Proceedings 1987 International Oil Spill Conference, API Publication No. 4452.

OIL-HOLDING CAPACITIES AND REMOVAL COEFFICIENTS FOR DIFFERENT SHORELINE TYPES TO COMPUTER SIMULATE SPILLS IN COASTAL WATERS

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ABSTRACT: *Two components have been developed and integrated into a coastline oil spill simulation model: (1) an oil holding capacity for different shoreline types to represent the amount of oil that can be brought onto the shoreline, and (2) a removal coefficient to reflect the amount of oil that can be removed from a beach during a rising tide. The oil holding capacity changes with oil viscosity. The combination of these two factors, delineated for seven shoreline types and tied to chemical weathering and surf zone transport submodels, enables the basic prediction of oil motion and persistence within most marine environments.*

The interaction of spilled oil with various coastal environments is beginning to be sufficiently understood to enable the computer simulation of oil spills onto and off beaches and other shoreline types. This paper presents a description of two key factors in model formulation:

1. The development of a shoreline holding capacity to realistically limit the amount of oil that can be placed on a particular shoreline segment during a simulation
2. The description of removal coefficients developed for each of seven shoreline types to simulate natural oil removal over time.

These two components form part of an oil/shoreline interaction submodel which will be integrated with several other submodels to enable simulation of the transport and weathering of spilled oil in the nearshore and coastal environment. Briefly, the full model, known as SMEAR, is composed of the following interconnected components:

- An offshore transport submodel
- A nearshore/coastal transport submodel
- An oil/shoreline interaction submodel
- A chemical weathering submodel
- A suspended sediment submodel (being developed)

The shoreline model will consider individual segments of shoreline, on the order of 1 to 3 km in length. The shoreline types selected for the model are: rocky cliffs, sand beaches (composed of fine- to coarse-grained sand), gravel beaches (sandy gravel, gravel, to cobbles), tidal flats, rocky shores (sheltered), marshes, and eroding peat scarps.

Calculation of oil-holding capacity

As spilled oil contacts the shoreline, beaching or oil stranding is possible. During large oil spills and onshore wind conditions, it is possible that a large quantity of oil may be placed along a given segment of shoreline. However, based on observed and reported oil spills, the capability of the beach to hold oil is limited.[5, 10] Owens refers to this process as "maximum oil loading".[5] Once this limit is reached, oil will remain offshore and be exposed to alongshore transport processes, possibly carrying the oil onto adjacent beaches.

The maximum amount of oil that can be contained on various beach types is dependent on surface oil thickness, the extent of oil incorporation into back-beach sediments, and beach slope. Since temperature and oil type play a large role in influencing the surface oil thickness and subsurface oil penetration, the preliminary model will calculate the oil holding capacity based on three categories of viscosity. (The chemical weathering submodel provides the viscosities which will be used). The viscosity divisions considered are:

1. Low-viscosity oil: < 30 cs (gasoline, kerosene, fresh light crude, and light fuel oils)
2. Mid-viscosity oils: 30–2,000 cs (most crudes and light bunkers)
3. High-viscosity oils: $> 2{,}000$ cs (weathered crudes and heavy bunkers)

Surface oil. Surface oiling of the shoreline can occur throughout the intertidal range and into the upper swash and splash zones. Incoming oil in large quantities tends to pile up on the beach (Figure 1).[3] In the oil/shoreline interaction submodel, oil accumulation occurs by the time-step addition of incoming oil (providing the appropriate environmental conditions exist). The accumulation of oil on the beach, in turn, is limited by gravity which causes the oil to flow down-slope or to be absorbed into the beach.

To determine the appropriate maximum thickness of oil on the major beach types, data from three major spills were researched. The shoreline types for which data were available are sand beaches (includes fine to coarse sand), gravel beaches (includes gravel as well as mixed sand and gravel beaches), tidal flats, and marshes. In each case, direct field measurements from three oil spills, as illustrated in Figure 2, were used.

Data from the *Amoco Cadiz* are published,[5] while those from Ixtoc I and *Urquiola* were derived from field notes and sketches. Only measurements from moderately to heavily oiled beaches were used since maximum thicknesses of oil onshore are required. Extremely high values, representing scour pits or other minor geomorphic features, were not included. The number of oil observations for each

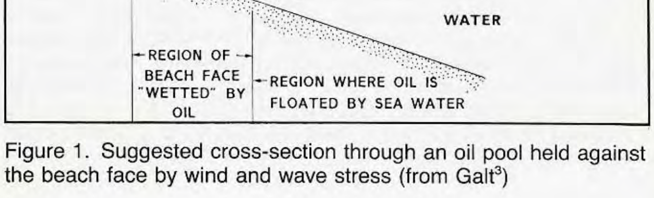

Figure 1. Suggested cross-section through an oil pool held against the beach face by wind and wave stress (from Galt[3])

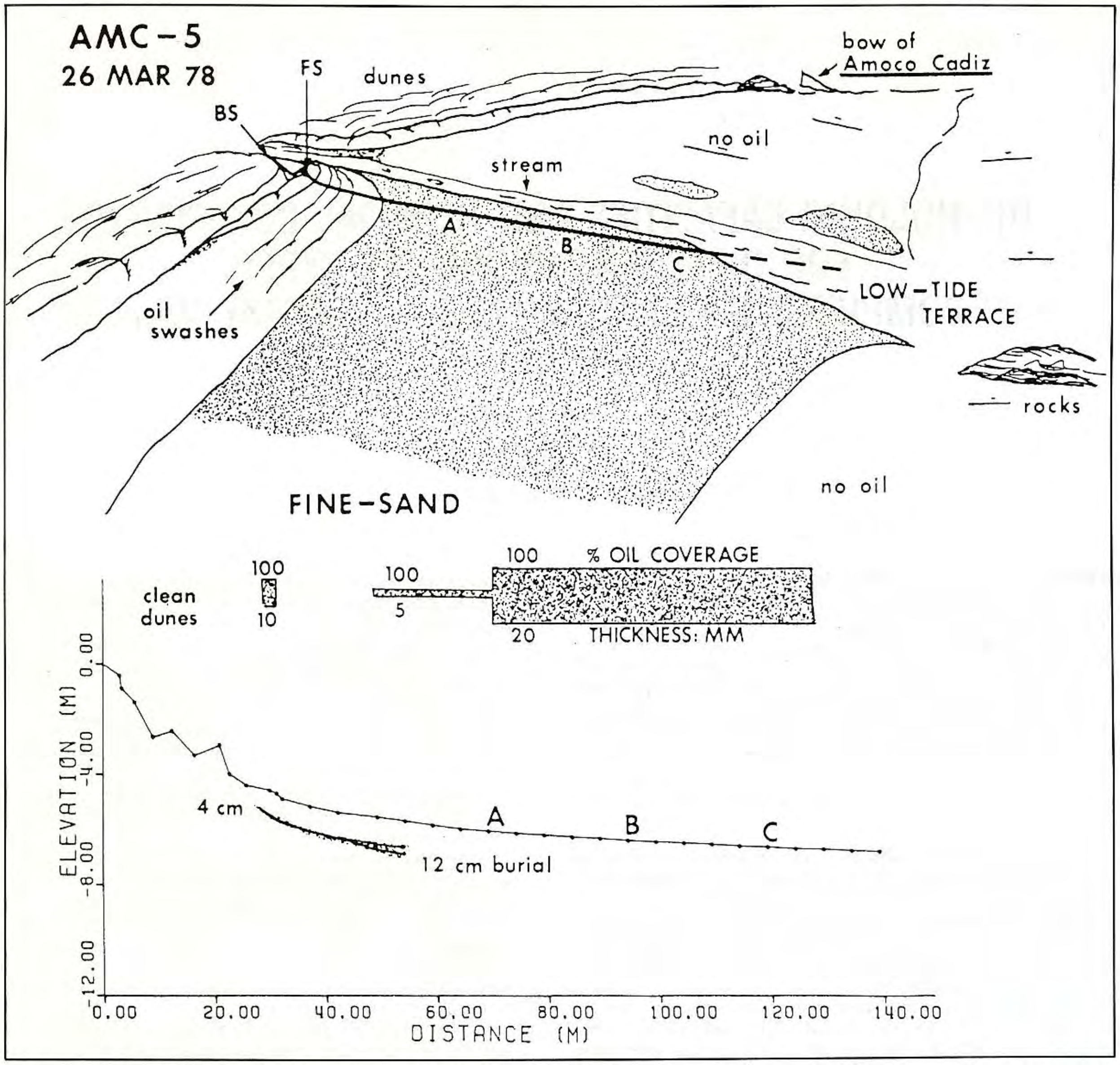

Figure 2. Example of information used in determining the maximum oil thicknesses on beaches—Oil thickness and percent coverage was measured along the indicated transect. (from Gundlach and Hayes[5])

shoreline type vary greatly and indicate a need for additional "spill-of-opportunity" data.

The viscosity of the oil varies by oil type and ambient temperature and also influences the thickness of oil measured on a beach. For the *Amoco Cadiz* and *Urquiola,* the oil type was Arabian crude, spilled in a cool (5–15°C) temperate environment. The Ixtoc I spill consisted of Campeche crude spilled under tropical (25–35°C) temperatures. Particularly on sand beaches, the Campeche crude formed thinner layers.

Results of the surface crude oil measurements are presented in Figures 3–5. For light-to-medium crude oils (considered as mid-viscosity oils), a summary of mean values and standard deviations for each shoreline type is presented in Table 1. In addition, to conform to the shoreline types considered in the model format, values for rocky cliffs and peat scarps are estimated at 2 mm and 4 mm respectively. (Peat scarps have a slightly higher value on the premises that oil could bind with the organic peat material and that these scarps may have gentler slopes). A value of 5 mm, less than for beaches but more than double that for exposed rocky shores, was estimated for sheltered rocky shores since these are composed of small pockets which tend to collect oil.

Estimates for probable maximum oil thickness for oils other than crude are also estimated in Table 1. Light oils tend to form very thin layers and are greatly affected by all water movement. On the other hand, heavy oils (either heavy crude or bunker oils) generally tend to form thicker surface layers on beaches than do light- to medium-grade crudes (e.g., at the *Alvenus* spill, 1984, of heavy Venezuelan crude along Galveston Island).

Subsurface oil. Oiling of sand and gravel subsurface sediments, commonly called buried oil, most often occurs in the back-berm areas or along the upper swash zone. Under maximum oiling, there exists the potential for the entire swash zone to absorb oil. The total subsurface oil holding capacity is, therefore, based on the depth of oil penetration, the oil content of the sediment and the width of the swash zone.

Along the upper part of sand and gravel beach types, incoming oil tends to percolate or sink into the sediments. The depth of penetration depends on such factors as grain size, sorting, compactness, water content of the beach sediments, level of the water table, and the degree of oil/sediment mixing caused by wave or tidal action. A compacted, clay-dominated tidal flat saturated with water is the beach type most resistant to oil penetration, while a dry, well-sorted cobble

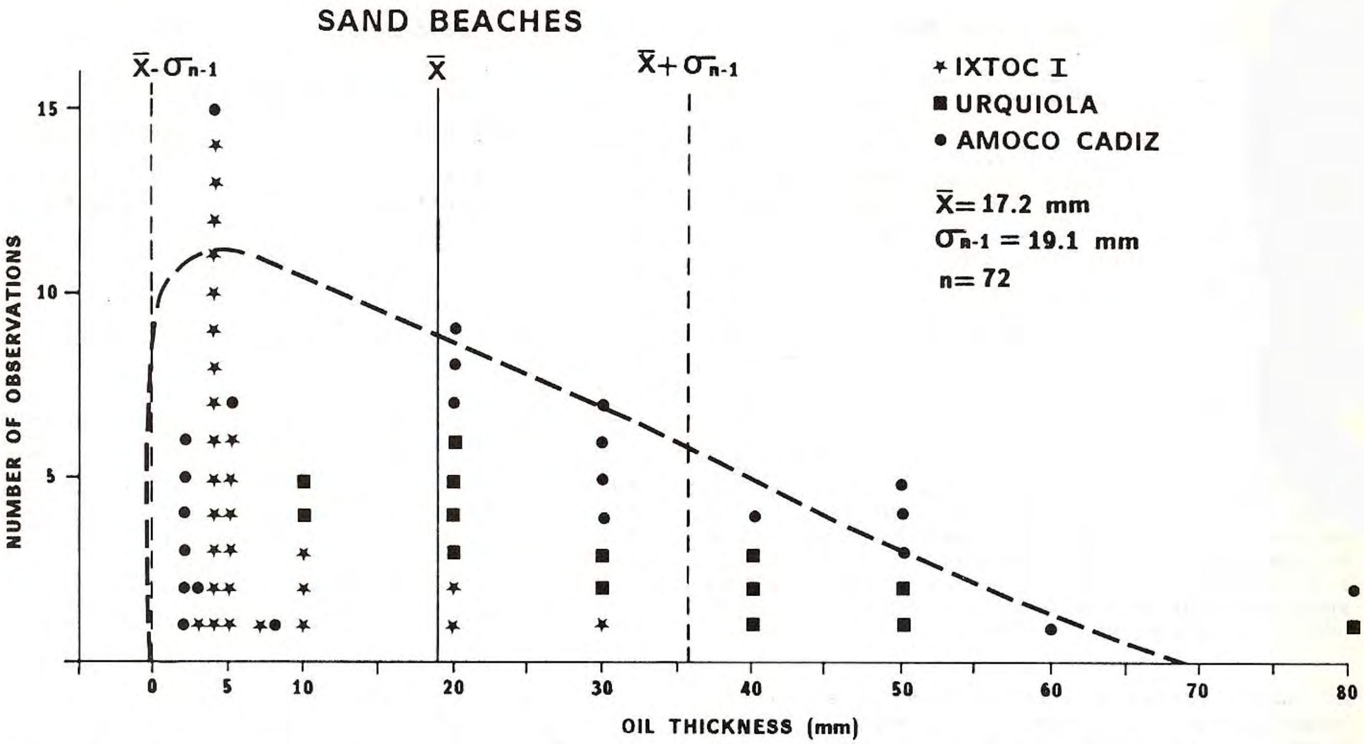

Figure 3. Measured upper limit of oil thicknesses on heavily oiled sand beaches—The data are from the Ixtoc I, *Urquiola*, and *Amoco Cadiz* oil spills. The heavy dashed line is estimated. (mean = 17.2 mm, standard deviation = 19.1 mm, and number of observations = 72)

beach has a very large capacity for incorporating oil. While there are no data available for oil on exposed peat scarps, it can be surmised that (1) penetration of oil into the peat is limited because of its compacted nature, and (2) burial is nonexistent since the shoreline type is erosional. Likewise, burial does not occur along a sheltered rocky shore, although oil may percolate into the substrate if it is boulder dominated. In the oil/shoreline interaction model, subsurface oil on rocky shores is considered to be zero.

To determine the range and average depths of oil penetration in beaches, original field data from the *Amoco Cadiz* and Ixtoc I oil spills, and published data from the *Urquiola* spill[8] were consulted. *Amoco Cadiz* data were derived from photographs of trenches cut into the oiled beaches, while Ixtoc I data were taken directly from field sheets. Beaches from all three spills were subdivided into categories of fine sand, medium sand, and coarse sand (collectively grouped as sand beaches); or mixed sand and gravel, gravel, and cobble (grouped as gravel beaches).

A graphic plot of the results obtained by this analysis is presented

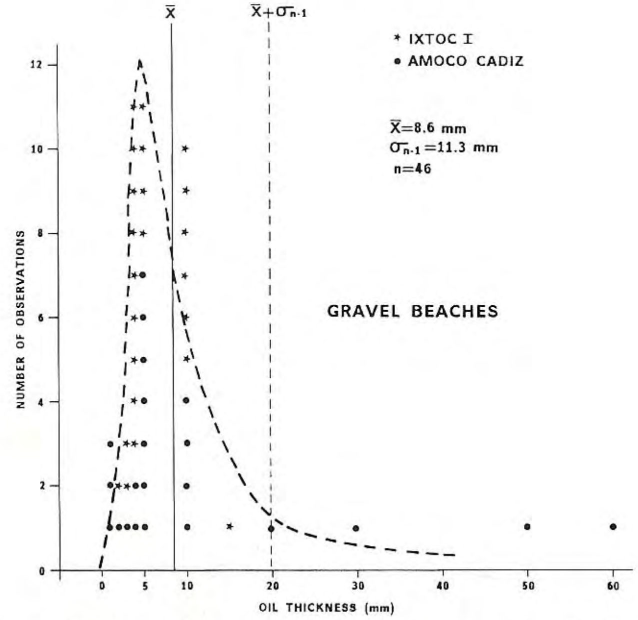

Figure 4. Measured upper limit of oil thicknesses on heavily oiled gravel beaches—The data are from the Ixtoc I, and *Amoco Cadiz* oil spills. The heavy dashed line is estimated. (mean = 8.6 mm, standard deviation = 11.3 mm, and number of observations = 46)

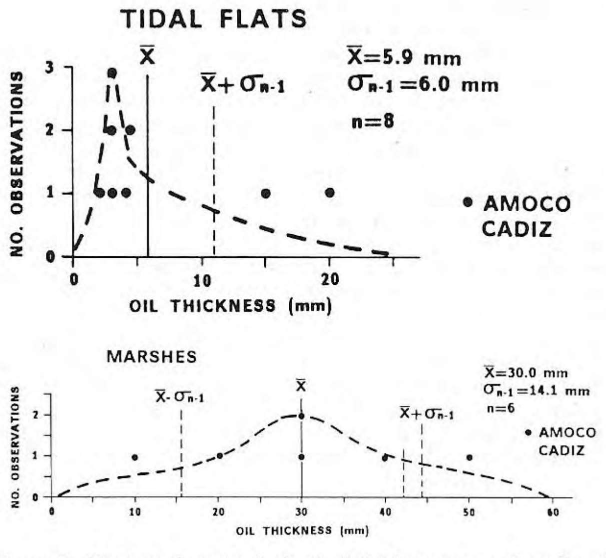

Figure 5. Measured upper limit of oil thicknesses on heavily oiled tidal flats and marshes—The data are from the *Amoco Cadiz* oil spill. The heavy dashed line is estimated. (means = 5.9 and 30 mm, standard deviations = 6.0 and 30.0 mm, and number of observations = 8 and 6)

Table 1. Oil thickness for each shoreline type

Shoreline type	Medium-viscosity oil[1] thickness (mm)	Medium-viscosity oil[1] standard deviation (mm)	Light oil[2] thickness (mm)	Heavy oil[2] thickness (mm)
1. Rocky cliffs (exposed)	2	NA	0.5	2
2. Sand beaches	17	19	4	25
3. Mixed sand and gravel	9	11	2	15
4. Tidal flats	6	6	3	10
5. Rocky shore (sheltered)	5	NA	1	10
6. Marshes	30	14	6	40
7. Eroding peat scarps	4	NA	1	10

1. For medium-viscosity oils, values are measured (see text). NA indicates data not available because thickness was not field derived, but estimated relative to field information.
2. Values for light- and heavy-viscosity oils are estimated and are proportionately correct to each other and to light-to-medium viscosity oils for which data are partially available.

in Figure 6. The average penetration was found to be limited to 5 cm in sand beaches and to 18 cm in gravel beaches. In a laboratory study, Harper et al.[9] found a similar relationship of increasing penetration with grain size for sandy tidal flats.

Oil content. The buried oil zone along the upper beach includes both oil and sediment. To determine the oil content, three spill incidents for which data were available were analyzed. For the *Metula* spill, Blount[2] measured the oil content of a variety of oiled beach and tidal flat sediments (but analyzed lightly oiled as well as heavily oiled sediments). For the Ixtoc I spill, six samples (4 heavily oiled, 2 moderately oiled) were analyzed by Gundlach and Finkelstein.[4] For the *Alvenus* spill, four heavily oiled samples were analyzed by the Conoco Oil Company as part of the U.S. federal spill response effort (unpublished). Owens and Robson[10] present additional data on the oil content of sediments based on analyses taken during the BIOS field oiling program.

The results of this evaluation are presented in Figure 7. The average volume-percent oil is 9.8 for sand beaches and 8.3 for gravel shores. Because Blount[2] analyzed both lightly and heavily oiled gravels, the value for gravel beaches is artificially low. The combined value for the sand and gravel beaches together is 9 percent (by volume), a value that more appropriately represents heavily oiled beaches in general.

In addition to beaches, oil can also penetrate or become incorporated into march and tidal flat sediments. In 1982, Boehm reported on a series of core analyses of both marshes and tidal flats after the *Amoco Cadiz* spill. Oil was commonly noted to a depth of 15 cm. The maximum concentration (pyrogenic and *Amoco Cadiz* oil) reached 22,000 µg/g, although more average concentrations were less than 1,000 µg/g or one part per thousand. A laboratory study of tidal flat sediments also showed relatively low (<1 percent) oil uptake in water-saturated sediments exposed to air for 12 hours or less.[9] Oil incorporation, limited to 3 cm or less, increased to near 5 percent oil as the flat was artificially exposed to air for 15 hours or longer.

Because these values are extremely low relative to other assumptions made in the computer simulation, it appears best that oil incorporation into subsurface tidal flat sediments be considered near or at zero. (In contrast, the very slow removal rate and possible thick oil accumulations on the marsh surface make surface oiling of the marsh particularly important).

Sample calculations

Since the thickness of surface and subsurface oiling has been determined (from field data), the maximum oil holding capacity of each horeline type is dependent on the slope of the shoreline. In this

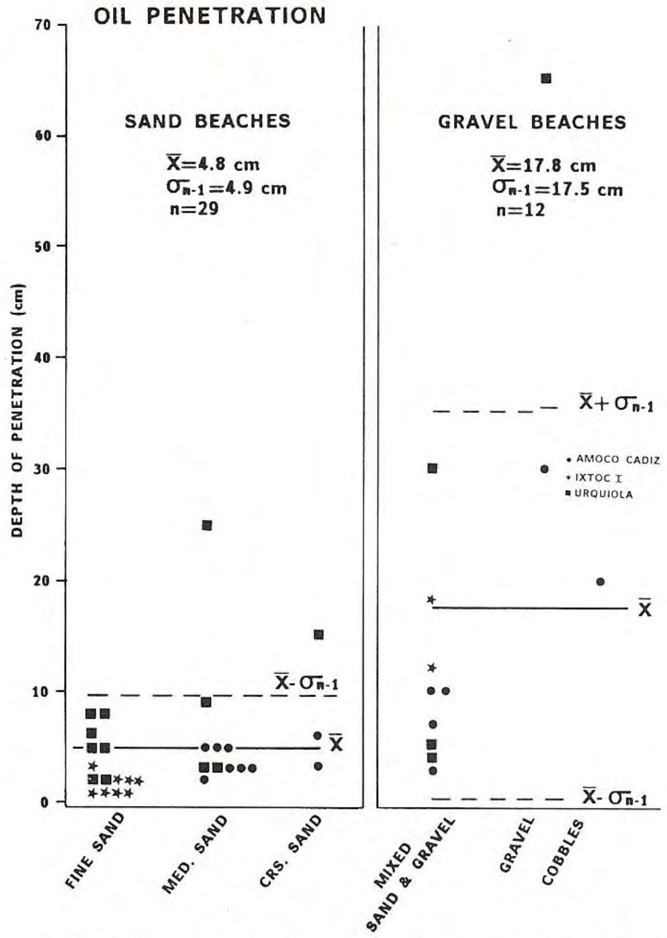

Figure 6. Measured depth of oil penetration in heavily oiled sand and gravel beaches (means = 4.8 cm and 17.8 cm, standard deviations = 4.9 and 17.5 cm, and number of observations = 29 and 12)

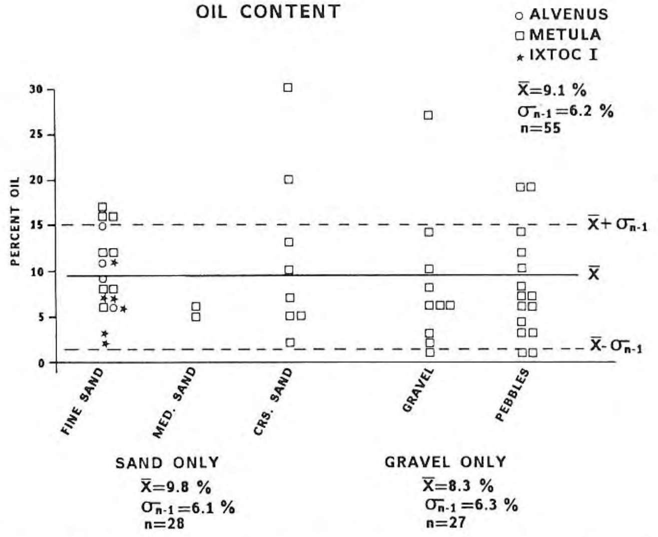

Figure 7. Measured oil content by volume of oily beach sediments (means = 9.8% and 8.3%, standard deviations = 6.1% and 6.3%, and number of observations = 28 and 27)—Owens[10] presents additional data from the BIOS field oil program.

example, for exposed rocky shores a near vertical slope (80°) is postulated, while marshes and tidal flats are assumed to be horizontal. (In the oil/shoreline interaction model, actual or default values can be entered.) The slope of sand and gravel beach types can vary considerably depending on grain size, wave length, and wave steepness. For coarse sand beaches (0.5–1.0 mm), Bascom[1] found that slopes can vary between 8 and 15 percent. In this example, typical measured beach face slopes for Bristol Bay beaches are 5 percent for sand and 9 percent for gravel. The sand beach type typically has a flatter backberm area (2.3 percent slope), while the gravel type does not.

Example results from these calculations are provided in Table 2. In the model, onshore oil accumulations will be added in a time-step fashion until the maximum holding capacity is reached. In the example, the calculations are based on a 4 m tide range and a 1 m swash zone (vertical height), with the hypothetical swash extending 0.5 m (vertical height) into the flatter backshore of the sand beach. Since the area of marsh and tidal flat environments that could be potentially oiled is related only to some of the full tidal range (e.g., a fringing marsh perched above a narrow tidal flat), an arbitrary cross-width of 10 m was used for the tidal flat and 20 m for the marsh.

From Table 2, it is evident that sand beaches can contain the largest quantity of deposited oil (2.16 m^3 oil/m width of beach), primarily because of their wide gently sloping beach faces. Gravel beaches have steeper slopes, a thinner oil coating across the beach face, but greater penetration into the upper swash zone. They are second in the capacity to absorb oil (0.68 m^3/m). The hypothetical fringing marsh (10 m in width) is next with an average spilled oil capacity of 0.30 m^3/m. Rocky shores, with no oil penetration and steep slopes, contain very little oil (0.01 m^3/m) considering the same tidal range and swash factors.

Oil removal coefficients

Once oil is deposited on a particular shoreline segment, its persistence is dependent on a variety of factors, including tidal and wave conditions and shoreline type. The net result is that for this model a series of oil removal coefficients were developed using the following first order decay function:

$$M_i = M_{io} e^{-K_f t}$$

Where: M_i = mass of oil within each beach segment, i

M_{io} = mass of oil originally deposited on the beach

K_f = the removal rate coefficient

t = time in days since original deposition

The seven geomorphic classes and proposed rate coefficients are presented in Table 3. The higher the value, the more rapid is the oil removal. As indicated, oil on gravel beaches is harder to remove than on sand beaches (due to the greater difficulty in moving gravel-sized sediment to release the trapped oil). Sand and gravel beach types and eroding peat scarps are further divided into two categories of wave energy (less than or greater than 1 m) to represent increased oil removal with higher waves. Sand and gravel beaches are differentiated into beach face and back-beach components to represent a slower removal of oil from the backshore than from the beach face.

Supporting field data for these removal rates are very difficult to locate. However, data derived from the BIOS field oiling project in the Canadian arctic indicates that between 29 and 90 percent of the deposited oil was removed within eight days by wave and tidal action, along both exposed and sheltered gravel beaches.[12] These data conform well to that estimated by the removal coefficient and first-order decay function.

Table 2. Example calculations of a maximum loading capacity for each shoreline type based on a 4 m tide range and having a 1 m (vertical) swash[1]

		Sand[2]				
	Rocky	Beach face	Backshore	Grvel[2]	Tidal flat	Marsh
Surface oil						
Beach slopes (degrees	80	2.9	1.3	5.1	0	0
Tidal range + swash (vert., m)	5.0	4.5	0.5	5.0	5.0	5.0
Surface distance (m)	5	90	22	56	20[3]	10[3]
Oil thickness, avg. (mm)	2	18	18	9	6	30
Oil thickness, +1 SD	NA[4]	34	34	20	0	16
Oil thickness, −1 SD	NA	2	2	0	12	44
Total Avg. [m^3/m]	0.01	1.62	0.40	0.50	0.12	0.30
Total (+1 SD)	NA	3.06	0.75	1.12	0	0.16
Total (−1 SD)	NA	1.80	0.04	0	0.24	0.44
Subsurface oil						
Beach slope (degrees)	NA	2.9	1.3	5.1	NA	NA
Swash range (vert., m)	NA	0.5	0.5	1.0	NA	NA
Swash zone distance (m)	NA	10	22	11	NA	NA
Oil penetration, avg. (cm)	NA	4.8	4.8	17.8	NA	NA
Oil penetration, +1 SD	NA	9.7	9.7	35.3	NA	NA
Oil penetration, −1 SD	NA	0	0	0.3	NA	NA
Oil content (%)	NA	9	9	9	NA	NA
Total Avg. [m^3/m]	NA	0.04	0.10	0.18	NA	NA
Total (+1 SD)	NA	0.09	0.19	0.35	NA	NA
Total (−1 SD)	NA	0	0	0	NA	NA
	Rocky	Sand		Gravel	Tidal flat	Marsh
Grand totals (m^3/m)						
Minimum (−1 SD)	0	1.84		0	0	0.16
Average	0.01	2.16		0.68	0.12	0.30
Maximum (+1 SD)	NA	4.09		1.47	0.24	0.44

1. Values are given as cubic meters of oil per linear meter of shorefront.
2. The order of filling compartments on the sand and gravel beach types is: (1) swash zone buried, (2) beach face surface, and (3) swash surface.
3. Surface distances are assumed for tidal flats and marshes.
4. NA = not applicable

Table 3. Preliminary daily oil removal rates as a fnction of shoreline type and wave energy

Shoreline type	Characteristics	Percent removed (1 day)	Percent removed (5 days)	K_f value[1]
Rocky shores				
• exposed	—Most oil readily lifts off uniform and wetted surface	60–63	99–99.3	0.90–0.99
• sheltered	—Long-term persistence due to reduced wave energy and rugged substrate	5–10	5–22	0.01–0.05
Eroding peat scarps	—Basically erosional but oil may adhere to substrate			
	—Under low wave (<1 m) activity	10–18	49–63	0.10–0.20
	—Under high wave (>1 m) activity	50–55	97–98	0.70–0.80
Sand beaches	—Mostly surface oiling, but some oil/sand adherence and mixing, particularly with coarse-sand beaches			
	—Generally easy oil removal from beach face, but longer oil persistence along backshore			
	—Under low wave (<1 m) activity:			
	Beach face	18–26	63–78	0.20–0.30
	Backshore	10–18	40–53	0.10–0.15
	—Under high wave (>1 m) activity	40–45	92–95	0.50–0.60
Gravel beaches	—Mostly surface oil on the beach face, but deep penetration and longer persistence along the backshore			
	—Under low wave (<1 m) activity:			
	Beach face	10–18	40–63	0.10–0.20
	Backshore	5–10	22–40	0.05–0.10
	—Under high wave (>1 m) activity	33–40	86–92	0.40–0.50
Tidal flats	—Most oil lifts off of wetted tidal flats	60–63	99–99.3	0.90–0.99
Marshes	—Oil tends to adhere to the marsh vegetation and soft, base sediments	0.1–1.0	0.5–5	0.001–0.01

1. K_f values reflect the amount of oil remaining within that particular segment of shoreline via application of the first-order equation discussed in the text.

Summary

The two components discussed—oil holding capacity and an oil removal coefficient—provide two elements in developing an oil/shoreline interaction model. In application, the oil is advected by wind and currents with the possibility of shoreline impacts. Concurrently, dispersion spreading, emulsification, and evaporation occur. Under the appropriate conditions, a unit of spilled oil (a "spillet") may contact the coastline. The extent of beaching depends on the exposed intertidal area. On an ebbing tide, oil will be deposited according to its thickness, radius, and distance from shore. If the tide is rising, oil will be resuspended according to its removal coefficient. Deposition of oil on the shoreline will occur unless its holding capacity is reached. Holding capacities will be based on observation or default values as described previously.

At the next time-step or tidal cycle the process begins again. Is the oil carried shoreward, alongshore, or offshore? What is the shoreline type? Is it a rising or ebbing tide? What are the wave and tidal height conditions? Has the holding capacity been reached? Which removal coefficient is applicable?

Development activities on this aspect of the model concern the application of the model to data derived during the *Amoco Cadiz* oil spill, including comparisons between the measured and computed extent of chemical weathering and the distribution of oil in the water column, on the bottom, and on the shoreline.

Notes and acknowledgment

This paper is the latest in a series of reports on the development of the integrated model which has been supported by the U.S. Minerals Management Service (Anchorage) for application in the Bristol Bay area of Alaska. Previous related articles include: Gundlach et al.[6] on the basic description of oil interactions within various coastal environments; Gundlach and Reed[7] on the description of oil interaction on peat-dominated shores and a summary of oil removal coefficients; and Reed et al.[11] on overall model formulation. The interim report on the development of this model (OCS Study MMS 85-0098) is available from U.S. Minerals Management Service, P.O. Box 101159, Anchorage, Alaska 99510. Since this model is still in the development stage, many of the specific numbers used for removal coefficients and as the oil holding capacity are subject to change as new information becomes available and the model undergoes testing.

This project was supported by the Minerals Management Service, U.S. Department of Interior, Anchorage, Alaska; Contract 14-12-0001-30130.

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