UNITED STATES
DEPARTMENT OF THE INTERIOR
GEOLOGICAL SURVEY

SOME POTENTIAL EFFECTS OF SPILLED PETROLEUM ON SHORELINES OF THE PORT TOWNSEND QUADRANGLE, CENTRAL PUGET SOUND REGION, WASHINGTON

by

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U. S. Geological Survey

OPEN FILE REPORT

80-724

This report is preliminary and has
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INTRODUCTION

Waterborne transport of crude oil into the Puget Sound region (fig. 1) has increased rapidly since 1972, and may take another sharp increase during the next few years. In 1972, waterborne delivery of petroleum averaged 45,000 bpd (barrels per day); by 1974 the average had increased to 105,000 bpd (Pizzo and others, 1978, p. 19). Thus far, most of the incoming petroleum has been used to meet regional needs; presently however (1980), proposals for crude-oil transshipment ports in this region, with pipelines connecting to the midwestern U.S., are being evaluated. If an oil transshipment facility is constructed, the future volume arriving at local ports could be as much as 1.3 million bpd (U.S. Bureau of Land Management, 1979, p. 1-1).

With increasing delivery of oil, there exists an increasing risk of spills. Effective evaluation of the risk includes identification of (a) those parts of the coast that are most likely to be reached by spilled oil, and (b) those that would be most adversely affected by a spill. This study examines the second of these aspects, some relative impacts of a spill. Geologic setting, coastal processes, and sediment characteristics of local shorelines are used to determine which shore segments are susceptible to accumulating and retaining spilled petroleum and which might cleanse themselves relatively quickly through natural processes. The map presents a numerical ranking of various coastal segments with "1" being the lowest and "10" the highest susceptibility to accumulation and retention of spilled petroleum. These numbers are keyed to table 1 where both the type of coastal setting and the factors which determine susceptibility are summarized. The accompanying text elaborates on the information in table 1 by presenting brief discussions on the behavior of spilled petroleum as influenced by geology and coastal processes. These descriptions, which involve a minimum of technical terms (explained where used), are provided for non-scientists who may be (a) responsible for making energy-facility siting decisions, (b) engaged in oil-cleanup operations, or (c) involved in coastal zone planning and management. Technical references are given for the reader interested in scientific studies dealing with various aspects of petroleum spills.

This study provides part of the information needed for a comprehensive assessment of the potential effects of a major petroleum spill. A number of related studies focus on other aspects of potential spills in this region; examples include: (a) Statistical analysis of spill risk (Oceanographic Institute of Washington, 1978), (b) oceanographic data gathering on water circulation and mixing leading to modeling of spilled-oil movement (Cannon, 1978), (c) collection of biological background or "baseline" data which allows characterization of different coastal habitats prior to a spill (Gardner, 1978; and Nyblade, 1978), and (d) behavior of spilled petroleum when mixed with suspended sediment in marine waters (Baker and others, 1978). Such studies by various specialists individually contribute to a complete evaluation of potential spill damage; in that context, this map complements previous and ongoing investigations. This is one of a

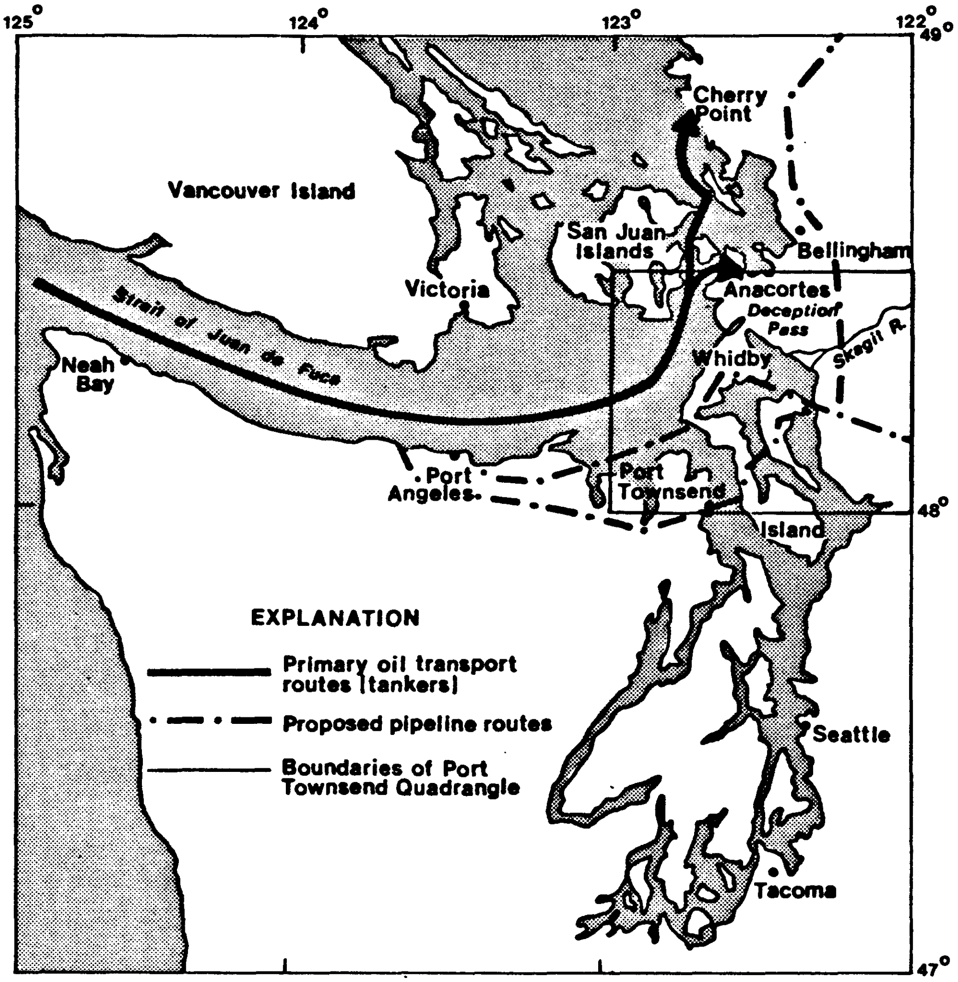

FIGURE 1.--Location map of the Puget Sound region showing proposed pipeline routes, primary oil-tanker routes, and boundaries of the Port Townsend quadrangle.

TABLE 1.--Ranking of coastal susceptibility to spilled petroleum (from Hayes and others, 1976; Gundlach and Hayes, 1978a)

Vulnerability Index number	Coastal setting	Principal oil accumulation, retention, and cleanup considerations
1	Cliffed, rocky shores with high wave energy	a) Oil tends to be held slightly offshore by wave reflection from cliffs. b) Oil is less likely to adhere well to wave- and spray-wetted surfaces. c) Horizontal surfaces and sediment on(in) which to accumulate oil are lacking. d) High wave energy promotes cleansing and dispersal of oil.
2	Eroding wave-cut platforms (typically found in high-wave-energy settings)	a) Impermeable surface and lack of a thick sediment cover helps prevent heavy oil accumulation. b) Thin sediment veneer, if present, is regularly moved and abraded which helps remove deposited oil.
3	Hard-packed, fine sand beaches (typical of oceanic coasts)	a) Penetration of oil usually limited to upper few centimeters. b) Oil burial is less rapid, and often not as deep as on coarser beaches.
4	Medium to coarse sand beaches	a) Percolation of oil is moderate (usually less than 10 cm). b) Oil burial is a potential cleanup problem but not as severe as on V.I. 6 and V.I. 7 beaches.
5	Relatively compact, sandy tidal flats (typically bordered by beaches)	a) Deep penetration of oil not common. b) Higher wave and current energy tends to move oil onto bordering beaches. c) Can accumulate heavy oil coating if extensive oil slicks repeatedly ground on the tidal flat.
6	Mixed sand, gravel, and cobble beaches	a) Significant oil percolation into sediment (20 cm is common). b) Burial of stranded oil can occur rapidly. c) Potential for reexcavation and transport of oil to other areas.
7	Gravel beaches	a) Deepest oil percolation of all sediment types (40-50 cm not uncommon). b) Burial of deposited oil is a very common occurrence. c) Potential for reexcavation same as V.I. 6 above. d) Difficult to clean because of large volume of sediment to be handled when deep percolation and burial occur. e) Percolation and burial encourages formation of asphalt-like deposits.
8	Low energy, rocky shores	a) Lack of wave reflection and spray-wetted surfaces allows oil to cling more readily. b) Lack of wave energy allows enhanced persistence. c) Difficult to clean long stretches of affected shoreline.
9	Protected, muddy estuarine tidal flats	a) High potential for biologic damage. b) Extremely difficult to clean because of poor load-bearing characteristics. c) Long residence time for petroleum-contaminated interstitial water.
10	Salt and brackish marshes, lagoons, and very low energy inlets	a) High potential for biologic damage. b) Very low wave and current energy does not promote natural cleanup. c) Vegetation available to trap and hold floating oil. d) Fine-grained sediment does not release hydrocarbons readily.
m	Artificial and highly modified shorelines (industrialized zones, boat basins, etc.)	a) Effects variable or unknown.

series of studies being made by the U.S. Geological Survey to present earth-science information and interpretations to assist land-use planning, resource development, and environmental protection in the Puget Sound region.

THE SHORELINE RANKING SYSTEM

To date (1980) petroleum spills into local waters have been small (less than 6000 barrels), have affected only short stretches of coast, and have not reached sensitive environments such as tidal flats. Therefore, the ranking of local shoreline susceptibility to spill damage cannot be based on experience with local oil spills; rather, it is based on some of the best-studied major spills in other regions where the coastal environments are similar to northwest Washington. Such similarity provides an opportunity to use observations of shoreline-petroleum interactions at previous spills to predict likely effects in this region. Spills that appear to have the most transfer value to this region are listed in table 2.

The shoreline ranking system used in this study closely follows the "vulnerability index" (V.I.) published by M.O. Hayes and his colleagues (Hayes and others, 1976, p. 83-85; Gundlach and Hayes, 1978a). This index is primarily based on geologic and physical characteristics of various coastal settings, although it does include biologic aspects in a very general way. The physical, geologic, and cleanup considerations include: (a) Geomorphic setting (e.g., sheer rock cliffs as compared to tidal flats), (b) the presence or absence of sediments in which to accumulate petroleum, (c) sediment texture, (d) wave energy, (e) persistence of petroleum in a given setting as observed during study of previous spills, and (f) constraints imposed by various shoreline types when artificial cleanup is attempted.

The generalized biologic consideration included in the ranking recognizes that certain coastal environments are not only susceptible to slow natural cleanup of pollutants in a physical sense, but typically are biologically rich and diverse habitats. For example, salt marshes are one of the most valuable coastal resources, often serving as nursery areas for the larval and juvenile stages of organisms. The low wave and current energy, and the abundance of aquatic vegetation, which make marshes a favorable habitat, also make them very susceptible to entrapment and accumulation of pollutants; hence, the high ranking (10) in the vulnerability index.

In addition to the 1-10 ranking originally used by Hayes and others (1976, p. 83-85), an eleventh category has been used on this map. This category is designated by the letter "m", indicating highly modified shoreline segments where the behavior and persistence of spilled petroleum are largely unknown or highly variable. These segments include industrialized areas with docks, artificial fill, boat basins, jettys, shore-defense structures, and other areas where little or no natural shoreline remains.

Data for this map were collected through detailed field study of the shoreline by the author and M.J. Chrzastowski. The map scale (1:100,000) has required some generalization of that detail; thus some short coastal segments (less than 150 meters long) may have conditions at variance with the ranking number displayed. Additionally, some shoreline segments have conditions which allow more than one V.I. number to be applied; a mixed-sand-and-gravel beach (V.I. 6) fronted by a sandy tidal flat (V.I. 5) is one example. In such areas, both numbers are displayed where the map scale permits separate delineation of each element; only the higher number is shown where the scale does not allow both.

TABLE 2.--Moderate-to-large petroleum spills affecting coastal environments similar to northwest Washington

essel	Year	Location	Type of petroleum	Estimated spill volume (metric tons)	Shoreline affected	Most similar elements of coastal environment	References
LORIDA barge)	1969	Cape Cod, Massachusetts	Number-2 fuel oil	600-640	?	a) Wave energy b) Air and water temperature c) Coastal sediments derived from erosion of glacial deposits	Blumer and others, 1971; Blumer and Sass, 1972b; Sanders, 1977; Burns and Teal, 1979
RROW	1970	Chedabucto Bay, Nova Scotia	Bunker-C fuel oil	15,000	300 km	a) Wave energy (seasonally) b) Water temperature (seasonally) c) Coastal geomorphology and sediments similar to San Juan Islands; (mixed rock and unconsolidated deposits; glaciated, embayed shoreline)	Owens and Drapeau, 1973; Owens and Rashid, 1976; Vandermeulen, 1977; Keizer and others, 1978
ETULA	1974	Strait of Magellan	Light, Saudi Arabian crude	47,000 (18,000-36,000 tons on shore)	150 km	a) Wave energy b) Water temperature c) Tidal range d) Coastal geomorphology and sediments similar to southeastern part of the Port Townsend quadrangle (coarse-grained beaches derived from eroding glacial deposits)	Hayes and Gundlach, 1975; Gunnerson and Peter, 1976; Blount, 1978
RQUIOLA	1976	Northwestern Spain	Persian Gulf crude	100,000 (23,000-27,000 tons on shore)	215 km	a) Wave energy b) Water temperature c) Tidal range d) Sheltered, embayed marsh settings e) Ria shoreline (drowned river valleys) similar to fjord-like Puget Sound system	Gundlach and Hayes, 1978a; Gundlach and others, 1978
MOCO CADIZ	1978	Northwestern France	Light, middle-eastern crude	200,000 (58,000 tons on shore)	390 km	a) Wave energy (partly) b) Water temperature c) Embayments and estuarine tidal flat-marsh complexes	Gundlach and Hayes, 1978b; Gundlach and Hayes, 1978c

The seaward extent of tidal flats is delineated on the map by the minus-one-meter depth countour, which is approximately the lowest water level during spring tides. Although most maps show the seaward extent of the intertidal zone to be the Mean Lower Low Water line, significantly more tidal flat area is exposed during spring-low tides (especially at deltas); thus, use of the minus-one-meter contour more accurately reflects the potential surface area that is frequently available for oil deposition.

SPILLED PETROLEUM IN COASTAL ENVIRONMENTS

Studies of spilled petroleum reaching shorelines in various parts of the world have shown that: (a) Marine sediments act as sinks that accumulate spilled oil (Blumer and Sass, 1972a; Meyers, 1976; Vandermeulen, 1977, p. 35); and (b) sediment type, geologic setting, and wave energy largely determine the susceptibility of a given shoreline segment to accumulating and retaining petroleum (Owens and Rashid, 1976; Gundlach and Hayes, 1978a). Spill volume and physical properties of the oil are other major factors influencing oil accumulation and retention. The combination of all these factors also determines how completely a shoreline can be artificially cleaned after a major spill without causing long-term environmental damage.

Shorelines With Beaches

When floating oil reaches a shoreline, the oil begins to be affected by a set of processes different from those in open water. Observations by Galt (1978, p. 16) and Hann (1976a, p. 15) indicate that incoming waves produce and hold thickening pools of oil against the beach face (as depicted in figure 2). If the pool held against the beach is narrow, oil is deposited in a band along the high tide level as the tide recedes. However, when the pool is wide (fig. 2), the trapped oil settles over the entire intertidal zone as the tide falls (fig. 3). In addition to this direct settling, oil left stranded on the upper beach commonly drains down the beach face and collects in pools on the low-tide terrace (fig. 3). Initially, oil grounded in the lower intertidal zone is refloated with each rising tide. Thus, there is only intermittent oil-sediment contact in the lower intertidal but contact is continuous at the high-tide level. This produces uneven oil distribution on the beach with the heaviest deposition commonly found around the high tide level (Galt, 1978, p. 16-18; Gundlach and Hayes, 1978b, figs. 4-35 and 4-39). After repeated groundings at low tide, the oil begins to bind with sediment in the lower intertidal zone and does not refloat (Gundlach and Hayes, 1978b, p. 113, 190). This binding provides a mechanism for oil deposition throughout the intertidal zone.

Repeated observations of petroleum spills on beaches show three principal modes of oil accumulation: (a) Mixing with and percolation into beach sediment as part of the initial deposition (Hann, 1976b), (b) burial of stranded oil by transported sediment (Hayes and others, 1976, p. 77-79), and (c) binding of weathering oil and sediment into asphalt-like deposits (Blount, 1978, p. III-13; Owens and Rashid, 1976, p. 921-926; Keizer and others, 1978, p. 530-531).

Oil percolation into beaches is mainly controlled by spill volume, oil viscosity, and beach-sediment texture. For oil of a given viscosity, far less penetration of a fine sand beach would be expected than of a beach composed only of coarse gravel. Exactly these conditions were observed by Owens and Rashid (1976, p. 914) and Gundlach and Hayes

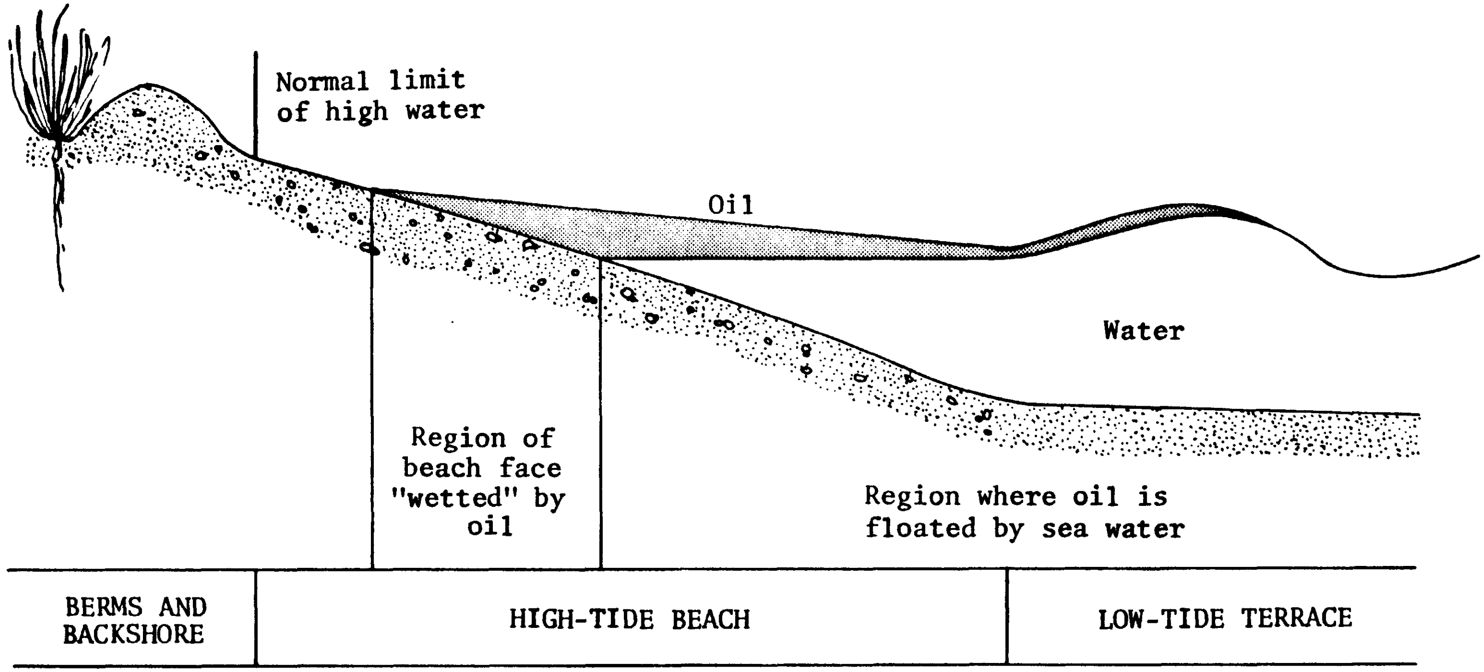

Figure 2.--Pool of oil being trapped and held against the beach by incoming waves at high tide (modified from Galt, 1978, p. 16).

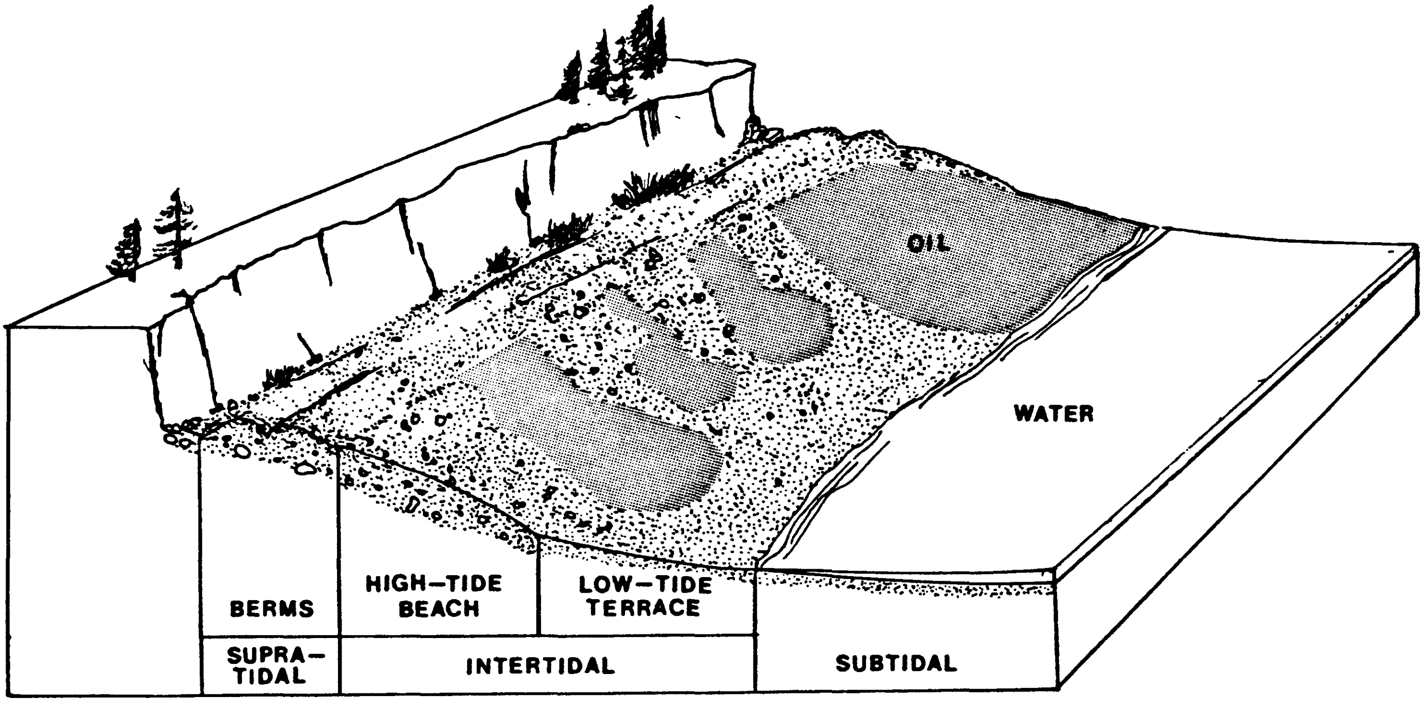

FIGURE 3.--Diagrammatic view illustrating beach features and distribution of petroleum. Oil is deposited not only on the highest part of the beach face, but can be deposited across the intertidal zone as the tide falls. At low tide, oil can flow down the beach and collect on the low-tide terrace.

(1978a, p. 19-22), who found that petroleum penetrated more than 0.5 m (meters) into gravel and cobble beaches, 10-20 cm (centimeters) into mixed-sand-and-gravel beaches, but was confined to the upper few centimeters on fine sand beaches. A common spill phenomenon which greatly increases the depth of oil percolation is the formation of water-in-oil emulsions (commonly called "mousse"). These mixtures form most readily from crude oil and water in the surf zone and, once formed, can be quite stable--that is, they do not readily separate into the original oil and water components. Hann and others (1978, p. 234-243) found the water content of mousse at the Amoco Cadiz spill to range between 20 and 90 percent, values around 70 percent were very typical. The high water content of mousse greatly increases the volume of the spill and the diluted mixture is less viscous than the original oil so it more readily percolates into sediments.

Burial of stranded oil by beach sediment is a commonly observed phenomenon (Owens, 1978, p. 566-568); Gundlach and others (1978, p. 137) report burial as deep as one meter, far deeper than the typical percolation depths cited above. Burial occurs more rapidly and commonly is deeper in gravel or mixed-sand-and-gravel beaches, which are abundant in the Puget Sound region, than on hard-packed, fine-sand beaches. Sediment moving either in a longshore direction or an offshore-onshore direction may contribute to oil burial. Beaches go through short-term cycles of erosion and deposition; these cycles can be biweekly (neap tide-spring tide cycle), aperiodic (storm-nonstorm cycle), or yearly (winter-summer cycle). The erosion-deposition effect is particularly pronounced during the winter storm season in the Pacific Northwest. Observations from summer to winter by the author and by J. Spasari (Western Washington University, written communication, 1978) show a 1-2 m lowering of some beach surfaces in the eastern Strait of Juan de Fuca during major winter storms. Thus, if oil were deposited on these coarse-grained beaches (mixed sand, gravel, and cobble) soon after a winter storm, there could be 10-50 cm of percolation plus an additional 1-2 m of burial under the rebuilding beach by the following summer. Burial of stranded oil often leads to reports of beaches being clean of oil soon after a spill when, in fact, the oil deposit will reappear with the next episode of sediment removal.

Asphalt-like mixtures of weathering oil and sediment (fig. 4) form during the weeks and months following a spill rather than during initial oil deposition. As petroleum weathers, the lighter, chemically less complex molecules evaporate, dissolve, and are metabolized by microorganisms. The residual material thus becomes relatively enriched in the heavier, more complex, tarry fractions over an extended period of time. (See complete discussions in Blumer and others, 1973; Clark and MacLeod, 1977, p. 102-134). Asphalt formation occurs where significant quantities of crude oil (or heavy distillates such as bunker-C) remain in the sediment, as at spills where there is no artificial cleanup, where cleanup was incomplete, or where percolation and (or) burial were deep. These petroleum deposits allow reexcavation and transport of oil to nearby areas and they provide a source for slow, continuous contamination of the intertidal sediment. The latter effect was reported by Vandermeulen and Gordon (1976); they found highly elevated concentrations of hydrocarbons in beach ground water more than five years after a spill due to leaching from sediment-bound, weathering oil. They suggest that this route--percolation through beach ground water--is the primary pathway for reintroduction of hydrocarbons into the water column. Thus, asphalt-like deposits cannot be considered as inert accumulations that are sequestered from the environment; rather, they are reservoirs for continuous pollution of the intertidal zone.

FIGURE 4.--Eroded margin of an asphalt-like deposit of sediment and weathered, light-crude oil. Beach material is mixed sand, gravel, and cobbles; scale is 30 cm. (photo courtesy of E.H. Owens)

Rocky Shorelines

Three types of rocky shoreline settings are distinguished on the basis of shoreline interaction with spilled petroleum: (a) High-wave-energy, cliffed settings, (b) eroding wave-cut platforms, and (c) low-energy, rocky shores.

In high-energy, cliffed locations (V.I. 1), waves typically break directly on the rock face and (or) are vigorously reflected from the face and return seaward. This reflection process, which is often effective in holding floating oil several meters or more offshore, has been reported from two different spill investigations (Gundlach and other, 1978, fig. 14; and Gundlach and Hayes, 1978b, plate 4-28). In addition to wave reflection, three other conditions help minimize oil accumulation in cliffed locations: (a) Scarcity of horizontal surfaces for oil deposition, (b) lack of sediment in which to accumulate oil, and (c) spray-wetted rock surfaces, which hamper the adherence of oil. If oil is deposited, high wave energy at these sites promotes relatively rapid physical removal (day-weeks). In the Port Townsend Quadrangle, such cliffed settings are found in southern Rosario Strait and on southern Lopez Island.

On rocky shores with wave-cut platforms (V.I. 2), some of the same conditions that are typical of cliffed shorelines are also present. Again, oil deposition is retarded by high wave energy and spray-wetted rock surfaces. However, platforms commonly have irregular, sub-horizontal surfaces and tide pools in which oil can collect. Additionally, some wave-cut platforms have a thin veneer of sediment in which oil can accumulate, but the high wave energy that is typical of platform settings regularly moves and abrades the sediment which aids in dispersal of any accumulated oil. The net effect of these interacting conditions is to allow more oil to accumulate on platforms than in high-energy, cliffed settings, yet oil-retention capabilities on platforms are low in comparison to other coastal environments. Clark and others (1975, p. 483) found that the most persistent oil deposits on a wave-cut platform were those clinging to rock faces above the normal high-water level; they attributed this oil deposition to floating oil being thrown high onto the rock faces during storms. Within the Puget Sound region, wave-cut platforms are not only found on rocky shores but also have been eroded into unconsolidated deposits. At these sites, oil deposition and persistence could be slightly longer than on rocky platforms because of the thicker sediment cover on unconsolidated platforms. This minor difference between rocky and unconsolidated platform settings is not considered to be enough to justify a separate position in the vulnerability index. Wave-cut platforms of both types are most abundant in the eastern Strait of Juan de Fuca, including the southern San Juan Islands, southwestern Skagit County, western Whidbey Island, and the shoreline west of Admiralty Inlet.

On low-energy, rocky shores (V.I. 8), the nearly constant spray-wetted surfaces and the vigorous wave reflection of the high-energy settings are absent. These conditions allow floating oil to be held against the rocks as on a beach face (fig. 2). Petroleum deposition at low energy, rocky sites usually occurs in the form of thin coatings on rocks, particularly around the high-tide level (Thomas, 1973, p. 85-88). Most low-energy rocky shores in the Port Townsend quadrangle are in the sheltered channels and bays of the San Juan Islands.

Another oil-transport and deposition mechanism on rocky shores is the selective filling, by floating oil, of small reentrants and coves along crenulate shoreline segments. Galt (1978, p. 17 and plate 2-8) observed that floating oil moving along the shore under the influence of oblique wave approach, can completely fill small coves until the oil spills out and rejoins the alongshore stream. Thus, coves act as low-energy natural traps which accumulate oil whereas the intervening headlands and non-dissected shoreline segments act as high energy settings. Within the Port Townsend quadrangle this type of rocky, cliffed shore with small embayments is found in the southern San Juan Islands and in the vicinity of Deception Pass. Portions of these embayments could be categorized as V.I. 6 and 7 (gravelly beaches), however, because of the preponderance of bedrock and because of the tendency to be selectively filled with oil, these coves and small embayments have been assigned in the V.I. 8 category (low energy rocky shores).

Tidal Flat Environments

On the map, two tidal flat environments are distinguished: (a) Sandy, relatively compacted flats (V.I. 5) typically bordered by beaches, and (b) soft, poorly compacted, mud flats (V.I. 9) associated with estuarine embayments at river mouths. The latter type is typically bordered by salt or brackish-water marshes.

On sandy tidal flats the relatively compact substrate usually does not allow deep penetration by oil. Also, as the tide falls and rises, the zone where waves break shifts seaward and landward across these flats; the mechanical energy provided by the waves and by tidal currents inhibits long-term oil deposition. Instead, oil is typically transported onto the bordering beach, unless the oil slick is so wide that it cannot be accommodated within the upper intertidal zone (fig. 2) and extends out over the tidal flat (Gundlach and Hayes, 1978a, p. 22). Sand flats are found throughout the Port Townsend quadrangle; their greatest concentration is in Saratoga Passage.

Muddy, estuarine tidal flats occur in areas that are sheltered from significant wave activity. The low permeability of the water-saturated, fine-grained sediment (fine sand, silt, and clay) does not allow oil to readily percolate into the sediment, but part of the oil is incorporated both by dissolution of the water-soluble fraction and by sorption onto the fine-grained sediment (Clark and MacLeod, 1977, p. 109-123) where it characteristically persists for years (table 4). The high vulnerability-index number (9) assigned to estuarine tidal flats is based on: (a) The low wave energy, (b) potential for long petroleum persistence, (c) severe problems with artificial cleanup (see discussion in subsequent section), and (d) high potential for damage to the rich biologic community that is typically present on these tidal flats. In the Puget Sound region, the muddy deltaic flats are primary areas of eelgrass beds, waterfowl concentrations, and commercial shellfish production (Washington Department of Natural Resources, 1972, plates 3, 6, and 12).

PETROLEUM PERSISTENCE IN COASTAL SETTINGS

Six factors which are the most important controls of petroleum persistence after a spill were discussed by Owens (1979, p. 85-86): (a) Type of petroleum, (b) volume of stranded oil, (c) air and water temperatures, (d) shoreline type, (e) depth of oil penetration and(or) burial in shoreline sediment, and (f) level of energy input at the shore, primarily the mechanical energy of waves and currents. These factors and their influence on persistence are summarized in table 3; factors (d), (e), and (f) are discussed in previous sections of this report because they are also principal controls of oil deposition during a spill.

TABLE 3. -- Principal factors that control petroleum persistence in coastal settings (modified from Owens, 1979, p. 58)

	Types of oil	Thickness of oil on shore	Depth of oil penetration or burial	Wave energy	Air and water temperatures
Increasing persistence ↓	Light, volatile	Thin (< 1 cm)	All oil exposed on shore surface	High energy (exposed coast)	High (> 25°C)
	↓	↓	↓	↓	↓
	Tarry	Thick (> 10 cm)	All oil buried below beach surface	Low energy (sheltered coast)	Low (< 0°C)

The possibilities for complex interaction of the six factors make it apparent that no two petroleum spills are likely to be identical. For example, if a small gasoline spill in a warm, high-energy setting were compared to a heavy-crude oil spill in a low-energy, arctic environment, the long-term fate of the petroleum from the two spills would be very different (table 4). However, in climatic settings ranging from temperate to subarctic (table 2), large spills of crude oil and of other common distilled products (bunker-C and number-2 fuel oil) often are remarkably similar in their persistence. An example of this similarity is long-term petroleum persistence in fine-grained sediment typical of detaic tidal flats, sheltered lagoons, and salt marshes (V.I. 9 and 10). Thomas (1978, p. 712-714) found high concentrations of hydrocarbons in lagoonal sediment six years after a bunker-C spill, and Burns and Teal (1979) continued to find high concentrations of hydrocarbons in marsh sediment eight years after a number-2 fuel-oil spill. In rocky coastal settings, petroleum persistence has been similar even though the investigators studied different kinds of petroleum products in widely separated parts of the world. For example, Gundlach and Hayes (1978a, p. 19-22) report fairly rapid (days-weeks), natural cleanup in high-energy, rocky areas but long-term persistence (years) in low-energy, rocky areas. Similarly, Thomas found (1973, p. 85-88) "in all but very sheltered areas, oil disappeared fairly rapidly from rocky shores."

For any extensive spill, differences in coastal and wave conditions tend to dominate the other factors affecting persistence. Owens (1979, p. 86) notes that, of the six factors listed above, the first three (petroleum type, volume, and air-water temperatures) tend to remain relatively constant for any particular spill. It is the latter three variables (geologic aspects of the shore, depth of oil penetration, and wave energy) that differ most from one site to another and, thus, most heavily influence persistence. The ranking system used in this study is largely based on these site-to-site variables, and thus, can be used to estimate relative persistence and effectiveness of natural processes in cleanup of different shore segments.

Vandermeulen (1977, p. 34-38) observed that present experience with petroleum spills seems to indicate two levels of oil persistence, (a) a short-term presence, the duration of which is closely linked to wave energy, and (b) long-term hydrocarbon persistence in sediments, which is dependent on dissolution and biochemical breakdown. The first can be considered as "visible" cleanup time--that is, the amount of time various coastal settings take to be naturally cleaned of obvious accumulations of petroleum. The persistence estimates given in table 4 apply to visible oil such as oil-stained sediment, oil draining from the beach at low tide, asphalt-like deposits (fig. 4), and oil stranded in crevices and on rock faces. The second type of persistence refers to petroleum that is not readily apparent as discrete deposits but exists in high concentrations in sediments (e.g. dissolved, adsorbed, dispersed, or deeply buried), especially in fine-grained marsh, tidal flat, and lagoonal sediments. The persistence of this type of stored hydrocarbons was estimated to be in excess of 20 years by Vandermeulen (1977, p. 35). Even though persistence estimates in table 4 are for short-term, visible cleanup, a parallelism seems to exist between short- and long-term persistence. That is, those environments that require the longest time to accomplish visible cleanup are also those susceptible to very long-term retention of hydrocarbons dispersed within the sediment. An example of this is petroleum persistence in marshes. Emerick (1977, p. 166) and Blount (1978, p. II-36) found that salt marshes in the Strait of Magellan retained surface deposits of petroleum that appeared almost unchanged during the first 2-3 years after the spill; both investigators estimate that the marshes will retain these visible petroleum deposits for at least ten years. In the less visible form, Burns and Teal (1979) found high concentrations of hydrocarbons dispersed in marsh sediment eight years after a spill.

TABLE 4.--Estimated time required for natural processes to accomplish visible cleanup of petroleum

Vulnerability ranking	Coastal environment	Typical persistence found in previous spills	References[a]
1	High-energy, rocky shores	Days/weeks	Thomas, 1973; Gundlach and Hayes, 1978a,b,c
2	Wave-cut platforms	↓	
3	Compact, fine-grained sandy beaches	↓	
4	Coarse sand beaches	Months	Gundlach and Hayes, 1978b
5	Compact, sandy tidal flats	↓	
6	Mixed sand and gravel beaches	Years	Keizer and others, 1978; Vandermeulen and Gordon, 1976
7	Gravel beaches	↓	
8	Low-energy, rocky shores	↓	Thomas, 1973
9	Muddy, estuarine tidal flats	↓	
10	Coastal marshes and lagoons	10 years	Blount, 1978; Emerick, 1977; Thomas, 1978
m	Highly modified shorelines	Unknown or variable	

[a] See also discussions in text.

They did not provide an estimate of total natural cleanup time; however, since the petroleum has remained in high concentrations for eight years, it likely will continue to persist for additional years to come.

The persistence estimates in table 4 are for areas without artificial cleanup or where large amounts of petroleum were left for natural processes to clean. If artificial cleanup is thorough, the persistence of visible petroleum deposits is greatly reduced; the exact amount of time reduction, however, involves many variables and is difficult to predict. Whether cleanup will markedly reduce the long-term persistence of oil dispersed through fine-grained sediments (e.g. marshes) is unknown. Furthermore, the ability of man to physically clean a specific coastal setting does not preclude severe biological damage that may occur before cleanup, or damage that may result from the cleanup methods employed.

Within the Puget Sound region, two broadly defined wave-energy regimes exist; a moderate-to-high-energy environment in the Strait of Juan de Fuca, and a moderate-to low-energy environment in the more sheltered channels and embayments in the rest of the region. Wave energy in the Strait of Juan de Fuca and directly adjacent waters is more typical of that found in the areas of the spills listed in table 2. Thus, petroleum persistence on various types of beaches (V.I. 3-7) in the Strait of Juan de Fuca is likely to be similar to that listed in table 4. However, many of the same beach types (e.g. mixed sand-and-gravel beaches) occur in both energy settings. Because wave energy is one of the main determinants of petroleum persistence, heavy oil deposition could be more persistent in a low-moderate energy setting than in the equivalent moderate-high energy setting. Low-energy inlets such as southern Discovery Bay, Kilisut Harbor, or Port Susan (see map) could be particularly susceptible to increased persistence. The lack of experience with spills in this region precludes a reliable estimate of how much the persistence might be increased.

CLEANUP CONSIDERATIONS

When artificial cleanup of a large oil spill is undertaken, constraints imposed by geologic and physical factors must be considered. Two obvious problems are the inability to use certain types of equipment during periods of high waves, and the general transportation difficulties associated with a very highly embayed shoreline as in the Puget Sound region. Less obvious are problems presented by the geomorphic setting of specific coastal sites and the nature of the geologic materials.

For artificial cleanup of beaches, a major consideration is the volume of sediment that must be moved. On hard-packed sand beaches the volume of oiled sediment may include only the upper few centimeters of the beach surface because the oil percolation depth is restricted by the relatively fine sediment. However, on coarse-grained beaches (V.I. 6 and 7), where deep percolation and burial of oil is common, complete cleanup can require not only the handling of contaminated sediment, but also the excavating of large volumes of clean sediment to expose oil that may be buried as deeply as a meter. Computations based on typical values for beach slope, width, and tidal range on high-tide beaches in the Puget Sound region indicate that typical volumes of sediment that may have to be handled are in the range of 5,000-15,000 m^3/km (cubic meters per kilometer) of shoreline. Under favorable conditions (oil penetration of 10 cm or less on narrow beaches) the sediment volumes could be as low as 1000 m^3/km. With very adverse conditions (oil burial as deep as a meter in a wide high-tide beach, plus oil deposition in the low-tide terrace) the volume could be 30,000 m^3/km or more.

Even though the entire volume of sediment on a beach is not likely to be contaminated, one of the most difficult problems faced during cleanup is the treatment of large volumes of oiled sediment. At various spills in other regions, responses to this problem have ranged from doing nothing and letting natural processes accomplish oil dispersal over an extended period of time, to flushing the oiled sediment with high-pressure water, to complete removal and landfill burial of contaminated sediment. For example, Owens (1972) found that removal of sediment from some Nova Scotia beaches during spill cleanup amounted to 3000-6000 m^3/km of shoreline. For small spills or in restricted shoreline segments, complete removal of contaminated sediment is a possibility; however, the logistics of excavating and hauling, and also finding a suitable disposal site for hundreds of thousands of cubic meters of sediment affected during a large spill, are likely to be prohibitive.

In addition to logistical and disposal problems, removal of large volumes of sediment from the beach presents a very real possibility of increased shoreline erosion (Owens and Drapeau, 1973). One of the more promising methods for cleanup of large volumes of gravelly sediment is bulldozing it down into the surf zone, as was tried after the Amoco Cadiz spill (Gundlach and Hayes, 1978b, p. 169). The higher wave energy in the surf zone moves and abrades the sediment, aiding natural cleanup and oil dispersal; waves also gradually move the sediment back up the beach, thus reestablishing the normal beach profile. This method has the distinct advantages of not risking increased erosion, and of avoiding the logistical and disposal problems associated with sediment removal. However, the procedure is effective only if sufficient wave energy is available during the post-spill period. After the Amoco Cadiz spill some bulldozed deposits retained a large amount of oil because wave energy during the summer months following the spill was insufficient to rework the sediment (Gundlach and Hayes, 1978c, p. 45); they noted that these bulldozed accumulations were subject to being cemented by weathering oil if waves or additional bulldozing did not break them up.

In addition to cleanup in the intertidal zone, cleanup may be required in supratidal areas (the zone landward of the normal highwater level; figs. 2 and 3) if storm activity has carried oil and oiled sediment beyond the active berm. Blount (1978) reported many instances of oil deposited in and landward of storm berms. Molnia and Wheeler (1978, p. 40-44) considered supratidal oil deposition to present such a severe cleanup problem that they ranked areas with wide backshores that are susceptible to storm washover in a separate vulnerability category. In the Puget Sound region, sediment washover occurs occasionally, but does not seem to be as potentially severe a problem as Molnia and Wheeler found in the Gulf of Alaska.

Within tidal flat environments, the poor load-bearing characteristics can present severe problems during cleanup. Field observations within the Port Townsend Quadrangle indicate that some sandy, relatively compact tidal flats (V.I. 5) are probably capable of supporting the weight of motorized equipment, but the complete geographic distribution of the flats with good load-bearing capabilities is unknown. Load-bearing limitations become especially severe on fine-grained, estuarine tidal flats (V.I. 9) found at the deltas of major rivers (e.g. the Skagit). In most of these delta areas, the sediment is so soft that even walking on it is very difficult; clearly, the use of heavy equipment there would be impractical. As these deltaic tidal flats are extensive, access by cleanup equipment is a major problem for the large areas that could be affected by grounded oil.

An associated common problem, repeatedly cited by Gundlach and Hayes (1978b), is the grinding of oil deep into beaches, tidal flats, and marshes by motorized equipment operating where the sediments are only marginally able to bear the load. The prospect for early recovery of such areas where oil, sediment and interstitial water become thoroughly mixed is doubtful.

Low-energy, rocky shores (V.I. 8) in this region present major problems in cleanup because of general inaccessibility and the lack of a suitable base or foundation from which to work. Most of these shore segments have steep or vertical rock faces, usually with no wave-cut platform. Thus, typically there is no surface on which to land a boat, stand, or walk along the shore. The problem of having to conduct cleanup operations from a floating platform is compounded by inaccessibility owing to remoteness. For example, many shore areas of the San Juan Islands and western Skagit County have no ferry service and few, if any, roads or shoreline access points.

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