites (e.g., Tongue Point, Morse Creek) were large and dense, biomass was often high for samples

Figure 7. Total density of epibenthic zooplankton at six nearshore sites along the Strait of Juan de Fuca. Mean densities in 11 microhabitats are designated by triangles; means and standard deviations at sites are designated by circles and vertical lines, respectively. Note log scale. (From Simenstad et al., 1980.)

collected in these habitats. Coarse sand/gravel beaches on Whidbey Island supported considerably fewer organisms than the cobble beach at Point Partridge.²³

DISCUSSION AND CONCLUSIONS

The objectives of this paper were described above as development of an overview of the physical/chemical fate of oil spills possibly resulting from the operation of the proposed NTPC facility and identification of critical biological areas that could be affected. These objectives were to be satisfied by an examination and synthesis of an extensive data base collected during a five-year multidisciplinary research project. While the results of the project by no means provide answers to all possible questions concerning the environmental impacts of the NTPC proposal, they do provide a basis for making certain conclusions.

Several alternative sites (at Ediz Hook or west) currently are under consideration for siting the NTPC port facility. Only one basic route for the underwater and overland pipeline has been proposed. Oil spills and/or leaks could occur anywhere in the system. However, those that might occur at the tanker dock facilities and along the submarine segments of the pipeline would pose the greatest threat to the marine system. Thus, within the study area, spills or leaks occurring near the shore at or west of Ediz Hook, between Ediz Hook and Green Point (assuming the port facility is located at Ediz Hook), between Port Williams and the vicinity of Protection Island, and between the vicinity of Protection Island and Point Partridge would be of greatest concern.

Partial loss of tanker cargo caused by accidents in transit or at berth could result in spills of widely varying volumes. Total loss of a tanker could result in a spill of over 2 million barrels of oil.²⁷ Total potential spill volumes of 12,000 to 25,000 barrels could be expected from segments of the submarine pipeline.²⁸

A wide variety of shoreline habitats occur along the Strait, ranging from exposed rock to sand and gravel beaches to protected mudflats. Each habitat type supports a biological community of a certain structure and range in productivity. Each is represented at numerous geographic locations. The available quantitative data strongly indicate that the rocky habitats and adjacent waters of the far western Strait and the protected mud and mixed coarse habitats and adjacent waters of the Dungeness Bay/Jamestown/Protection Island/Sequim Bay/Discovery Bay area are highly important biologically.

Marine bird populations in the Cape Flattery/Tatoosh Island subregion are among the most dense in the study area. It is second most important as a breeding colony site, following Protection Island. Tens of thousands of marine birds often occur in late summer and early fall in the open water over Swiftsure Bank and in the western Strait. Biomass of epibenthos on rock habitats at

Cape Flattery, between Slip Point and Pillar Point, and between Tongue Point and Observatory Point (as represented by data from Pillar Point and Tongue Point) are very high. These areas could be affected by oil spilled locally (in the western Strait) due to tanker-related accidents or spills resulting from a port facility, if located nearby. However, nearshore currents along the southern Strait are often eastward and would tend to carry oil spilled, say near Slip Point eastward away from the Cape Flattery area. Oil spilled offshore (e.g., over Swiftsure Bank) or in the northern sector of the western Strait could be carried ashore at these biologically-important areas by westerly winds, particularly during storm-associated surface current reversals.

Microbial degradation and sedimentation of spilled oil in the open waters of the western Strait would likely proceed slowly. However, wave action in exposed areas would aid in weathering of oil. Exposed rocky habitats would not likely retain oil because of their steep slope, the tendency of waves to refract off vertical rock formations, and the vigorous cleansing and mechanical weathering action of waves.²⁹ Thus, though the western Strait may become oiled by a spill, the important attached biota associated with rock habitats may suffer relatively minor, or, at least, short-term effects.

The nearshore habitats in the eastern Strait protected by Dungeness Spit are highly important to prey groups such as birds, mammals, and fish. The marine bird populations there are the largest along the Strait and rivaled in density (birds/km²) by only Smith Island (also in the eastern Strait) and Cape Flattery. Many of the species found in this region are known to be susceptible to the effects of oil. Harbor seals are very abundant at Protection Island. The largest population of breeding birds in the study area is also located at Protection Island. Nearshore demersal fish communities at the mouth of Discovery Bay are among the most dense observed in the study area. Though these predator groups are highly visible and important, the abundant prey populations and the geomorphology of the region are possibly of greater ecological significance.

Detrital-based food webs may be most susceptible to the effects of oil in the study area, and detritivores are the major prey group that supports the higher trophic level species. The epibenthic planktonic organisms that graze mostly on detrital material are closely associated with or burrow into the bottom sediments. These organisms, particularly gammarid amphipods and harpacticoid copepods, are most concentrated in the protected habitats, such as the mud, mixed coarse, mud/eelgrass, sand/eelgrass and saltmarsh environments, found southeast of Dungeness Spit. They also constitute the largest prey group for nearshore fishes and some birds. For example, harpacticoid copepods are a major prey item for juvenile salmonids. The incorporation of hydrocarbons into fine-grained sediments and detrital particles and their subsequent sedimentation could result in prolonged uptake and recycling of persistent

compounds through the detritus-decomposer-detritivore food webs. Oil sorbed to suspended matter could be transported to and trapped in the low-energy depositional zones behind Dungeness Spit.

The mudflats there would tend to trap and retain oil. Receding tides would tend to layer floating oil upon exposed mudflats. Weak wave action in this protected area would provide little cleansing or mechanical weathering action.²⁹ Numerous crustacean and mollusc burrows would facilitate penetration of oil to considerable depths in the sediments. Benthic invertebrates and epibenthic zooplankton, including those that may repopulate areas previously stressed by water-column hydrocarbons, would be exposed to oil-contaminated habitats and food. The effects of oil, then, could include severe losses to important prey species, the impacts of which could be felt at higher trophic levels. As opposed to the situation at exposed, rocky shores, the effects of oil in protected habitats such as exist in the lee of Dungeness Spit, could be very long-lasting.

Spilled oil could reach the region southeast of Dungeness Spit via a variety of routes. Obviously, ruptures or leaks of pipeline segments traversing the region would immediately affect it. Tidally-induced eddies that form between Dungeness Spit, Miller and Quimper Peninsulas would tend to spread floating oil throughout the region. Very little is known of subsurface currents there; it is possible they behave the same as surface currents. Ruptures or leaks of the submarine pipeline under considerable pressure would likely result in surfacing of some, or most, of escaping oil.

Oil spilled at or west of Port Angeles could affect the region behind Dungeness Spit, and, under certain meteorologic conditions, very quickly. Summer westerly winds along the western Strait could transport floating oil eastward. Surface current reversals during (mostly winter) storms could transport oil eastward along the entire south shore of the Strait. Transport times of 2-3 days from Cape Flattery to Protection Island are entirely possible. Northerly transport of surface currents was never observed in the western Strait, whereas southerly components to eastward and westward transport were often recorded.

Oil spilled at Ediz Hook or between it and Green Point would likely be dispersed over much of the surface of the Port Angeles harbor and vicinity by winds and tidally-induced eddies. The natural surface spreading of spilled oil and transport caused by surface currents and prevailing westerly winds would likely result in oil exiting the harbor. Oil exiting the harbor would be subject to the eastward littoral drift in the area between Ediz Hook and Dungeness Spit. This littoral drift appears to form as a backwash of the predominantly westward surface flow of the main channel of the Strait, and, though relatively weak, often results in transport of floating and suspended materials toward and beyond Dungeness Spit. Surface drifter experiments initiated inside Ediz Hook almost invariably resulted in trajectories to the shore

east of the release site, often ending on or eastward beyond Dungeness Spit. Thus, oil exiting the harbor could be transported to the critical biological populations on and behind Dungeness Spit. That portion of surface-borne oil that might move beyond the Spit would be subject to dispersal by tidally-induced eddies that form there and deposition in the low-energy hydrographic regime.

Oil spilled in the far eastern Strait could go most any direction. Oceanographic observations, surface drifter experiments, and trajectory model runs conducted there have provided highly variable results. Rapid surface trajectories eastward to Whidbey Island, westward out the Strait, southward to Dungeness Spit, and northward to the San Juan Islands and eastern Vancouver Island have been observed. Entrainment of oil in deeper water column strata due to downwelling and vertical mixing in Admiralty Inlet could occur, resulting in transport at depth into the Puget Sound main basin. Smith Island and southern Lopez Island and adjacent rocks, critical areas for marine birds and mammals, could be endangered by northerly and westerly trajectories of spills in the eastern Strait. Critical habitats in the Dungeness Spit/Protection Island area and biota in the Puget Sound main basin could be threatened by southern and western trajectories of surface spills in this area. Oil spilled near the sediment/water interface in the eastern Strait would most likely be transported southeastward through Admiralty Inlet with incoming Pacific Ocean bottom water. Its likely fate in the main basin of Puget Sound is unknown, though subsequent resurfacing is possible.

The winds, tides, and currents combine in a complex set of along-channel and cross-channel transport possibilities for spills in the Strait. The chances of spilled oil exiting the Strait to the Pacific Ocean without beaching decrease as the hypothetical point of entry is moved eastward into the Strait. The southward and northward components of any spill trajectory scenario would tend to transport oil ashore. Thus, though the exact trajectory of a spill would be difficult or impossible to predict, fouling of Canadian and/or U.S. beaches is a strong possibility, especially so if oil entered the system in the eastern Strait. It is highly likely that if a spill were to occur in the study area, marine organisms would be exposed quickly to relatively unaltered oil following initiation of the spill event and that the oil would remain unaltered for a relatively long time, especially in protected areas. The most important biological communities and those also most susceptible to long-term effects of oil are located along the south shore of the eastern Strait, particularly in the region protected by Dungeness Spit. The chances of a spill not adversely affecting these communities, thus, also decrease as a hypothetical point of entry is moved eastward into the Strait. However, important meteorological/oceanographic conditions frequently occur, especially during the winter, which could result in rapid surface transport of oil spilled in the western Strait to these communities.

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