OCS Study
MMS 2007-063

Review of the State-of-the-Art on Modeling Interactions between Spilled Oil and Shorelines for the Development of Algorithms for Oil Spill Risk Analysis Modeling

Final Report

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U.S. Department of the Interior
Minerals Management Service

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Minerals Management Service Purchase Order No. 0106PO39962

Published by

U.S. Department of the Interior
Minerals Management Service

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Citation

Etkin, D.S., D. French-McCay, and J. Michel. *Review of the State-Of-The-Art on Modeling Interactions between Spilled Oil and Shorelines for the Development of Algorithms for Oil Spill Risk Analysis Modeling.* MMS OCS Study 2007-063. Environmental Research Consulting, Cortlandt Manor, New York. MMS Contract 0106PO39962. 157 pp.

Acknowledgements

This project was conducted under Minerals Management Service (MMS) Contract 0106PO39962. The authors gratefully acknowledge the input of Jeff Ji and Walter Johnson of the MMS Oil Spill Modeling Group, Michel Boufadel and Hailong Li of Temple University Department of Civil and Environmental Engineering, and Gary Sergy of Environment Canada.

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List of Abbreviations and Acronyms

ANS	Alaska North Slope
BIOS	Baffin Island Oil Study
cm	centimeter
COSS	Coastal Oil Spill Simulation
cS	centiStokes
ESI	Environmental Sensitivity Index
g	gram
kg	kilogram
km	kilometer
kt	knot
L	liter
m	meter
mg	milligram
mm	millimeter
MMS	Minerals Management Service
ng	nanogram
NOAA	National Oceanic and Atmospheric Administration
PAH	polycyclic aromatic hydrocarbons (also called polynuclear aromatic hydrocarbons)
SSC	Scientific Support Coordinator
NEPA	National Environmental Policy Act
OMA	oil-mineral aggregation
OSRA	oil spill risk analysis
ppm	parts per million
s	second
SCAT	Shoreline Cleanup Assessment Team
SERF	Shoreline Environment Research Facility
SOCSEX	Subsurface Oil in Coarse Sediments Experiments
µm	micrometer
µg	microgram
WI	Weathering Index

Review of the State-Of-The-Art on Modeling Interactions Between Spilled Oil and Shorelines For the Development of Algorithms for Oil Spill Risk Analysis Modeling

EXECUTIVE SUMMARY

OBJECTIVES: The MMS requested a review of the state-of-the-art of spilled oil interactions with sediments on beaches and an identification of information gaps in this state. This report provides a comprehensive review of case studies, empirical data from past spills, technical literature, and conference proceedings related to the physical and chemical interactions between various oil types and the range of shoreline types that occur in the first 10 to 30 days after shoreline oiling (see Appendices).

The review of case studies includes analyses of anecdotal and observational data and analyses of shoreline cleanup assessment team (SCAT) data. A methodology to derive shoreline oil-holding capacity as derived from beach hydraulics modeling is introduced. The report includes recommendations on the way in which the data gathered might be integrated into OSRA modeling and the types of research that might fill remaining information gaps.

In particular, an estimate of oil retention in the sediments from 10-30 days after a spill is desirable for modeling the trajectory of on oil spill as it impacts a shoreline and either strands on and/or penetrates into the sediment or re-floats to be deposited elsewhere. A comprehensive literature review of empirical studies, laboratory research, and oil-shoreline modeling was conducted. For a spill risk model to be applied in a stochastic manner, a relatively simple and practical method to estimate the oil oil-holding capacity of shoreline sediments based on shoreline type and oil properties was derived from empirical SCAT data and a theoretical hydraulics model.

DESCRIPTION: A literature review was conducted, which revealed 220 relevant studies, in addition to interviews with prominent researchers in the field. The study results and significance to the understanding of oil-shoreline interactions were summarized. The relevance of study findings for inclusion in oil spill risk analysis (OSRA) modeling was considered and outlined. In addition, detailed shoreline cleanup assessment team (SCAT) survey data from a number of spills were analyzed for patterns in oil penetration and oil-holding capacity by shoreline sediment type and oil type for potential application in modeling algorithms. A methodology derived from beach hydraulics modeling was also evaluated. A methodology for incorporating oil-holding capacity was recommended based on the study results. Information gaps were identified and recommendations for potential future studies were outlined. An electronically-searchable database on the literature studies reviewed was developed.

SIGNIFICANT CONCLUSIONS: The researchers concluded that the values of oil-holding capacity by shoreline type that would be most practically applied in a simple stochastic oil risk or oil trajectory/fate model would be a combination of 1) the Boufadel methodology (hydraulic oil-holding capacity model) for light oils that would easily penetrate beach sediments and not be expected to have any appreciable surface buildup; and 2) the SCAT methodology for medium-heavy oils that would both partially penetrate beach sediments and accumulate on the shoreline surface. The recommended holding capacities that could be used in a basic stochastic oil spill risk analysis model that incorporates short-term impacts of oil to the shoreline for the purpose of determining trajectory and extent of shoreline impact can be preliminarily derived from the hydraulic oil-holding capacity model for lighter oils, including light fuels and light crude oils, which tend to penetrate and saturate the shoreline substrate. A table provides such values for a 1-m tide range (H) typical of the US Gulf of Mexico coast. The calculated values should be verified with further field and tank testing.

For medium crude oils and heavier oils, the process of shoreline oiling is different than that for the lighter oils because there is considerable deposition of oil on the shoreline surface, which does not generally occur with lighter oils. Viscosity and other complex factors determine the degree to which the medium and heavier oils penetrate the substrate. Until further verification can be done, the SCAT data from the

Exxon Valdez may be used for estimating holding capacities for medium crude oils, which are comparable to those values originally modeled by Gundlach (1987), as analyzed in by Cheng et al. (2000), but based on more detailed SCAT data such that the results are less variable and more closely related to sediment type than the Gundlach (1987) data.

The more limited data for the PEPCO pipeline, Athos I, and Selendang Ayu spills may not provide enough reliable SCAT data upon which to base reliable algorithms for oil-holding capacity for heavier oils. Further analyses of field SCAT data that are enhanced with core sampling to measure oil penetration and sediment saturation, along with tank test or laboratory experimentation will provide better estimates of oil-holding capacity for modeling and other purposes. Until further verification can be done, it is proposed that the calculated values for heavier oils, as shown in a table, provide the most accurate estimate of oil-holding capacity.

Despite the large body of published research on shoreline oiling, there remain significant information gaps with regard to the dynamic processes involved in shoreline oiling even over the relative short-term that would be most directly and practically applicable to oil spill risk analysis modeling. Recommendations for further experimentation in spill-of-opportunity studies in the form of core sampling during the SCAT survey process, as well as experimentation in test tanks are presented in this report.

Review of the State-Of-The-Art on Modeling Interactions Between Spilled Oil and Shorelines For the Development of Algorithms for Oil Spill Risk Analysis Modeling

1.0 Introduction

1.1 Background of Study

The Minerals Management Service (MMS) recognizes the importance of understanding the interactions of spilled oil with shorelines for oil spill risk analysis (OSRA) modeling. Because many environmental resource areas are located along and/or near the coast, MMS needs to accurately estimate the rates of the spilled oil stranding on the shorelines, especially on sediment beaches. Ideally, representation of the oil-shoreline interaction should be considered as a component of the entire simulation of the evolution of oil spills along the coasts. While the interactions can significantly affect the stranding of spilled oil on shorelines, the current OSRA model does not include such processes. Also, because this kind of interaction can affect assessments of oil spill impact on environments, having such information should help MMS to evaluate exploration and development plans, and prepare National Environmental Policy Act (NEPA) documents.

1.2 Study Objectives

The MMS requested a review of the state-of-the-art of spilled oil interactions with sediments on beaches and an identification of information gaps in this state. This report provides a comprehensive review of case studies, empirical data from past spills, technical literature, and conference proceedings related to the physical and chemical interactions between various oil types and the range of shoreline types that occur in the first 10 to 30 days after shoreline oiling (see Appendices).

The review of case studies includes analyses of anecdotal and observational data and analyses of shoreline cleanup assessment team (SCAT) data. A methodology to derive shoreline oil-holding capacity as derived from beach hydraulics modeling is introduced. The report includes recommendations on the way in which the data gathered might be integrated into OSRA modeling and the types of research that might fill remaining information gaps.

In particular, an estimate of oil retention in the sediments from 10-30 days after a spill is desirable for modeling the trajectory of on oil spill as it impacts a shoreline and either strands on and/or penetrates into the sediment or re-floats to be deposited elsewhere. A comprehensive literature review of empirical studies, laboratory research, and oil-shoreline modeling was conducted. For a spill risk model to be applied in a stochastic manner, a relatively simple and practical method to estimate the oil oil-holding capacity of shoreline sediments based on shoreline type and oil properties was derived from empirical SCAT data and a theoretical hydraulics model[1].

2.0 Literature Review

2.1 Overview of Oil Behavior at Shoreline

A comprehensive review of literature on shoreline oiling emphasized that the behavior of oil, as it first becomes deposited or stranded on a shoreline, is complex and depends on a number of interrelated factors:

- The type and characteristics of the oil (e.g., viscosity);
- The thickness of oil already on the shoreline;
- Time until shoreline contact[2];

[1] A synopsis of this approach is also presented in Etkin et al. 2008.
[2] Time until shoreline impact affects the degree of weathering (based on oil type, weather, and water characteristics).

- Timing of the spill oil's arrival with regard to tides;
- Shoreline type (see Appendix A)
- Weather at the time of and after the spill; and
- Wave energy at the shoreline (see Appendix H).

The adhesiveness of oil to shoreline substrates depends on the oil type and its characteristics, especially viscosity. Fresh oils tend to be less adhesive than more weathered oils. Light fuels (e.g., diesel) or volatile distillates (e.g., jet fuel or gasoline) tend to be relatively non-adhesive. Heavier fuels (e.g., intermediate fuel oils or No. 6 fuel oil) tend to be more adhesive than lighter oils. The degree of weathering can have a significant impact on oil viscosity. Evaporation increases viscosity. For example, if 40 percent by weight of an oil evaporates, its viscosity can increase as much as a thousand-fold (Fingas, 2001).

Weathering can also cause emulsification, which can also change the viscosity of the oil, changing it from a liquid to a heavy, viscous mass. The degree of emulsification depends on the chemical composition of the oil, especially with respect to the asphaltene, resin, and aromatic content. The degree of weathering that occurs is related to the oil type and environmental conditions. Temperature, wind, light conditions, and other environmental factors can influence the rate of weathering (see Appendix H).

Crude oils become more adhesive with weathering. The formation of tar balls[3] or tar mats while the oil is at sea will also affect the manner in which oil is deposited on the shoreline.

Substrate penetration will also depend on oil type (Appendix C). All other things being equal (e.g., shoreline permeability), heavier oils will penetrate less than lighter oils. Oil adhesion on the shoreline increases with viscosity. The more adhesive the oil, the lower its penetration potential (Fingas 2001).

Oil thickness on the shoreline is a factor of the amount spilled, the spill trajectory, the characteristics of the oil (viscosity and adhesiveness), steepness of the shoreline slope, tidal conditions at the time of shoreline impact, and the porosity of the surface.

Shoreline surface oiling is generally described with regard to both surface oil cover, as shown in Table 1, and by the thickness of the oil, as shown in Table 2[4]. The descriptions of shoreline oiling as described in Tables 1 and 2 and as shown in the photographs of surface oil cover categories and oil thickness categories in Appendix A were developed as a convention for the use of shoreline cleanup assessment teams (SCAT) in visually describing the shoreline conditions in the aftermath of oil spills. These verbal descriptions are often found in SCAT data provided after spill surveys and need to be compared with these tables to estimate a more quantitative assessment of shoreline oiling conditions.

Table 1: Surface Oil Cover Category (*width x surface distribution data*)[5]
As Used by Convention in Shoreline Cleanup Assessment Team Data

		Width of Oiled Area			
		Wide (>6 m)	**Medium (3 – 6 m)**	**Narrow (0.5 – 3 m)**	**Very Narrow (<0.5 m)**
Distribution	**Continuous (91 – 100%)**	Heavy	Heavy	Moderate	Light
	Broken (51 – 90%)	Heavy	Moderate	Light	Light
	Patchy (11 – 50%)	Moderate	Moderate	Light	Very Light
	Sporadic (1 – 10%)	Light	Light	Very Light	Very Light
	Trace (<1%)	Very Light	Very Light	Very Light	Very Light

[3] Agglomerations of oil into balls of less than 10 centimeters in diameter. Larger accumulations of oil up to about 1 meter are called "tar mats"
[4] These categories are used by convention in shoreline cleanup assessment team (SCAT) data.
[5] Owens and Sergy 2000, Michel et al. 1998.

Table 2: Surface Oil Category *(surface oil cover category x thickness data)*[6] As Used by Convention in Shoreline Cleanup Assessment Team Data					
		Surface Oil Cover Category			
		Heavy	**Moderate**	**Light**	**Very Light**
Thickness	**Pooled (>1.0 cm)**	Heavy	Moderate	Moderate	Light
	Cover (>0.1 – 1.0 cm)	Heavy	Moderate	Light	Very Light
	Coat (>0.01 – 0.1 cm)	Moderate	Moderate	Light	Very Light
	Stain/Film (≤ 0.01 cm)	Light	Light	Very Light	Very Light

Oil behavior at the shoreline is also highly dependent on the shoreline characteristics, particularly permeability. (Shoreline type is often described by Environmental Sensitivity Index (ESI) classification, as shown in Table A1 and Figures A10 – A24 in Appendix A.)

The degree of penetration into the shoreline substrate depends in large part on the permeability of the substrate (Harper, Sergy, and Sagayama, 1995; Harper and Sergy, 2007). Reviews of studies on oil penetration are presented in Appendices C and G. The structure of the substrate is essential to determining oil penetration. Oil penetration will be less on a beach with very fine substrate granules that are packed closely together. Penetration will be greater in a more coarse-grained substrate. If the pores are large and inter-connected, the substrate will be more permeable and allow deeper penetration and even lateral movement through capillary action.

The pore space, and in turn the permeability, will depend on the size of the granules on the beach, as in Table 3 (see also Appendix B), as well as the way in which the granules are positioned with regard to each other.

Table 3: Sediment Grain Size Scale[7]		
Description (Wentworth Scale)		**Grain Diameter**
Boulder		>256 mm
Cobble		64 – 256 mm
Pebble		4 – 64 mm
Granule		2 – 4 mm
Sand	**Very Coarse**	1 – 2 mm
	Coarse	0.5 – 1.0 mm
	Medium	0.25 – 0.50 mm
	Fine	0.125 – 0.250 mm
	Very Fine	0.0625 – 0.125 mm
Silt		0.004 – 0.625 mm
Clay		0.00024 – 0.004 mm

Bedrock shorelines[8] are largely impermeable to oil except when it is able to enter crevices or fractures in rock surfaces. Gravel beaches tend to have large inter-connected pore spaces that will allow oil to readily penetrate. Sand and mud beaches tend to have tightly packed sediments with small pore spaces that are less permeable to oil, though some lighter oils can penetrate.

Some shorelines have features that can influence oil retention and penetration that are not related to granule size. Tidal flats often have holes from burrowing animals that will allow oil penetration (Howard and Little 1987). Oil adhesion can be influenced by the presence of vegetation, such as in wetlands or mangroves (Michel, Lehmann, and Henry, 1998; Lytle and Lytle, 1987; Baca et al., 1983) (see Appendices E and M). Ice is another substrate that can cause variations in oil adhesion and penetration

[6] Owens and Sergy 2000, Michel et al. 1998.
[7] Based on Owens and Sergy 2000, Michel et al. 1998.
[8] Man-made shoreline structures, such as docks, walls, and breakwaters, are generally constructed of concrete, wood, and/or steel, which usually act much like bedrock.

based on its nature (tightly packed, granular, smooth, or rough) (Owens and Sergy, 2004) (see Appendix D).

Wave energy at the shoreline can affect the degree of initial deposition and penetration (Humphrey, 1993). (Studies on the impact of wave energy are reviewed in Appendix I.) The effectiveness of wave energy in removing or re-floating oil is dependent on the permeability of the shoreline substrate and the oil type and weathering condition with respect to adhesiveness. Wave energy can effectively remove oil from a bedrock shoreline where there is little, if any, penetration. Wave action can also cause the shoreline substrate to redistribute itself, as in the case of gravel or sand. This action can affect the degree of oil retention and re-floating (see Appendix J). The extent of oiling on the shoreline is also dependent on the tidal stage at the time of oil deposition.

The interrelationship between these various processes is depicted in Figure 1.

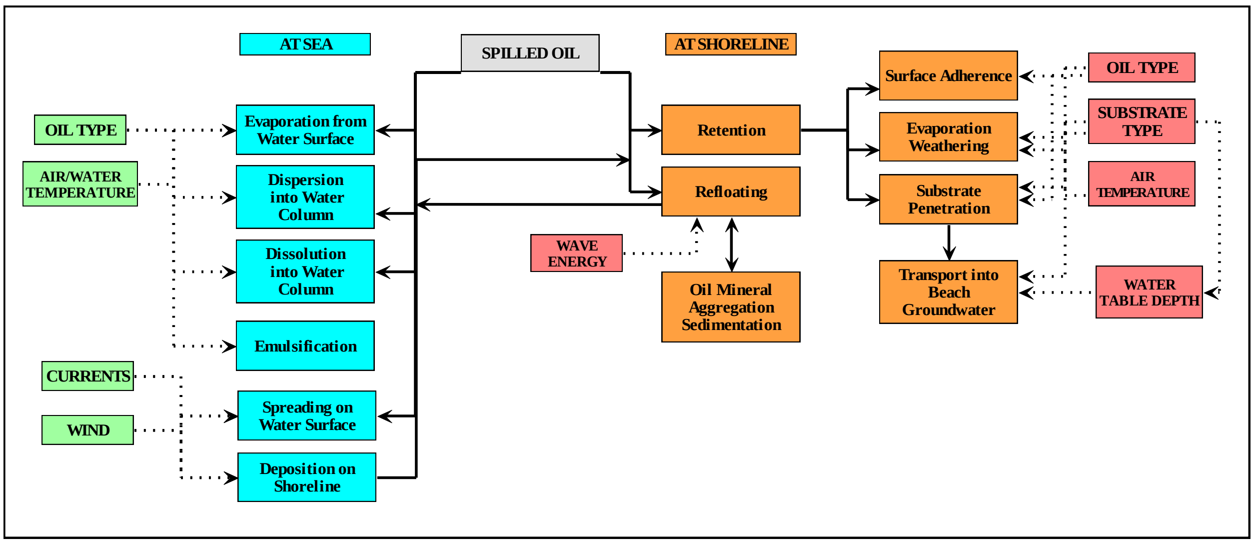

Figure 1: Schematic Representation of Interrelated Oil Fate Processes at the Shoreline

Once stranded, oil will continue to weather and several additional physical processes become important such as re-flotation, penetration into the substrate, erosion by wave action, and retention/transport in the beach-groundwater system. The interrelated factors and processes that affect the short-term fate (days to weeks) of the stranded oil include the permeability of the substrate (which controls the depth of penetration into sediments); wave energy at the shoreline (which affects re-floating of oil from the surface and erosion of oiled sediments); and air temperature (which influences viscosity and evaporation rates).

Longer-term fate (months to years[9]) is controlled by the depth of oil penetration and/or burial, the seasonal wave energy at the shoreline, oil-fines interaction, reworking by biological processes, and microbial degradation. (Studies on oil persistence in beach sediments and subtidal sediments are reviewed in Appendices K and L, respectively.)

Weathering that occurs after the oil has been deposited on the shoreline will change the nature of the oil with respect to adhesiveness and thus the degree to which the oil can further penetrate the substrate or be re-floated by wave action.

The degree of re-flotation of the oil after stranding will be dependent on oil type, weathering, wave energy, tidal changes, and degree of penetration. The penetration of the oil into the substrate after initial deposition on the shoreline is, in turn, dependent on a complex set of factors, including oil type,

[9] Longer-term fate is outside the scope of this study.

weathering, and characteristics of the substrate, particularly with regard to granular size, and pore size and inter-connectivity.

High-energy wave action, especially on a highly exposed shoreline, can erode oil from the shoreline and re-deposit it into the water, where it may or may not be re-stranded on the shoreline. On the other hand, oil can remain adhered to shorelines for decades in sheltered coves and beaches. Storms can create unusually high-energy waves that can re-float and remove large amounts of oil that may be stranded even above the high-tide line. Along with the degree and duration of wave energy, the condition of the oil with regard to oil type and degree of weathering, as well as the depth of penetration into the shoreline substrate, will influence the amount of oil that will be eroded during normal wave action or re-floated during storms.

Once oil has penetrated the shoreline substrate it may become incorporated into the groundwater system of the beach. The degree to which oil is retained and/or transported in this system depends on a number of factors, such as the depth of the water table, the depth of oil penetration, the permeability of the shoreline substrate, and the structure of the beach.

Another process in the nearshore area that should be considered is “oil-mineral aggregation” (OMA), which is reviewed in greater detail in Appendix N. Oil near and on shorelines sometimes interacts with fine mineral particles (sometimes called “fines”) that are suspended in the water column near the shoreline and may move onto the shoreline with tidal and wave action. Oil may adhere to these particles and be transferred into the water column and sediment. The oil may then detach and re-float. The process may be dynamic with the oil alternately adhering and detaching from the particles.

The interaction of fine mineral particles with stranded oil in an aqueous medium reduces the adhesion of oil to solid surfaces, such as sediments or bedrock. The net result is the formation of stable, micron-sized, oil droplets that can be dispersed into the water column by wave action. In turn, the increase in surface area makes the oil more available for biodegradation. In general, the evidence examined indicates that OMA does not play a significant role in the fate of oil in the *early* stages after oil deposition on the shoreline, and, as such, is of relatively minimal importance to MMS in its shoreline-oil interaction modeling efforts. In this regard, Reed, Kana, and Gundlach (1988) had concluded that the OMA formation process was not important in the surf zone relative to transport processes. OMA may, however, play a role in longer-term shoreline processes (Fingas, 2001), and would be relevant in some situations in longer-term models. It may be very important in areas where there are significant concentrations of fines, such as glacial-fed rivers. It may be relevant in longer-term shoreline-oiling modeling.

2.2 Existing Shoreline Oiling Models

Complex oil-shoreline interactions present challenges for spill modelers. At the most basic level, models are usually used to simulate the trajectory and spread of oil, including degree of shoreline impact for risk analysis or planning purposes.

Modeling of oil-shoreline interactions has been handled in a number of ways, including:

- Assuming all oil reaching a shoreline accumulates on that shore segment;
- Assuming all oil reaching a shoreline strands on the shore segment if the tide is receding;
- Using empirical data, relating the maximum amount of oil retained on shore to shore type and oil viscosity, to quantify a oil-holding capacity (e.g., Gundlach, 1987); and
- Utilizing a complex shoreline interaction model based on shore geography and hydraulic interactions (i.e., the COZOIL model developed by Applied Science Associates, Inc. for MMS: Reed et al., 1986, 1988, 1989; Gundlach, 1987; Coastal Science & Engineering, 1986, 1988; Reed and Gundlach, 1989a,b; and the surf zone oil transport model by Cheng et al., 2000).
- Using a statistical approach, i.e., a simple regression model to predict the lengths of coastline that would be impacted by an oil slick based on observational data from actual oil spills.

The simplest modeling approach is to accumulate oil on shore when floating oil reaches a shore segment, regardless of the oil type, weathering characteristics, shore type, amount of oil already on the shore, current and turbulence conditions, and so forth. Many models use this simplification, as does the current version of OSRA. However, it is desirable to incorporate some of the processes and relationships described in the preceding sections into the model such that not all intersecting oil would necessarily be retained on a shore segment.

The next simplest approach would be to only strand the oil as the tide recedes. This algorithm requires tidal constituents to be modeled, along with water levels on shore such that a falling tide may be identified. This amount of detail in tidal dynamics may not be practical for large scale models and spills originating offshore. Moreover, tidal currents are typically not important in offshore areas. While the stranding of oil on falling tides increases realism slightly, it really only delays the timing of oil stranding on a shore segment if it arrives on an in-coming tide, unless the wind changes before the next high tide. Thus, this approach would provide little advantage over the simplest approach of accumulating all intersecting oil on shore.

Accumulation of oil on shore up to an empirically derived oil-holding capacity is used by most oil spill models that include some kind of shore interaction algorithm (Gundlach and Reed, 1986; Gundlach, 1987; French et al., 1996; Reed et al., 1999, 2000; Cheng et al., 2000; French McCay, 2004). The advantage of this approach is that it is simple to implement. However, considerable data are required to derive appropriate holding capacities. In spite of this limitation and the need for additional data to quantify holding capacities, we recommend this approach for most oil spill modeling applications.

The coastal zone oil spill model, COZOIL (Reed et al., 1986, 1988, 1989; Reed and Gundlach, 1989a,b; Howlett, 1998) includes a dynamic representation of processes controlling oil distribution in the coastal zone. In applying COZOIL, the foreshore is the shoreline between mean low and high water (tidal range) and the backshore is the shoreline above mean high water. When oil comes ashore, if the tide is lower than the high tide level and the tide is receding, the oil is deposited if the foreshore has not already reached its oil-holding capacity for oil. If the water level is at or exceeds the mean high tide level, oil is deposited on the backshore by the waves (in the splash zone). The maximum holding thickness is a function of oil viscosity and shore type. However, data to quantify these holding thicknesses and the width over which they should be applied are limited and have not been reviewed or updated in two decades. Additionally, the COZOIL model includes other algorithms that are difficult to apply because the needed input data have not been compiled, making it impractical to include in such models as MMS's OSRA model. For example, if oil is to be left ashore only on a receding tide, tidal hydrodynamics and modeling of wet-dry cycles in the intertidal zone must be included. This detail may not be practical for applications involving spills from the offshore areas of the Gulf of Mexico and elsewhere.

Finally, some authors have attempted to develop statistical models related oil volume in nearshore waters to amount of oil retained on shorelines (Ford, 1985; Seip et al., 1986). While correlations exist, this type of statistical approach does not take into account known relationships to shore type and oil viscosity. There are too many compounding factors. In fact the variation in amount of oil on a shoreline based on shoreline length (as shown in Appendix P) can vary by several orders of magnitude Thus, this approach has not been pursued in other modeling efforts. A more detailed review of existing shoreline oiling models is presented in Appendix O.

3.0 Development of an Algorithm for Shoreline Oiling

While the literature review of shoreline oiling research and case studies provided a fairly solid background on the complex processes involved, much of the data found did not provide the type of information that would be most useful for the development of a robust algorithm for improving the manner in which oil spill risk analysis models handle oil-shoreline interaction components. The most relevant studies and approaches were used in developing a recommended algorithm for estimating shoreline oiling.

For a spill risk model to be applied in a stochastic manner, as for MMS's OSRA model, a relatively simple and practical method to estimate the oil oil-holding capacity of shoreline sediments based on shoreline type and oil properties is recommended and needed to be derived. The literature was reviewed for the most appropriate methodology for developing an algorithm for this purpose. In addition, empirical SCAT data and a theoretical hydraulics model were also analyzed and evaluated for the development of this algorithm.

3.1 Calculations of Oil-holding capacity from Empirical Field Data

Gundlach (1987) developed oil-holding capacity and oil removal coefficients for different shoreline types for use in computer simulation models based on empirical data from the Amoco Cadiz, Urquiola, and Ixtoc I spills. Oil thicknesses by shoreline and oil types are shown in Table 4. Calculated holding capacities for different shoreline types (of typical slopes for the type), and for an example (large) tidal range (4 m) and swash zone width (1 m), are shown in Table 5. Sand beaches contain the largest quantity of deposited oil, 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 in the upper swash zone. Rocky shores with little oil penetration and steep slopes hold very little oil.

Table 4: Oil Thickness by Shoreline Type and Oil Type (from Gundlach 1987)

Shoreline Type	Oil Type			
	Medium-viscosity		Light Oil	Heavy Oil
	Thickness (mm)	Standard Deviation (mm)	Thickness (mm)	Thickness (mm)
Rocky cliffs (exposed)	2	NA	0.5	2
Sand beaches	17	19	4	25
Mixed sand and gravel	9	11	2	15
Tidal flats	6	6	3	10
Rocky shore (sheltered)	5	NA	1	10
Marshes	30	14	6	40
Eroding peat scarp	4	NA	1	10

Table 5: Calculated Maximum Oil-holding capacity by Shoreline Type for Linear Meter of Shorefront Based on a 4-Meter Tide Range and 1-Meter Vertical Swash (from Gundlach 1987)

Location	Measurement	Shoreline Type				
		Rocky	Sandy Beach*	Gravel	Tidal Flat	Marsh
Surface Oil	Total holding average (m^3/m)	0.1	2.02	0.50	0.12	0.30
	Total holding +1 SD (m^3/m)	NA	3.81	1.12	0	0.16
	Total holding -1 SD (m^3/m)	NA	1.84	0	0.24	0.44
Subsurface Oil	Total holding average (m^3/m)	NA	0.14	0.18	NA	NA
	Total holding +1 SD (m^3/m)	NA	0.28	0.35	NA	NA
	Total holding -1 SD (m^3/m)	NA	0	0	NA	NA
Grand Totals	**Total holding average (m^3/m)**	**0.01**	**2.16**	**0.68**	**0.12**	**0.30**
	Total holding +1 SD (m^3/m)	**0**	**4.09**	**1.47**	**0.24**	**0.44**
	Total holding -1 SD (m^3/m)	**NA**	**1.84**	**0**	**0**	**0.16**

*includes beach face and back shore

Gundlach (1987) and Reed et al. (1989) concluded that the oil-holding capacity of a shoreline is dependent on both the oil and beach characteristics. The capacity consists of two components – maximum surface loading and maximum subsurface loading. Cheng et al. (2000) expressed this as:

$$M_* = \rho_o (L_t T_m + C_v D_p L_s)$$

Where: T_m = maximum oil thickness

L_t = beach width including intertidal and swash zone[10]
D_p = depth of penetration
C_v = oil content of sediment
L_s = width of swash zone
ρ = density of oil

The parameters of oil thickness (T_m), sediment oil content (C_v), and depth of penetration (D_p) were derived from empirical values from Gundlach (1987) by Cheng et al. (2000), as shown in Table 6. Note that, according to the above equation, Cheng et al. (2000) only considered subsurface oil in the swash zone, and did not include subsurface oil in the intertidal zone proper. However, L_s could be interpreted as equal to L_t to include subsurface oil in the intertidal zone.

Table 6: Oil-Holding Capacities Extrapolated from Cheng et al. (2000) and Gundlach (1987) With Estimated Unit Area Holding Capacities

Shoreline Type	Maximum Surface Oil Thickness (mm) By Viscosity			Subsurface Oil-holding capacity		Estimated Maximum Oil-holding capacity (m^3 Oil/m^2 Sediment)*		
	Light <30 cS	Medium 30 – 2,000 cS	High >2,000 cS	Oil Depth (mm)	Oil content by volume (%)	Light <30 cS	Medium 30 – 2,000 cS	High >2,000 cS
Rocky cliff	0.5	2	2	0	0	0.0005	0.0020	0.0020
Sand beach	4	17	25	50	9.8	0.0040	0.0170	0.0250
Sand/gravel	2	9	15	180	8.3	0.0021	0.0091	0.0151
Tidal flat	3	6	10	0	0	0.0030	0.0060	0.0100
Rocky shore	1	5	10	0	0	0.0010	0.0050	0.0100
Marsh	6	30	40	-	-	0.0060	0.0300	0.0400
Peat scarp	1	4	10	0	0	0.0010	0.0040	0.0100

*Based on addition of maximum oil surface thickness (assuming 100% coverage) to subsurface oil content.

Holding capacities in Table 6 may be applied in a model by specifying a tide range and beach slope, which infers a beach width over which the volume per area capacity applies. This approach was used by French et al. (1996): e.g., sand beaches were characterized with a slope of 0.10-0.22 and the tide range along US coastlines of the Gulf of Mexico was 1 foot (0.3 m).

3.2 Calculations of Oil-holding capacity Based on SCAT Data

Appendix C contains summaries of studies on shoreline oil loading and holding capacities following oil spills. In order to use any of these observations in a model algorithm defining maximum oil-holding capacity (as oil volume per unit area of shoreline for general categories of oil type and weathering state), data resulting from appropriate measurements are needed for heavily oiled shorelines of known shore type after spills under natural conditions (as opposed to purposeful loading of oil directly on a shoreline).

Several studies (other than Gundlach, 1987) that included an analysis of holding capacities, as discussed above, indicated a maximum oil-holding capacity of crude oil in sediments on heavily oiled beaches to be about 10-12%, presumably by volume (11%, Torrey Canyon [Smith, 1968]; 10%, Amoco Cadiz [Blount, 1978]; 12%, Peck Slip [Robinson, 1979]). In other spills, maximum oil content, as weight per weight of sediment, was about 20-50 g/kg (20,000 ppm, Arco Anchorage [Chamberlain et al., 1987; Lindstedt-Siva et al., 1987; Pearson et al., 1986]; 50,000 ppm, Sivand [Little, 1987]). In other studies, the data and observations were not measured in a way (or were not in a format) that could be interpreted as a oil-holding capacity per volume of sediment. In order to translate these data to holding capacities per unit area of shoreline, the volume of oiled sediment per unit area would need to be estimated. Such data are only available in detailed SCAT studies.

[10] The authors described this as "tide range" but meant "beach width".

When well-collected, SCAT data from past spills provide a wealth of information that can be used for modeling purposes and to establish measures of oil behavior on different shoreline types (e.g., Etkin, 2003). (SCAT studies are presented in greater detail in Appendix Q). It can also be used to calculate shoreline oil-holding capacity when the pertinent details of oil thickness, depth of penetration, area, coverage, and shoreline type have been duly recorded in the SCAT process. Indeed, the holding capacities developed by Gundlach (1987) were derived from detailed data of this type. Data from several more recent detailed SCAT studies were analyzed (discussed in Appendix P). (Many SCAT surveys were found to be insufficiently detailed for the purpose of determining shoreline oil loading because there were little, if any, data on oil penetration and/or the data do not have the quantitative details required as when there are only qualitative descriptions of oiling conditions). These data were used to estimate the distribution of oil loading, and, in particular, *maximum* oil loading. These factors could be used to calibrate shoreline oiling models with regard to the point at which oil would "saturate" a particular type of substrate and surface and then fail to adhere further to that particular shoreline segment.

During 1989, in the aftermath of the Exxon Valdez spill, SCAT surveys were conducted on 5,221 km of shoreline of eight major types in Prince William Sound, Alaska. Only 1989 pre-shoreline treatment data were considered in order to focus on shoreline impacts in the first month post-spill. This also eliminated analysis of shorelines to which any treatment may have been applied or where natural weathering had occurred. SCAT data were analyzed for oil penetration depth by shoreline substrate type (as in Appendix A). Shoreline penetration depth was previously shown (Etkin, 2003) to vary by the degree of oiling as described in the SCAT surveys. As expected, penetration depth was found to increase with degree of oiling. There were also shown to be variations in the penetration depth between shoreline types and within each shoreline type by the degree of oiling.

Distributions of shoreline penetration by Alaskan North Slope crude oil are in Table 7. Cobble beaches showed the greatest maximum penetration. Volumes of oil-saturated sediment are shown in Table 8.

Table 7: Exxon Valdez Oil Spill Shoreline Oiling 1989: Depth of Penetration

Shore Type	N	Penetration Depth (m)		
		Maximum	Mean	SD
Cobble	163	1.270	0.077	0.131
Boulder	235	0.762	0.079	0.114
Rocky	399	0.508	0.066	0.104
Pebble	104	0.406	0.067	0.094
Cliff	23	0.305	0.050	0.080
Sandy	62	0.305	0.035	0.069
Gravel	71	0.203	0.018	0.047
Mudflat	3	0.102	0.038	0.049

Table 8: Exxon Valdez Oil Spill Shoreline Oiling 1989: Volume of Oiled Sediment

Shore Type	N	Volume Oiled Sediment (m^3)/Area (m^2)		
		Maximum	Mean	SD
Cliff	23	0.2438	0.0339	0.0660
Boulder	235	0.4115	0.0532	0.0811
Rocky	399	0.5029	0.0405	0.0815
Cobble	163	1.1430	0.0617	0.1206
Pebble	104	0.4064	0.0458	0.0770
Gravel	71	0.1828	0.0118	0.0347
Sandy	62	0.2540	0.0132	0.0353
Mudflat	3	0.1016	0.0341	0.0584

This volume needed to be adjusted to subtract the volume of the substrate itself and to calculate the interstitial pore space between grains filled to capacity with oil (Figure 2).

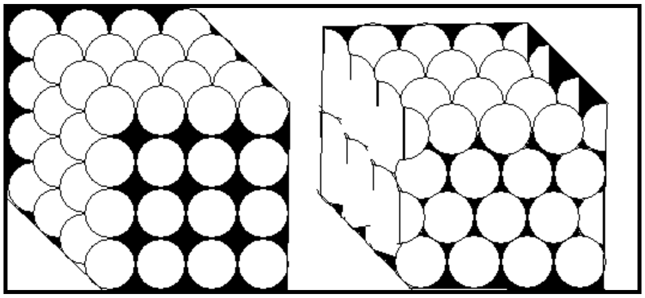

Figure 2: Idealized diagram of interstitial pore space between grains filled to capacity with oil. Oil in a saturated substrate will be *less* since in nature the grains are tightly packed, as shown on right.

Oil in a completely saturated substrate would be represented by:

$$Vol_{oil} = 1 - \left[\left(\frac{1}{2}r\right)^3\left(\frac{4}{3}\pi r^3\right)\right]$$

or = 0.4764 m^3 oil/m^3 substrate [125 gallons/m^3 or 476.8 liters/m^3], *regardless* of grain diameter *if* the sediment is packed as shown on left in Figure 2. Oil in a saturated substrate will be *less* if the grains are tightly packed, as shown on the right. The 476.8 liters/m^3 represents the theoretical *maximum* saturation. In nature, the grains are not all uniform in size and thus the smaller grains tend to be packed even more densely in the larger grain pore spaces. For cobble beaches, for example, where between the cobbles are pebbles, granules, and sand, the permeability and oil-holding capacity are better represented by the smaller grain sizes, not the larger cobble.

If the pore spaces are 50 – 100% saturated or if there is repacking of the substrate as in the right portion of Figure 2, an average of 200 – 400 liters/m^3 of oil will be in the substrate that is saturated, as described in Gillie, Harper, and McCullough (1999). It is expected, however, that in most cases only 10 – 20% of pore space on a beach could actually be filled with oil with the remainder being filled with air and water, based on studies of water saturation in soils (van Genuchten, 1980).

Assuming that sediment is saturated and that the maximum pore space that can be filled is 20% of available pore space, the volume of oiled sediment (Table 8) was multiplied by 80 liters/m^3 to derive the amount of oil in the sediment per unit area (Table 9). Because some oil would remain on the surface, it would be necessary to add that amount of surface oil to the subsurface oil to determine the total oil loading. Surface oiling is shown in Table 10. The subsurface and surface oil were summed, as shown in Table 11.

Table 9: Exxon Valdez Oil Spill Shoreline Oiling 1989: Subsurface Oil Volume Per Unit Area

Shore Type	N	Total Volume of Subsurface Oil (m^3)/Area (m^2)		
		Maximum	Mean	SD
Cliff	23	0.01950	0.00272	0.00528
Boulder	235	0.03292	0.00426	0.00648
Rocky	399	0.04024	0.00324	0.00652
Cobble	163	0.09144	0.00494	0.00964
Pebble	104	0.03252	0.00366	0.00616
Gravel	71	0.01462	0.00094	0.00278
Sandy	62	0.02032	0.00106	0.00282
Mudflat	3	0.00812	0.00272	0.00468

Table 10: Exxon Valdez Oil Spill Shoreline Oiling 1989: Volume of Surface Oil				
Shore Type	N	Volume Surface Oil (m³)/Area (m²)		
		Maximum	Mean	SD
Cliff	23	0.0200	0.0054	0.0072
Boulder	235	0.0200	0.0066	0.0077
Rocky	399	0.0200	0.0034	0.0058
Cobble	163	0.0200	0.0061	0.0078
Pebble	104	0.0200	0.0039	0.0066
Gravel	71	0.0180	0.0017	0.0046
Sandy	62	0.0200	0.0009	0.0033
Mudflat	3	0.0200	0.0068	0.0114

Table 11: Exxon Valdez Oil Spill Shoreline Oiling 1989: Total Volume per Unit Area							
Shore Type	N	Total Volume of Subsurface Oil and Surface Oil (m³)/Area (m²)					
		m³/Area (m²)			grams/Area (m²)		
		Maximum	Mean	SD	Maximum	Mean	SD
Cliff	23	0.0395	0.0081	0.0125	35,471	7,292	11,207
Boulder	235	0.0529	0.0109	0.0142	47,504	9,752	12,734
Rocky	399	0.0602	0.0066	0.0123	54,060	5,963	11,063
Cobble	163	0.1114	0.0110	0.0174	100,037	9,914	15,661
Pebble	104	0.0525	0.0076	0.0128	47,145	6,789	11,458
Gravel	71	0.0326	0.0026	0.0074	29,275	2,371	6,627
Sandy	62	0.0403	0.0020	0.0061	36,189	1,760	5,496
Mudflat	3	0.0281	0.0095	0.0161	25,234	8,549	14,440

Similar calculations were performed for the SCAT data from the 2000 PEPCO pipeline spill in which 126,000 gallons (430 tonnes) of a combination of No. 6 and No. 2 fuels were spilled in Chalk Point, Maryland, USA, as shown in Table 12.

SCAT data from two other heavy oil spills were analyzed. Results from analyses of SCAT data from the Athos I spill (265,000 gallons of heavy crude oil spilled into the Delaware River, New Jersey, USA, in 2004) were analyzed as in Table 13. Results from analyses of the Selendang Ayu spill (442,000 gallons heavy fuel oil in the Alaskan Aleutian Islands) are in Table 14.

Table 12: PEPCO Pipeline Oil Spill Shoreline Oiling										
Shore Type	N	Oil Thickness on Surface (m)[11]			Volume Oil (m³) per Area (m²)			Grams per Area (m²)		
		Max	Mean	SD	Max	Mean	SD	Max	Mean	SD
Sheltered Rock	12	0.015	0.005	0.005	0.006	0.002	0.002	5,388	1,796	1,796
Rock-Gravel	21	0.005	0.001	0.002	0.004	0.000	0.001	3,592	0	898
Rocky Platform	24	0.015	0.003	0.004	0.014	0.001	0.003	12,572	898	2,694
Rock-Coarse Sand	17	0.015	0.001	0.004	0.011	0.001	0.003	9,878	898	2,694
Fine Sand	12	0.015	0.004	0.006	0.009	0.001	0.003	8,082	898	2,694
Rocky	16	0.005	0.001	0.002	0.000	0.000	0.000	0	0	0
Salt Marsh	239	0.015	0.003	0.004	0.014	0.001	0.002	12,572	898	1,796
Gravel	43	0.015	0.003	0.003	0.003	0.000	0.001	2,694	0	898
Freshwater Marsh	32	0.020	0.004	0.005	0.006	0.001	0.002	5,388	898	1,796
Exposed Tidal Flat	41	0.015	0.003	0.004	0.004	0.001	0.001	3,592	898	898
Coarse Sand	71	0.015	0.002	0.003	0.004	0.000	0.001	3,592	0	898
Coarse Sand/Salt Marsh	123	0.015	0.003	0.004	0.010	0.001	0.002	8,980	898	1,796

[11] Penetration into the substrate was not specifically measured or recorded in this shoreline cleanup team assessment (SCAT). Only oil thickness on the substrate surface was measured.

Table 13: Shoreline Oil Loading in Athos I Oil Spill								
ESI		N	Oil Loading (m^3/m^2)			Oil Loading (g/m^2)		
			Average	SD	Maximum	Average	SD	Maximum
1B	Exposed Seawalls	7	0.0003	0.0002	0.0005	232	215	453
3	Fine Sand	11	0.1009	0.0033	0.0033	90,645	2,939	2,939
5	Mixed Sand/Gravel	9	0.0024	0.0048	0.0142	2,130	4,304	12,773
6A	Gravel Beach	7	0.0020	0.0027	0.0071	1,768	2,381	6,387
6B	Riprap Structures	6	0.0004	0.0008	0.0020	361	728	1,825
10A	Salt/Brackish Marsh	2	0.0001	0.0001	0.0001	49	60	91

Table 14: Shoreline Oil Loading in Selendang Ayu Oil Spill							
Substrate	N	Oil Loading (m^3/m^2)			Oil Loading (g/m^2)		
		Average	SD	Maximum	Average	SD	Maximum
Bedrock	25	0.06	0.13	0.59	58,070	114,132	533,412
Pebble-cobble	23	0.41	3.12	5.60	365,656	2,801,887	5,028,800
Sand	4	0.18	0.76	0.53	157,850	680,132	471,989

3.3 Calculations of Oil-holding capacity from Bench-Scale Experimentation

Laboratory experiments have also been used to estimate oil-holding capacity. In the most recent of the Subsurface Oil in Coarse Sediments Experiments (SOCSEX), Harper and Sergy (2007) conducted bench-top experiments to simulate oiling of coarse-sediment beaches to determine oil penetration and retention values. (The chronological development of the SOCSEX studies is reviewed in Appendix G.) The experimental design involved applying oil to the top of vertical sediment columns and included:

- Sixteen sediment types (ranging from 0.75-mm coarse sand to very large pebbles of 43 mm);
- Five test oils (three crude oils and two fuel oils)
- Different oil weathering levels
- Temperature and tidal cycling

Oil penetration and oil retention were found to vary inversely. Highly permeable sediments were found to have low retention and low permeability sediments were found to have high retention. Most test oils were found to freely penetrate coarse sediment (very large pebbles). Retention rates were found to be less than 100 liters/m^3 – with a mean of 44.8 liters/m^3. Most oils were found not to penetrate coarse sand, where retention concentrations were found to be on the order of 100 – 200 liters/m^3 – with a mean of 150.8 liters/m^3. The degree of weathering and temperature were found to strongly affect oil penetration and increased retention. More heavily weathered oils showed lower penetration. Higher temperatures, which lowered viscosity, increased penetration. Heavy fuel oils showed lower penetration potential and greater retention potential than crude oils.

The results of tidal cycling experiments suggested that smaller pore spaces resulted in greater oil stability (i.e., the oil was less likely to flush out) and that larger pore spaces promoted oil mobility. The initial loading level appeared to be more stable for fine sediment than coarse sediments. Tidal cycling showed little change for fine sediments (very coarse sand and granules) after initial oiling, but coarse sediments (medium pebbles) showed more than 40% reduction from the initial oiling value.

No single oil property (e.g., viscosity) was found to correlate with penetration or retention potential. Some relatively non-viscous oils had low penetration potential. In summary, oil penetration potential was found to be related to the fluid properties of oil and sediment size. For a given sediment type, penetration increased with increasing *penetration potential*, an oil property that appeared to be a complex interaction of viscosity, adhesion, and oil components:

- *For a given oil type*, penetration increased with increasing grain size with small changes in sediment size strongly affecting penetration.

- *For a given oil type*, penetration was greater under warmer conditions (which would lower viscosity).
- *For a given oil type*, penetration was greater with less weathering (and so inversely related to viscosity).
- Crude oils were likely to penetrate further than heavy fuel oils; the latter typically being more viscous but oils with more adherent properties penetrated less and were retained more than other oils.

Oil retention was calculated by the following formula:

$$\left(\frac{volume_{oil}}{volume_{sed}}\right) = \frac{t_0 - t_1 \;\cdot A}{d \cdot A}$$

Where: t_0 = oil thickness at start of experiment
t_1 = oil thickness at end of experiment
d = depth of oiling
A = cross-sectional area of the column

Their results are shown in Tables 15 and 16. The oil-holding capacity by shoreline type could be derived from the Harper and Sergy (2007) results from the subsurface retention values added to any calculated surface oil thickness. However, penetration into the substrate in this bench-top experimentation may actually have been enhanced by gravity because of the experimental design and the lack of wave action that would be experienced on an actual shoreline. Thus, while these experimental data are informative and provide insight into mechanisms involved, the actual quantities of oil penetrating the sediment on a natural shoreline may not be represented by the laboratory experiment.

Table 15: Oil Penetration Observations as Function of Oil Type and Sediment Type

Penetration Potential	Sediment Type[12] (cm Penetration into Sediment)[13]								Oil Type[14] Weathering Temperature
	Coarse Sand[15]	Very Coarse Sand[16]	Granule[17]	Small Pebble[18]	Medium Pebble[19]	Marble[20]	Large Pebble[21]	Very Large Pebble[22]	
1	2.75	2	2	2.1	2.5	2	3	3.5	Hibernia Crude, 26%, 2ºC
2	1	1.5	1.5	3	4.5	5	6	7	Federated Crude, 27%, 2ºC
3	4.5	3.5	3	5	5	5.5	7	10	Hibernia Crude, 18%, 2ºC
4	0.5	2	2.5	9	9.4	-	10	10	Bunker C, 0%, 2ºC
5	-	-	2.5	5.5	9.2	10	10	10	Bunker C, 6%, 2ºC
6	1.5	3	4.5	9.0	10	-	10	10	Bunker C, 0%, 15ºC
7	-	-	4	10	10	10	10	10	Bunker C, 6%, 15ºC
8	-	-	6	10	10	-	10	10	Bunker C, 0%, 5ºC

[12] Note: shaded cells indicate maximum penetration >9.5 cm.
[13] Harper and Sergy (2007)
[14] ANS (Alaska North Slope) crude = low adhesion (moderate adhesion at 22% weathering), low viscosity; Bunker C fuel oil = high adhesion, very high viscosity; Federated crude = low adhesion, low viscosity; Hibernia crude = moderate adhesion, moderate viscosity; IFO-180 fuel oil = high adhesion, high viscosity.
[15] Coarse sand = mean size 0.75 mm
[16] Very coarse sand = mean size 1.70 mm
[17] Granules = mean size 3.40 mm
[18] Small pebbles = mean size 6.75 mm
[19] Medium pebbles = mean size 14.5 mm
[20] Marbles = mean size 15.0 mm
[21] Large pebbles = mean size 22.0 mm
[22] Very large pebbles = mean size 43.0 mm

Table 15: Oil Penetration Observations as Function of Oil Type and Sediment Type									
Penetration Potential	Sediment Type[12] (cm Penetration into Sediment)[13]								Oil Type[14] Weathering Temperature
	Coarse Sand[15]	Very Coarse Sand[16]	Granule[17]	Small Pebble[18]	Medium Pebble[19]	Marble[20]	Large Pebble[21]	Very Large Pebble[22]	
9	2	4	7	10	10	10	10	10	Federated Crude, 18%, 2ºC
10	2	5	8.5	10	10	10	10	10	ANS Crude, 22%, 2ºC
11	2	4	10	10	10	10	10	10	IFO, 2.5%, 2ºC
12	-	-	10	10	10	10	10	10	Bunker C, 0%, 10ºC
13	8	5.5	10	10	10	10	10	10	Hibernia Crude, 26%, 15ºC
14	3.5	7	10	10	10	10	10	10	Hibernia Crude, 18%, 15ºC
15	3.5	8	10	10	10	10	10	10	ANS Crude, 15%, 2ºC
16	4	9	10	10	10	10	10	10	IFO, 2.5%, 15ºC
17	6.5	9	10	10	10	10	10	10	Federated Crude, 27%, 15ºC
18	5	10	10	10	10	10	10	10	ANS Crude, 22%, 15ºC
19	6.3	10	10	10	10	10	10	10	Federated Crude, 18%, 15ºC
20	7.5	10	10	10	10	10	10	10	ANS Crude, 15%, 15ºC

Table 16: Subsurface Oil Retention Observations (L/m^3) as Function of Oil Type and Sediment Type									
Penetration Potential	Sediment Type								Oil Type Weathering Temperature
	Coarse Sand	Very Coarse Sand	Granules	Small Pebble	Medium Pebble	Marbles	Large Pebble	Very Large Pebble	
1	109	175	150	357	180	150	117	29	Hibernia Crude, 26%, 2ºC
2	100	200	200	217	355	340	308	221	Federated Crude, 27%, 2ºC
3	33	185	200	230	330	300	300	280	Hibernia Crude, 18%, 2ºC
4	500	305	220	223	197	-	94	77	Bunker C, 0%, 2ºC
5	-	-	200	273	288	185	157	85	Bunker C, 6%, 2ºC
6	127	116	111	50	52	-	68	5	Bunker C, 0%, 15ºC
7	-	-	75	175	168	163	104	25	Bunker C, 6%, 15ºC
8	-	-	279	221	213	-	130	51	Bunker C, 0%, 5ºC
9	375	175	250	250	215	380[23]	257	33	Federated Crude, 18%, 2ºC
10	100	120	247	75	30	25	15	10	ANS Crude, 22%, 2ºC
11	75	175	170	168	60	40	30	5	IFO, 2.5%, 2ºC
12	-	-	220	185	155	-	47	24	Bunker C, 0%, 10ºC
13	19	209	247	255	250	255	100	20	Hibernia Crude, 26%, 15ºC
14	43	157	230	80	30	10	15	10	Hibernia Crude, 18%, 15ºC
15	29	94	75	5	10	15	0	0	ANS Crude, 15%, 2ºC
16	37	128	180	40	18	15	5	0	IFO, 2.5%, 15ºC
17	69	139	135	30	15	10	15	10	Federated Crude, 27%, 15ºC
18	100	115	64	5	5	10	0	0	ANS Crude, 22%, 15ºC
19	48	55	60	20	10	15	30	10	Federated Crude, 18%, 15ºC
20	60	65	55	5	15	15	10	0	ANS Crude, 15%, 15ºC

[23] Unusually high retention rate attributed to first-time use of marbles that may have been coated.

3.4 Theoretical Oil-holding capacity Calculations from Beach Hydraulic Modeling

The simplest approach to calculating oil-holding capacity for subsurface oil would be to calculate the "volume" of the beach that could retain oil and then calculate the effective porosity of the beach, i.e., that portion of the pore space that could actually hold oil and is not taken up by water and/or air.

The structure of the sediment is an important factor. Hardisty (1990) suggested that natural beach sediments have porosities ranging from 0.36 to 0.40. Well-packed flattened particles, such as those that form near storm berms of gravel beaches, may have a much lower porosity.

In another approach, Humphrey, Owens, and Sergy (1993) concluded that the maximum capacity of a beach can be assumed to be:

$$C_{max} = L(m) \cdot W(m) \cdot D(m) \cdot \eta_{eff}$$

Where: L = length of beach in meters
W = width of beach in meters
D = depth of beach in meters
η_{eff} = effective porosity

These researchers assumed that residual loading or oil-holding capacity is related to the residual film thickness of 0.02 mm on each sediment particle. This could then be applied to different particle sizes in a beach substrate. The oil oil-holding capacity of a beach is, however, more complex in a beach subjected to tides. In this case, the oil-holding capacity depends on beach hydraulics and oil properties (i.e., viscosity, density, and adhesiveness). If one considers an extensive duration of exposure (e.g., two weeks), then it is reasonable to assume that the beach will fill up with oil as long as the oil remains fluid (i.e., more so with lower viscosity oils and in higher temperatures). The volume of oil (V_o) can thus be written as:

$$V_o = V_b n f$$

Where: V_b = volume of the unsaturated portion of the beach at low tide
n = porosity
f = coefficient for volume fraction of beach sediment pore space that entraps oil.

For simplicity, the unsaturated volume can be approximated by a wedge (triangle) bounded by the beach surface from above, by the water table from below, and by the maximum depth D to the water table on the landward side (see Figure 3).

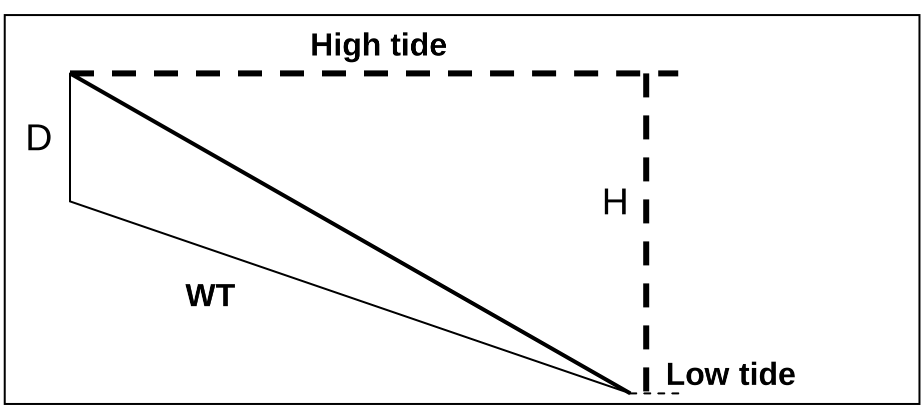

Figure 3: Beach segment where WT = water table, H = tidal range (high tide minus low tide levels), and D = maximum depth of water table on the landward side.

If the tidal range *H* (high tide minus low tide levels), the beach slope, and *D* are specified, then one can compute the volume of the beach wedge. While the first two parameters are relatively easy to obtain, Boufadel et al.[24] observed that the value of *D* depends on a variety of factors, such as the extent of seaward groundwater flow (i.e., recharge), the slope of the beach, and the falling speed of the tide with respect to the value of the hydraulic conductivity of the beach, K.

For this study, Boufadel et al. investigated the response of the beach water table to tide and proposed the data plotted in Figure 4 to predict the depth of the unsaturated zone, *D*, based on the tidal range, the beach slope, the beach hydraulic conductivity, and whether the beach is connected to the landward regional water table (i.e., the inland recharge replenishes the beach as the tide falls) or separated from it (i.e., the beach water table is only affected by the falling speed of tide and the drainage of the pores).

The method requires evaluating the "dimensionless tidal period", *T*, as in (Equation 1):

$$T = \frac{T^{*}K}{H}$$

where *T** is the tidal period (e.g., 12.25 hours for a semidiurnal tide), *K* is the hydraulic conductivity of the beach sediments, and *H* is the tidal range, equal to the difference between the high tide level and the low tide level.

The hydraulic conductivity of sandy sediments can be estimated based on the grain size distribution using, for example, the Kozeny-Carmen equations:

$$K = \frac{\rho g}{\mu} C_k f_k(n) d_{10}^2$$

$$f_k(n) = \frac{n^3}{(1-n)^2}$$

where:	K	= hydraulic conductivity of beach sediments
	f	= volume fraction that entraps oil
	ρ	= density
	g	= acceleration due to gravity
	μ	= dynamic viscosity
	C_k	= 8.3 x 10^{-3}
	n	= porosity
	d_{10}	= 10% cumulative passing (geotechnical grain size distribution).

[24] Michel Boufadel, Hailong Li, and others at Temple University Department of Civil and Environmental Engineering

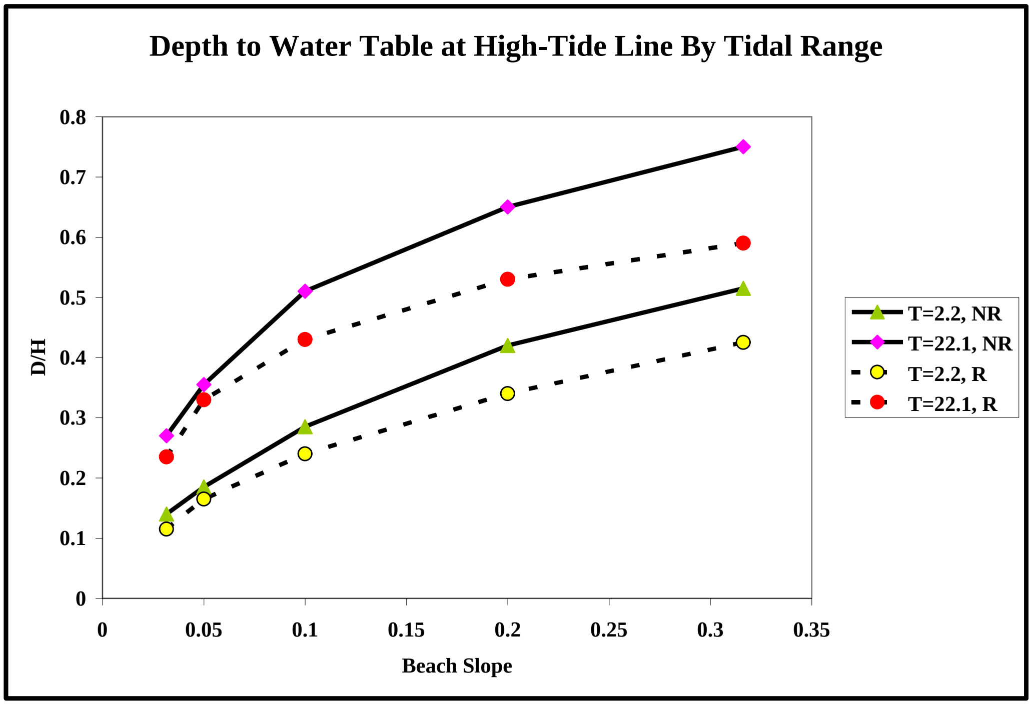

Figure 4: Depth to the water table at the high tide line for fine sand beaches by dimensionless tidal range, T (R = with inland recharge [ground water flow] from inland areas); NR = with no inland recharge).

Figure 4 shows the ratio *D/H* as a function of beach slope and tidal range. Based on Equation 1, one concludes that the ratio D/H of two beaches is the same as long as the value of T is the same (and the slope is the same). For example, if *T** = 12.25 hours (semidiurnal tide), K = 0.1 cm/s, and H = 200 cm, one obtains T = 22.05. One would obtain the same value of T if, for example, the beach is more permeable K = 0.2 cm/s and the tidal range is larger, H = 400 cm.

Thus, the value of D/H remains unchanged as long as T is the same. If, for example, K = 0.01 cm/s and H = 200 cm, one obtains T = 2.1. For values of T that fall between the two values reported herein (2.1 and 22.1), one could interpolate the results in Figure 2 to get the appropriate D/H. However, there is no guidance, at this stage if the computed values of T fall outside of the range (2.1 – 22.1). Note that the values of K = 0.01 cm/s to 0.1 cm/s represent fine sand (Freeze and Cheery, 1979). The results presented in Figure 4 are based on the theory presented in prior works (Boufadel, 2000; Naba, Boufadel et al., 2002; Li et al., 2007).

There is much theoretical discussion on the effect of sediments sorting and arrangement on the porosity. However, based on field observations, the porosity is generally about 25% to 30%, because the small pores are always filled with smaller sediments.

The parameter, *f*, represents the volume fraction that "entraps" oil. Such a fraction depends on the size of the small pores in which the "residual" oil gets entrapped. More precisely, this fraction increases with a decrease in the median size of the pores (it is not easy to measure the median pore size and one could use the median size of the sediments as surrogate). In other words, a gravelly beach entraps less oil than a fine sand beach (as percentage of porosity). This is, thus, an unresolved issue requiring further investigation. However, as a first approximation, one could use information of water-air systems, where the residual saturation of water is usually 10 to 20% of porosity (van Genuchten, 1980). Thus, it is reasonable at this juncture to assume that *f* is equal to 0.1 to 0.2 for low viscosity oils and fuels that would penetrate to this degree. However, higher viscosity oil would penetrate less, and at some viscosity level, oil would be too viscous to penetrate the sediments. Thus, the value of f should decline and asymptotically approach zero at some high viscosity level. The quantification of this relationship would need to be based on experimental or observational data.

These formulae were used to calculate the oil-holding capacity by shoreline type after making the following assumptions. Assuming a tidal range $H = 3$ m, $n = 0.275$, $f = 0.15$, and the values of D/H as a function of beach slope from Figure 4, the volume of oil per square meter of oiled beach at maximum capacity may be calculated. Beach slopes typical of sand beaches are used. The calculated holding capacities are shown in Table 17. These values are of the same order of magnitude as the maximum volumes of subsurface oil estimated for sandy beaches oiled during the Exxon Valdez oil spill[25] (Table 9). However, in most locations the entire beach did not contain subsurface oil, such that less than the entire hydraulic wedge was filled. The hydraulic oil-holding capacity model would likely overestimate the amount of oil that would immediately penetrate the beach for viscous and sticky oils that adhere to sediment, such as medium-heavy and weathered oils.

Table 17: Maximum Shoreline Loading on Sand Beaches for a Penetrating (Light) Oil Based on the Hydraulic Oil-holding capacity Model (Oil Loading, m^3/m^2) assuming H = 3 m

Slope	Intertidal Zone Width (m)	No Inland Recharge		With Inland Recharge	
		T = 2.2	T = 22.1	T = 2.2	T = 22.1
0.032	94.9	0.009	0.017	0.007	0.015
0.050	60.1	0.011	0.022	0.010	0.020
0.100	30.1	0.018	0.032	0.015	0.027
0.200	15.3	0.026	0.040	0.021	0.033
0.316	9.9	0.032	0.046	0.026	0.037

Moreover, these theoretical holding capacities would only include oil penetrated into and retained by the sediment and would not include any oil that built up on the surface. The hydraulic oil-holding capacity model may be appropriate for light fuels and light crude oils that tend not to create a thick surface layer and easily penetrate the shoreline sediments. At this point, with the state of knowledge and data available, the oil-holding capacity of medium-heavy fuels and crude oils would be best estimated by empirical data collected in field studies of oiling on shoreline (such as from the SCAT data described above). In addition, oil pushed ashore in the swash zone (again, more important for medium-heavy crude oils and fuels) would not be accounted for by this beach hydraulic model.

4.0 Recommendations for Oil-Holding-Capacity Algorithm

The values of oil-holding capacity by shoreline type most practically applied in a simple stochastic oil risk or oil trajectory/fate model would be a combination of 1) the Boufadel methodology (hydraulic oil-holding capacity model) for light oils that would easily penetrate beach sediments and not be expected to have any appreciable surface buildup; and 2) the SCAT methodology for medium-heavy oils that would both partially penetrate beach sediments and accumulate on the shoreline surface.

The recommended holding capacities that could be used in a basic stochastic oil spill risk analysis model that incorporates short-term impacts of oil to the shoreline for the purpose of determining trajectory and extent of shoreline contact can be preliminarily derived from the hydraulic oil-holding capacity model for lighter oils, including light fuels[26] and light crude oils[27], which tend to penetrate and saturate the shoreline substrate. Table 18 provides such values for a 1-m tide range (H) typical of the US Gulf of Mexico coast. The calculated values should be verified with further field and tank testing.

For medium crude oils[28] and heavier crude oils[29] and heavy fuels[30], the process of shoreline oiling is different than that for the lighter oils since there is considerable deposition of oil on the shoreline surface,

[25] The tidal range in Prince William Sound is 3 meters throughout most of the year and 5 meters in the spring.
[26] Light fuels include No. 2 fuel and diesels.
[27] Light crude oils include those crudes with a specific gravity of less than 0.85.
[28] Medium crude oils are defined as those crudes with a specific gravity of 0.85 to less than 0.90.
[29] Heavy crude oils are defined as crudes with a specific gravity of 0.90 and higher.
[30] Heavy fuels include intermediate fuel oils, bunker fuels, heavy fuel oil, No. 4 fuel, No. 5 fuel, and No. 6 fuel.

which does not generally occur with lighter oils. Viscosity and other complex factors determine the degree to which the medium and heavier oils penetrate the substrate. Until further verification can be done, the SCAT data from the Exxon Valdez may be used for estimating holding capacities for medium crude oils, as shown in Tables 11, which are comparable to those values originally modeled by Gundlach (1987), as analyzed by Cheng et al. (2000) and shown in Table 6, but on more detailed SCAT data such that the results are less variable and more closely related to sediment type than the Gundlach (1987) data.

Table 18: Maximum Shoreline Loading on Sand Beaches for a Penetrating (Light) Oil Based on the Hydraulic Oil-holding capacity Model (Oil Loading, m^3/m^2) assuming H = 1 m

Slope	Intertidal Zone Width (m)	No Inland Recharge		With Inland Recharge	
		T = 2.2	T = 22.1	T = 2.2	T = 22.1
0.032	31.6	0.003	0.006	0.002	0.005
0.050	20.0	0.004	0.007	0.003	0.007
0.100	10.0	0.006	0.011	0.005	0.009
0.200	5.1	0.009	0.013	0.007	0.011
0.316	3.3	0.011	0.015	0.009	0.012

The more limited data for the PEPCO pipeline, Athos I, and Selendang Ayu spills may not provide enough reliable SCAT data upon which to base reliable algorithms for oil-holding capacity for heavier oils. Further analyses of field SCAT data that is enhanced with core sampling to measure oil penetration and sediment saturation, along with tank test or laboratory experimentation will provide better estimates of oil-holding capacity for modeling and other purposes. Until further verification can be done, it is proposed that the calculated values for heavier oils, as shown in Table 6, provide the most accurate estimate of oil-holding capacity.

5.0 Information Gaps and Recommendations for Future Research

A comprehensive review of the literature and data on shoreline oiling processes through field observations and laboratory research, as presented in Appendices C through Q, have confirmed the complex nature of the interactions between oil and shorelines in the aftermath of an oil spill. A model to accurately simulate these interactions taking into account all of the characteristics of the oil, the shore, waves, and other environmental factors, while useful for some purposes, is impractical for an oil spill risk analysis modeling application that is run in a stochastic manner. A more simplified approach is required.

The conclusions of this current study are that oil-holding capacity based on shoreline type and oil type is the best methodology to achieve this goal of a simplified approach to shoreline oiling interactions in oil spill risk analysis modeling.

The data and results from field and laboratory studies that currently exist have shed some light on this issue, as presented in this study. Most of these studies were not specifically designed to provide the inputs to the oil spill risk analysis modeling as required by MMS. As a result, there are a number of significant information gaps that remain. Research into these areas might provide a means to develop a relatively simple algorithm to estimate shoreline oiling while improving the accuracy of the estimation to provide for better oil spill risk analysis modeling for MMS's purposes.

The information gaps on oil-holding capacity that were identified include:

- More accurate measurements of shoreline oil-holding capacity by shoreline type by grain size, as well as for variable-structure shorelines;
- Identification of effective porosity by shoreline sediment character and oil type; and
- Measurement of the effect that changes in oil properties, such as viscosity (due to oil type, temperature, or through weathering changes), have on oil-holding capacity.

Oil-holding capacity of the shoreline, as discussed in this report is, under field conditions, not static. There are continuous changes in the amount of oil that is retained by the shoreline due to remobilization and effects of tides, weathering, and groundwater even during the 10 – 30 day post-spill window considered to be short-term. These changes need to be measured more carefully to more accurately reflect the actual nature of shoreline oiling. An understanding of these processes to develop simple, but more robust, algorithms of a dynamic shoreline oiling process will further increase the reliability of the oil spill risk analysis modeling that MMS is employing.

There are four venues under which shoreline oiling experimentation and research can occur – field testing, spill-of-opportunity field studies, laboratory (bench-scale) studies, and test tank experimentation.

Field testing (i.e., the intentional spilling of oil in field conditions with the intent of measuring various factors and conducting scientific experimentation) has limited potential in that it is extremely difficult to get the necessary permits to conduct these types of studies in US waters. There is some testing that is going on in other countries, though most of this is in the form of offshore spills that never impact shorelines. These types of studies would not have any practical application in shoreline testing.

Spill-of-opportunity studies offer a good venue for testing real-life oil spill situations in field conditions. There are limitations to these studies, however. The most significant limitations are the difficulty of getting funding approved and organizing staff, resources, and a good study plan under emergency conditions. Furthermore, the proposed studies should not interfere with on-going spill response and monitoring operations.

Nevertheless, there is, however, an excellent opportunity to conduct "small science" shoreline studies as part of the already established SCAT surveys and procedures. As described in this report, SCAT surveys often provide data on the degree of oiling, coverage, oil thickness, and depth of penetration that can be used to estimate shoreline sediment oil-holding capacity. The missing factor in this estimation process is the amount of oil that is really contained in the pore space. In the algorithm described in this report, an "educated guess" was applied to the percentage of pore space that would be occupied by oil rather than by water or air.

Taking core samples of truly saturated sediments, as well as sediments oiled to varying degrees, during the SCAT process might provide a means to better estimate the effective net pore space occupied by oil. Measuring the actual oil content of core samples could also provide a way to calibrate the SCAT oil classifications with regard to true oil content in comparison to visually observed shoreline classifications. This could be of value in determining impacts and supporting decision making on appropriate shoreline cleanup methods and endpoints. There is strong support for conducting studies during spills of opportunity to advance the state of knowledge of spill behavior and impacts. For example, the Coastal Response and Restoration Center, University of New Hampshire has funds set aside for such studies. As long as the proposed study does not interfere with response operations, there is likely to be strong support by the response organization. It is recommended that MMS coordinate with the National Oceanic and Atmospheric Administration (NOAA) Scientific Support Coordinators (SSCs) and ask them to identify spills where such studies might be appropriate.

Laboratory studies have yielded important and useful data that are applicable to the modeling of shoreline oiling in oil spill risk analysis modeling, but the degree to which laboratory studies, such as sand column experimentation, simulate real spill situations is of concern. These studies do shed light on the amount of oil that can be contained in a particular kind of sediment at various environmental conditions. The laboratory venue provides for excellent controls on environmental variables. At the same time, the fact that shoreline oiling is a dynamic process in which tides and groundwater, as well as other environmental factors, can have a significant effect on oil-holding capacity limits the applicability of these studies to actual spill situations and the accurate modeling of those spills.

Meso-scale test tanks offer an opportunity to measure shoreline oiling under controllable circumstances. Two existing test tank facilities in the US that are specifically designed simulate shorelines subjected to wave action. (These facilities are described in greater detail in Appendix R.) One facility allows for outdoor testing adjacent to the Gulf of Mexico in conditions that are the relative equivalent of those that would likely be experienced during an actual spill event in the Gulf of Mexico. The second facility provides a smaller-scale test tank that allows for greater control of environmental variables and accurate measurement of oil and water concentrations within the substrate.

Both of these facilities could be used for experimentation to further shed light on existing information gaps, particularly with regard to the manner in which wave action and other environmental variables have an impact on the dynamic processes involved in shoreline oiling.

6.0 Conclusion

The values of oil-holding capacity by shoreline type that would be most practically applied in a simple stochastic oil risk or oil trajectory/fate model would be a combination of 1) the Boufadel methodology (hydraulic oil-holding capacity model) for light oils that would easily penetrate beach sediments and not be expected to have any appreciable surface buildup; and 2) the SCAT methodology for medium-heavy oils that would both partially penetrate beach sediments and accumulate on the shoreline surface. The recommended holding capacities that could be used in a basic stochastic oil spill risk analysis model that incorporates short-term impacts of oil to the shoreline for the purpose of determining trajectory and extent of shoreline impact can be preliminarily derived from the hydraulic oil-holding capacity model for lighter oils, including light fuels and light crude oils, which tend to penetrate and saturate the shoreline substrate. Table 18 provides such values for a 1-m tide range (H) typical of the US Gulf of Mexico coast. The calculated values should be verified with further field and tank testing.

For medium crude oils and heavier oils, the process of shoreline oiling is different than that for the lighter oils because there is considerable deposition of oil on the shoreline surface, which does not generally occur with lighter oils. Viscosity and other complex factors determine the degree to which the medium and heavier oils penetrate the substrate. Until further verification can be done, the SCAT data from the Exxon Valdez may be used for estimating holding capacities for medium crude oils, as shown in Tables 8 and 9, which are comparable to those values originally modeled by Gundlach (1987), as analyzed in by Cheng et al. (2000) and shown in Table 6, but based on more detailed SCAT data such that the results are less variable and more closely related to sediment type than the Gundlach (1987) data.

The more limited data for the PEPCO pipeline, Athos I, and Selendang Ayu spills may not provide enough reliable SCAT data upon which to base reliable algorithms for oil-holding capacity for heavier oils. Further analyses of field SCAT data that are enhanced with core sampling to measure oil penetration and sediment saturation, along with tank test or laboratory experimentation will provide better estimates of oil-holding capacity for modeling and other purposes. Until further verification can be done, it is proposed that the calculated values for heavier oils, as shown in Table 6, provide the most accurate estimate of oil-holding capacity.

Despite the large body of published research on shoreline oiling, there remain significant information gaps with regard to the dynamic processes involved in shoreline oiling even over the relative short-term that would be most directly and practically applicable to oil spill risk analysis modeling. Recommendations for further experimentation in spill-of-opportunity studies in the form of core sampling during the SCAT survey process, as well as experimentation in test tanks are presented in this report.

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APPENDIX A: Shoreline Oiling Classifications and Shoreline Types

Surface oil cover categories are in Figures A1 – A4[32]. Oil thickness categories are in Figures A5 – A9.

Figure A1: Continuous Shoreline Cover

Figure A2: Broken Shoreline Cover

Figure A3: Patchy Shoreline Cover

Figure A4: Sporadic Shoreline Cover

Figure A5: Pooled Thickness

Figure A6: Cover Thickness

[32] Photographs courtesy of Miles Hayes and Jacqueline Michel, Research Planning, Inc. Based on Owens and Sergy 2000, Michel et al. 1998.

Figure A7: Coat Thickness

Figure A8: Stain Thickness

Figure A9: Film Thickness

Shoreline type is often described by Environmental Sensitivity Index (ESI) classification, as shown in Table A1 and Figures A10 – A24[Error! Bookmark not defined.].

Table A1: Environmental Sensitivity Index (ESI) Classifications

ESI Number	ESI Classification Description
1A	Exposed Rocky
2	Rocky Platform
3	Fine Sand
4	Coarse Sand
5	Mixed Sand/Gravel
6A	Gravel Beach
6B	Riprap Structures
7	Exposed Tidal Flat
8A	Sheltered Rocky
8B	Sheltered Solid
9	Sheltered Tidal Flat
10A	Salt/Brackish Marsh
10B	Freshwater Marsh
10C	Swamp
10D	Mangrove

Shoreline type is often described by Environmental Sensitivity Index (ESI) classification, as shown in Table A1 and Figures A10 – A24.

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8B	Sheltered Solid
9	Sheltered Tidal Flat
10A	Salt/Brackish Marsh
10B	Freshwater Marsh
10C	Swamp
10D	Mangrove

Figure A10: ESI 1A: Exposed Rocky

Figure A11: ESI 2: Rocky Platform

Figure A12: ESI 3: Fine Sand

Figure A13: ESI 4: Coarse Sand

Figure A14: ESI 5: Mixed Sand/Gravel

Figure A15: ESI 6A: Gravel Beach

Figure A16: ESI 6B: Riprap

Figure A17: ESI 7: Exposed Tidal Flat

Figure A18: ESI 8A: Sheltered Rocky Shore

Figure A19: ESI 8B: Sheltered Man-Made

Figure A20: ESI 9: Sheltered Tidal Flat

Figure A21: ESI 10A: Salt-Brackish Marsh

Figure A22: ESI 10B: Freshwater Marsh

Figure A23: ESI 10C: Swamp

Figure A24: ESI 10D: Mangrove

APPENDIX B: Shoreline Sediment Grain Size Distribution

Because particle diameters typically span many orders of magnitude for natural sediments, there is a need for a convenient system to describe wide-ranging data sets. The base two logarithmic Φ (phi) scale is one useful and commonly used way to represent grain size information for a sediment distribution. A tabular classification of grain sizes in terms of Φ units, millimeters, and other commonly used measurement scales is shown in Table B1 for purposes of comparison. Logarithmic phi (Φ) values (in base two) are calculated from particle diameter size measures in millimeters as follows:

$$\Phi = -\log_2 d = \left[\frac{\log_{10} d}{\log_{10} 2}\right]$$

Where: Φ = particle size in Φ units
D = diameter of particle in mm

A negative sign is affixed so that commonly encountered sand sized sediments can be described using positive Φ values.

Table B1: Grain Size Classification Table

US Standard Sieve Mesh	Millimeters (Fractional)	Millimeters	Microns	Phi (Φ)	Wentworth Size Class
Wire squares used		1 km		-20	
		4,096		-12	
		1,024		-10	Boulder (-8 to -12Φ)
		256		-8	Cobble (-5 to -8Φ)
		64		-6	
		16		-4	Pebble (-2 to 5Φ)
5		4		-2	
6		3.36		-1.75	
7		2.83		-1.5	Granule (-1 to -2Φ)
8		2.38		-1.25	
10		2		-1	
12		1.68		-0.75	
14		1.41		-0.5	Very coarse sand (0 to -1Φ)
16		1.19		-0.25	
18		1		0	
20		0.84		0.25	
25		0.71		0.5	Coarse sand (1 to 0Φ)
30		0.59		0.75	
35	1/2	0.5	500	1	
40		0.42	420	1.25	
45		0.35	350	1.5	Medium sand (2 to 1Φ)
50		0.3	300	1.75	
60	1/4	0.25	250	2	
70		0.21	210	2.25	
80		0.177	177	2.5	Fine sand (3 to 2Φ)
100		0.149	149	2.75	
120	1/8	0.125	125	3	
140		0.105	105	3.25	
170		0.088	88	3.5	Very fine sand (4 to 30Φ)
200		0.074	74	3.75	
230	1/16	0.0625	62.5	4	

Table B1: Grain Size Classification Table					
US Standard Sieve Mesh	**Millimeters (Fractional)**	**Millimeters**	**Microns**	**Phi (Φ)**	**Wentworth Size Class**
270		0.053	53	4.25	
325		0.044	44	4.5	Coarse silt (5 to 4Φ)
Analyzed by pipette or hydrometer		0.037	37	4.75	
	1/32	0.031	31	5	
	1/64	0.0156	15,6	6	Medium silt (6 to 5Φ)
	1/128	0.0078	7.8	7	Fine silt (7 to 6Φ)
	1/256	0.0039	3.9	8	Very fine silt (8 to 7Φ)
		0.002	2	9	
		0.00098	0.98	10	Clay
		0.00049	0.49	11	
		0.00024	0.24	12	
		0.00012	0.12	13	

APPENDIX C: Studies on Oil Loading, Penetration, and Retention

Based on the literature review, the following studies presented relevant data or findings in the area of oil loading, penetration, and retention, which might provide information useful for determining shoreline oil-holding capacity for oil. Because many of the studies addressed several of these factors and they are interrelated, these studies are grouped together here in general chronological order. [A separate Appendix section is devoted to the SOCS and SOCSEX studies.]

Smith (1968)

Smith (1968) estimated the oil content of oiled sediment samples from the Torrey Canyon spill to vary from 0.5% to 11.0%.

Gundlach et al. (1978)

Gundlach et al. (1978) showed that depths of oil penetration in the Urquiola spill site in Spain increased significantly with increasing sediment grain size.

Blount (1978)

The percentage oil within oiled sediments after the Amoco Cadiz spill was determined by Blount (1978) to be a maximum of roughly 10%.

Robinson (1979)

The oiled sediments in the Peck Slip spill in Puerto Rico ranged from 5 to 12% oil content, according to field studies by Robinson (1979).

de Pastrovich et al. (1979)

Empirical measures of residual soil capacity, such as, were made by de Pastrovich et al. (1979) as in Table C1.

Table C1: Residual Capacity of Soils for Light Fuel Oil[33]

Approximate Mean Grain Size (Φ)[34]	Residual Capacity (L/m^3)
-3	5
-2	6.5
-1	8
0	11
1	14
2	18
3	25
4	40

McLaren (1980)

McLaren (1980) showed the relationship between sediment grain size characteristics between a possible sediment source and a deposit area to infer the transport path for sediment movement. The transport path could then be used to predict the probable direction and fate of oil in the coastal environment. McLaren (1980) developed a sediment trend matrix and sediment transport path that suggests the following with respect to the fate and behavior of oil in the coastal zone:

- Oil transported up onto the berm will remain stranded or become buried.
- Oil on the beach face could be buried or deposited onto the berm during periods of high wave activity.

[33] From Humphrey, Owens, and Sergy (1993), as derived from de Pastrovich et al. (1979).

[34] Φ is the negative logarithm of particle diameter in mm.

- Oil on the beach face will tend to move in one direction during longshore transport of sediments, which will result in natural cleaning through abrasion during wave activity, but not the oil being removed from the beach face to the offshore.
- If oil is dispersed prior to reaching the shoreline, different trajectories may be followed:
    - Oil in the water column may follow the path of suspended sediment and be deposited in deeper water where it will become buried.
    - Oil on the sediment surface of the shallow nearshore environment may become buried by ice scouring or adhere to sediments that migrate toward the beach face. Wave activity will be more effective in moving oil onshore as the water becomes shallower.

If sediment trends suggest burial of oil rather than erosion and dispersal to the offshore, the shoreline should be considered sensitive in terms of oil persistence in the environment.

Finkelstein and Gundlach (1981)

Finkelstein and Gundlach (1981) devised a methodology for calculating the volume of oil that came ashore during the Amoco Cadiz[35] spill by utilizing aerial photography, sediment sampling, and accurate measurements of the oil depth, width, and length on numerous oiled beaches. The quantity of surface oil was calculated by the formula:

$$\sum_{\text{interval}} (LWD)(\%C)(SG)(\%O)/10^6$$

Where: L = length (cm) of oiled beach at each sample interval
W = width (cm) of oiled beach at each sample interval
D = depth (cm) of surface mousse at each sample interval
$\%C$ =% mousse coverage at each sample interval
SG = specific gravity of oil (g/cm^3)
$\%O$ =% oil in mousse

The quantity of buried oil incorporated into beach sediments was calculated by the formula:

$$Oil_{buried} = LL_bT_b \quad \%O \quad SG \ /10^6$$

Where: L = length (cm) of oiled beach at each sample interval
L_b = length (cm) of buried oil-sediment layer measured perpendicular to the shore
T_b = thickness (cm) of the buried layer
$\%O$ =% oil within the layer
SG = specific gravity of oil (g/sm^3)

Oil quantities for the Amoco Cadiz spill were calculated as shown in Table C2.

Table C2: Oil Quantity per Length of Beach after Amoco Cadiz Spill[36]

Station	Length of beach (km)	Oil content (metric tons)		
		3 – 14 days	35 – 43 days (post cleanup)	
		Heavy coverage	Light coverage	Heavy coverage
1	0.50	50.2	-	7.3
2	0.25	1.8	-	2.4

[35] The tanker Amoco Cadiz spilled 68.7 million gallons of light Arabian crude off Brittany, France, in March 1978.
[36] From Finkelstein and Gundlach (1981).

Table C2: Oil Quantity per Length of Beach after Amoco Cadiz Spill[36]				
Station	Length of beach (km)	Oil content (metric tons)		
		3 – 14 days	35 – 43 days (post cleanup)	
		Heavy coverage	Light coverage	Heavy coverage
3	0.25	44.6	-	5.5
4	0.20	284.1	-	2.5
5	1.25	1,146.9	2.5	-
6	0.20	51.8	1.0	-
7	0.20	102.5	1.7	-
8	0.20	9.6	0.4	-
9	2.00	1,039.4	10.6	-
10	1.25	46.3	6.0	-
11	0.45	175.2	-	1.0
12	0.40	357.7	-	6.3
13	0.55	248.3	0.6	-
15	0.30	83.3	-	3.9
16	0.40	81.2	-	66.3
17	0.30	136.4	1.6	-
Subtotal	**8.70**	**3,859.1**	**24.2/(5.9 km)**	**95.2/(2.75 km)**
Total (tonnes/km)		**443.6**	**4.1**	**34.6**

The authors calculated that 27% of the oil spilled came ashore.

Pertile (1986)
Pertile (1986) described stranded oil on remote shorelines:

- The penetration of an oil slick will vary as the granular size of the beach sediment. Finer-grained sediments allow less penetration than coarser-grained sediments, such as gravel.
- Oil penetration increases as oil viscosity decreases.
- Oil thickness on sediment increases with grain size and the age of the spilled oil.

Lower viscosity oils (more recently spilled) on a large grain-sized beach were found to create a thick oil sediment.

Pearson et al. (1986)
Lindstedt-Siva et al. (1987)
Chamberlain et al. (1987)
Chamberlain et al. (1987), Lindstedt-Siva et al. (1987), and Pearson et al. (1986) reviewed the aftermath of the Arco Anchorage oil spill[37] with particular emphasis on beach sediment oil entrainment, as shown in Table C3 and Table C4.

[37] The December 1985 grounding of the tanker Arco Anchorage in Port Angeles Harbor, Washington, spilled 239,000 gallons of Prudhoe Bay crude oil. There was heavy oiling of intertidal zones in the Strait of Juan de Fuca, especially on the coarse sediments on the inside of Ediz Hook, in the Port Angeles Harbor, and on the outer edge of Dungeness Spit, a National Wildlife Refuge.

Table C3: Sediment Oil Concentration Data after Arco Anchorage Spill[38]						
Sampling Location	**Number Sites Sampled**	**Oil Concentration (ppm, total weight basis)**				
		Before Beach Agitation		**After Beach Agitation[39]**		**Mean Reduction (%)**
		Range	**Mean**	**Range**	**Mean**	
Upper beach (approx. +6.0 (MLLW)	50	<100 – 20,000	2,900	<50 – 7,500	1,100	62
Middle beach (approx. +4.0 (MLLW)	41	<50 – 20,000	2,000	<50 – 7,500	600	70
Lower beach (approx. +2.5 (MLLW)	28	<50 – 7,500	800	<50 – 20,000	200	75
Total beach	119	<50 – 20,000	2,100	<50 – 7,500	700	67

Table C4: Total Hydrocarbon Measurements in Beach Sediments after Arco Anchorage Spill[40]				
Location	**Days after Spill**	**Sedimentary Concentrations (ppm)**		
		Beach	**Intertidal**	**Subtidal**
North side Dungeness Spit	2	8,800		ND[41]
	30	26 – 105		33 – 72
Outer Dungeness Bay	3	21 – 160		ND
	30	20 – 42	77 – 200	48 – 360
Inner Dungeness Bay	2		49	ND
	30	21 – 41		98 – 260
Green Point	30			25 – 91
Port Angeles Harbor	30	215 – 1,400	130 – 160	120 – 220
Freshwater Bay	30	26	61	52
Crescent Bay	30	42	110	75
Agate Bay	30	ND – 30		75
Whiskey Creek	30	ND – 20		

Beach sediment contamination ranged from 100 to approximately 20,000 ppm, with the upper beach showing the heaviest contamination. The mean sediment contamination level was 2,900 ppm.

Miller (1987)
Oil penetration depths of two to 12 inches after the Arco Anchorage spill in Port Angeles Harbor, Washington, were reported by Miller (1987). Six weeks after the spill, hydrocarbon concentrations in beach sediments ranged from 50 to 20,000 ppm with a mean of 2,900 ppm (weight basis).

Little (1987)
Little (1987) measured oil concentrations in sediments on two shorelines (a sand flat and a muddy shore) impacted by the Sivand spill in the Humber Estuary, UK[42]. Immediately after the spill, total hydrocarbons concentrations (THC) were greater than 50,000 ppm in the sand flat. These concentrations decreased to about 3,000 ppm over the course of 12 months. The mud flats were initially less contaminated, with THC

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[38] From Lindstedt-Siva et al. (1987).
[39] A shoreline treatment consisting of physical agitation combined with high-pressure water jet washing was used to remove entrained oil from beach sediments. The oil reduction after this treatment sheds some light on the degree to which natural processes of sediment reworking can remove oil in the intertidal zone.
[40] Based on data from Pearson et al. (1986) as reported in Lindstedt-Siva et al. (1987).
[41] ND = not detectable
[42] The tanker Sivand spilled 6,000 tonnes (about 1.76 million gallons) of crude oil into a highly turbid estuary in September 1983.

of about 2,000 ppm. The concentrations reduced only slightly in the year following. Core sampling data are shown in Table C5 and Table C6.

Table C5: Gravimetric Hydrocarbon Data: Humberston Fitties (Sand Flat) after Sivand Spill[43]						
Depth (cm)	Hydrocarbon Concentration (ppm) 142 Days			Sediment %		
	Aliphatic	Aromatic	THC	Mud	Organics	Moisture
0 – 2	31,838	21,822	53,660	10.36	5.54	16.20
2 – 7	2,783	983	3,766	9.48	2.01	18.20
7 – 12	122	52	174	4.44	1.45	18.20
12 – 17	20	12	32	3.40	1.35	18.90
17 – 22	25	15	40	2.46	1.29	19.40

Table C6: Gravimetric Hydrocarbon Data: Blacktoft Sand (Mud Flat) after Sivand Spill[44]						
Depth (cm)	Hydrocarbon Concentration (ppm) 142 Days			Sediment %		
	Aliphatic	Aromatic	THC	Mud	Organics	Moisture
0 – 5	1,542	822	2,364	83.25	8.02	41.60
5 – 10	939	426	1,365	77.83	7.45	38.00
10 – 15	1,128	417	1,545	82.25	8.28	42.10
15 – 20	436	306	742	7.14	7.86	41.30

Howard and Little (1987)

Howard and Little (1987) observed that the presence of infaunal burrows facilitated penetration of a medium fuel oil mousse into subsurface sediments to a greater depth than similar sediments that lacked a burrow structure. The increased penetration appeared to be related to better drainage characteristics resulting from the burrow structure. Oil was found to penetrate burrows of all sizes down to 1 mm in diameter within 24 hours. About three times as much oil was able to penetrate sediments that had an infaunal burrow structure.

Owens et al. (1987)

Owens et al. (1987) reported on the fate of stranded oil on a sheltered gravel beach in the BIOS experimental spill of 15 m^3 (3,963 gallons) of aged Lago Medio crude oil. The oil covered 8,750 m^2 of shoreline. Sampling data for hydrocarbon concentrations in the first month are shown in Table C7.

Table C7: Summary of Total Extractable Hydrocarbons in Baffin Island Oil Spill (BIOS) Project[45]						
Location	Sample Area	Total Extractable Hydrocarbons (mg/kg)				
		Day 0	Day 8		Day 25	
			mg/kg	% change from Day 0	mg/kg	% change from Day 8
Surface	Upper intertidal	8,800	7,000	-20.5%	7,100	+1.4%
	Middle intertidal	3,800	8,000	+110.5%	6,800	-15.0%
	Lower intertidal	8,600	5,000	-41.9%	3,800	-24.0%
	Mean	7,100	6,600	-7.0%	5,900	-10.6%
Subsurface	Upper intertidal	260	210[46]	-19.2%	70	-66.7%
	Middle intertidal	90	290	+222.2%	310	+6.9%
	Lower intertidal	150	360	+140.0%	260	-27.8%
	Mean	170	210	+23.5%	210	0%

43 From Little (1987).
44 From Little (1987).
45 From Owens et al. (1987).
46 In the published paper (Owens et al., 1987), had the value “2,100” in this space. This is assumed to be a typographical error.

Fischel (1987)
Fischel (1987) measured concentrations of oil in a Louisiana marsh after the spillage of 12,600 gallons of South Louisiana crude oil[47]. Sediment concentrations ranged from 0.3 g/kg to 24.8 g/kg.

Vandermeulen, Harper, and Humphrey (1988)
Vandermeulen, Harper, and Humphrey (1988) examined the physical and sedimentological parameters that determine the retention and penetration of oil slicks into fine sediments in a simulated tidal system.

Oil loading experiments with surface slicks of different thicknesses (0.5 to 10 mm) showed that increasing thicknesses of surface-applied oil resulted directly in increasing concentrations of hydrocarbons in the sediments. Ninety-six to 100% of the oil was found primarily in the top two cm, with little penetration below 2 cm in fine-sand cores.

Both penetration and hydrocarbon concentrations within the contaminated sediments varied inversely with mud content as an index of fineness. Penetration in the well-sorted fine sand sediments became increasingly less at a mud concentration of >2%. The relationship between hydrocarbon penetration and mud content[48] was described by the function:

$$\log_{10}\left[hydrocarbon\right] = 5.04 - 0.426\ \%mud$$
$$r = -0.97$$

Where: $[hydrocarbon]$ = the hydrocarbon concentration in mg/kg.

Penetration was also influenced by tidal emergence. Penetration and subsurface hydrocarbon concentrations were considerably higher in sediments that were tidally exposed for 57% or longer of the tidal cycle, while submergence for 33% of longer of the tidal cycle resulted in much lower penetration and contamination. Maximum concentrations reached 30,000 to 40,000 mg/kg at 62.5% submergence with no further increases observed up to 100% submergence.

The researchers concluded that slightly muddy tidal flats sediments (0.35 – 5.0% mud) may be less vulnerable to oiling than had been previously thought, with greater than 95% of the oiling restricted to the top 2 cm of homogeneous sediments.

Penetration was sensitive to small increases in sediment permeability and mud content. Persistence of stranded oil was significantly influenced by the location of intertidal oiled sites relative to the mean water level. Their results are shown in Tables C8 – C11.

Table C8: Penetration of Weathered Alberta Mixed Sweet Blend Oil in Experiment Cores of Tidal Flat As Function of Oil Loading[49]

Oil Loading[50]	Core Number	Visible Oil Limit (cm)	Hydrocarbon Concentration (mg/kg)		
			0 – 2 cm	2 – 4 cm	4 – 6 cm
0.5 mm	21	0.4	810	170	14
	22	0.9	2,800	18	20
1.0 mm	23	0.6	3,700	110	12

[47] A Shell pipeline break in April 1985 spilled 300 barrels of oil near Nairn, Louisiana, impacting about 50 acres of marsh.
[48] Mud content is defined as having a grain size <63µm, based on the terminology of Folk (1974).
[49] From Vandermeulen, Harper, and Humphrey (1988).
[50] Thickness of oil slick applied on water surface over sediment cores.

Table C8: Penetration of Weathered Alberta Mixed Sweet Blend Oil in Experiment Cores of Tidal Flat As Function of Oil Loading[49]					
Oil Loading[50]	Core Number	Visible Oil Limit (cm)	Hydrocarbon Concentration (mg/kg)		
			0 – 2 cm	2 – 4 cm	4 – 6 cm
	24	0.6	3,900	27	12
5.0 mm	25	0.7	27,900	190	61
	26	0.8	29,700	120	11
10.0 mm	27	0.5	27,500	1,100	290
	28	1.0	18,900	160	45

Table C9: Penetration of Weathered Crude Oil in Cores Oiled with 5 mm Oil Layer in Fine Sand Sediments[51]					
Core	Oil Percentage	Visible Recovery (cm)	Hydrocarbon Concentration (mg/kg) Oil Limit		
			0 – 2 cm	2 – 4 cm	4 – 6 cm
30	97	0.2	26,200	110	39
31	93	0.3	28,700	880	440
25	92	0.7	27,900	190	61
26	93	0.8	29,700	120	11
13	109	1.5	25,800	210	16
14	99	2.5	46,000	280	8
48	91	0.7	24,600	240	250
49	98	0.8	31,500	160	300

Table C10: Penetration of Weathered Crude Oil in Cores Oiled with 5 mm Oil Layer in Fine Sand Sediments[52]						
Tidal Emergence		Core	Visible Oil Limit (cm)	Hydrocarbon Concentration (mg/kg)		
h/24 h	%			0 – 2 cm	2 – 4 cm	4 – 6 cm
0/24	0%	15	0.5	4,000	80	8
		16	0.5	1,400	62	25
12/24	50%	17	2.0	2,400	88	230
		18	2.0	1,900	198	95
13.6/24	57%	30	0.2	26,200	110	39
		31	0.3	28,700	880	440
		25	0.7	27,900	198	61
		26	0.8	29,700	120	11
		48	0.7	24,600	240	250
		49	0.8	31,500	160	300
15/24	62.5%	13	1.5	25,800	210	16
		14	2.5	46,000	280	8
22.5/24	91.5%	11	2.5	49,500	980	15
		12	3.0	52,600	4,500	16
24/24	100%	19	0.8 – 2.5	29,100	2,600	150
		110	1.5	44,300	1,700	140

[51] From Vandermeulen, Harper, and Humphrey (1988).
[52] From Vandermeulen, Harper, and Humphrey (1988).

Table C11: Relationship between Sediment Grain Size and Oil Penetration[53]						
Sediment		Core	Visible Oil Limit (cm)	Hydrocarbon Concentration (mg/kg)		
Mean Grain Size ± sd (µm)	Mud Content (%)			0 – 2 cm	2 – 4 cm	4 – 6 cm
130±48	4.69	36	0.2	650	610	210
134±49	4.69	37	0.3	1,900	330	110
140±38	1.53	34	0.8	20,700	180	16
140±39	1.53	35	0.6	26,500	74	25
-	1.27	25	0.7	27,900	190	61
-	1.27	26	0.8	29,700	120	11
150±28	1.27	30	0.2	26,200	110	39
140±26	1.27	31	0.3	28,700	880	440
-	1.27	48	0.7	24,600	240	250
-	1.27	49	0.8	31,500	160	300
210±74	1.14	38	1.5	53,100	1,600	13
210±74	1.14	39	1.5	61,400	1,800	31
280±120	0.35	32	3.0	70,600	5,200	41
290±170	0.35	33	2.0 – 4.0	74,300	5,200	22

Humphrey, Sergy, and Owens (1990)
In their studies at the Baffin Island Oil Spill (BIOS) project, Humphrey, Sergy, and Owens (1990) concluded that shoreline length was not a good measure of shoreline oiling since it does not account for the *multidimensional* distribution of the oil.

The researchers concluded that oil penetration and concentration data are very difficult to determine accurately, and these measures dramatically affect any attempt to calculate volumetric values. The team recommended the use of shoreline *area* oiled rather than shoreline length as the best consistent measure of shoreline oiling.

Owens (1991)
Owens (1991) reported on the shoreline conditions following the Exxon Valdez spill as of the fall of 1990, 18 months after the spill. The potential for oil penetration as a function of shoreline characteristics in Prince William Sound is shown in Table C12.

After one year (spring 1990), a shoreline survey showed that in 25% of the 782 kilometers of oiled shoreline there was no subsurface oil in sediments, and 71.6% of the shoreline was bedrock that had no subsurface oil. Subsurface oil four to 12 inches deep (10 to 30 cm) was present in 1.6% (12.5 km) of the shoreline. Subsurface oil deeper than 12 inches (30 cm) was present in 1.8% (14.1 km) of the shoreline.

Table C12: Potential for Oil Penetration as Function of Shoreline Character in Prince William Sound[54]			
Shore Type	Shoreline Character	% Affected Coast	Relative Oil Penetration
EXPOSED COASTS			
Bedrock	Rock alone is not as common as rock with rubble veneer	32%	None
Mixed Sediments	Often surface layer/armor of large cobbles; fines filling spaces in subsurface	12%	Limited to a few inches
Pebble-	Open spaces between particles	1.5%	High[55]

[53] From Vandermeulen, Harper, and Humphrey (1988).
[54] From Owens (1991)

Table C12: Potential for Oil Penetration as Function of Shoreline Character in Prince William Sound[54]			
Shore Type	**Shoreline Character**	**% Affected Coast**	**Relative Oil Penetration**
Cobble			
Sand	Well sorted, fine-grained	0%	Top two inches
SHELTERED COASTS			
Bedrock	Bare rock found at headlands, elsewhere usually with rubble veneer	40%	None
Mixed Sediments	Surface layer coarse material on mixed fine/coarse sediments	12%	Few inches
Pebble-Cobble	Open spaces between particles	2%	High[56]
Sand	Well sorted, fine-grained	0%	Top two inches
Marsh-Mud	Mud and silt	<1%	No penetration

Gundlach et al. (1991)

Shoreline surveys of surface oiling and sediment oiling for the state of Alaska after the Exxon Valdez oil spill were conducted by Gundlach et al. (1991). Their results are shown in Table C13 and Table C14.

Table C13: Subsurface Oiling and Surface Oil Coverage Pre- and Post-Winter 1989/90 for Exxon Valdez Spill[57]								
Measure	**Oiled Sediment (m^3/m)**				**Surface Oil Coverage (m^2/m)**			
	1989	**%**	**1990**	**%**	**1989**	**%**	**1990**	**%**
Total (N = 21)	75.9	100	44.7	59	396.4	100	75.7	19
Average	9.8	100	6.0	61	49.5	100	8.0	16
SD	6.3		6.7		14.3		8.2	

Table C14: Exxon Valdez Oiled Shoreline Lengths: ADEC Fall Surveys and Joint Spring Assessment Survey[58]					
Region	**Oiling Level**	**Fall 1989 (km)**	**Spring 1990 (km)**	**Net Change (km)**	**Percent Change**
Prince William Sound	**Heavy**	75. 6	20.8	-54.8	-72.5%
	Moderate	64.4	45.9	-18.5	-28.7%
	Light	131.9	79.8	-52.1	-39.5%
	Very Light	308.9	273.4	-35.5	-11.5%
	Total Surveyed	**1,160.0**	**1,107.0**	**-53.0**	**-4.6%**
Kenai	**Heavy**	9.7	2.6	-7.1	-72.3%
	Moderate	12.9	7.7	-5.2	-40.3%
	Light	24.1	15.8	-8.3	-34.4%
	Very Light	82.9	84.9	+1.9	+2.3%
	Total Surveyed	**129.5**	**400.0**	**+270.5**	**+208.8%**
Kodiak	**Heavy**	0.55	0. 6	-0.07	-12.7%
	Moderate	1.9	5.1	-3.2	+168.4%
	Light	8.3	6.8	-1.5	-18.1%
	Very Light	66.3	94.9	+28.6	+43.1%

[55] Accessible to rapid wave washing and abrasion.
[56] Very small percentage of beaches affected.
[57] From Gundlach et al. (1991)
[58] From Gundlach et al. (1991)

Table C14: Exxon Valdez Oiled Shoreline Lengths: ADEC Fall Surveys and Joint Spring Assessment Survey[58]					
Region	**Oiling Level**	**Fall 1989 (km)**	**Spring 1990 (km)**	**Net Change (km)**	**Percent Change**
	Total Surveyed	**156.2**	**451.9**	**+295.7**	**+189.3%**
All Regions	**Heavy**	85.8	24.0	-62.0	-72.3%
	Moderate	78.9	58.7	-20.2	-25.6%
	Light	164.8	102.4	-62.4	-37.9%
	Very Light	458.1	452.5	-5.6	-1.2%
	Total Surveyed	**1,446.1**	**1,958.9**	**+512.8**	**+35.5%**

Hayes et al. (1993)

Hayes et al. (1993) described the development of "bubble sand", a sponge-like sand deposit with porosities as high as 50%, in sheltered coarse-grained beaches and intertidal sand flats of bays on the Saudi Arabian coast after the 1991 Gulf War spillage. The high porosity of these formations is the result of entrapment of air between the water table that is lowered during low tide, and water flooding of the surface sediment during rising tides. Depths of penetration into the bubble sand were shown to exceed 40 cm in several locations. Depths of penetration in the Gulf area (15 – 20 cm) were found to be higher than those found in other spills, which averaged 5 cm with a maximum of 8 cm (Gundlach, 1987).

Four mechanisms were found by Hayes et al. (1993) to enhance oil penetration – penetration of oil from the surface into coarse sediments, the presence of faunal burrows, the occurrence of bubble sand, and the increased porosity created by the growth of evaporite crystals[59].

Michel et al. (1993)

Michel et al. (1993) measured subtidal sediment contamination in nearshore areas in Saudi Arabia from the 1991 Gulf War spill. Subtidal sediments were shown to be contaminated at levels ranging from 20 to 2,000 mg/kg petroleum hydrocarbons, with the highest contamination levels in sheltered muddy basins, suggesting that sorption onto fine-grained muds is the primary mechanism. Since there was little or no removal of stranded oil, this spill provided the opportunity to study natural removal processes and rates.

Sveum and Bech (1993)

Sveum and Bech (1993) examined changes in oil concentrations (crude oil, emulsified crude oil, and diesel fuel) in experimental plots on gravel beaches, sandy beaches, and mudflats in an Arctic location. The researchers found that crude oil retention was low in both the upper and lower zones of the gravel beach. Most of the oil was removed (re-floated) immediately after contamination. The oil concentration in the lower beach zone was lower than in the upper zone likely due to the higher water content in the lower zone which allowed the oil to be re-floated in the first tidal cycle. Emulsified oil was retained at higher concentrations than the crude oil or diesel fuel. Oil loading was again found to be closely related to water content of the sediment. Oil concentrations by shoreline type and oil type are summarized in Table C15.

Table C15: Crude Oil Retention in Arctic Beaches[60]									
Oil Type	**Shoreline Type**	**Oil Retention in Sediments (ppm)**							
		36 hours		**9 days**		**31 days**		**42 days**	
		Upper Zone	**Lower Zone**	**Upper Zone**	**Lower Zone**	**Upper Zone**	**Lower Zone**	**Upper Zone**	**Lower Zone**
Crude oil[61]	Gravel	10,000	6,000	6,800	3,000	500	100	10	1
	Sandy	14,000	2,000	7,000	1,900	1,000	1,500	100	1,300

59 Primarily from gypsum-calcium sulphate.
60 Based on Sveum and Bech (1993)
61 Statfjord crude oil.

Table C15: Crude Oil Retention in Arctic Beaches[60]									
Oil Type	Shoreline Type	Oil Retention in Sediments (ppm)							
		36 hours		9 days		31 days		42 days	
		Upper Zone	Lower Zone	Upper Zone	Lower Zone	Upper Zone	Lower Zone	Upper Zone	Lower Zone
	Mudflat[62]	20		20		20		20	
Emulsified crude oil	Gravel	18,000	4,000	5,300	3,000	100	2,200	10	2,100
	Sandy	6,000	2,000	500	1,900	100	1,300	100	1,200
	Mudflat	50		50		50		50	
Diesel fuel	Gravel	18,000	11,000	16,000	9,000	15,000	7,000	15,000	6,000
	Sandy	1,000	1,000	500	1,000	100	1,000	80	1,000
	Mudflat	21,000		19,000		19,000		19,000	

Owens et al. (1995)
Owens et al. (1995) reported on shoreline oiling conditions after the 1993 Tampa Bay spill[63], as shown in Table C16.

Table C16: Shoreline Oiling in Tampa Bay Spill[64]				
Observations		Location		
		Madeira Beach	Treasure Island	St. Petersburg Beach
Survey beach length (km)		3.7	4.8	6.0
Surface Oil	Profiles with oil	0	9	22
	Maximum width (m)	-	4.5	25
	Average width (m)	-	2.13	15.0
	Maximum distribution (%)	-	95	95
	Average distribution (%)	-	90	50
Buried Oil	Profiles with oil	19	29	27
	Maximum width (m)	5.5	7.5	12
	Average width (m)	2.6	3.13	3.2
	Maximum depth (cm)	41	27	33
	Average depth (cm)	22.8	12.1	11.7
	Maximum thickness (cm)	3	10	5
	Average thickness (cm)	1.3	3.3	1.8

Owens and Sergy (1996)
Owens and Sergy (1996) published a state-of-knowledge review of oil on shorelines, including oil behavior, fate, and persistence. The following conclusions were made on oil penetration:

- Oil more easily penetrates coarse-sediment (pebble-cobble) as compared with fine-sediment (sand/granule) beaches.
- Penetration is increased in coarse sediments due to fewer grain-grain contacts per unit volume, so that there are fewer constrictions through which oil must pass to penetrate more deeply.
- The larger void spaces between grains also mean that a larger volume of oil can enter and be stored in the material of a coarse-sediment beach.

[62] There was no upper or lower zone designation for the mudflat since it was relatively level.
[63] A three-vessel collision spilled an estimated 328,000 gallons of No. 6 fuel oil at the entrance to Tampa Bay, Florida.
[64] From Owens et al. (1995).

Little et al. (1998)

Little et al. (1998) reported on the shoreline response operations for the 1996 Sea Empress spill[65] off Milford Haven, United Kingdom. Shoreline survey results for the first month and two to eight months after the spill are shown in Table C17. More detailed results for the second survey are shown in Table C18. The oil budgets for the spill are shown in Table C19.

Table C17: Linear Oiling Data for the Countryside Council Wales Surveys after Sea Empress Spill[66]

Oil Category	1 Month after Spill (February/March 1996)				2 – 8 Months after Spill (April/September 1996)			
	km	oil mass (tonnes)	tonnes/km	gal/km	km	oil mass (tonnes)	tonnes/km	gal/km
Heavy	98	5,290	54	15,900	10	540	54	15,900
Moderate	34	18.4	0.54	159	25 – 30	16.2	0.54 – 0.65	159 – 191
Light	66	1.2	0.018	5.3	45	0.8	0.018	5.3
Total	**198**	**5,310**	**-**	**-**	**80-85**	**557**	**-**	**-**

Table C18: Countryside Council Wales Shoreline Oil Surveys after Sea Empress Spill (2 - 8 Months Post-Spill)[67]

Oiling Category	km	Surface Oil Mass (t)	Surface Oil (t/km)	Sub-surface Oil (t)	Total Oil Mass (t)	Total Oil (t/km)
Heavy	10.03	114 – 253	11.4 – 25.2	80	194 – 333	19.3 – 33.2
Moderate	25.56	5.96 –26.6	0.23 –1.04	63	68.9 –89.6	2.7 –3.5
Light	45.16	0.24 –1.94	0.005 –0.043	27	27.2 –28.9	0.60 –0.64
Total	**80.79**	**120.2 – 281.5**	**-**	**170**	**290 – 451**	**-**

Table C19: Approximate Oil Budgets on Shorelines Impacted by Sea Empress Spill[68]

Site Type	Time Period		
	February 1996 (1st Month)	May 1996 (4th Month)	September 1996 (8th Month)
Most exposed rock/gravel	57 – 111 tonnes/km	8 – 44 tonnes/km	4 – 8 tonnes/km
Moderately exposed sands/rock	25 – 55 tonnes/km	0.1 – 0.7 tonnes/km	2 – 22 tonnes/km
Sheltered gravel/rock	39 – 115 tonnes/km	37 – 94 tonnes/km	38 – 101 tonnes/km
Very sheltered gravel/rock	6 – 64 tonnes/km	0.4 – 4 tonnes/km	11 – 22 tonnes/km
Exposed sand/rock	n/s[69]	n/s	<0.1 – 0.03 tonnes/km

- There is a larger surface area per unit volume in fine sediments, so that more oil adheres to sediment surfaces leaving less oil available for removal through flushing.

A combination of oil properties, such as adhesion and viscosity, and sediment properties, particularly grain size and sorting, affect oil penetration and retention in beach sediments. Long-term retention of

[65] Over 21 million gallons of light crude oil (Forties Blend) and some heavy fuel oil spilled.
[66] Little et al. (1998)
[67] Little et al. (1998)
[68] Little et al. (1998)
[69] n/s = not surveyed

subsurface oil in sediments is largely determined by initial oiling, but any oil that can penetrate fine-grained or mixed, sandy-gravel beaches is likely to be retained in the subsurface of those beaches.

Sergy et al. (1998)
Sergy et al. (1999)
Studies on an experimental oil spill[70] in Svalbard, Norway[71] were conducted by Sergy et al. (1998) and Sergy et al. (1999). The impacts to three sites described in Table C20.

Table C20: Svalbard Shoreline Oilspill Field Trials Site Impacts[72]

Criteria		**Site 1**	**Site 3**
Wave exposure/fetch (km)		Low/3 km	High/40 km
Sediments (sand:granule:pebble)		44:16:40	21:5:74
Location of oiling		upper intertidal zone	supra upper intertidal zone
Length of shoreline oiled		40 m	80 m
Width of shoreline oiled		3 m	3 m
Total area oiled		120 m^2	240 m^2
Volume of oil applied		900 L	2,400 L
Resulting loading		7.5 L/m^2	10 L/m^2
Equivalent slick thickness		7.5 mm	10 mm
Depth of penetration		half that of Site 3	twice that in Site 1
Total oil (kg) per m^2	Day 1	1.15 kg/m^2	3.33 kg/m^2
	Day 5	0.15 kg/m^2	3.17 kg/m^2
	Day 10	0.23 kg/m^2	3.13 kg/m^2
	Day 60	0.03 kg/m^2	2.92 kg/m^2

The oil in Site 3 was not significantly reduced two months after the initial oiling, as opposed to Site 1 in which oiling was reduced by 97% by natural washing and flushing. The oil in Site 3 penetrated to twice the depth of that in Site 1 due to the presence of coarser sediments. The supra upper intertidal zone location also meant that the oil in Site 3 was only exposed to tide and wave action only during spring tides and high wave activity.

Gillie, Harper, and McCullough (1999)
Gillie, Harper, and McCullough (1999) reported on concentrations of subsurface oil found using ultraviolet sensors, as shown in Table C21.

Table C21: Subsurface Oil Characteristics and Relative Concentrations[73]

Subsurface Term	**Oil Character**	**Concentration (L/m^3)**	**Void Volume Filled**
Asphalt pavement (AP)	Cohesive mixture of weathered oil and sediment situated completely below surface layers	Usually > 200	> 50%
Oil-filled pores (OP)	Pore spaces in sediment matrix completely filled with oil; often characterized by oil flowing out of sediments when disturbed.	200 – 400	50 – 100%
Partially-filled pores (PP)	Pore spaces filled with oil, but oil generally does not flow out when disturbed.	100 – 200	25 – 50%
Cover or coat	Cover (0.1 to 1.0 cm) or coat (0.01 to 0.1 cm) of oil	10 – 100	2.5 – 25%

[70] The experimental oil was IF-30, an intermediate fuel oil with an APIº of 18.3 and a viscosity of 757 cP.
[71] The Svalbard Shoreline Oilspill Field Trials were part of the *In situ* Treatment of Oiled Sediment Shorelines (ITOSS) Programme.
[72] From control site data in Sergy et al. (1998) and Sergy et al. (1999)
[73] From Gillie, Harper, and McCullough (1999)

Table C21: Subsurface Oil Characteristics and Relative Concentrations[73]			
Subsurface Term	**Oil Character**	**Concentration (L/m^3)**	**Void Volume Filled**
(OR/C)	residue on sediments and/or some pore spaces partially filled with oil.		
Oil residue or stain (OR/S)	Stain (0.01 cm) or film oil residue on sediment surfaces; non-cohesive	< 10	None
Trace (TR)	Discontinuous film or spots of oil on sediments, or odor or tackiness with no visible evidence of oil	<1	None
No oil (NO)	No visual or apparent evidence of oil	0	None

Page et al. (1999)
The fate of Arabian crude oil (and chemically-dispersed crude) in a near-shore sandy beach mesocosm environment (Coastal Oil Spill Simulation System) was investigated by Page et al. (1999). Very little oil was found below 5 cm of depth in the sandy sediment. Their results are in Table C22.

Table C22: TPH Concentrations in Sediments (0 – 5 cm) in Oiled COSS Tank[74]					
Treatment Tank	**Sampling Location**	**Time of Sampling (hr)**			
		12	**24**	**96**	**240**
Tank 1	High tide mark	1μg/g	1,153 μg/g	12 μg/g	1,050 μg/g
	Low tide mark	12 μg/g	230 μg/g	2,544 μg/g	364 μg/g
Tank 2	High tide mark	2 μg/g	1,171 μg/g	13 μg/g	1,171 μg/g
	Low tide mark	984 μg/g	371 μg/g	1,613 μg/g	83 μg/g
Tank 3	High tide mark	2,453 μg/g	1,561 μg/g	34 μg/g	27 μg/g
	Low tide mark	55 μg/g	30 μg/g	14 μg/g	18 μg/g

Hayes and Michel (2001)
Hayes and Michel (2001) described the features of gravel beaches that enhance oil persistence:

- High porosity and permeability that allow deep penetration from the surface.
- Potential for deep and rapid burial by clean sediments.
- Presence of localized, sheltered areas where oil can persist for years.
- Complex patterns of sediment reworking during storms.
- Slow rates of natural replenishment.

Highly exposed, coarse-grained gravel beaches can have deep penetration of oil that is deposited on the storm berm during storms. Natural removal rates are low due to the fact that the sediments are seldomly reworked. Oil tends to accumulate at and deeply penetrate the high-tide berms up to one meter. Surface oil deposits can be removed within days by normal wave activity. Normal erosion or deposition cycles can rework the top 10 – 25 cm of the berms in days to weeks.

Intermittently exposed, coarse-grained gravel beaches can form armors, though oil can penetrate greater than 75 cm into the subsurface sediments below the armor. Natural oil removal from below the armor is very slow.

Fine-grained gravel beaches allow oil to penetrate to more than one meter particularly at the high-tide line where the water table is the deepest. Oil behaves similarly on shell-carbonate beaches, though oil also penetrates porous clasts. The roundness of gravel clasts, which is caused by abrasion of clasts against each other during transport by breaking waves, is also related to oil removal rates. If gravel on a beach is

[74] From Page et al. (1999). Variations in measurements between sampling times reflect tidal cycles imposed.

well-rounded, surface oil should be removed by wave action in days to weeks. If the gravel is more angular, removal may take months to years.

Owens, Sergy, and Prince (2002)
Owens, Sergy, and Prince (2002) concluded the following from studies of a heavy oil spill in a low-energy environment in the Baffin Island Oil Spill (BIOS) Project: Even on a low-energy shore, if a large quantity of oil is stranded such that it exceeds the loading capacity of the sediments, excess oil will be removed rapidly in the first few tidal cycles by the simple lifting action of the rising tides.

Kerambrun (2003)
Kerambrun (2003) described the shoreline impacts of the Erika oil spill[75]. Shoreline impacts included oiling of areas with very steep and craggy cliffs. Oil was observed in patches of dozens of square meters as high as 35 meters up the cliff face. Oil was also trapped in caves at the foot of cliffs.

Etkin (2003)
During 1989, after the Exxon Valdez spill, SCAT surveys were conducted on 5,221 km (3,245 miles) of shoreline of eight major types in Prince William Sound, Alaska[76]. The SCAT data[77] were analyzed for oil penetration depth by shoreline substrate type. Shoreline penetration depths were shown (Etkin 2003) to vary by the degree of oiling as described in the SCAT surveys, as shown in Figure C1. Not surprisingly, penetration depth increases with the degree of oiling. There were also shown to be variations in the penetration depth between shoreline types and within each shoreline type by the degree of oiling, as shown in Figure C2. Distributions of shoreline penetration depth by crude oil are shown in Table C23 in decreasing order of penetration depth. Cobble beaches showed the greatest maximum penetration depth.

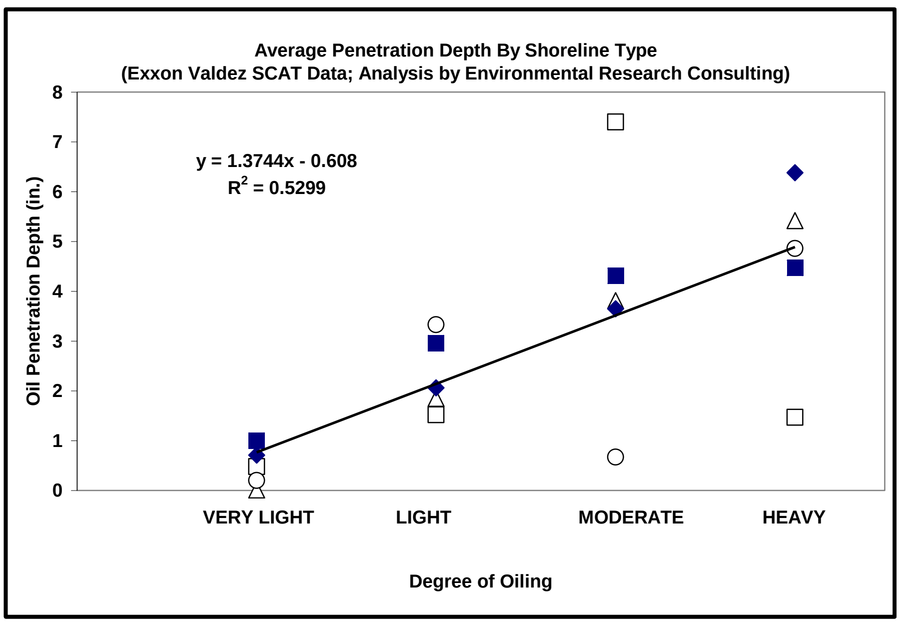

Figure C1: Average Penetration Depth by Shoreline Type for 1989 Exxon Valdez SCAT data (Etkin, 2003)

[75] In December 1999, the tanker Erika spilled 5.9 million gallons of heavy fuel oil off the Brittany coast of France.
[76] Only 1989 pre-shoreline treatment data were considered in this analysis since MMS had an interest only in shoreline impacts in the first month after a spill. This also eliminated analysis of shorelines to which any treatment or natural weathering that may have been applied after the spill.
[77] The raw SCAT data were provided to ERC by Robert Pavia of NOAA, Seattle, WA. These data also included estimations of labor required to remove oil, which were not relevant to this current study.

Table C23: Average Penetration Depth for Exxon Valdez-Impacted Sediments[78]								
Degree of Oiling	Penetration (cm) by Sediment Type							
	Rock	Boulder	Cobble	Gravel	Pebble	Sand	Mud	Vertical Cliff
Heavy	13.59	11.35	13.77	12.34	16.21	3.73	17.78	7.19
Moderate	10.8	10.29	9.68	1.7	9.27	18.8	0	7.62
Light	3.2	8.92	4.7	8.46	4.8	3.86	25.4	1.52
Very Light	2.69	0.81	0.03	0.2	1.8	1.42	0	0
All	**7.47**	**8.89**	**8.64**	**2.01**	**7.34**	**4.11**	**22.86**	**5.18**
Sample Size (N)	339	209	150	66	92	51	3	23

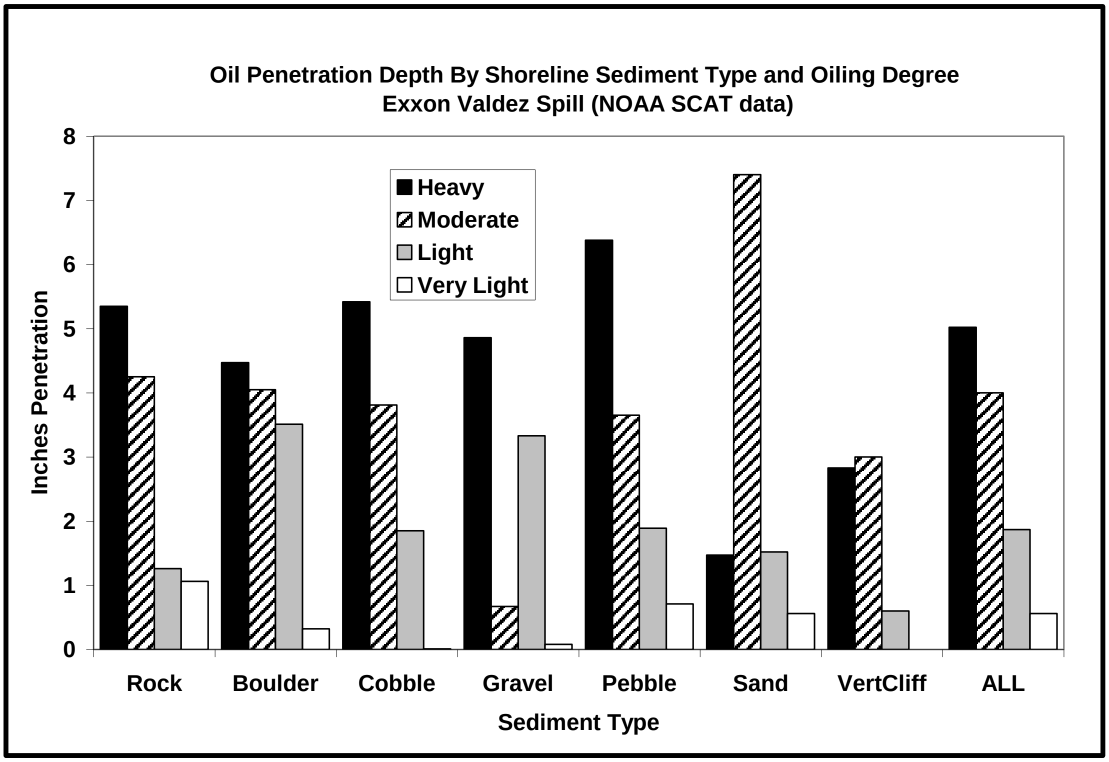

Figure C2: Oil Penetration Depth by Shoreline Type and Oiling Degree for Exxon Valdez SCAT data (Etkin, 2003)

Bernabeu et al. (2006)

Bernabeu et al. (2006) studied the oil contamination of the intertidal area of two beaches impacted by heavy oil from the Prestige spill[79]. The characteristics of the heavy oil would indicate a low capacity for penetration into sediment. However, oil was found embedded up to 2.38 meters and below the groundwater. Hydrocarbon concentrations measured in different locations and at different depths are summarized in Table C24. The researchers concluded that the morphodynamic behavior of the beach contributed to the burial of the oil in the sediment (see Figure C3). Four types of buried oil were identified – tarballs (cm), particles (mm), oil coatings on sediment grains, and emulsion. The distribution patterns of the types of buried oil were determined by the degree of wave exposure. Mechanical processes were shown to strengthen when the microbial activity slows down.

[78] From Etkin (2003).

[79] The Prestige spilled 20.6 million gallons of heavy fuel oil off the northwestern coast of Spain in November 2002.

Table C24: Mean Concentrations of Aliphatic and PAH Hydrocarbons in Different Sediment Samples[80]			
Location	**Sample Depth (cm)**	**Aliphatic Hydrocarbons (µg/g)**	**PAHs (µg/g)**
Nemiña Beach[81]	10	2.46	24.12
	30	2.81	46.20
	150	2.79	24.23
	170	2.7	26.87
O Rostro Beach[82]	10	9.8	229.01
	30	13.9	569.63
	50	7.6	171.57
	70	3.2	66.74
	110	6.0	82.93
	130	6.2	227.73
	150	7.1	113.93
	170	3.9	105.66
	190	5.7	110.76
O Rostro Intertidal	0	3.1	62.60
	6	2.9	54.59
	16	2.1	29.83
	40	2.7	36.55
	60	2.2	34.97
	80	1.8	33.08
	100	2.8	50.12
	120	2.77	55.35
	140	1.07	44.94
	160	1.19	41.20
	180	1,21	42.13
	200	1.38	21.72
	220	1.11	23.01

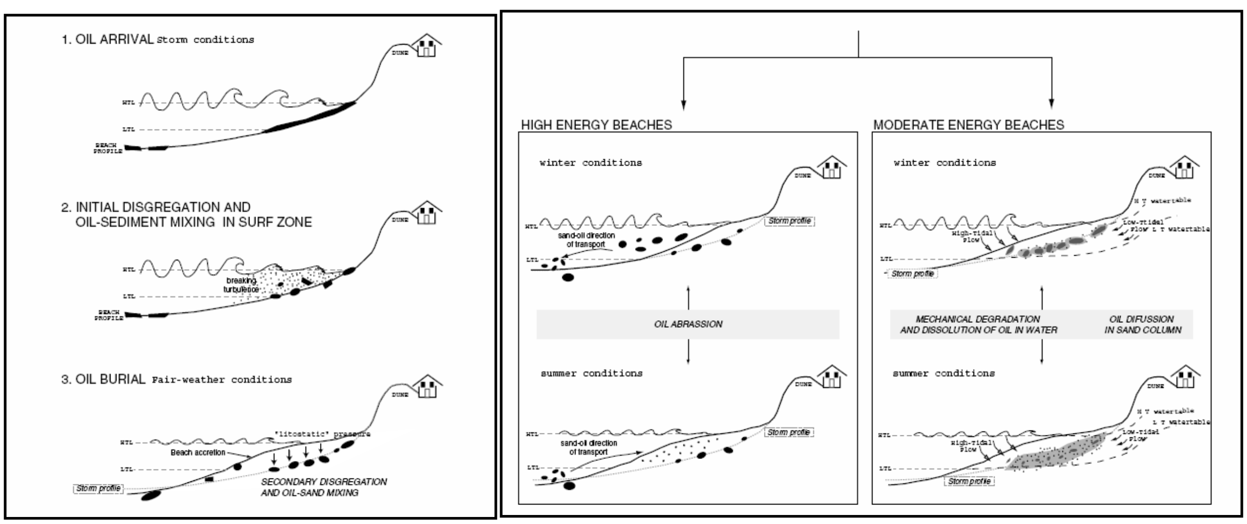

Figure C3: Model of burial and subsequent evolution of oil in the sediment of intertidal zone of beach (From Bernabeu et al., 2006)

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80 From Bernabeu et al. (2006)

81 Nemiña Beach is composed of medium sand with a mean grain size between 0.33 and 0.5 mm.

82 O Rostro Beach has a mean sand grain size of 0.38 – 0.75 mm.

APPENDIX D: Shoreline Oiling in Snow and Ice

The nature of shoreline oiling under snow and ice conditions is somewhat different than for granular substrate or rocky shorelines. A chronological synopsis of studies on oiling under these conditions is presented here.

Mackay (1974)

Mackay (1974) showed that crude oil can penetrate 50 to 60 cm into snow cover.

Bech and Sveum (1991)

Bech and Sveum (1991) conducted field experiments to measure the spread of two types of oil – Oseberg crude oil and marine diesel – in snow on both horizontal and sloping planes. When released on horizontal planes, the oil spread was circular with a maximum spreading radius of 6.5 meters (with 1,000 liters of oil) for diesel and less for the crude oil.

Snow is essentially a porous medium with the rate of oil retention being dependent on the properties of both the snow and the oil. Darcy's equation for flow in porous media (Mackay et al., 1974) is valid for describing the transport of oil in snow. [83]

Darcy's law is a simple proportional relationship between the instantaneous discharge rate through a porous medium, the viscosity of the fluid and the pressure drop over a given distance.

$$Q = \frac{-k \cdot A \ P_b \cdot P_a}{\mu \cdot L}$$

The total discharge, Q (units of volume per time, e.g., cm^3/s) is equal to the product of the permeability of the medium, k, the cross-sectional area to flow, A, and the pressure drop, all divided by the viscosity, μ and the length the pressure drop is taking place over. The negative sign is needed because fluids flow from high pressure to low pressure. So if the change in pressure is negative (in the z direction) then the flow will be positive (in the x direction). Dividing both sides of the equation by the area and using more general notation leads to:

$$q = \frac{-k\nabla P}{\mu}$$

Where q is the flux (discharge per unit area, with units of length per time, m/s) and ∇P is the dimensionless pressure gradient vector. This value of flux, often referred to as the Darcy flux, is not the velocity which the water traveling through the pores is experiencing. The pore velocity (v) is related to the Darcy flux (q) by the porosity (n). The flux is divided by porosity to account for the fact that only a fraction of the total formation volume is available for flow. (Figure D1). The pore velocity would be the velocity a conservative tracer would experience if carried by the fluid through the formation.

$$v = \frac{q}{n}$$

[83] Darcy's equation may also describe the transport of oil on a porous beach if it is water accommodated (as applied in COZOIL), though this may be most relevant for lighter fuel spills (*e.g.*, diesel).

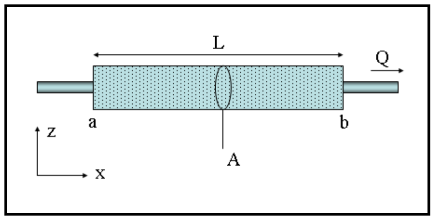

Figure D1: Reference diagram for calculation of Darcy flux.

Liukkonen et al. 1995
Liukkonen et al. (1995) found that oil adhered weakly to ice.

Owens, Dickins, and Sergy (2005)
Studies and observations of the behavior of oil on snow- and ice-covered shorelines were reviewed by Owens, Dickins, and Sergy (2005). The reviewers found that the porosity of snow has been commonly quoted to be 20%.

APPENDIX E: Shoreline Oiling on Peat Shorelines

Little et al. (1992) described the behavior of oil on peat[84] shorelines, which are common along the margins of the Arctic Ocean and form approximately 70% of the Beaufort Sea coastline in Alaska. Peat shorelines include: peat-covered beaches, beaches with peat slurries immediately offshore, peat islands and spits, tundra scarps, and low-lying peat shores. Heavy oils will not penetrate far into peat on a peat-covered shoreline, even when the peat is dewatered and dry on the surface. Lighter oils and refined products will penetrate further into the peat and may have a longer residence time. Heavy oils can persist when buried by sediments or new peat deposits. The residence time is similar to that of a sand-gravel beach. Biodegradation occurs very slowly since the peat depletes oxygen in pore waters.

Oil may become incorporated into a peat slurry on a shoreline by dispersion of the floating oil, by evaporation of low-molecular weight hydrocarbons, or by reworking of the shoreline sediment. Dry peat can sorb about three to 10 times its weight in oil. Oil-coated peat fibers will move to areas of low wave energy (i.e., offshore, in tidal flats, or below wave base). Oil behavior on a tundra scarp will be influenced by the height of the oil impact on the shore, as well as sediment grain size, wave fetch, and oil type and volume. Oil penetration will be greater when the oil is dry or fractured. The rate of tundra scarp retreat may be as high as 10 meters per year (Owens, 1985), which may preclude concerns over lengthy oil residence time.

Owens and Michel (2003) described the impacts of oil on Arctic shorelines, as summarized in Table E1. They found that dry peat can hold large amounts of oil – 1 to 5 kg of oil per kg of dry peat.

Table E1: Oil Behavior on Arctic Shorelines[85]

Shoreline Type	Percent Arctic Shoreline[86]	Shoreline Characteristics	Oil Behavior
Tundra Cliff	15.6%	Cliff that exposes ground ice with erosion; tundra and peat materials fall to cliff base. Eroded material may be in form of mud slurry or fragmented, irregular blocks. Erosion rates vary with wave exposure and cliff height – 0.5 meters/year (less than 0.2 meters per month in open-water season) to 4.0 meters/year (1.0 – 1.5 per open-water month). Beaches are narrow with eroded peat transported alongshore.	Oil is unlikely to adhere unless air temperatures are below freezing; Oil flows back down beach. Oil may pool in spaces within and between fragmented blocks at top of beach. Oil may splash over low cliff on tundra surface where it would persist beyond reach of water or wave action. Persistence is short due to natural erosion.
Peat Shoreline	15.5%	Spongy, fibrous peat with high water content (80 – 90% by weight) behaves like liquid. Peat accumulates in low-energy, sheltered areas.	Heavy oils, including crude, will not penetrate deeply into peat mat even if dewatered, but may become buried if reworked. Lighter refined oils may penetrate the peat mat. Oils that make contact with peat slurry are likely to remain mixed and accumulate in low-energy areas.

[84] Peat is an unconsolidated deposit of semi-carbonized plant remains accumulating in a water-saturated environment. The composition of peat varies between and within deposits. A peat deposit may be classified according to the relative proportions of wood, grass, and moss. Peat forms from unaltered plant components after a limited period of initial aerobic decay, typically in bogs, marshes, and swamps. Water comprises approximately 80 – 90% of the weight of fresh peat.
[85] Based on Owens and Michel (2003).
[86] Based on survey conducted in Owens and Michel (2003) Alaskan Beaufort and Chukchi Seas from Canadian border to Point Hope, Alaska.

Table E1: Oil Behavior on Arctic Shorelines[85]			
Shoreline Type	**Percent Arctic Shoreline[86]**	**Shoreline Characteristics**	**Oil Behavior**
Inundated Low-Lying Tundra	22.8%	Complex, convoluted shoreline with combination of peat mats, brackish lagoons, and small seasonal streams.	In summer season, oil is restricted to surface areas due to water-logged nature of peat. Oil may be pushed to backshore by wave action.

Henry et al. (2003)
The impact of oil on floating freshwater coastal marshes, which make up as much of 70% of the coastal marshes in Louisiana was described by Henry et al. (2003). Oil typically collects at or below the marsh surface. Oil often gets trapped in the dense peat matrix of the upper root mat. Oil often becomes trapped because horizontal water flow is extremely slow or nonexistent. Marsh peat has a high water retention capability, trapping as much as 300 times its own dry weight in water. Oil can persist for years due to the anoxic conditions just below the surface.

Owens and Sergy (2004)
A shoreline cleanup assessment team (SCAT) manual for Arctic regions and cold climates was developed by Owens and Sergy (2004). The manual included the summary of key features of peat and tundra shorelines shown in Table E2.

Table E2: Summary of Key Features of Arctic Peat and Tundra Shorelines[87]		
Shoreline Type[88]	**Physical Character**	**Oil Behavior**
Tundra Cliff: Ice Rich	• Usually tundra vegetation mat overlies peat layer and exposed ground ice (permafrost) • Unstable with erosion rates >1 m/month in open-water season • Produce slumped tundra-peat blocks or mud slurries in intertidal zone	• Persistence is short due to natural erosion, but could be extended if oil buried by block falls or incorporated into peat slurry • Oil is absorbed by peat and may pool between blocks • Oil does not stick to wet mud slurries, but could mix with them
Tundra Cliff: Ice Poor	• Eroding, unconsolidated sediment cliffs with surface tundra mat • Usually with sand or sand-gravel beach at base supplied by products of cliff-face erosion • More stable than ice-rich tundra cliffs	• Same as sand or sand-gravel beach • Penetration only for light oils • Medium, heavy, or weathered oils would remain on surface unless buried by wave action
Inundated Low-Lying Tundra	• Complex, convoluted shoreline of interconnected ridges and shallow ponds • Produced by drowning of low-land tundra an by polygon breaching • Combination of vegetated flats, peat mats, and salt or brackish lagoons	• Vegetation often water-saturated, which limits penetration • Oil may remain on water surface in ponds • Oil may be deposited some distance inland during storm surge
Peat Shoreline	• Spongy cohesive or granular material produced from tundra erosion • May be un-cohesive wet or dry beach deposit with low bearing capacity or mobile slurry mat	• Crude or heavy oils do not penetrate • Medium and light oils are absorbed by dry peat • Peat slurry similar to loose granular sorbent, which reduces spread of oil

[87] Based on table in Owens and Sergy (2004)
[88] Classifications based on Owens and Michel (2003)

APPENDIX F: Shoreline Oiling with Heavy Oils

Heavy oils exhibit behavior on shorelines that differs significantly from lighter oils and crudes due to their high viscosity and other characteristics.

National Research Council (1999)

A National Research Council (1999) study on non-floating oils made the following conclusions about the impact of these oils on shorelines:

- Non-floating oils are less likely to be stranded, but once stranded are stickier and thicker.
- Viscous oils are less likely to penetrate porous sediments.
- Non-floating oils often strands as tar balls on beaches.
- Non-floating oils are less likely to coat vegetation in wetlands and tidal flats as the oil is likely to remain in the intertidal zones.

Michel (2000)

Michel (2000) investigated the impacts of a spill of 300,000 gallons of marine fuel oil[89] in Guanabara Bay, Brazil. The bay is very shallow (often less than one meter). The spill occurred during spring tides so the oil covered the higher intertidal and backshore areas of the shoreline, which included sandy beaches, rocky shores, man-made structures (riprap and seawalls), and sheltered mangroves, to the maximum extent. There was a lot of trash debris in the wrack line[90] on the beaches.

Light accumulations of heavy fuel oil form "bathtub ring" at high tide line. Heavier accumulations pooled at surface rather than penetrate sediments. There was limited penetration into the muddy and water-saturated sediments in the mangroves. Oil collected on mangrove roots and trunks, and pooled in crab burrows.

Zengel et al. (2001)

Zengel et al. (2001) reported that a spill of 5,000 – 10,000 gallons of No. 6 fuel oil released from a refinery in Bayamon, Puerto Rico, penetrated up to 60 cm in a freshwater marsh. The oil was shown to have penetrated through vegetation root channels, animal burrows, and desiccation cracks in the clay soils.

Michel, Henry, and Thumm (2003)

The aftermath of the Westchester spill[91] of Nigerian crude oil[92] was reported on by Michel, Henry, and Thumm (2003). The viscous oil remained as a thick layer on the substrate with no penetration into the underlying substrate. Shoreline oiling from this spill is summarized in Table F1.

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[89] Blend of diesel and residual (heavy) low flash point fuel oil.

[90] The wrack line, or tidal wrack, is the line of dead or dying seaweed, marsh grass, and other debris left on the upper beach by the last high tide. There may be other lines of wrack higher up, created by former spring or storm tides, but the lowest line indicates limit of the most recent high tide.

[91] The tanker Westchester spilled 554,400 gallons of Nigerian crude oil at Mile 38 of the Mississippi River in November 2000.

[92] Nigerian crude oil has a specific gravity of 0.8428 and a low viscosity (8.3 cS at 20ºC) because of its low asphaltene content. Because of its high paraffin content and pour point of 7ºC, it behaved differently than most light-to-medium crude oils. The oil formed thick buoyant slicks. The spilled oil formed a stable emulsion in 24 hours.

Table F1: Shoreline Oiling from Westchester Spill[93]						
Shoreline Type	**Oil Behavior**	**Total Shoreline Oiling (hectares)**				
		All	**Heavy[94]**	**Medium[95]**	**Light[96]**	
Riprap[97]	Oil coated rocks and penetrated deeply into crevices; in some cases oil entirely filled pores.	4.51	2.86	1.00	0.65	
Freshwater marsh	Oil created narrow band along outer fringe with little penetration into vegetation.	0.35	0.34	0.01	0	
Freshwater slough edge	Free oil pooled against shoreline and fringing vegetation.	0.21	0.21	0	0	
Sand flats	Oil covered fine-grained sand flats with bands 1 – 3 cm thick to 15 meters wide; no penetration into water-saturated sediments; some areas of burial in sediment; oil pooled in roots of willow trees and other vegetation.	2.93	2.93	0	0	
Mud flats	Isolated patches of thick oil (often > 3 cm thick); oil sheens during water flushing.	6.23	0	6.23	0	
Total		**14.23**	**6.34**	**7.24**	**0.65**	

93 From Michel, Henry, and Thumm (2003).
94 Heavy oil is a band of oil at least 1 meter wide and greater than 50% distribution.
95 Medium oil is defined as deposits between 10 and 50% distribution.
96 Light oil is defined as less than 10% of distribution.
97 Riprap revetments, or shoreline structures formed from cobble- to boulder-sized pieces of rock.

APPENDIX G: SOCSEX Studies

An extensive body of work on the loading capacity, penetration, and retention of oil in coarse sediments has been carried out in a group of studies known as SOCS and SOCSEX (Subsurface Oil in Coarse Sediments Experiments).

Humphrey, Owens, and Patrick (1992)

Humphrey, Owens, and Patrick (1992) presented findings on the development of a coarse sediment and oil database and fate model (SOCS). Model algorithms were compared with data from the Exxon Valdez spill. The algorithms on maximum loading capacity are summarized below. The effective porosity of a sediment is expressed as:

$$C_{\max} = L\ m \cdot W\ m \cdot D\ m \cdot \phi_{eff}$$

$$\phi_{eff} = \frac{r_m - r_b}{r_m - r_f}$$

Where: ϕ_{eff} = effective porosity

r_m = matrix density

r_b = bulk density

r_f = fluid density

The maximum loading of a beach, C_{max}, is a volume (m^3):

$$C_{\max} = L\ m \cdot W\ m \cdot D\ m \cdot \phi_{eff}$$

The loading is not greatly sensitive to effective porosity, perhaps only by factors of two or three. To obtain oiling equal to C_{max} or greater a slick thickness of $D\ m \cdot \phi_{eff}$ or greater is required. For a beach with a total sediment thickness of 10 cm, with an effective porosity of 12% (a low value), a slick of 1.2 cm in thickness is required to fully saturate the beach. This would be a fairly thick slick, but has been reported in some cases. For example, the Amoco Cadiz spill had slick thicknesses of 10 cm. It is thus possible that beaches could exceed beach capacity at initial oiling.

Humphrey and Harper (1993)

Humphrey and Harper (1993) conducted a series of oil[98] penetration and tidal flushing experiments in columns containing sediments of two grain sizes – granules and pebbles. The experiments included changes to oil properties by weathering and emulsification. The results for permeability are shown in Table G1.

Table G1: Permeability of Coarse Sediment in Experimental Falling Head Tube Test[99]

Sediment	Mean Diameter (mm)	Relative Permeability (Q)[100]	
		Water	Oil
Pebble	5	1,300	1,000 – 1,400
Granule	2	150	22
50:50 Mixture	3.5	150	26

[98] Federated sweet crude oil (Group 32 crude with APIº 38.7, pour point -10ºC).
[99] From Humphrey and Harper (1993)
[100] Measured as rate of drop of fluid level in tube

Porosity is a property of the sediment alone and is defined as the void space within the sediments and depends primarily on the shape characteristics of the sediment particles and their packing. For fluids other than water, *effective* porosity is a better measure to apply. Effective porosity reflects the amount of space within the sediment that fluid can occupy. Viscous fluids, such as oil, cannot enter all of the void spaces in the sediment because they cannot pass through all the channels between particles. Effective porosity changes with the wetness characteristics of the sediment since water in the interstitial channels will inhibit entry of oil from some void spaces. Measured effective porosities in this series of experiments are shown in Table G2.

Table G2: Porosity to Weathered Oil as Measured by Humphrey and Harper (1993)

Experiment #	Sediment Type	Mean Diameter (mm)	Temp. Range (ºC)	Viscosity (cP)	Porosity		
					% Measured	% Effective	Porosity Ratio
1	granule	2.0	20 – 23	10	41%	29%	0.71
4	granule	2.0	20 – 23	10	41%	27%	0.65
5	granule	2.0	20 – 23	10	41%	26%	0.65
mean	**granule**	**2.0**	**20 – 23**	**10**	**41%**	**27%**	**0.67**
10	granule	2.0	4 – 5	42	36%	24%	0.65
11	granule	2.0	4 – 5	42	39%	26%	0.66
mean	**granule**	**2.0**	**4 – 5**	**42**	**38%**	**25%**	**0.66**
3	p/g mix	3.5	20 – 23	10	28%	19%	0.68
8	p/g mix	3.5	20 – 23	10	29%	19%	0.67
9	p/g mix	3.5	20 – 23	10	34%	20%	0.60
mean	**p/g mix**	**3.5**	**20 – 23**	**10**	**30%**	**19%**	**0.65**
14	p/g mix	3.5	4 – 5	47	33%	23%	0.70
15	p/g mix	3.5	4 – 5	47	33%	26%	0.78
mean	**p/g mix**	**3.5**	**4 – 5**	**47**	**33%**	**25%**	**0.74**
2	pebble	5.0	20 – 23	10	40%	37%	0.91
6	pebble	5.0	20 – 23	10	38%	38%	0.99
7	pebble	5.0	20 – 23	10	39%	38%	0.97
mean	**pebble**	**5.0**	**20 – 23**	**10**	**39%**	**38%**	**0.96**
12	pebble	5.0	4 – 5	42	39%	35%	0.91
13	pebble	5.0	4 – 5	42	39%	33%	0.84
mean	**pebble**	**5.0**	**4 – 5**	**42**	**39%**	**34%**	**0.88**

The residual capacity of a sediment is the amount of oil that does not wash out, i.e., the oil that is trapped by viscous forces within the sediment and is no longer susceptible to tidal flushing. The experimental data indicate that for the granules or sediment mixture, the residual capacity ranged from 30 to 50 liters per cubic meter of sediment at a temperature (21ºC) and low viscosity to 100 liters per cubic meter of sediment at a lower temperature (5 ºC) and higher viscosity.

Emulsions have very high viscosities and penetrate only a few centimeters on all beaches, decreasing the total beach load but increasing the local load to the maximum capacity. The rates of emulsion removal are much lower than for weathered oil.

Humphrey, Owens, and Sergy (1993)
The development of the Stranded Oil in Coarse Sediment (SOCS) model was described by Humphrey, Owens, and Sergy (1993). The researchers identified factors that affected the fate and persistence of oil on beaches as summarized in Table G3.

Table G3: Factors Affecting the Fate and Persistence of Oil in Beach Sediments[101]

Material framework	Oil properties	Physical properties	Temperature	
			Density	
			Viscosity	
			Pour point	
			Surface tension	
		Composition	Alkanes SHWR	
			Aromatics AWR	
			Polars	
			Asphaltenes	
			Resins	
	Slick properties	Volume	Length	
			Width	
			Thickness	
		Oil age		
	Sediment properties	Solid properties	Size	Grain size distribution
				Modality
				Kurtosis
				Skewness
			Shape	Sphericity
				Angularity
			Mineralogy	
		Bulk properties	Packing	
			Wetting	
		Beach properties	Beach dimensions	
			Beach slope	
			Porosity	
			Permeability	Anisotropy
			Biota	Algae
Environmental processes	Climatology	Wind	Speed	
			Direction	
			Frequency	
		Precipitation	Frequency	
			Amount	
		Temperature		
	Oceanography	Waves	Fetch	
			Angle of exposure	
			Breaker type	
			Edge waves	
			Height	
			Frequency	
			Length	
			Occurrence statistics	
		Tides	Range	
			Type	
		Currents	Speed	
			Direction	
Oil weathering	Evaporation	Air volume		
		Air movement		
		Temperature		
	Dissolution	Water exchange		
	Photooxidation	Sunlight intensity		
	Biodegradation	Bacterial count		
		Nutrient availability		
		Oxygen availability		
	Dispersion	Dispersability		
Beach capacity	Theoretical	Beach dimensions		
		Beach porosity		
	Actual	Permeability		
		Tidal properties		
		Slick properties		
Residual capacity	Sediment properties			
	Oil properties			

[101] Based on Humphrey, Owens, and Sergy (1993).

Maximum capacity was shown to be primarily a function of porosity of the sediment. Determining the porosity of a beach is not trivial. For a perfectly-packed sediment of spherical particles, the porosity can be determined from basic geometry. The actual porosity of mixtures of particle sizes and shapes is essentially not calculable. Porosity of well-rounded particles is between 0.12 and 0.46.

Effective porosity depends upon the nature of the fluid filling the void. For example, a fine sediment is more porous to a gas than to water or other liquid, as some fraction of the void space is inaccessible to the fluid due to capillary interactions in the joining throats between larger voids. Effective porosity decreases as the fluid viscosity increases. For coarse sediments, the throat diameters are large compared to the distances across which capillary forces act, so that differences in effective porosity due to viscosity are small.

The researchers concluded that a beach can reach maximum oil-holding capacity only if there is sufficient oil in the slick and time for the oil to penetrate the beach sediments. The time required for penetration is determined by the permeability of the sediments to the oil, and is dependent on the sediment grain size and oil viscosity.

Oil penetration based on crude oil weathering degree and sediment grain size, are in Table G4.

Table G4: Penetration of Oil of Varying Viscosities into Sediments of Different Grain Sizes[102]

Oil	Grain Size (Φ)[103]	Time (hours) for 1 cm Penetration
Fresh Crude	-1	0.20
	-2	0.10
	-3	0.05
	-4	0.01
	-5	0.01
	-6	0.01
Crude, 9% Aged	-1	0.25
	-2	0.12
	-3	0.03
	-4	0.02
	-5	0.01
	-6	0.01
Crude, 10% Aged	-1	0.30
	-2	0.15
	-3	0.07
	-4	0.03
	-5	0.01
	-6	0.01
Crude, 11% Aged	-1	0.25
	-2	0.13
	-3	0.04
	-4	0.02
	-5	0.01
	-6	0.01
Crude, 24% Aged	-1	2.40
	-2	0.50
	-3	0.20
	-4	0.03

102 Estimated from graphical presentation in Humphrey, Owens, and Sergy (1993).
103 Φ is the negative logarithm of particle diameter in mm.

Table G4: Penetration of Oil of Varying Viscosities into Sediments of Different Grain Sizes[102]		
Oil	Grain Size (Φ)[103]	Time (hours) for 1 cm Penetration
	-5	0.01
	-6	0.01
Emulsion, 70% Water	-1	1.65
	-2	0.40
	-3	0.15
	-4	0.03
	-5	0.02
	-6	0.01

Oil stranded on a beach penetrates only during the tidal period when that part of the beach is above the tidal level, so that penetration in the upper intertidal zone is expected to be greater than in the lower intertidal zone. For beaches made up of a mixture of granules and pebbles (gravel), the time required for penetration to more than a few centimeters may require more than one tidal cycle, especially if the oil is weathered or emulsified.

Residual capacity of a beach occurs when the particles are covered by a film of oil that is held intact against buoyancy or gravity forces by the interfacial tension between the oil and the other fluid (air or water) in the void spaces, and when oil occupying the void spaces and around the particle contact points is stable. The amount depends on particle size. As particles increase in size, distances between contact points increase, as do throat sizes. Stable film thickness, which depends on interfacial tension, becomes smaller relative to particle diameter, and film volume becomes a smaller portion of beach volume. Empirical measures of residual soil capacity shown in Figure G1.

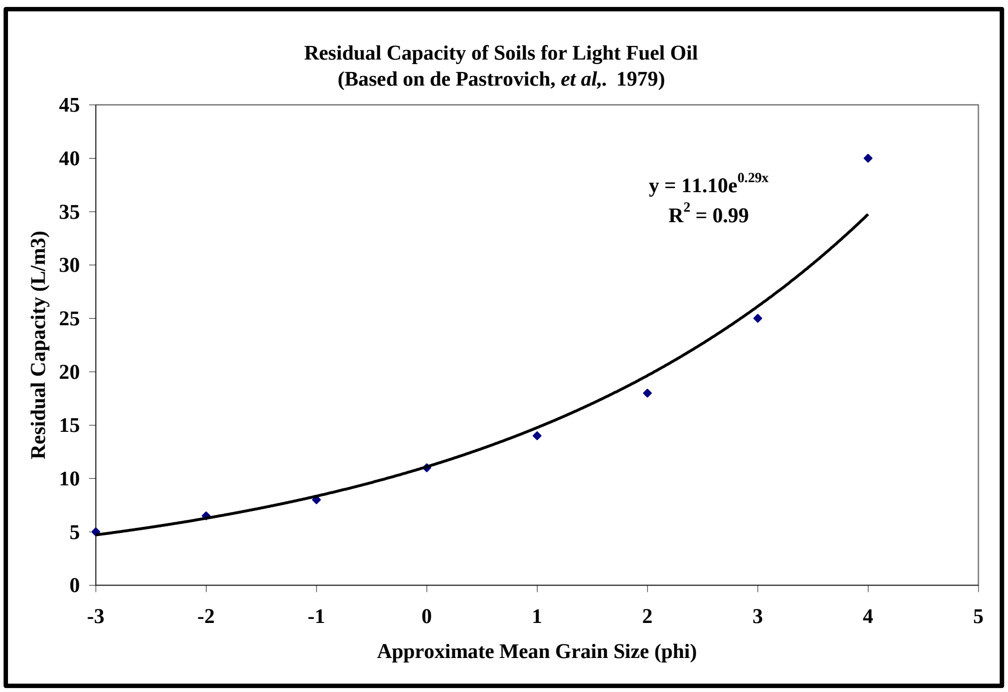

Figure G1: Residual Capacity of Light Fuel Oil in Sediments Based on Grain Size (From Humphrey, Owens, and Sergy, 1993, as derived from de Pastrovich et al., 1979).

Total petroleum hydrocarbon values in contaminated sediments were calculated as shown in Table G5.

Table G5: Total Petroleum Hydrocarbon Values by Sediment Type [104]	
Sediment Type	**Residual Oil Concentrations**
Fine sand	3.9%
Coarse sand	1.5%
Coarse gravel	0.5%

The researchers compared the characteristics of oil interactions on coarse and fine sediment, as shown in Table G6.

Table G6: Oil Interaction Factors of Coarse and Fine Sediments[105]			
Factors	**Coarse Sediments**	**Fine Sediments**	**Very Fine Sediments**
Effective porosity	0.12 – 0.46	0.12 – 0.46	0.12 – 0.46
Permeability	High	Low	Low
Penetration	High	Low	Low
Maximum loading	High	Low	Low
Residual loading	Low	High	Low

Humphrey (1994)
Humphrey (1995)
The revised Stranded Oil in Coarse Sediments (SOCS) model was used by Humphrey (1994, 1995) to hindcast the fate of oil stranded on Baffin Island in 1981 as part of the Baffin Island Oil Spill (BIOS) project. The changes in the model reflected the empirical relationship between sediment oiling and oil viscosity.

The previous SOCS model had assumed that oil would penetrate coarse beach sediments and essentially fill pore spaces. Oil in excess of this capacity would be removed in a few tide cycles as floating oil. Subsequently, oil that had penetrated the beach would be removed by flushing with tides until the remaining oil was stable in grain to grain contacts with a thin surface film of oil on each grain.

Oil viscosity appeared to be an important factor in determining the degree of sediment penetration. The temperature dependency of oil viscosity was found to be easily determined from the equation:

$\log \eta_{est} = \log \eta_{T=0} + k_{\eta,T} \times T_{ambient}$, where η = viscosity, T = temperature, and $\eta_{0,T}$ and $k_{\eta,T}$ are empirically determined for each oil.

Oil penetration for each oil type was plotted against the estimated viscosity for different sediment grain sizes (Φ). For grain sizes less than or equal to -1, there are two inflection points in the graph plots in very scattered data. For Φ less than or equal to -5, there is an inflection point at η_{est} = 15,000 cP and for other grain sizes, there is an inflection point at about η_{est} = 1,500 cP.

Harper and Kory (1995)
A series of experiments known as the "Stranded Oil in Coarse Sediments Experiments" (SOCSEX II) were conducted by Harper and Kory (1995). In these experiments, a variety of oils were applied to several sediment types to measure penetration and retention in vertical columns.

The sediment types used in the SOCSEX II experiments are shown in Table G7.

[104] From Humphrey, Owens, and Sergy (1993).
[105] From Humphrey, Owens, and Sergy (1993).

Table G7: Summary of Sediment Characteristics for SOCSEX II Experiments[106]					
Test Sediment	Mean Diameter (mm)	Number of Clasts/m^3	Mean Clast Area (cm^2)	Surface Area per Unit Volume (m^2/m^3)	Grain-to-Grain Contacts (number/m^3)
Coarse sand (CS)	0.75	976,000,000	0.0199	1,940	5,859,000,000
Very coarse sand (VCS)	1.7	167,000,000	0.102	1,700	1,002,000,000
Granules (G)	3.4	34,580,000	0.408	1,420	209,000,000
Small pebbles (SP)	6.75	1,250,000	3.08	385	7,810,000
Medium pebbles (MP)	14.5	219,000	8.63	189	1,030,000
Marbles (M)	15	289,000	7.07	205	1,300,000
Large pebbles (LP)	22	77,100	18.3	141	360,000
Very large pebbles (VLP)	43	12,100	64.8	78.2	57,000

The major conclusions of the study were:

- Penetration and retention of oil in sediments could not be related to any single oil property (viscosity, adhesion, wax content, *etc.*).
- The ability of oil to penetrate sediment is reduced with weathering and cooling of the oil.
- Heavy fuel oils penetrate coarse sediments more easily than most crude oils.
- Crude oils penetrate fine sediments more readily than fuel oils.
- For a given oil, the penetration increases with sediment coarseness.
- In fine sediments, penetration is sensitive to small changes in grain size.
- Oil retention is inversely related to penetration potential. Oils that penetrate sediments more easily have lower oil retention, whereas oils that are penetration-limited often have high oil retention.
- Oil retention in excess of 200 L/m^3 (an oil-in-sediment content of >10% by weight) were documented.
- For a given oil, retention decreases in coarser sediments.
- Each oil shows unique retention patterns.
- Heavy fuel oils show maximum retention in coarse sands whereas crude oils show maximum retention in granules.
- Very small changes in grain size in mixed sediments can result in substantial changes in oil retention.
- There are orders of magnitude difference in oil coating thickness on clast surfaces. Bunker C oils showed coatings of 40 – 60 mg/cm^2 compared with 4 – 5 mg/cm^2 for Alaskan Slope and Federated crude oils. The researchers concluded that the oiling mechanism for Bunker C may be primarily through coating of clasts whereas the crude oils may be retained by grain-to-grain contacts.

Oil penetration potential by oil type and sediment type is summarized in Table G8. Subsurface oil retention by oil type and sediment type is shown in Table G9.

Table G8: Oil Penetration Potential by Oil Type and Sediment Type[107]											
Oil Penetration (cm) by Sediment Type[108]								Oil Type	Weathering	Temp.	Dynamic Viscosity Ranking[109]
Sand		Gravel									
CS	VCS	G	SP	MP	M	LP	VLP				
2.75	2	2	2.1	2.5	2	3	3.5	Hibernia	26%	2ºC	12
1	1.5	1.5	3	4.5	5	6	7	Federated	27%	2ºC	9
4.5	3.5	3	5	5	5.5	7	**≥9.5**	Hibernia	18%	2ºC	10

[106] From Harper and Kory (1995)
[107] From Harper and Kory (1995)
[108] Shaded cells have full penetration (≥9.5 cm), limit of experimental column
[109] Relative ranking of dynamic viscosity with 20 as the highest viscosity and 1 and the lowest.

Table G8: Oil Penetration Potential by Oil Type and Sediment Type[107]											
Oil Penetration (cm) by Sediment Type[108]								Oil Type	Weathering	Temp.	Dynamic Viscosity Ranking[109]
Sand		Gravel									
CS	VCS	G	SP	MP	M	LP	VLP				
0.5	2	2.5	8	9.4	-	**≥9.5**	**≥9.5**	Bunker C	0%	2ºC	19
-	-	2.5	5.5	9.2	**≥9.5**	**-**	**≥9.5**	Bunker C	6%	2ºC	20
1.5	3	4.5	9.0	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Bunker C	0%	15ºC	15
-	-	4	**≥9.5**	**≥9.5**	**≥9.5**	**-**	**≥9.5**	Bunker C	6%	15ºC	16
-	-	6	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Bunker C	0%	5ºC	18
2	4	7	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Federated	18%	2ºC	5
2	5	8.5	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	ANS	22%	2ºC	11
2	4	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	IFO	2.5%	2ºC	14
-	-	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Bunker C	0%	10ºC	17
8	5.5	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Hibernia	26%	15ºC	8
3.5	7	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Hibernia	18%	15ºC	4
3.5	8	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	ANS	15%	2ºC	6
4	9	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	IFO	2.5%	15ºC	13
6.5	9	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Federated	27%	15ºC	3
5	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	ANS	22%	15ºC	7
7.3	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	Federated	18%	15ºC	1
7.3	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	**≥9.5**	ANS	15%	15ºC	2

Table G9: Subsurface Oil Retention by Oil Type and Sediment Type[110]											
Oil Retention (L/m^3) by Sediment Type[111]								Oil Type	Weathering	Temp.	Dynamic Viscosity Ranking[112]
Sand		Gravel									
CS	VCS	G	SP	MP	M	LP	VLP				
109	175	150	357	180	150	117	29	Hibernia	26%	2ºC	12
100	200	200	217	355	340	308	221	Federated	27%	2ºC	9
33	185	200	230	330	300	300	**280**	Hibernia	18%	2ºC	10
500	305	220	223	197	-	**94**	**77**	Bunker C	0%	2ºC	19
-	-	200	273	288	**185**	**157**	**85**	Bunker C	6%	2ºC	20
127	116	111	50	**52**	**-**	**68**	**5**	Bunker C	0%	15ºC	15
-	-	75	**175**	**168**	**163**	**104**	**25**	Bunker C	6%	15ºC	16
-	-	279	**221**	**213**	**-**	**130**	**51**	Bunker C	0%	5ºC	18
375	175	250	**250**	**215**	**380**	**257**	**33**	Federated	18%	2ºC	5
100	120	247	**75**	**30**	**25**	**15**	**10**	ANS	22%	2ºC	11
75	175	**170**	**168**	**60**	**40**	**30**	**5**	IFO	2.5%	2ºC	14
-	-	**220**	**185**	**155**	**-**	**47**	**24**	Bunker C	0%	10ºC	17
19	209	**247**	**255**	**250**	**255**	**100**	**20**	Hibernia	26%	15ºC	8
43	157	**230**	**80**	**30**	**10**	**15**	**10**	Hibernia	18%	15ºC	4
29	94	**75**	**5**	**10**	**15**	**0**	**0**	ANS	15%	2ºC	6
37	128	**180**	**40**	**18**	**15**	**5**	**0**	IFO	2.5%	15ºC	13
69	139	**135**	**30**	**15**	**10**	**15**	**10**	Federated	27%	15ºC	3
100	**115**	**64**	**5**	**5**	**10**	**0**	**0**	ANS	22%	15ºC	7
48	**55**	**60**	**20**	**10**	**15**	**30**	**10**	Federated	18%	15ºC	1
60	**65**	**55**	**5**	**15**	**15**	**10**	**0**	ANS	15%	15ºC	2

Average oil retention for all oil types is shown in Figure G2.

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[110] From Harper and Kory (1995)
[111] Shaded cells have full penetration (≥9.5 cm), limit of experimental column.
[112] Relative ranking of dynamic viscosity with 20 as the highest viscosity and 1 as the lowest.

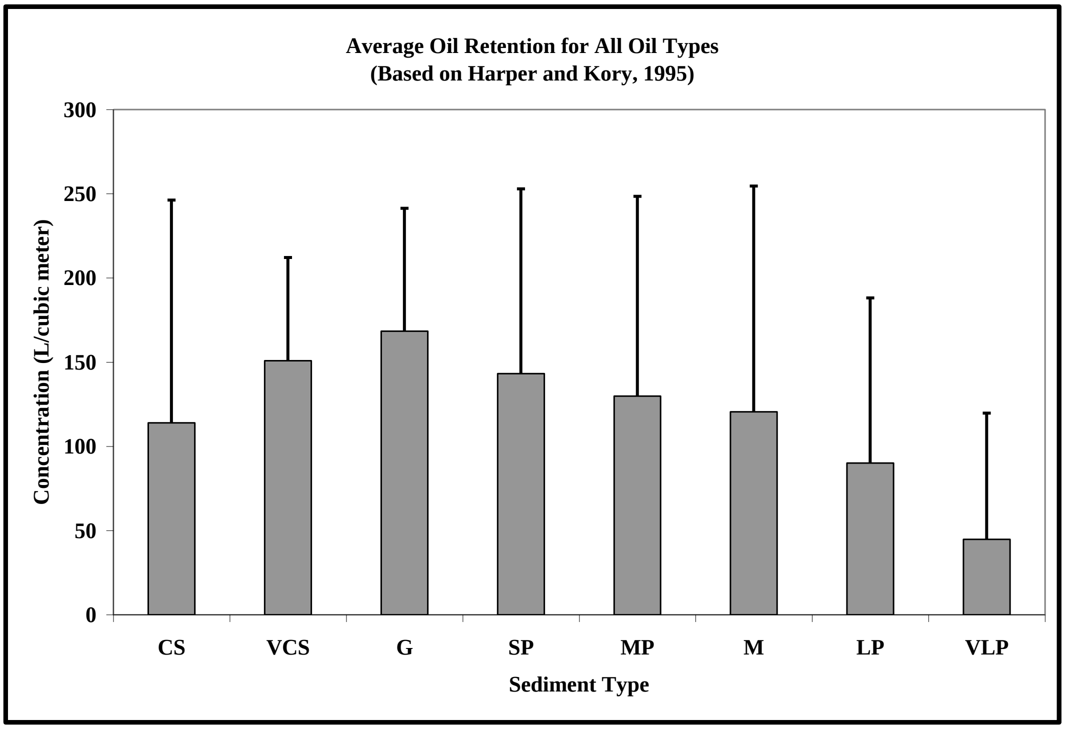

Figure G2: Average Oil Retention by Sediment Type for All Oil Types (standard error bar shown). Based on Harper and Kory (1995)

Several tests were run to evaluate the effect of multiple oil loadings on oil retention to test the hypothesis that final oil retention is strongly determined by initial oiling and once oil is in the sediments, changes in concentration are likely to be slow in the absence of mechanical wave action. The tests were inconclusive. The tests did show that in most cases, additional oil loadings resulted in relatively small positive changes to initial oil retention (≤ 10%). The results for the tests with Bunker C were radically different in that large changes in oil retention occurred after initial oiling. The researchers hypothesized that this effect may be due to the larger grain size of the test sediments. The results were consistent with observations made in the aftermath of the Exxon Valdez spill in which stranded oils appeared to be relatively easily remobilized from coarse sediments.

Harper, Sergy, and Sagayama (1995)

The results of the Subsurface Oil in Coarse Sediments Experiments (SOCSEX II), which were conducted in the aftermath of the Exxon Valdez oil spill, in which a large proportion of the cleanup effort was devoted to the 10% of coarse-sediment shoreline oiled were reported by Harper, Sergy, and Sagayama (1995).

Five oils were tested for oil penetration and oil retention in sediment column experiments for eight unimodal- and eight mixed sediment types (Table G10) under two temperature regimes.

Table G10: Summary of Clast[113] Surface Area and Contact Estimates[114]					
Sediment	**Mean Diam. (mm)**	**Clasts/m^3 (x 1,000)**	**Mean Clast Area (cm^2)**	**Surface Area Per Unit Volume (m^2/m^3)**	**Grain-Grain Contacts (#/m^3 x 10^6)**
Coarse sand (CS)	0.75	976,600	0.0199	1,940	5,859
Very coarse sand (VCS)	1.7	167,000	0.102	1.700	1,002
Granules (G)	3.4	34,850	0.408	1,420	209
Small pebbles (SP)	6.75	1,250	3.08	385	7.81
Medium pebbles (MP)	14.5	219	8.63	189	1.03
Marbles (M)	15	289	7.07	205	1.30
Large pebbles (LP)	22	77.1	18.3	141	0.36
Very large pebbles (VLP)	43	12.1	64.8	78.2	0.57
90% s. peb/10% gran	6.42	4,610	-	489	-
80% s. peb/20% gran	6.08	7,970	-	592	-
70% s. peb/30% gran	5.75	11,300	-	696	-
60% s. peb/40% gran	5.41	14,700	-	800	-
90% l. peb/10% s. peb	20.5	194	-	165	-
80% l. peb/20% s. peb	19.0	312	-	190	-
70% l. peb/30% s. peb	17.4	429	-	214	-
60% l. peb/40% s. peb	15.9	546	-	238	-

The results showed two general types of oil-sediment interactions – *penetration-limited*, where oil "plugs" within the sediments limiting further penetration, and *free-penetration*, where oil flows freely into the subsurface sediments.

Maximum oil retention occurs in sediment *slightly* coarser than the "penetration-limiting sediment" with typical retention values of 100 – 200 liters/m^3. In sediments *significantly* coarser than the "penetration-limiting sediment", the retention values are typically low, less than 25 liters/m^3. Oil retention values do not correlate well with individual oil viscosity, oil adhesiveness, or oil chemical components indicating that oil retention is related to a complex interaction among the oil variables.

The ranking of oil types as a function of penetration potential is shown in Table G11. Oil retention values in various oil-sediment combinations are shown in Table G12.

[113] A clast is a grain of sediment, silt, sand, gravel, etc., especially as a constituent fragment of a clastic rock formation, as distinguished from a chemical or biogenic component of such a formation.
[114] From Harper, Sergy, and Sagayama (1995)

Table G11: Ranking[115] of Oil Types by Sediment Penetration Potential[116]										
Sediment Types								Oil Type	Weathering	Temp.
Sand		Gravel								
CS	VCS	G	SP	MP	M	LP	VLP			
□	□	□	□	□	□	□	□	Hibernia	26%	2ºC
□	□	□	□	□	□	□	□	Federated	27%	2ºC
□	□	□	□	□	□	□	■	Hibernia	18%	2ºC
□	□	□	□	□	■	■	■	Bunker C	0%	2ºC
□	□	□	□	□	■	■	■	Bunker C	6%	2ºC
□	□	□	□	■	■	■	■	Bunker C	0%	15ºC
□	□	□	■	■	■	■	■	Bunker C	0%	15ºC
□	□	□	■	■	■	■	■	Hibernia	26%	15ºC
□	□	□	■	■	■	■	■	Federated	18%	2ºC
□	□	□	■	■	■	■	■	Bunker C	6%	15ºC
□	□	□	■	■	■	■	■	ANS	22%	2ºC
□	□	■	■	■	■	■	■	IFO	2.5%	2ºC
□	□	■	■	■	■	■	■	IFO	2.5%	15ºC
□	□	■	■	■	■	■	■	Hibernia	18%	15ºC
□	□	■	■	■	■	■	■	Federated	27%	15ºC
□	□	■	■	■	■	■	■	ANS	15%	2ºC
□	■	■	■	■	■	■	■	ANS	22%	15ºC
□	■	■	■	■	■	■	■	ANS	15%	15ºC
□	■	■	■	■	■	■	■	Federated	18%	

Table G12: Oil Retention Values (L/m^3) for Various Oil-Sediment Combinations[117]										
Sediment Types								Oil Type	Weathering	Temp.
Sand		Gravel								
CS	VCS	G	SP	MP	M	LP	VLP			
								Hibernia	26%	2ºC
								Federated	27%	2ºC
							280	Hibernia	18%	2ºC
						94	77	Bunker C	0%	2ºC
					183	157	85	Bunker C	6%	2ºC
				52	-	68	4	Bunker C	0%	15ºC
Limited Penetration Oil-Sediment Combinations			255	250	255	100	20	Hibernia	26%	15ºC
			250	215	380	257	33	Federated	18%	2ºC
			175	168	163	104	25	Bunker C	6%	15ºC
			75	30	25	15	10	ANS	22%	2ºC
		170	168	60	40	30	5	IFO	2.5%	2ºC
		180	40	18	15	5	0	IFO	2.5%	15ºC
		230	80	30	10	15	10	Hibernia	18%	15ºC
		135	30	15	10	15	10	Federated	27%	15ºC
		75	5	10	15	0	0	ANS	15%	2ºC
	115	64	5	5	10	0	0	ANS	22%	15ºC
	65	55	5	15	15	10	0	ANS	15%	15ºC
	55	60	20	10	15	30	10	Federated	18%	15ºC

The concept of oil penetration and retention is shown in Table G13for IFO-180 fuel oil. The highest retention is in the layer immediately above the layer of penetration limit.

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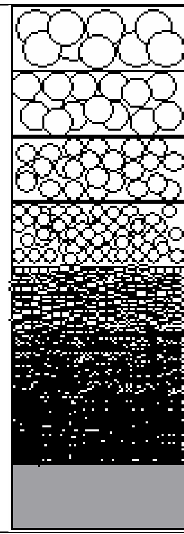
115 ■ = full penetration; □ = limited penetration
116 From Harper, Sergy, and Sagayama (1995)
117 From Harper, Sergy, and Sagayama (1995)

Table G13: Conceptual Diagram of Oil Penetration and Retention For Weathered[118] IFO-180 Fuel Oil[119]

Sediment Type		Oil Concentration (L/m^3)
Very large pebbles (VLP)		0
Large pebbles (LP)		<5
Marbles (M)		15
Medium pebbles (MP)		18
Small pebbles (SP)		40
Granules (G)		180 (Highest retention)
Very coarse sand (VCS)		127
Coarse sand (CS)		↑ **Penetration Limit** ↑

The researchers found that oil penetration or retention potential could not be predicted as a function of any one oil property (i.e., viscosity, adhesion, and hydrocarbon group components). Oil adhesion seemed to be most likely to be related to penetration and retention, but was not tested under different temperature regimes. Viscosity and penetration potential seemed to be extremely sensitive to temperature.

Harper and Sergy (2007)

Harper and Sergy (2007) conducted bench-top experiments to simulate the oiling of coarse-sediment beaches to determine oil penetration and retention values. The experiment design included:

- Sixteen sediment types (ranging from 0.75-mm coarse sand to very large pebbles of 43 mm);
- Five test oils (three crude oils and two fuel oils)
- Different weathering levels
- Temperature and tidal cycling

Oil penetration and oil retention were found to vary inversely. Highly permeable sediments were found to have low retention and low permeability sediments were found to have high retention.

Most test oils were found to freely penetrate coarse sediment (very large pebbles). Retention rates were found to be less than 100 liters/m^3 – with a mean of 44.8 liters/m^3. Most oils were found not to penetrate coarse sand. Retention concentrations were found to be on the order of 100 – 200 liters/m^3 – with a mean of 150.8 liters/m^3.

The degree of weathering and temperature were found to strongly affect oil penetration and increased retention. Fuel oils showed lower penetration potential and greater retention potential than crude oils.

[118] Weathered 2.5% at 15ºC.
[119] From Harper, Sergy, and Sagayama (1995)

The results of tidal cycling experiments suggested that smaller pore spaces resulted in greater oil stability (*i.e*, the oil was less likely to flush out) and that larger pore spaces promoted oil mobility. The initial loading level appeared to be more stable for finer sediment than coarse sediments.

Tidal cycling showed little change for fine sediments (very coarse sand and granules) after initial oiling, but coarse sediments (medium pebbles) showed more than 40% reduction from the initial oiling value.

No single oil property (e.g., viscosity) was found to correlate with penetration or retention potential. Some relatively non-viscous oils had low penetration potential. In summary, oil penetration potential was found to be related to the fluid properties of oil and sediment size.

For a given sediment type, penetration increased with increasing *penetration potential*, an oil property that appeared to be a complex interaction of viscosity, adhesion, and oil components:

- For a given oil type, penetration increased with increasing grain size with small changes in sediment size strongly affecting penetration.
- For a given oil type, penetration was greater under warmer conditions.
- For a given oil type, penetration was greater with less weathering.
- Crude oils were likely to penetrate further than fuel oils.

Oil retention was calculated by the following formula:

$$\left(\frac{volume_{oil}}{volume_{sed}}\right)=\frac{t_0-t_1 \bullet A}{d\bullet A}\left(\frac{volume_{oil}}{volume_{sed}}\right)=\frac{t_0-t_1 \bullet A}{d\bullet A}$$

Where:	t_0	= oil thickness at start of experiment
	t_1	= oil thickness at end of experiment
	d	= depth of oiling
	A	= cross-sectional area of the column

Results are shown in Tables G14 and G15.

Table G14: Oil Penetration Observations as Function of Oil Type and Sediment Type									
Penetration Potential	**Sediment Type[120] (cm Penetration into Sediment)[121]**								**Oil Type[122] Weathering Temperature**
	Coarse Sand[123]	**Very Coarse Sand[124]**	**Granules[125]**	**Small Pebbles[126]**	**Medium Pebbles[127]**	**Marbles[128]**	**Large Pebbles[129]**	**Very Large Pebbles[130]**	
1	2.75	2	2	2.1	2.5	2	3	3.5	Hibernia Crude, 26%, 2ºC
2	1	1.5	1.5	3	4.5	5	6	7	Federated Crude, 27%, 2ºC
3	4.5	3.5	3	5	5	5.5	7	10	Hibernia Crude, 18%, 2ºC
4	0.5	2	2.5	9	9.4	-	10	10	Bunker C, 0%, 2ºC
5	-	-	2.5	5.5	9.2	10	10	10	Bunker C, 6%, 2ºC
6	1.5	3	4.5	9.0	10	-	10	10	Bunker C, 0%, 15ºC
7	-	-	4	10	10	10	10	10	Bunker C, 6%, 15ºC
8	-	-	6	10	10	-	10	10	Bunker C, 0%, 5ºC
9	2	4	7	10	10	10	10	10	Federated Crude, 18%, 2ºC
10	2	5	8.5	10	10	10	10	10	ANS Crude, 22%, 2ºC
11	2	4	10	10	10	10	10	10	IFO, 2.5%, 2ºC
12	-	-	10	10	10	10	10	10	Bunker C, 0%, 10ºC
13	8	5.5	10	10	10	10	10	10	Hibernia Crude, 26%, 15ºC
14	3.5	7	10	10	10	10	10	10	Hibernia Crude, 18%, 15ºC
15	3.5	8	10	10	10	10	10	10	ANS Crude, 15%, 2ºC
16	4	9	10	10	10	10	10	10	IFO, 2.5%, 15ºC
17	6.5	9	10	10	10	10	10	10	Federated Crude, 27%, 15ºC
18	5	10	10	10	10	10	10	10	ANS Crude, 22%, 15ºC
19	6.3	10	10	10	10	10	10	10	Federated Crude, 18%, 15ºC
20	7.5	10	10	10	10	10	10	10	ANS Crude, 15%, 15ºC

[120] Note: shaded cells indicate maximum penetration >9.5 cm.
[121] Harper and Sergy (2007)
[122] ANS (Alaska North Slope) crude = low adhesion (moderate adhesion at 22% weathering), low viscosity; Bunker C fuel oil = high adhesion, very high viscosity; Federated crude = low adhesion, low viscosity; Hibernia crude = moderate adhesion, moderate viscosity; IFO-180 fuel oil = high adhesion, high viscosity.
[123] Coarse sand = mean size 0.75 mm
[124] Very coarse sand = mean size 1.70 mm
[125] Granules = mean size 3.40 mm
[126] Small pebbles = mean size 6.75 mm
[127] Medium pebbles = mean size 14.5 mm
[128] Marbles = mean size 15.0 mm
[129] Large pebbles = mean size 22.0 mm
[130] Very large pebbles = mean size 43.0 mm

Table G15: Subsurface Oil Retention Observations (L/m³) as Function of Oil Type and Sediment Type[131]									
Penetration Potential	Sediment Type[132]								Oil Type[133] Weathering Temperature
	Coarse Sand	Very Coarse Sand	Granules	Small Pebbles	Medium Pebbles	Marbles	Large Pebbles	Very Large Pebbles	
1	109	175	150	357	180	150	117	29	Hibernia Crude, 26%, 2ºC
2	100	200	200	217	355	340	308	221	Federated Crude, 27%, 2ºC
3	33	185	200	230	330	300	300	280	Hibernia Crude, 18%, 2ºC
4	500	305	220	223	197	-	94	77	Bunker C, 0%, 2ºC
5	-	-	200	273	288	185	157	85	Bunker C, 6%, 2ºC
6	127	116	111	50	52	-	68	5	Bunker C, 0%, 15ºC
7	-	-	75	175	168	163	104	25	Bunker C, 6%, 15ºC
8	-	-	279	221	213	-	130	51	Bunker C, 0%, 5ºC
9	375	175	250	250	215	380[134]	257	33	Federated Crude, 18%, 2ºC
10	100	120	247	75	30	25	15	10	ANS Crude, 22%, 2ºC
11	75	175	170	168	60	40	30	5	IFO, 2.5%, 2ºC
12	-	-	220	185	155	-	47	24	Bunker C, 0%, 10ºC
13	19	209	247	255	250	255	100	20	Hibernia Crude, 26%, 15ºC
14	43	157	230	80	30	10	15	10	Hibernia Crude, 18%, 15ºC
15	29	94	75	5	10	15	0	0	ANS Crude, 15%, 2ºC
16	37	128	180	40	18	15	5	0	IFO, 2.5%, 15ºC
17	69	139	135	30	15	10	15	10	Federated Crude, 27%, 15ºC
18	100	115	64	5	5	10	0	0	ANS Crude, 22%, 15ºC
19	48	55	60	20	10	15	30	10	Federated Crude, 18%, 15ºC
20	60	65	55	5	15	15	10	0	ANS Crude, 15%, 15ºC

[131] Harper and Sergy (2007)
[132] Note: shaded cells indicate maximum penetration >9.5 cm.
[133] ANS (Alaska North Slope) crude = low adhesion (moderate adhesion at 22% weathering), low viscosity; Bunker C fuel oil = high adhesion, very high viscosity; Federated crude = low adhesion, low viscosity; Hibernia crude = moderate adhesion, moderate viscosity; IFO-180 fuel oil = high adhesion, high viscosity.
[134] Unusually high retention rate attributed to first-time use of marbles that may have been coated.

APPENDIX H: Oil Weathering Processes after Stranding

Spilled oil undergoes a series of physical and chemical changes after stranding on a shoreline. Oil weathering processes on shorelines are summarized in Table H1. Studies on these processes are presented here in chronological order.

Table H1: Weathering Processes of Oil on Shoreline Relative to Surface Slicks[135]			
Processes	**Oiling at Capacity**	**Residual Capacity**	**Long-Term Effects**
Evaporation	Slow, at surface only; subsurface oil does not evaporate	Rapid, as oil in film on sediment surface; occurs during low-tide stage	Probably little effect, as for weathered slicks
Dissolution	Slow, at surface only.	Rapid, as oil in film on sediment surface; occurs during high-tide stage	Probably little effect, as for weathered slicks
Dispersion	Slow, little oil-water interaction	Slow under quiet wave conditions; rapid under high wave conditions	Rapid during storm events; otherwise slow
Emulsification	Slow, little oil-water interaction	Possibly rapid due to local turbulence within sediment channels	Probably little effect; process probably complete for emulsifiable oils
Biodegradation	Slow, due to bulk of oil	Possibly rapid as bacteria and nutrients provided by sea water washing	Possibly a major effect in quiet periods, as bacteria and nutrients provided, biodegradation products removed by flushing
Asphalt pavement formation	Not expected	Not expected	High probability, as substrate (sediment) and emulsion present

Page et al. (1989) investigated the long-term weathering of Amoco Cadiz oil in soft intertidal sediments. Their results are shown in Table H2.

Table H2: Hydrocarbon Analyses on Sediment Samples after Amoco Cadiz Spill[136]							
Location	**Depth (cm)**	**Date[137]**	**Concentrations (ppm)**				**OG/TOTHC[138]**
			Oil/Grease (OG)	**Aliphatics**	**Aromatics**	**Total Hydrocarbons (TOTHC)**	
Aber Benoit							
Site 1	0 – 10	12/79	29,800	17,000	5,550	22,550	1.3
	0 – 10	12/80	5,570	2,120	877	3,000	1.8
	0 – 10	3/86	2,140	212	188	400	6.5
Site 2	0 – 5	12/80	14,500	4,870	2,030	6,900	2.1
	0 – 5	7/84	8,850	2,010	1,960	3,970	2.2
	0 – 10	10/85	12,100	2,770	2,820	5,590	2.2
	0 – 5	3/86A	15,000	2,350	2,160	4,510	3.3
	0 – 5	3/86B	6,316	547	210	757	8.3
	5 – 20	3/86A	3,470	33	97	130	26.6
	5 – 20	3/86B	23,100	16	20	37	628
Site 3	0 – 10	10/85	4,500	1,110	1,000	2,110	2.1

[135] From Humphrey, Owens, and Sergy (1993).
[136] From Page et al. (1989)
[137] The Amoco Cadiz spill occurred in March 1978
[138] OG/TOTHC is he concentration of total solvent-extractable material divided by concentration of total hydrocarbons. As naturally-occurring oils waxes make a greater contribution to total extractable (OG) value, this ratio will have a larger value and be a semi-quantitative index of weathering. Because of natural hydrocarbon contents of the spill area, it was inappropriate to define a zero endpoint for petroleum weathering in the sediments.

Table H2: Hydrocarbon Analyses on Sediment Samples after Amoco Cadiz Spill[136]							
Location	Depth (cm)	Date[137]	Concentrations (ppm)				OG/TOTHC[138]
			Oil/Grease (OG)	Aliphatics	Aromatics	Total Hydrocarbons (TOTHC)	
Site 4	0 – 10	6/79	6,440	2,440	740	3,180	2.0
	0 – 10	12/79	2,910	761	905	1,670	1.7
	0 – 10	12/80	8,130	2,430	1,150	3,580	2.3
	5 – 10	7/84	2,280	349	247	596	3.8
	0 – 10	3/86	2,460	209	168	377	6.5
L'Odet River Reference Area (Baie de Kerogan)							
Site A	0 – 5	3/86A	37,000	388	206	594	62.4
Site B	0 – 5	3/86B	5,090	493	168	661	7.7

The overall rate of biodegradation was observed to decrease as the more rapidly biodegraded fractions became depleted.

Burns et al. (1991)

Burns et al. (1991) studied sediment chemistry related to the 1986 Bahia Las Minas spill in Panama. The research included measurements of oil content as shown in Table H3and H4.

Table H3: Oil Content in Sediments Six Months after Bahia Las Minas Oil Spill[139]				
Location Type	Oil Content (μg/g dry weight)			
	Heavy	Moderate	Light	Unoiled
Mangroves	>200,000 to >2,000	<2,000	<1,000	<200
Seagrass	>2,000	<2,000	<100	nd[140]
Coral Reefs	<300	<200	<50	nd

Table H4: Oil Content in Mangrove Sediments over Time After Bahia Las Minas Oil Spill[141]				
Location	Depth	Oil Content log [(μg/g dry weight)]		
		6 months	2.5 years	3.5 years
Samba Bonita Channel South	0 – 2 cm	5.5	5.3	5.0
	8 – 10 cm		4.6	4.6
	18 – 20 cm	3.9	3.6	2.6
Samba Bonita Channel East[142]	0 – 2 cm		5.5	4.7
	8 – 10 cm		5.3	5.4
	18 – 20 cm		4.0	5.4
Largo Remo River North/South[143]	0 – 2 cm	4.2	4.2	5.0
	8 – 10 cm		3.7	4.9
	18 – 20 cm	3.0	2.5	4.2
Isla Mina Mangrove[144]	0 – 2 cm		4.2	4.7
	8 – 10 cm		3.1	3.5
	18 – 20 cm		1.9	3.7

139 From Burns et al. (1991)
140 Not detectable
141 From Burns et al. (1991)
142 Mangroves in a channel with oysters as the dominant bivalves on mangrove roots.
143 Mangroves in a river with mussels as the dominant bivalves on mangrove roots.
144 Mangroves on open coast with barnacles as dominant bivalves on mangrove roots.

Brown, Goodman, and Nicholson (1992)
Brown, Goodman, and Nicholson (1992) conducted laboratory experiments to measure the evaporation rate of a medium gravity weathered crude oil on various wet shore substrates. The results indicated that shoreline substrates with high surface areas (e.g., mixes of large rocks and shell fragments) lose oil to evaporation more readily than well sorted sandy substrates.

Bech, Guénette, and Sveum (1993)
In one field study, Bech, Guénette, and Sveum (1993) conducted a series of experiments to measure evaporation rates of crude oil[145] and diesel from dry gravel beaches under Arctic summer conditions. The results indicated that while evaporation rates were considerable, they were not as high as from the water surface or ground. The researchers found that the most significant factors that influenced the evaporation rate were exposure time, oil loading, amount of clean gravel covering contaminated gravel (i.e., the exposure level), and environmental factors. While evaporation rates for oil only (i.e., oil in the absence of gravel) followed an exponential curve, oil in or under gravel showed little or no exponential evaporation.

Prince et al. (1994)
Prince et al. (1994) developed a multiple regression model on oil degradation based on field studies after the Exxon Valdez spill. The best-fitting model was expressed as:

$$Q = A\rho v \Delta t\, C_h(t) = \alpha\left[1-p(t)\right]^{\gamma} e^{\delta r(t)+\omega t}\varepsilon$$

Where: $C_h(t)$ = the time-varying hopane-normalized concentration of the analyte
p = the polar fraction of the oil
r = the ratio of the average residual nitrogen concentration to oil loading
ε = the assumed multiplicative error term
$\alpha, \delta, \gamma, \omega$ = fitting parameters determined by the multiple regression analysis

Gilfillan et al. (1995)
Gilfillan et al. (1995) noted that oil from the Exxon Valdez spill that impacted coastal areas in the Gulf of Alaska were much more highly weathered than those in Prince William Sound closer to the site of the spill. They postulated that the oil weathering, which resulted in the loss of volatile constituents and significant portions of two-ringed aromatic hydrocarbons, occurred while the oil was at sea. Oil also continued to weather extensively *after* being deposited on the shoreline. Weathering on the shoreline was greatly accelerated due to the increase in the surface-area-to-volume ratio by spreading on the shoreline. Shoreline weathering includes *biodegradation* as well as loss of more volatile components.

Venosa et al. (1996)
Venosa et al. (1996) developed the following first-order rate decay relationship for oil biodegradation on a beach based on work on an experimental light crude spill in Delaware Bay:

$$\left(\frac{A}{H}\right) = \left(\frac{A}{H}\right)_0 e^{-kt}$$

Where: (A/H) = time-varying hopane-normalized concentration of an analyte
$(A/H)_0$ = value of (A/H) at time 0

145 Statfjord crude oil with density of 0.832 g/ml and viscosity of 10.0 cP

The regression formula for alkanes, was found to have an intercept of 171.1 and a k of -0.026 day^{-1} (r^2 = 0.879). Aromatics had an intercept of 17.4 and a k of -0.021 day^{-1} (r^2 = 0.839). The first-order biodegradation rate coefficients ranged from 0.026 to 0.056 day^{-1} for total resolvable alkanes and from 0.021 to 0.031 day^{-1} for total resolvable PAHs.

The researchers concluded that actual first-order biodegradation rates are not constant, but are a function of the residual nutrient concentration, so that:

$$k_{obs} = k_{\max}\left(\frac{N}{K_n + N}\right)$$

Where: k_{obs} = observed first-order hydrocarbon biodegradation rates (day^{-1})
k_{max} = maximum first-order hydrocarbon biodegradation rates (day^{-1})
K_n = the half-saturation concentration for a specific nutrient (mg/liter)
N = the interstitial pore water residual nutrient concentration

The K_n for nitrate is approximately 0.5 mg N/liter.

Sugai, Lindstrom, and Braddock (1997) showed that biodegradation was a major mechanism for removing oil from shorelines impacted by the Exxon Valdez spill. Studying hexadecane, phenanthrene, and naphthalene mineralization potentials of hydrocarbon-degrading microorganisms and the accompanying hydrocarbon concentrations from intertidal and shallow subtidal sediments, they found that mineralization potentials were not directly dependent on sediment substrate concentrations. They concluded that environmental factors, such as intensity of physical mixing and the availability of alternative carbon sources, influenced the ability of microbial populations to mineralize polycyclic aromatic and aliphatic compounds.

Miller and Mudge (1997)

Miller and Mudge (1997) measured rates of removal and weathering characteristics of crude oil in sand columns. The weathering index (WI) for crude oil samples on the surface and after washing through sediment were measured, as shown in Table H5 and Table H6.

Table H5: Changes in Weathering Index (WI) of Crude Oil with Time

Oil Sample	Liquid/Liquid Extracted Oil (t = 0)	Soxhlet Extracted Oil (t = 0)	Length of Sediment Contamination			
			1 day	3 days	7 days	14 days
Oil washed through sediment	3.99	-	3.03	1.55	1.42	0.28
Surface sediment	-	0.47	0.34	0.13	0.12	0.09

Table H6: Weathering Index (WI) of Crude Oil after 14 Days by Depth

Depth in Sediment	Weathering Index (WI)
Surface	0.09
5 cm	0.34
10 cm	3.23

The weathering index increases exponentially with depth in the sand sediment, as shown in Figure H1. The oil extracted at progressively deeper depths was characterized by a relatively higher proportion of low boiling point compounds and a relatively higher proportion of higher boiling point compounds than can be explained by volume reduction alone.

The authors proposed that, in addition to the weathering process, the sand column was acting as fractionation column whereby the smaller, low boiling point compounds were preferentially transported to deeper depths, and the larger, more viscous compounds were retained in the surface layers.

$$WI = \left(\frac{n-C_{10} + n-C_{12} + n-C_{14} + n-C_{16}}{n-C_{22} + n-C_{24} + n-C_{28} + n-C_{30}} \right)$$

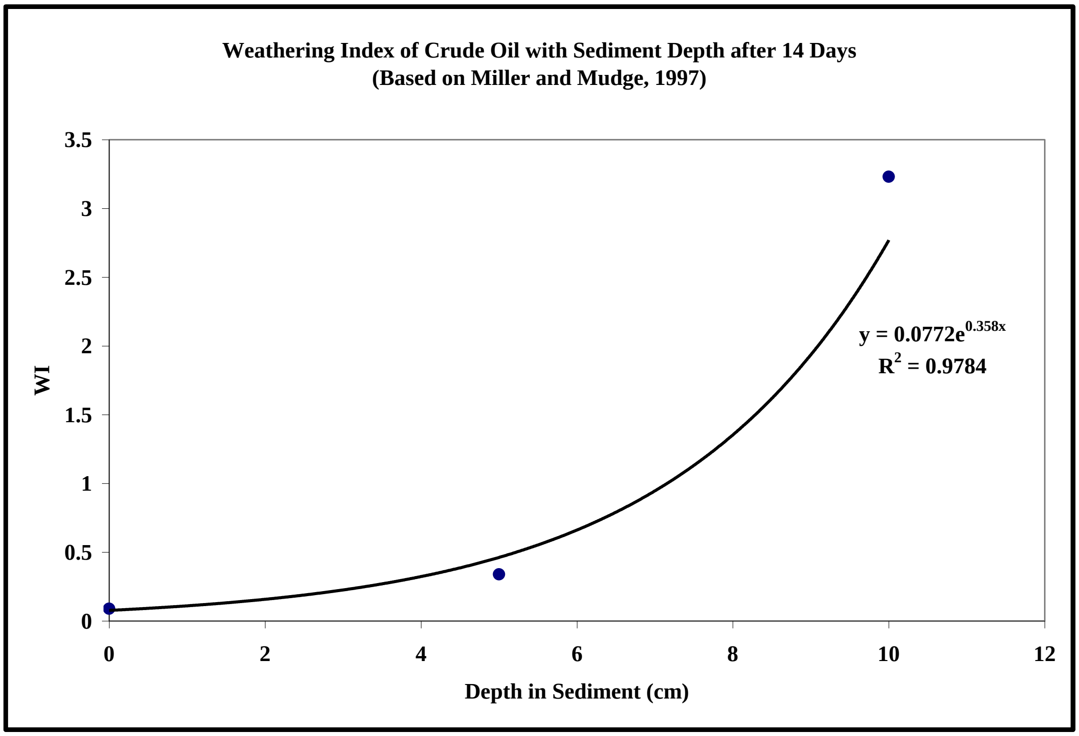


Figure H1: Weathering Index (WI) of Crude Oil in Sand Sediment after 14 Days by Sediment Depth (From Miller and Mudge, 1997).

Once transported to the deeper layers by diffusion and dissolution, the low boiling point compounds are incapable of being evaporated, since they have no contact with air and remain in association with sediment particles at this depth. The relatively high concentration of low boiling point compounds after 14 days suggests that the rate of microbial degradation at these depths must be low. The processes are summarized in Figure H2.

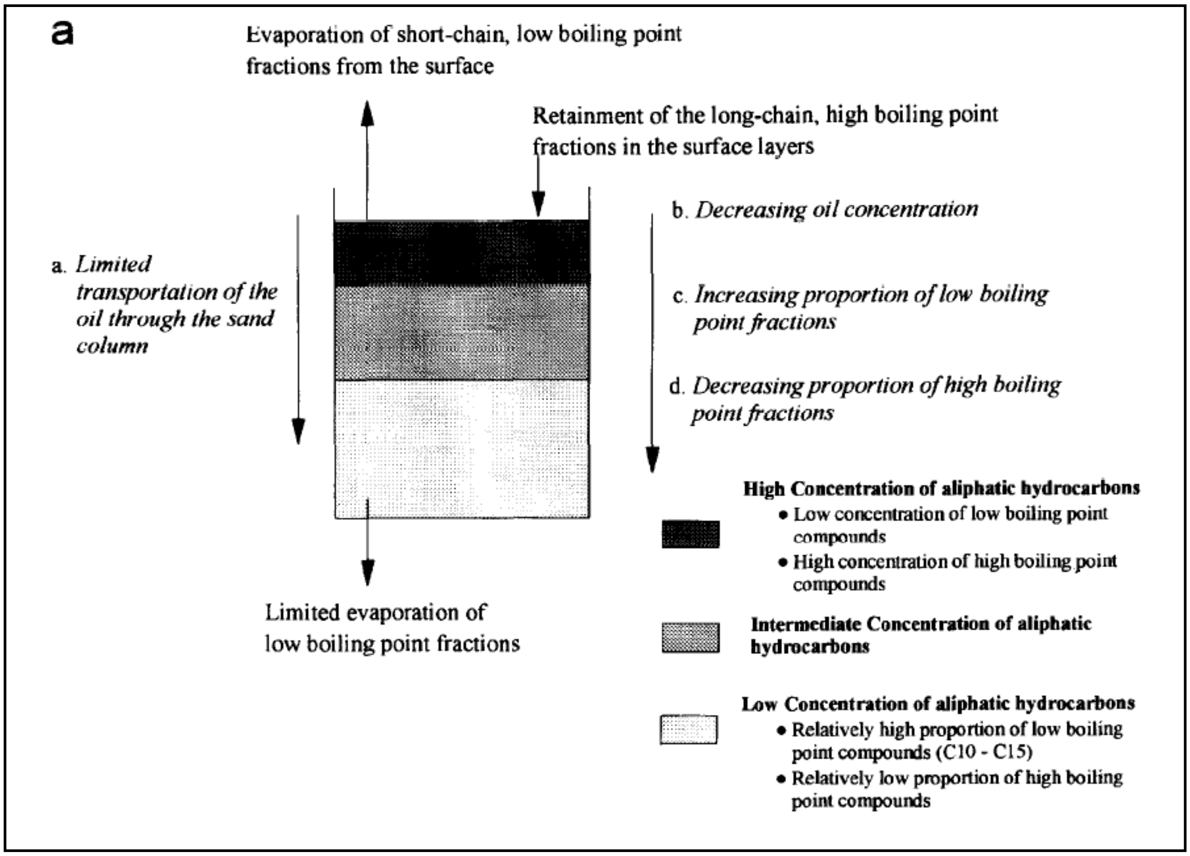


Figure H2: Schematic representation of the processes and concentration changes in *n*-alkanes from crude oil (From Miller and Mudge, 1997).

Bergueiro et al. (1998)

Bergueiro et al. (1998) studied the influence of solar radiation and wind velocity on the evaporation of Arabian light crude oil at sea and on beach sands. Oil evaporation was found to be related to the following equation:

$$F_m = a \bullet \ln\ 1 + bt$$

Where: F_m = mass fraction evaporated
a, b = constants
t = time (in minutes)

The constants for this formula for different sand types and wind velocities are shown in Table H7. The evaporation rates for two substrate types under different wind velocities are shown in Figure H3.

Table H7: Values of Constants "*a*" and "*b*" for Evaporation of Arabian Light Crude Oil [146]

Type of Sand	Wind Velocity							
	0 m/s		1.0 m/s		5.7 m/s		6.8 m/s	
	a	$b \cdot 10^3$	***a***	$b \cdot 10^3$	***a***	$b \cdot 10^3$	***a***	$b \cdot 10^3$
Medium-sized (0.25 – 0.5mm)	14.891	2.703	15.148	2.698	16.600	2.617	17.030	2.707
Normal (Mixed)	9.129	5.690	6.837	8.952	7.617	8.901	7.688	8.984
Coarse (0.5 – 1.0 mm)	7.109	9.801	5.556	18.020	6.172	14.770	6.204	15.050
None	5.932	130.000	5.564	176.00	6.282	228.000	5.896	228.000

[146] From Bergueiro et al. (1998)

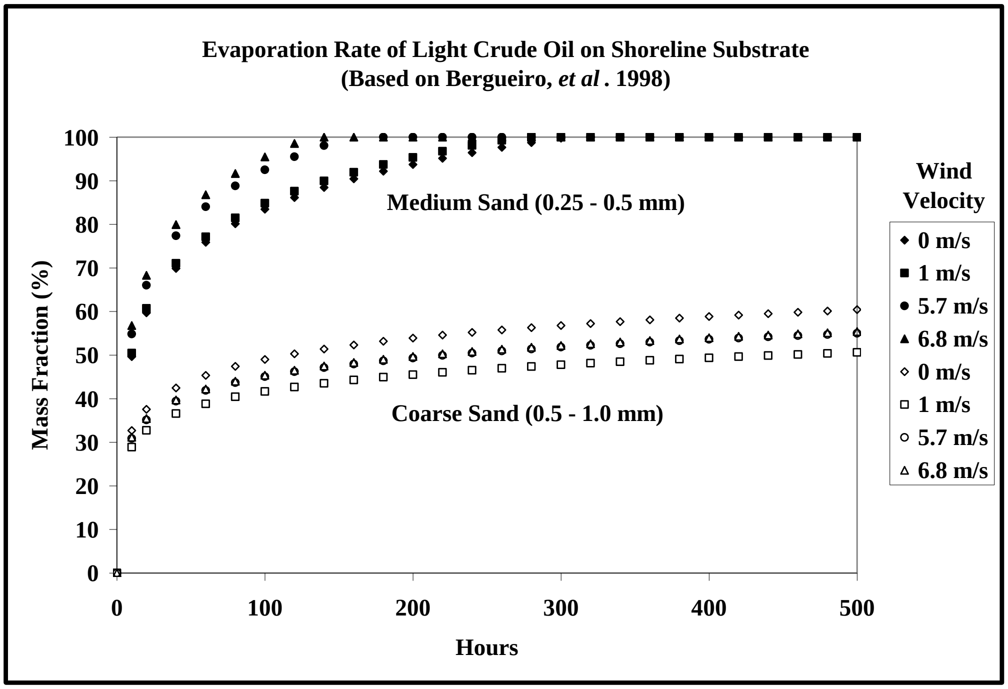


Figure H3: Estimated evaporation rate of light crude oil from two shoreline substrate types based on formula in Bergueiro et al. (1998)

Rallo et al. (1999)

Rallo et al. (1999) studied the evaporation of Cuban Pina crude oil[147] on calcareous beach sand. The researchers found that oil spilled onto sand had a 10% lower evaporation rate than oil spilled onto sea water. Maximum evaporation after 28 days was 39% at sea and 35.4% on sand. Oil of varying thicknesses on the shoreline did not differ significantly in evaporation rate. The difference in evaporation rate between a one-mm oil thickness and a five-mm thickness was only two percent. The findings led to the conclusion that in calm atmospheres, the air boundary layer is more influential than the liquid boundary layer in determining evaporation rates.

Buist (2000)

Evaporation of oil has been shown to be a significant process even if the shoreline is covered with snow or oil is entrapped within snow on a shoreline. Buist (2000) found that evaporation is the single most important weathering process for oil entrapped in snow. Evaporation rates exceeding 50% by volume after six days exposure at 0ºC (10 kt wind) were measured. Although evaporation is slower on ice in winter, eventually the oil will evaporate, even if covered by snow, to approximately the same degree as if the oil were spilled on water in warm weather.

Guyomarch and Merlin (2000)

Guyomarch and Merlin (2000) conducted experiments on the weathering properties of several crude oil, including changes in oil adhesion with weathering. Oil adhesion was found to increase with weathering time, provided weathering is linked with oil viscosity. The following relationship between weathering time and adhesion was found:

[147] ºAPI = 30.4; viscosity = 0.63 cP.

$$Adhesion = Ad_0 + A_3\left\langle 1 - e^{-k_3 t}\right\rangle$$

Where A_3 = maximum increase of adhesion
Ad_0 = initial adhesion (g/m^2)
k_3 = rate constant ($hours^{-1}$)
t = weathering time (hours)

Results for four crude oils are shown in Table H8.

Table H8: Physical-Chemical Properties of Crude Oils[148]				
Parameter	Crude Origin			
	Angola	United Arab Emirates	Argentina	North Sea
Test temperature (ºC)	26	20	20	20
Test duration (hours)	145	145	107	40
Maximum viscosity (mPa.s at 20ºC, 10 s^{-1})	5,500	4,800	2,500	2,100
90% maximum viscosity (hours)	70	65	93	25
Maximum emulsion density	0.997	1.001	0.926	0.972
Maximum oil density	0.937	0.929	0.868	0.922
Maximum water content (%)	83	83	33	78
90% maximum water content (hours)	8	45	30	18
Evaporation percentage	30	30	10	25
Oil adhesion (g/m^2)	800	3,100	650	1,550

Santas and Santas (2000) investigated the effects of wave action on biodegradation of Iranian light crude oil in two mecocosm experiments that simulated Mediterranean shores. Maximum biodegradation in sediments was observed with moderate wave action. Lower biodegradation was observed in high wave action. No biodegradation occurred under no wave action.

Owens et al. (2000)
Mauseth and Martin (2001)
Owens, LaMarch, and Martin (2001)
In some cases, significant weathering of the oil occurs *before* it hits the shoreline causing the formation of tar balls. Sandy beaches are particularly susceptible to the accumulation of pelagic tarballs. Owens et al. (2000), Mauseth and Martin (2001), and Owens, LaMarch, and Martin (2001) documented the formation and stranding of tar balls in the M/V New Carissa spill in Oregon[149].

An estimated 700 gallons of oil stranded onto sandy beaches in the first couple of weeks after the spill. This oil formed an estimated 8.9 million tar balls varying in size from less than 0.25 inches to two inches in diameter. The majority of tar balls contained less than 0.001 gallons (3.4 grams) of oil.

Wong et al. (2002)
Wong et al. (2002) studied sediment contamination levels in a mangrove swamp after the spillage of 60,720 gallons of crude oil in Hong Kong. Their results are shown in Table H9.

[148] From Guyomarch and Merlin (2000)
[149] The M/V New Carissa ran aground off Coos Bay, Oregon, carrying 400,000 gallons of fuel oils. Oil was released into the nearshore surf zone, an area with high wave-energy levels. About 25,000 to 70,000 gallons of No.2 and No. 4 fuel oils were released.

Table H9: Concentrations of Aliphatic, Aromatic, and Total Hydrocarbons in Mangrove Sediments[150]											
Area	% water	% silt/clay	Aliphatic hydrocarbons (µg/g)[151]			Aromatic hydrocarbons (µg/g)			Total hydrocarbons (µg/g)		
			1 mo.	4 mo.	7 mo.	1 mo.	4 mo.	7 mo.	1 mo.	4 mo.	7 mo.
1	70.8	53.0	2,433 (2,180)	556 (648)	3,829 (3,834)	429 (363)	313 (385)	2,293 (1,892)	2,862 (2,280)	869 (1,030)	6,122 (5,498)
2	21.8	7.0	35.4 (8.9)	9.3 (2.9)	75.9 (67.7)	14.9 (7.7)	4.1 (1.1)	51.3 (47.9)	50.3 (15.8)	13.4 (2.7)	127.2 (115.1)
3	21.8	10.9	7.9 (2.1)	6.4 (1.9)	12.1 (1.8)	2.7 (0.7)	3.6 (0.8)	6.3 (0.2)	10.6 (2.8)	10.1 (1.2)	18.4 (2.0)
4	19.0	15.0	10.1 (2.8)	6.3 (1.3)	10.9 (1.1)	5.5 (1.4)	3.0 (2.5)	11.5 (2.0)	15.5 (4.1)	9.3 (1.5)	22.4 (1.0)
5	15.5	11.8	18.7 (6.5)	18.8 (8.0)	53.9 (0.7)	8.6 (2.9)	7.6 (5.9)	15.1 (10.7)	27.3 (9.0)	26.3 (13.3)	68.9 (11.0)

Oil sediment concentrations for the most heavily oiled area by depth are shown in Table H10.

Table H10: Total Petroleum Hydrocarbon Concentrations in Most Heavily Oiled Mangrove Area[152]		
Depth of Core Sections	Four Months Post-Spill (µg/g)[153]	Seven Months Post-Spill (µg/g)
0 – 5 cm	1,455.08 ± 1,234.63	695.53 ± 351.20
5 – 10 cm	282.89 ± 311.70	181.50 ± 12.76
10 – 15 cm	107.61 ± 74.38	110.84 ± 20.87
15 – 20 cm	83.68 ± 62.74	99.92 ± 27.54

Sediment cores indicated that the oil penetrated to as much as 20 cm, with decreasing concentrations with depth. Oil in the deeper sediments biodegraded relatively slowly due to the anoxic conditions. Persistence of spilled oil in mangroves is possible despite warm temperatures and twice-daily tidal flushing.

Zhu et al. (2001)
According to Zhu et al. (2001), the Prince et al. (1994) model was limited in application because the data set used in the regression was limited to a small, non-replicated field area.

[150] Wong et al. (2002)
[151] Means with standard deviations in brackets, N = 3.
[152] Wong et al. (2002)
[153] Grams of total hydrocarbons per gram of sediment.

APPENDIX I: Oil Removal by Wave Action

Research on the removal of oil by wave action is presented here in chronological order.

Owens et al. (1983) and **Owens et al. (1987)** had observed that wave exposure is an important parameter for the rate of removal of oil from the beach surface.

Mancini et al. (1989) reported on the impacts of the 1985 Arco Anchorage spill in Port Angeles, Washington, including mean intertidal and subtidal oil concentrations, as shown in Table I1.

Table I1 Mean Oil Concentration in Sediments of Ediz Hook after Arco Anchorage Spill[154]

Location	Oil Concentration (ppm total weight basis)				
	January 1986[155]	April 1986	July 1987	October 1987	January 1988
Intertidal Zone	2,240	670	110	140	150
Subtidal Zone	2,300	460[156]	110	410	260

Hayes, Michel, and Noe (1991)

Hayes, Michel, and Noe (1991) analyzed the factors controlling initial deposition and long-term fate of spilled oil on gravel beaches. Spilled oil on gravel beaches is likely to persist for a long time (up to decades), because of the potential for deep penetration and burial of oil in coarse sediments. The detailed, three-dimensional configuration of gravel beach deposits is affected by the internal characteristics of the reflective or dissipative waves shaping the beach. Reflective waves typically produce steep, coarse, cuspate berms that allow for deep penetration and burial in the beach face/berm areas. Dissipative waves typically build intertidal swash bars that may move landward and bury oil deposits, such as asphalt pavements. The formation of armoring (structural strengthening) of a gravel beach surface impedes erosion and sediment transport. Armored beaches are likely to retain buried oil longer.

The researchers showed that oil in deeper, mixed sediments is retained because it is sheltered or "armored" from direct wave action, abrasion, and hydraulic erosion by the surface sediments. This phenomenon occurred after the Exxon Valdez spill when oiled passed through a surface boulder-cobble layer and penetrated into the deeper mixed sand-gravel beach sediments.

The researchers cautioned that care should be taken in interpreting total hydrocarbon concentrations in sediments as a measure of the impact of a particular oil spill**.** Hirvi (1989), for example, showed that sandy sediments in relatively *clean* areas of the southern Baltic Sea had concentrations of total hydrocarbons between 10 and 30 µg/g (dry weight), compared to sediments in polluted areas that had concentrations to up to 130 µg/g.

Even high-viscosity oils can penetrate coarse sediment beaches. Oil that remains can persist below the level of wave action. Penetrated oil can also be protected from physical weathering.

Jahns et al. (1991)

Jahns et al. (1991) investigated sediment oil concentrations on high- and low-to-moderate energy beaches in Prince William Sound in the year after the Exxon Valdez oil spill, as shown in Table I2 and Figure I1.

[154] From Mancini et al. (1989).
[155] The Arco Anchorage spill occurred on 21 December 1985.
[156] August 1986.

Table I2: Prince William Sound Sediment Oil Content[157]			
Month (Months after Spill)	**Number samples**	**Average concentration (% by weight)**	**Maximum value (% by weight)**
High-Energy Beaches			
September (6)	26	0.45	3.9
October (7)	41	0.32	4.39
November (8)	27	0.30	4.08
December (9)	30	0.10	1.04
January (10)	28	0.07	0.29
March (12)	47	0.22	4.28
Total	**199**		
Low-to Moderate-Energy Beaches			
September (6)	50	0.28	2.35
October (7)	41	0.11	0.83
November (8)	-	-	-
December (9)	39	0.05	0.45
January (10)	45	0.06	0.51
March (12)	43	0.07	1.04
Total	**218**		

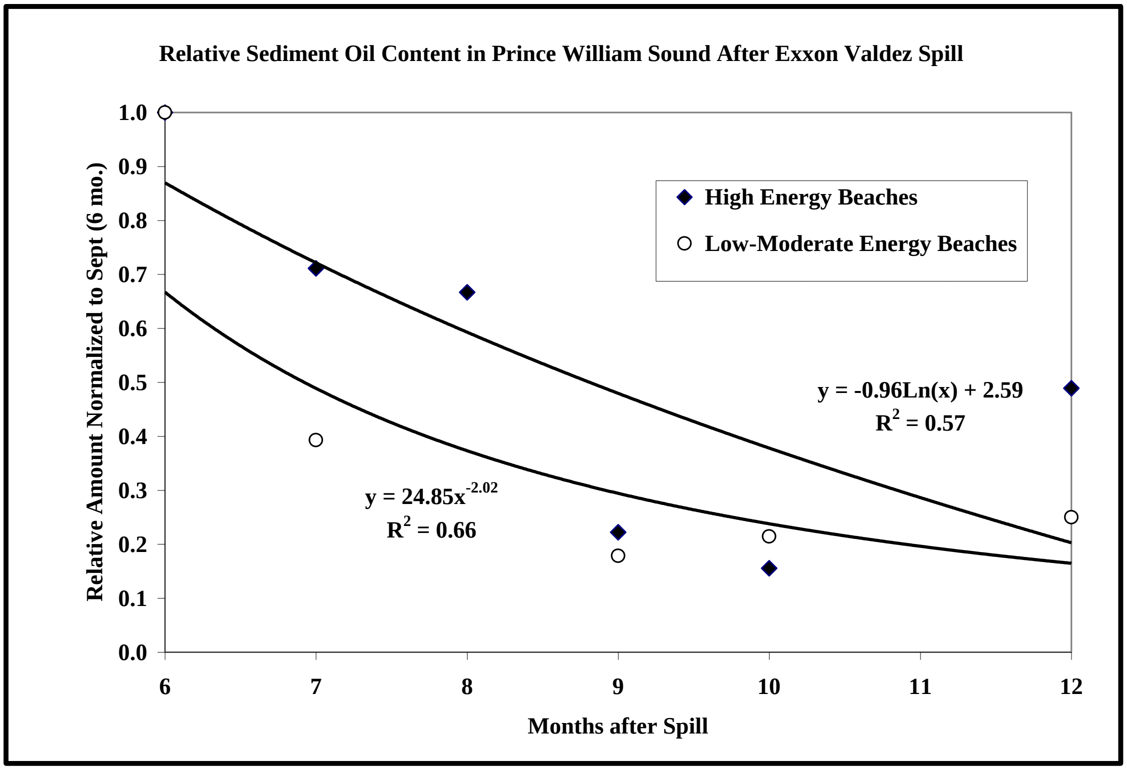


Figure I1: Relative concentrations of oil in sediment in Prince William Sound after the Exxon Valdez spill (Based on Jahns et al., 1991).

Data from the Exxon Valdez spill presented in Jahns et al. (1991) showed a lower removal rate constant of about 0.1 per month. A higher than normal wave energy would increase the transition rate. Higher oil viscosity would decrease the transition rate.

[157] From Jahns et al. (1991)

Storm events enhance the mobility of the oil attached to particles when the particles grind against each other. If the depth of penetration of the added wave energy exceeds the depth of oil penetration, one would expect complete oil removal and an enhanced rate for the transition period. Oil stranded below the depth of energy penetration would exhibit normal transition rate constants. The relative energy of storm events can be related to the Beaufort scale (Table I3) since wave energy is a function of wave height.

Table I3: Beaufort Scale[158]

Beaufort Level	Wind Velocity (kts)	Wind Description	Wave Height (m)	Relative Wave Energy[159]
Force 0	<1	Calm	0	0
Force 1	1 – 3	Light air	0.1	1
Force 2	4 – 6	Light breeze	0.2 – 0.3	2.5
Force 3	7 – 10	Gentle breeze	0.6 – 1	3.5
Force 4	11 – 16	Moderate breeze	1 – 1.5	4.5
Force 5	17 – 21	Fresh breeze	2 – 2.5	7
Force 6	22 – 27	Strong breeze	3 – 4	11
Force 7	28 – 33	Near gale	4 – 5.5	13
Force 8	34 – 40	Gale	5.5 – 7.5	14.5
Force 9	41 – 47	Strong gale	7 – 10	15.5
Force 10	48 – 55	Storm	9 – 12.5	20.5
Force 11	56 – 63	Violent storm	11.5 – 16	26.5
Force 12	64+	Hurricane	> 16	30

Weathering was assumed to be a related to a first-order decay with a rate constant of 0.0001 on a daily basis or 0.00005 for a tidal cycle. Long-term reduction would then have a half-life of eight years under calm conditions.

Humphrey, Owens, and Sergy (1991)

Humphrey, Owens, and Sergy (1991) reported on long-term results from the Baffin Island Oil Spill (BIOS) Project in which 15 m^3 (3,963 gallons) of Lago Medio crude oil was spilled on a sheltered Arctic beach. About two-thirds of the oil was removed within days. Over 90% of the oil was removed within 17 months of open water by natural processes. A summary of their results is shown in Table I4.

Table I4: Changes in Estimated Oil Content of Beaches in Baffin Island Oil Spill Project[160]

Year	Total Area Oiled (m^2)	Average Surface Oil Cover (%)	Equivalent Area of 100% Oil Cover (m^2)	Percentage of Beach Area Oiled (%)	Percentage of Initial Oil Remaining (%)
1981	8,570	57	4,850	58	100
1982	9,600	34	3,282	65	67
1983	3.925	34	1,337	25	28
1985	4,440	27	1,200	30	33
1987	2,240	36	800	15	17
1989	1,600	41	631	10	13

Michel et al. (1991)

Michel et al. (1991) analyzed trends in natural removal from shorelines impacted by the Exxon Valdez spill. The researchers found that natural processes during the storm season in the winter after the March

[158] Based on National Oceanic and Atmospheric Administration and International Maritime Organization data, as presented in Etkin 1999.
[159] Based on graph in Humphrey, Owens, and Sergy (1993)
[160] From Humphrey, Owens, and Sergy (1991)

1989 spill removed up to 90% of surface oil from exposed and intermittently-exposed shorelines. Even shorelines that were relatively sheltered experienced removal rates of up to 50%. Subsurface oil, the deepest of which occurred on exposed cobble/boulder beaches, was removed by sediment reworking of the top 20 cm on most beaches and deeper at the high-tide berm. Oil below these depths showed an average 40% reduction.

Humphrey, Owens, and Sergy (1993)
Humphrey, Owens, and Sergy (1993) concluded that the transition from maximum oil capacity (or first loading) to residual loading, without storm interaction, is the critical period. Oil is removed during a tide cycle by washing of particles. The rate of removal depends on the oil viscosity and the attractive forces between the oil and the substrate. Data from the BIOS project were used to estimate residual load, which came to 4.5 L/m^3. The natural rate of removal during the transition stage was estimated as:

$$[OIL]_t = [OIL]_{init} \bullet e^{(-kt)}$$

where k is 0.2 on a monthly basis, or 0.006 on a daily basis. For two tides per day, the transition rate constant would be about 0.003 on a tide cycle basis. The half-life for oil in the transition period is thus about 100 tide cycles.

Harper, Sergy, and Sagayama (1995)
Harper, Sergy, and Sagayama (1995) concluded that oil that penetrates pebble or cobble sediment or is buried by natural sediment redistribution can both enter and leave the sediment due to few constrictions. In finer sediments there are orders of magnitude more grain-to-grain contacts and oil that penetrates or is buried in these sediments is not easily flushed out. In finer sediments, there is also a large surface area per unit volume allowing more oil to adhere to the sediment surfaces.

Bragg and Owens (1995)
Bragg and Owens (1995) reported on natural shoreline oil removal by interactions between oil and fine mineral particles. The amount of oil removed based on different water flow rates is shown in Table I5.

Table I5: Oil Removal from Three-Foot Deep Bed of Oiled Sediment in Prince William Sound[161]

Type of Water Flow	Water Flow Rate	Oil Removal (% Initial Oil on Sediment)
Tidal flow	0.03 ft/min	1%
Higher velocity flow	11.00 ft/min	12%
Storm waves	19.00 ft/min	58%

Short, Sale, and Gibeaut (1996)
Short, Sale, and Gibeaut (1996) studied nearshore transport of hydrocarbons and sediments after the Exxon Valdez spill and concluded:

- Finer-grained intertidal sediments contaminated by oil from the Exxon Valdez spill were transported to adjacent shallow subtidal areas by waves associated with winter storms and beach treatment activities.
- Residence time of oil-contaminated sediments in the shallow subtidal areas adjacent to oiled beaches depended primarily on energy available to transport these sediments to deeper, lower-energy sites. Most sites had residence times of less than one year.
- Conditions that promoted accumulation of oil-contaminated sediments in the shallow subtidal areas adjacent to oiled intertidal beaches include:

[161] Based on graph in Bragg and Owens (1995).

- Beaches prone to onshore/offshore sediment transport caused by winter storms or treatment; and
- Low-energy subtidal conditions caused by low tidal current velocities, low wave energy, or uneven bathymetry that forms pockets protected from tidal or wave action.

Hayes (1996)

Hayes (1996) developed an exposure index for oiled shorelines to estimate the impact of wave action for removing oil from shorelines for which no recorded wave data exists. Wind gauge data correlated with three effective fetch distances measured perpendicular to and at 45º to the shoreline were used to calculate the exposure index. The exposure index was calculated for Prince William Sound as follows:

$$EI_{PWS} = \left[EFP \cdot WD_{10-20mph} + EFP \cdot \left[WD_{>20mph} \right]^2 \right] + \left[EP45^o L \cdot WD_{10-20mph} + EP45^o L \cdot \leq \left[WD_{>20mph} \right]^2 \right] + \left[EF45^o R \cdot WD_{10-20mph} + EF45^o R \cdot \left[WD_{>20mph} \right]^2 \right]$$

Where: *EFP* = Effective fetch perpendicular to the shoreline
EF45ºL = Effective fetch 45º to the shoreline (looking left)
EF45ºR = Effective fetch 45º to the shoreline (looking right)
$WD_{10\text{-}20mph}$ = Number of days (24 h) that wind blew 10 – 20 mph
$WD_{>20mph}$ = Number of days (24 h) that wind blew > 20 mph[162]

Calculated exposure indices for beaches in Prince William Sound correlated well with a measure of gravel roundness for individual clasts on each beach, as shown in Figure I2.

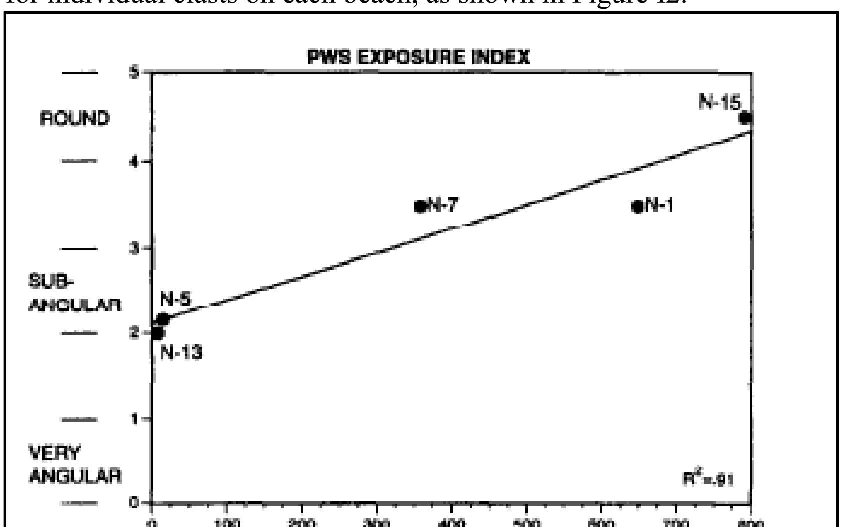


Figure I2: Plot of average roundness of beach gravel versus the exposure index calculated for five of the geomorphology/chemistry stations in Prince William Sound (From Hayes, 1996).

Gravel roundness is a measure of the smoothness of the outer margin of a sediment particle or gravel clast (Figure I3) which is caused by the abrasion of particles against one another during transport by water or wind.

[162] The number of days with wind velocities over 20 mph are squared in the equation because wave energy flux is much greater for waves generated by the very strong winds than for relatively mild winds of 10 – 20 mph.

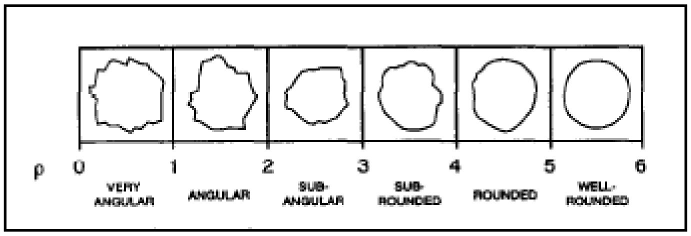


Figure I3: Classification of roundness of sediment particles (From Hayes, 1996)

Lee et al. (1997)
Lee et al. (1997) reported that surf washing removed the majority of stranded oil emulsion in less than one week in the Sea Empress spill[163]. This time was short compared to the 50% oil removal in six months reported for the Exxon Valdez spill by Michel et al. (1991). The relatively high rate of oil removal was attributed to the presence of fine-grained sediment resuspended within nearshore waters. It was hypothesized that some of the sediment was in suspension when the oil emulsion came ashore and minimized contact of oil directly with the cobbles on the shoreline.

Owens (1998)
Owens (1998) concluded that the processes by which oil is removed naturally from beaches include:

- Weathering processes, such as evaporation, dispersion, photo-oxidation, and biodegradation;
- Physical abrasion as a result of wave action and contact between moving sediments; and
- Oil and fine-particle interactions.

The rate at which oil is removed naturally is a function of the type and amount of oil, the intensity of the degradation processes, and the availability of the oil. A small amount of a light oil on the surface of an exposed, high wave-energy beach could be removed in hours or days. If that same oil penetrated beach sediments and was retained below the limit of wave action in an anaerobic environment, it could persist for months or years. Oil stranded above the normal limit of wave action or that has penetrated below the depth of sediment reworking is also not available for natural removal processes. Owens (1998) promotes the use of sediment reworking and tilling as a response strategy to enhance natural oil removal processes for these types of situations.

Little et al. (1998)
Little et al. (1998) reported on the shoreline response operations for the 1996 Sea Empress spill[164] off Milford Haven, United Kingdom. The removal rate was more than twice that observed after the Exxon Valdez spill. This is due to the generally higher shoreline energy levels in western Wales and the higher proportion of oil initially affecting the Alaskan shorelines.

Santas and Santas (2000)
Santas and Santas (2000) investigated the effects of wave action on biodegradation of Iranian light crude oil in two mecocosm experiments that simulated Mediterranean shores. Maximum biodegradation in sediments was observed with moderate wave action. Lower biodegradation was observed in high wave action. No biodegradation occurred under no wave action.

[163] In February 1996, the tanker Sea Empress spilled 72,000 tonnes (over 21 million gallons) of Forties Blend crude oil and 370 tonnes (109,000 gallons) of heavy fuel oil near Milford Haven, UK. 10,000 to 15,000 tonnes (2.9 million to 4.4 million gallons) of emulsion reached the coastline.
[164] Over 21 million gallons of light crude oil (Forties Blend) and some heavy fuel oil spilled.

Owens, Sergy, and Prince (2002)
Owens, Sergy, and Prince (2002) concluded the following from studies of a heavy oil spill in a low-energy environment in the Baffin Island Oil Spill (BIOS) Project:

- Even on a low-energy shore, if a large quantity of oil is stranded such that it exceeds the loading capacity of the sediments, excess oil will be removed rapidly in the first few tidal cycles by the simple lifting action of the rising tides.
- The initial short, unstable period is followed by a long, stable period during which the oil is removed only slowly. Persistence of residual oil in the intertidal zone may be on the order of months to years. Oil at the high-tide level, which is above the limit of most wave action, will likely persist for years to decades.
- After oil is apparently removed from the beach surface, subsurface oil may remain. Subsurface oil removal is a function of penetration depth and the depth of sediment reworking by beach processes. If sediment reworking depth is minimal, oil may remain in the interstitial spaces of the uppermost sediment layer.
- Wave abrasion and sediment reworking are not the only processes important in low-energy environments. Biodegradation and fine-particle interaction also play an important role in the long-term weathering and removal of residual oil. In an Arctic environment, freeze-thaw action may also contribute.

APPENDIX J: Oil Re-flotation

Owens et al. (2005)
Owens et al. (2005) reported on re-flotation (also called "remobilization") of oil in the grounding of the bulk carrier M/V Selendang Ay on Unalaska Island in the Aleutian Chain, Alaska, on 8 December 2004 that resulted in the spillage of 340,000 gallons of fuel oil[165]. The spill impacted 54.2 km of shoreline, as shown in Table J1. Oil from the heavily oiled shorelines was remobilized and deposited on previously unoiled beaches.

Table J1: Shoreline Oiling Survey for M/V Selendang Ayu Spill on Unalaska Island[166]

Surface Oil Category	Kilometers Impacted	Miles Impacted
Heavy	14.0	8.7
Moderate	5.0	3.1
Light	13.4	8.3
Very Light	0.6	0.4
Tar Balls	21.2	13.2
No Oil Observed	241.2	150.0
Total Length Oiled	**54.2**	**33.7**
Total Survey Length	**295.6**	**183.7**

[165] Mixture of diesel and IFO 380.
[166] From Owens et al. (2005)

APPENDIX K: Persistence

Observations on the persistence of oil on shorelines and in sediments near shorelines have been reported for a number of spills and locations. Research papers on this topic are presented here in chronological order.

Berne et al. (1980)

Many studies have noted that the persistence and gradual rate of removal or disappearance of oil from shorelines is related to first-order decay kinetics over time. This type of decay rate allows for a calculation of half-lives of the oil on the shoreline. Berne et al. (1980) reported a half-life of 2.4 months for sandy intertidal areas oiled by the Amoco Cadiz spill.

Robilliard et al. (1980)

Robilliard et al. (1980) described oil-shoreline interactions under Arctic conditions. Oil persistence was found to be influenced by a combination of physical processes controlling oil deposition, penetration, and removal. The deeper the oil penetration, the more likely the oil will persist, since penetration and burial insulate the oil from surface radiation and mechanical energy. Lighter oils penetrate substrates more than heavier oils. The colder the air and water temperatures, the more likely the oil will persist. The processes are summarized in Table K1.

Table K1: Processes that Alter the Impact and Persistence of Stranded Oil

Process	Impact Reduction/Increased Oil Breakdown	Impact Increase/Decreased Oil Breakdown
Waves	Increasing wave-energy levels: Mix/break down oil in breaker, surf, wash zones Sediments become abrasive tools Redistribute or erode oil on shore Reflected waves mix/break down oil before reaching shoreline	Decreasing wave-energy levels: Bury oil by beach accretion or longshore migration of sediments Reduce oil temperature Throw oil above normal level of wave activity by splashing action of breakers
Winds	Increase evaporation rates Increase dispersion	Redistribute sediments and bury oil on backshore Generate storm surges that deposit oil in lagoons and backshore Onshore winds trap oil on coast during surge; deposition occurs above normal wave level
Ice	Ice foot prevents oil deposition on shore Ice push breaks up stranded oil Ice foot prevents oil from reaching shoreline	Prevents wave generation and lowers wave-energy levels Ice foot can enclose oil Ice push can bury oil Ice push moves oil above zone of maximum wave activity
Tides	Low water levels cause oil deposition in sections later subject to waves/currents	High water levels cause oil deposition above normal wave/current action Can carry oil onto marsh surface
Currents	Increase oil dispersion into water column Transport oil offshore	Concentrate oil in eddies/low current areas Transport oil to previously non-impacted areas.

Teal and Howarth 1984

Teal and Howarth 1984 observed that oil can persist in marsh sediments for many years.
A number of studies have noted that oil can persist in marsh sediments for many years.

Little and Scales (1987)

Using both visual oil cover data and hydrocarbon analysis, Little and Scales (1987) measured the persistence or residence time of crude oil and mousse (emulsified crude oil) on a wide range of shoreline types. Residence times on the shorelines varied from three days to more than a year and were shown to depend on energy level, drainage, and sediment textural gradients. Their results are shown in Table K2.

Table K2: Oil Residence Times in Different Shoreline Types[167]				
Experimental Plots (Decreasing Energy Level)	Shoreline Type	Vulnerability Index[168]	Oil Residence Time (days)[169]	
			From % Oil Cover	Hydrocarbon Analysis
Westdale Bay	Very exposed, medium-to-coarse sand pocket beach, shallow sediments, rocky platform beneath, well drained	4	7	7
Freshwater West	Very exposed fine sand and pebbles, sand dunes, well drained	3	8	18
Broadhaven	Moderately exposed fine sand, bar and trough beach, sand dunes, well drained	3	20	25
Blue Anchor	Moderately exposed current-rippled sand flat, occasional cohesive mud lenses, plan bedding, better drainage	5	3	3
Angle Bay	Sheltered sandy gravel, poorly drained	5	30 – 60	38 – 67
Sandyhaven 5 & 6	Sheltered muddy sand, well drained	6	30	60
Sandyhaven 3 & 4	Sheltered ripple find sand, well drained	9	110	130 – 380
Sandyhaven 1 & 2	Sheltered sandy mud, well drained	10	60	380
Steart Saltmarsh	Moderately sheltered sandy clay, moderately drained	10	20	67 – 380

The longest residence time in the Little and Scales (1987) study was 380 days, just over one year. In some cases, much longer-term persistence has been observed.

Miller (1989) reported a half-life of 1.4 months for a coarse intertidal beach oiled with Alaska North Slope crude oil by the Arco Anchorage spill in Puget Sound.

Delaune et al. 1990
Delaune et al. 1990 presented observations on long-term persistence of oil in marsh sediments.

Humphrey, Sergy, and Owens (1990)
Humphrey, Sergy, and Owens (1990) investigated the persistence of stranded medium crude oil in cold climates by comparing data from the Baffin Island Oil Spill (BIOS) project sites. The results are shown in Table K3.

Table K3: Baffin Island Oil Spill Project Shoreline% Oiling Measurements[170]						
Year	Open Water (months)	Length Shoreline Oiled	Total Area Shoreline Oiled	Equivalent Oiled Area	Oil Volume Ashore	Oiled Sediment Volume
1981	0	100%	100%	100%	100%	100%
1982	3	90%	113%	68%	67%	112%
1983	5	80%	45%	28%	28%	43%
1985	9	67%	51%	25%	25%	51%
1987	13	58%	26%	16%	10%	22%
1989	17	58%	19%	13%	5%	19%

[167] From Little and Scales (1987).
[168] Based on vulnerability index in Hayes, Gundlach, and Getter (1980). 10 = most vulnerable.
[169] Range shown when there were major differences between crude oil and mousse.
[170] From Humphrey, Sergy, and Owens (1990)

The most rapid rate of change in surface oiling was found in the first six months of exposure (1981 – 1983)[171]. There was very little mechanical energy in the form of waves at the spill site. Most of the residual oil concentrated in a narrow asphaltic band on the upper beach slope. Remaining subsurface oil was relatively fresh.

The Exxon Valdez oil spill has been studied extensively, and is still being studied even 18 years later, with regard to persistence of the oil on the shoreline. Neff et al. (1995) reported on shoreline oiling conditions in the aftermath of the Exxon Valdez spill, noting that the extent of oiling declined substantially between 1980 and 1992. In 1989, 783 km of shoreline were oiled. Two years later, 96 km remained oiled. In 1992, only 10 km contained oil. (See Table K4.)

Approximately one-third of the oiled areas contained subsurface oil in 1989. The areal extent of shoreline oiling decreased by 70% between 1991 and 1992.

Table K4: Shoreline Surface Oiling in Prince William Sound after Exxon Valdez Spill[172]

Year	Surveyed (km)			Oiling Category (km)				
	Segments	Subdivisions	km	Very Light	Narrow/ Light	Medium/ Moderate	Wide/ Heavy	Total Oiled
1989	550	--	1,450	223	326	94	141	783
1990	493	711	1,109	323	80	46	21	420
1991	305	432	386	68	15	12	0.1	96
1992	59	76	32	8.7	0.8	0.6	0.2	10

Sergy, Humphrey, and Owens (1991) concluded that the two most commonly used parameters to describe shoreline sediment contamination – length and total petroleum hydrocarbons (TPH) have the greatest limitations with regard to predicting fate and persistence of stranded oil. Length data do not account for multidimensional oil distribution. TPH data, used to compute oily sediment and oil volume, are discrete, and rarely can be extended to describe large areas. The experience of the researchers showed that TPH data permits confidence only in observed changes of at least one order of magnitude. They recommended using TPH data only with one significant figure expressed by weight rather than as ppm or mg/kg. For coarse-grained sediments, they recommended that TPH data only be used as a general indicator of change. Equivalent area methods were recommended as consistently providing a good estimate of surface oil cover in the short- to medium term. They noted that since subsurface oil is reduced more slowly than surface oil, the latter becomes les representative of total oil conditions over time.

Humphrey, Owens, and Sergy (1993) found that asphalt pavement formation is common on coarse sediment beaches. The process is likely a combination of emulsion formation with the availability of non-carbon nucleation sources, such as sediment, shell fragments, or biota. Asphalt formation has been observed in the Arrow, Metula, Exxon Valdez, and Amoco Cadiz spills.

Owens (1993) reported on shoreline oiling observations from five spill events: 1970 T/V Arrow[173], 1993 T/V Braer[174], 1974 T/V Metula[175], and 1989 T/V Exxon Valdez[176]:

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[171] The oil was only exposed to open water for a limited time each year due to ice formation.
[172] From Neff et al. (1995)
[173] 2.5 million gallons of Bunker C fuel oil spilled at Cerberus Rock, 6.5 km offshore form the coast in northern Chedabucto Bay, Nova Scotia, Canada (Source: ERC International Oil Spill Database).
[174] 25 million gallons of Norwegian Gullfaks crude oil at Shetland Islands, Scotland, UK (Source: ERC International Oil Spill Database).
[175] 13.86 million gallons of Arabian light crude at Straits of Magellan, Satellite Bank port, Chile (Source: ERC International Oil Spill Database).

- *1970 T/V Arrow spill:* With a few localized exceptions, the coast was free of oil within three years after the spill, indicating that some of the 260 km shoreline oiled with heavy Bunker C fuel self-cleaned in low wave-energy environments where physical abrasion and hydraulic activity are minimal.
- *1993 T/V Braer spill:* Despite the large volume of crude oil spilled and the proximity of the spill to the shoreline, only tens of meters of shoreline were oiled. The turbulent mixing along the shore produced an oil-in-water emulsion that did not strand on the beaches or stain rock outcrops. The oil was described as "not sticking" to the beach. The lack of stickiness was attributed to encapsulation of the physically dispersed oil within water. The oil was then carried away by local and regional currents.
- *1974 T/V Metula:* Approximately 250 km of coast were oiled in this incident, with 120 km near the spill site having heavy or moderate concentrations of emulsified oil and bunker fuel. Some oil stranded during very high spring tides and wind-induced spurges. Some of this stranded oil produced asphalt-like pavements that were persistent.
- *1989 Exxon Valdez:* The released oil spread out over 9,500 km of coastline. The oil on the shoreline rapidly declined in the year following the spill through natural cleaning, especially during the winter months.

Owens (1993) concluded that for the 1991 Gulf War spills, the distance of oil transport was relatively small – only 250 km from the original spill sites despite the fact that vast amounts of oil were released[177]. The oil loading was about 84,000 gallons per kilometer. The shoreline types impacted are shown in Table K5.

Table K5: Shoreline Oiling in 1991 Gulf War Spillage (Kuwait Border to West of Abu Ali)[178]

Shore Type	Length (km)	Oiled (km)	Length (%)	Oiled Sediment Volume (1,000 m^3)
Seawalls, piers	12.4	9.0	73	0.3
Rocky shores	55.5	36.9	66	3.2
Riprap	9.9	9.9	100	0.1
Fine sand beaches	60.3	57.3	95	22.9
Coarse sand beaches	271.1	263.3	95	22.9
Exposed tidal flats	0.4	0.4	100	2.3
Sheltered tidal flats	132.5	131.0	99	554.6
Marshes	141.2	124.4	99	677.7
Mangroves	8.7	8.7	100	38.7
Not classified	17.6	3.5	20	-
Islands	55.4	-	-	-
Total	**765.0**	**644.4**	**84**	**1,367**

Owens et al. (1993) reported that surveys conducted 22 years after the T/V Arrow spill showed that oil remained on the shoreline in areas where the oil is:

[176] 11 million gallons of North Slope crude oil in Prince William Sound, Alaska (Source: ERC International Oil Spill Database).
[177] According to the ERC databases, a total of 521.7 million gallons of crude oil were intentionally spilled into the Arabian Gulf from sources in Kuwait, Saudi Arabia, and Qatar during January through March 1991: 281.4 million spilled from two marine terminals, 178.9 million gallons spilled from eight tankers, 24.7 million gallons spilled from a pipeline, 17.6 million gallons spilled from various storage tanks, 14.9 million spilled from four refineries, and 4.2 million gallons spilled from coastal trenches at a facility.
[178] MEPA, 1991.

- Outside the zone of the physical wave action (e.g., sheltered lagoons) that is necessary to move sediments and/or abrade the oil;
- In areas of nearshore mixing where there are no fine sediments to weather the oil by biophysical processes (clay-oil flocculation and biodegradation); and
- Areas in which oil has weathered to a crust so that biodegradation processes are inactive.

Carlson and Kvenvolden (1996)
Carlson and Kvenvolden (1996) found residues of previous spillage in the areas of Prince William Sound impacted by the Exxon Valdez oil spill. They identified the tar residues as originating from Californian oil rather than Alaskan North Slope oil, as had spilled from the Exxon Valdez. The sources were hypothesized to be asphalt tanks that spilled during the 1964 Great Alaska Earthquake. This suggested that the oil had persisted from those spills for over 32 years.

Page et al. (1999) conducted surveys of the Exxon Valdez shoreline sites in 1998, nine years after the spill, and found that weathered remnants of the spill were present at a small number of sites. During the time period 1991 through 1998, the concentrations of petroleum hydrocarbons at the most heavily oiled boulder/cobble sites had decreased dramatically (by over 67%). Remaining oil residues at the boulder/cobble sites were in the uppermost parts of the intertidal zone, which is covered only during the highest spring tides and storm tides, which occur only about 20 days per year.

Rozas et al. 2000
Rozas et al. 2000 reported on long-term persistence of oil in marsh sediments.

Payne et al. (2005)
Payne et al. (2005) found evidence of subsurface oil in middle and intertidal sediments oiled by the Exxon Valdez spill 13 years after the spill. Concentrations of dissolved-phase total PAHs averaged 1,200 ng/L, ranging from 76 to 4,600 ng/L compared to 18 – 27 ng/L for reference sites.

APPENDIX L: Subtidal Persistence

Humphrey (1993)

Humphrey (1993) conducted a literature review on the persistence of oil in subtidal sediments and analyzed the data to determine oil decay rates. The research found that the rate of disappearance of subtidal oil fits a first-order decay kinetics of the form:

$$\frac{OIL_t}{OIL_o} = e^{k_1 t}$$

Where: k_1 = first-order decay constant and t is time.

The half-life is then determined from the equation:

$$\text{Half life} = \frac{\log_2}{k_1}$$

Humphrey's literature review indicated that the rate of disappearance of oil from subtidal sediments varied widely, with times for removal of 99% of subtidal oil of between 300 to 5,000 days.

Shore-stranded oil may weather and be washed into the subtidal zones, sometimes associated with sediment. The fate of the buried oil will depend on a combination of processes: weathering by loss of components to the water column; ingestion by organisms; microbial degradation; burial by subsequent sedimentation, bioturbation, or reworking of the sediment by waves, currents, or ice; and resuspension into the water column on sediment particles by waves and currents, or ice.

Oil is removed from subtidal sediments through dissolution to interstitial water, biodegradation (microbial degradation), and reworking. The fate of the oil is determined by the amount of oil reaching the sediment and the physico-chemical conditions found in the sediment.

Humphrey concluded that fine sediments can retain oil longer than coarse sediments for the following reasons:

- Microbial degradation and loss to interstitial water are increased with flushing in coarser sediments;
- Microbial degradation requires nutrients and oxygen, which are increased with flushing; and
- Fine-grained sediments are often anoxic[179], which inhibits breakdown of hydrocarbons, including lighter fractions.

A summary of the derived rate constants and half-lives for the disappearance of oil from subtidal sediments based on the literature review of Humphrey (1993) is shown in Table L1.

[179] Oxygen-depleted.

Table L1: Summary of Literature-Derived Rate Constants and Half-Lives For Oil Disappearance from Subtidal Sediments						
Oil Fraction	**Reference**	**k_1**	**R^2**	**Half-Life (days)**	**Spill Type**	**Location**
Alkanes	Haines and Atlas (1982)	-0.0006	0.3	538	Experimental	Beaufort Sea
	Anderson et al. (1978)	-0.0075	*	40	Experimental	Str. Juan de Fuca
	Anderson et al. (1978)	-0.0013	0.9	232	Experimental	Str. Juan de Fuca
	Anderson et al. (1978)	-0.0079	0.9	38	Experimental	Str. Juan de Fuca
PAH	Haines and Atlas (1982)	-0.0005	0.3	579	Experimental	Beaufort Sea
	Teal et al. (1978)	-0.0004	0.5	753	Two spills	Buzzards Bay
	Anderson et al. (1978)	-0.0078	0.8	39	Experimental	Str. Juan de Fuca
	Anderson et al. (1978)	-0.0057	*	53	Experimental	Str. Juan de Fuca
	Anderson et al. (1978)	-0.0013	0.7	232	Experimental	Str. Juan de Fuca
	Lee et al. (1981)	-0.0030	*	100	Experimental	Georgia
	Alongi et al. (1983)	-0.0044	0.9	68	Experimental	Chesapeake Bay
	Alongi et al. (1983)	-0.0056	1.0	54	Experimental	Chesapeake Bay
	Alongi et al. (1983)	-0.0067	0.5	45	Experimental	Chesapeake Bay
Total Hydrocarbon	Davies and Tibbetts (1987)	-0.0027	0.4	111	Experimental	Scotland
	Davies and Tibbetts (1987)	-0.0042	0.9	72	Experimental	Scotland
	Anderson et al. (1978)	-0.0065	0.9	46	Experimental	Str. Juan de Fuca
	Anderson et al. (1978)	-0.0058	*	52	Experimental	Str. Juan de Fuca
	Anderson et al. (1978)	-0.0005	0.7	602	Experimental	Str. Juan de Fuca
	Vanderhorst et al. (1980)	-0.0016	0.8	188	Experimental	Str. Juan de Fuca
	McCain et al. (1978)	-0.0041	0.8	73	Experimental	Aquaria
	Marchand and Caprais (1981)	-0.0020	0.1	151	*Amoco Cadiz*	Morlaix
	Marchand and Caprais (1981)	-0.0020	*	151	*Amoco Cadiz*	Aber Benoit
	Marchand and Caprais (1981)	-0.0030	*	100	*Amoco Cadiz*	Aber W'Rach
	Boehm (1982)	-0.0020	*	151	*Amoco Cadiz*	Brittany
	Hyland et al. (1985)	-0.0014	0.7	221	Experimental	Narragansett Bay
	Hyland et al. (1985)	-0.0010	*	301	Experimental	Narragansett Bay
	Hyland et al. (1985)	-0.0059	0.8	51	Experimental	Narragansett Bay
	Hyland et al. (1985)	-0.0017	0.3	181	Experimental	Narragansett Bay
	Alongi et al. (1983)	-0.0125	1.0	24	Experimental	Chesapeake Bay
	Alongi et al. (1983)	-0.0005	0.0	602	Experimental	Chesapeake Bay
	Alongi et al. (1983)	-0.0040	1.0	76	Experimental	Chesapeake Bay
* Too few points for R^2 determination.						

Based on Table L1, the predicted times for rapid and slow oil degradation are shown in Table L2. The environmental factors that would determine whether oil would degrade rapidly or slowly are summarized in Table L3.

Table L2: Predicted Times for Rapid and Slow Oil Degradation		
Remaining Oil	**Rapid Degradation**	**Slow Degradation**
50%	50 days	750 days (2 years)
10%	150 days	2,500 days (6.8 years)
1%	300 days	5,000 days (13.7 years)
0.1%	450 days	7,500 days (20.5 years)
Mean k_1 = -0.0036. Standard deviation = 0.0032		

Table L3: Environmental Factors Influencing Rapid and Slow Oil Degradation		
Process or Effect	**Short Half-Life**	**Long Half-Life**
Ice cover	Mostly ice-free	Mostly ice-covered
Water temperature[180]	Above 0ºC	Below 0ºC
Sediment depth	Shallow	Deep
Wave energy	High	Low
Bottom currents	High	Low
Grain size	Coarse	Fine
Nutrients	Unlimited	Limited
Oxygen	High	Low
Sedimentation	Low	High
Sediment reworking	Active	Rare

Humphrey (1993) summarized the effects of various factors in determining oil degradation in sediments as follows:

- *Oil type:* Lighter hydrocarbons degrade more quickly initially with the rapid biodegradation and dissolution of low molecular weight alkanes. More weathered oil degrades more slowly
- *Availability of oxygen and nutrients:* Oil buried in anoxic sediments degrades very slowly.
- *Sinking:* Oil can become heavier than water by incorporating mineral particles or debris and then sinking.
- *Sedimentation:* Oil reaches the sea floor by sedimenting with other materials or by being ingested by macro- or micro-organisms that evacuate fecal pellets.
- *Burial:* Sedimented particles can be buried by continued sedimentation over them and by reworking of the sediment by bioturbation or physical processes[181].
- *Reworking:* Reworking of the sediment can also bring oil particles back to the surface or water column. When reworking is active, oxygen concentration is also likely to be high.
- *Biodegradation:* Rates of biodegradation are high when lower molecular weight oil components are present. More weathered oil degrades more slowly as fewer lighter ends remain. The presence of oxygen increases rates of biodegradation.
- *Dissolution:* Lower molecular weight oil components and biodegradation products will often dissolve in interstitial water and be carried to the sediment surface through flushing.

Boehm et al. (1995)

Boehm et al. (1995) analyzed the environmental half-lives of total polycyclic aromatic hydrocarbons (TPAHs) in intertidal surface sediments after the Exxon Valdez spill, with results as shown in Table L4.

Table L4: Environmental TPAH Half-Lives in Prince William Sound Intertidal Surface Sediments[182]		
Tide Zone	**May 1989 to August 1990**	**August 1990 to August 1991**
Upper intertidal	2.0 months	7.4 months
Middle intertidal	2.5 months	10.6 months
Lower intertidal	3.8 months	16.0 months

[180] It is likely than any temperature effect is masked by the effects of other factors. If biodegradation is the most important mechanism for oil removal from the sediment, temperature may not be an important factor at all, since the microbes from native populations would most likely be adapted t o the local temperature regime. Temperature *would* have an effect if the sediment is frozen for part of the year (Humphrey, Owens, and Sergy, 1991).

[181] Bottom current scouring and suspension, wave action, and ice action.

[182] From Boehm et al. (1995)

Carlson and Kvenvolden (1996) tracked oil transport from beaches to deepwater sediments in Prince William Sound for 17 months after the Exxon Valdez oil spill. Two months after the spill, oil had not reached deepwater sediments. During the second summer after the spill, oil was migrating down insular slopes of the beaches to depths approaching 120 meters.

Wolfe et al. (1996) measured concentrations of total petroleum hydrocarbons in intertidal and subtidal sediments affected by the Exxon Valdez spill in 1989. Their results are shown in Table L5.

Table L5: Total Petroleum Hydrocarbons in Sediments Impacted by the Exxon Valdez Spill

Location	Depth (m)	Mean (ppm)	SD	Range	N
Prince William Sound (18 sites)	0	841.30	2,414.76	0.59 – 9,800	17
	3	22.70	46.07	1.4 – 1.90	18
	6	8.83	12.21	1.5 – 50	18
	20	11.70	19.79	1.4 – 87	18
	40	6.36	3.54	1.1 – 12	18
	100	5.85	3.54	0.16 – 11	17
Kenai Peninsula (14 site)	0	7.66	14.78	0.44 – 55	14
	3	3.85	4.63	0.55 – 17	14
	6	4.28	6.09	0.7 – 23	14
	20	11.30	12.64	0.37 – 46	14
	40	12.53	23.16	0.33 – 77	13
	100	6.41	5.62	0.76 – 21	13
Kodiak and Shelikof Strait area (11 sites)	0	7.25	13.26	0.40 – 37	11
	3	1.11	0.72	0.34 – 2.6	11
	6	2.83	4.28	0.4 – 15	11
	20	4.77	6.97	0.34 – 19	11
	40	4.65	7.41	0.26 – 26	11
	100	4.49	6.86	0.94 – 20	7

Mulhare and Therrien (1997) reported on the persistence of No. 2 fuel in sand following two spills in Narragansett Bay, Rhode Island. Beaches oiled by the World Prodigy spill[183] were shown to have a first-order decay rate (*k*) of 0.0025 day^{-1}. Residual oil concentration was calculated using the equation:

$$c_t = c_0 e^{-kt}$$

The initial concentration of fuel oil in the sand was 15,000 ppm. It was estimated that it would take 2,000 days for the concentration to reach 100 ppm.

Weise and Lee (1997) conducted small-scale shaker flask experiments over 56 days to measure the significance of clay-oil flocculation on natural biodegradation rates of weathered crude oil. The researchers found that in this time frame there were negligible rates of oil biodegradation for the crude oil adhering to solid surfaces. The flocculation process enhanced the physical removal of oil from solid surfaces, which enhanced the overall rate and extent of *n*-alkane degradation. After 56 days, the final concentrations of *n*-alkanes were 25% in the mineral-amended oiled flasks, compared with 48% in the control flasks.

Taylor and Reimer (2005) reported on shoreline surveys in Prince William Sound thirteen years after the Exxon Valdez spill. They found continued but slow weathering processes occurring in oil sequestered in mixed (coarse and fine) sediments on beaches where boulders and outcrops, shallow bedrock asperities, or boulder-armoring limit effective physical weathering action.

[183] World Prodigy spilled 273,000 gallons of No. 2 fuel oil into Narragansett Bay and Rhode Island Sound in 1989.

APPENDIX M: Impact of Marsh Vegetation

Vegetation in marshes can change the oil-holding capacity of a shoreline. Research on this topic are presented here in chronological order.

Baca et al. (1983)

The impact of a heavy fuel oil spill on a marsh area that was dominated by *Spartina*, *Scirpus*, and *Juncus* vegetation was examined by Baca et al. (1983). Geometric formulae were developed to estimate the amount of oil adhering to the vegetation. For example, the formula for *Spartina* was determined to be:

$$n \; A_L + N \; A_S = A_T$$

$$A_T \; m = H$$

$$n \; A_L + N \; A_S = A_T$$

Where:
- n = # leaves/m^2
- A_L = oiled surface area/leaf
- N = # plants/m^2
- A_S = stem surface area oiled
- A_T = total area oiled

This formula determines the total oiled surface area per square meter of marsh, A_T. This then needs to be multiplied by the oil thickness on the plant, m, to get the equivalent oil thickness on the ground per square meter, H :

$$A_T \; m = H$$

Using shoreline maps of species distribution and widths of 100 percent oil coverage, the average equivalent oil thickness on the ground can be calculated. *Spartina alterniflora*, a common marsh plant, was found to absorb an equivalent thickness, *H,* of 1.0 to 2.8 cm of oil per square meter of 100 percent coverage. For *Scirpus olneyi*, the equivalent thickness value was 0.3 cm of oil per square meter of 100 percent coverage.

Lytle and Lytle (1987) investigated the role of marsh vegetation (*Juncus roemerianus*) in oil removal from oil-impacted sediments in marshes. Levels of hydrocarbons found in *J. roemerianus* and marsh sediments after experimental spillage of Iranian crude oil are shown in Table L6. *J. roemerianus* was found to remove more hydrocarbons than other marsh plants, such as *Spartina alterniflora.*

Table L6: Uptake of Hydrocarbons from Iranian Crude Oil by *Juncus roemerianus* [184]

Hydrocarbon	Measurement Type	Leaves		Roots	Sediments
		10 days	30 days	30 days	30 days
Aliphatics	gravimetric, ppm (dry wt)	78.2	65.5	24.0	35.8
	gas chromatography, ppm (dry wt)	47.3	49.5	4.33	5.95
Aromatics	gravimetric, ppm (dry wt)	728	650	147	32.1
	gas chromatography, ppm (dry wt)	37.7	26.5	6.13	1.74
Aliphatics/Aromatics	%	126%	186%	70.6	343%
n-alkanes	ppm (dry wt)	28.1	19.0	2.54	3.43
n-alkanes/aliphatics	%	59.3	38.5	62.4	57.6
Lipid	ppm (dry wt)	11,100	9,760	9,140	1,540

[184] From Lytle and Lytle (1987).

Table L6: Uptake of Hydrocarbons from Iranian Crude Oil by *Juncus roemerianus* [184]					
Hydrocarbon	**Measurement Type**	**Leaves**		**Roots**	**Sediments**
		10 days	**30 days**	**30 days**	**30 days**
Naphthalene	ppm (dry wt)	nd[185]	nd	0.00364	0.00136
Chrysene	ppm (dry wt)	nd	nd	0.0238	nd

Fraser et al. (1989)

Fraser et al. (1989) noted that a 1988 spill of 9,400 bbl (394,800 gallons) of San Joaquin Valley crude oil into Carquinez Strait and Suisun Bay near Martinez, California, resulted in contamination of saltmarsh sloughs. Contamination of the sloughs was largely confined to a narrow band at the high-tide line. Some oil was on the soil, but the majority clung to the stems of marsh vegetation.

Michel, Lehmann, and Henry (1998)

Michel, Lehmann, and Henry (1998) reported that the 1996 T/V Julie N incident in Portland Harbor, Maine, which resulted in the spillage of 179,634 gallons of No. 2 fuel and IFO 380 fuel[186], impacted pebble/cobble beaches, medium-grained sand beaches, and man-made structures, in addition to fringing marshes with mud or sand flats in the intertidal zone.

The researchers measured oil adherence to the stems of *Spartina alterniflora*, the predominant marsh vegetation in the outer fringe marshes, as shown in Table L7.

Table L7: Oil Adherence to Stems of *Spartina alterniflora* after T/V Julie N Spill[187]			
Site	**8 Days Post-Spill**	**42 Days Post-Spill (18 Days Post Major Storm)**	**% Oiling Reduction**
Long Creek (moderately oiled)	1.4 grams/stem	0	100%
Thompson Point (heavily oiled)	4.1 grams/stem	1.8 grams/stem	44%
Thompson Point (heavily oiled)	4.6 grams/stem	2.6 grams/stem	57%

The heavy weathered oil adhered to individual stems of the marsh plant. The oil washed off the vegetation during a major storm that occurred three weeks after the spill, reducing oiling by 100% in a moderately oiled area and by about 50% in more heavily oiled areas.

185 Not detectable.

186 86,436 gallons of No. 2 home heating oil and 93,198 gallons of IFO 380. Most of the impacts were attributed to the IFO 380, which after weathering is similar to No. 6 fuel oil.

187 From Michel, Lehmann, and Henry (1998).

APPENDIX N: Oil-Mineral Aggregation

Oil-mineral aggregation (also referred to as "clay-oil flocculation") is a process that has been heavily studied. OMA formation has been examined as a potential tool for enhancing or even replacing shoreline treatments for certain situations. Some researchers believe that the circumstances for OMA formation may well be more common than not. OMA formation has been observed in actual field situations with breaking wave heights of less than 30 cm **(**Owens et al.*,* 1995; Sergy et al., 1999), which suggests that there is sufficient hydraulic energy in most beach sediments. In general, however, the evidence examined indicates that OMA does not play a significant role in the fate of oil in the early stages after oil deposition on the shoreline, and, as such, is of relatively minimal importance to MMS in its shoreline-oil interaction modeling efforts. In this regard, Reed, Kana, and Gundlach (1988) had concluded that the OMA formation process was not important in the surf zone relative to transport processes.

OMA may, however, play a role in longer-term shoreline processes (Fingas 2001), and would be relevant in some situations in longer-term models. It may be very important in areas where there are significant concentrations of fines, particularly in areas with coarse gravel with open spaces. It may be relevant in longer-term shoreline-oiling modeling. The research papers on this topic are presented here in chronological order.

Reed, Kana, and Gundlach (1988)

Research by Reed, Kana, and Gundlach (1988) that showed that more than 100 mg/L of mineral fines were required for OMA to be a significant process. The researchers concluded that the OMA formation process was not important in the surf zone relative to transport processes.

Owens, Humphrey, and Sergy (1994)

The OMA process had first been observed in field studies. Owens, Humphrey, and Sergy (1994) described natural "self-cleaning" that occurred in the absence of both wave energy and coastal erosion for oil that was stranded within the tidal zone through a process called "clay-oil flocculation", as well as photo-oxidation and biodegradation.

Bragg and Owens (1994)
Owens, Bragg, and Humphrey (1994)

In two of the earliest OMA studies, Bragg and Owens (1994) and Owens, Bragg, and Humphrey (1994) presented their findings on an ongoing study of clay-oil flocculation:

- The process of "clay-oil flocculation"[188] had been observed at a number of spill sites – Exxon Valdez, T/V Arrow, T/B Bouchard (Tampa Bay), T/V Metula, and T/V Nosac Forest, as well as in the Baffin Island Oil Spill experiments.
- Fine mineral sediments required for clay-oil flocculation were present at most sites, but the rate of flocculation and removal of flocculated oil from shorelines was dependent on oil viscosity, as well as hydraulic energy from wave motion.

Owens, Humphrey, and Sergy (1994)

In the Baffin Island Oil Spill (BIOS) project (Owens, Humphrey, and Sergy, 1994), in which there was an intentional nearshore release of 15 cubic meters (3,963 gallons) of aged[189] crude oil, 6.8 cubic meters (1,800 gallons) of the oil stranded on a beach with two bedrock outcrops[190]. Between the two outcrops there is a gravel-cobble ridge that gives way to silt and sand. The upper intertidal zone is a sand-gravel beach. During the first three months after the spill, approximately 70% of the stranded oil was removed,

[188] Earlier studies of OMA often referred to this phenomenon as "clay-oil flocculation".
[189] The Lago Medium crude oil was artificially weathered to 8% weight loss.
[190] Described in Dickins et al. (1987)

despite the fact that there is little wave action in this location. The sediments are poorly sorted and contain large concentrations of fines. The Arctic location of the spill had a significant impact on the removal of the oil since the beach was fully encapsulated in ice by the end of the summer months.

The researchers concluded that OMA occurs because of the electrostatic attraction between oil and mineral particles. The process requires: the presence of oil with polar ends; an oil viscosity that is sufficiently low to allow droplet formation in the presence of the water energy at the site; water with sufficient ionic strength to provide the medium in which the processes can occur; and the presence of very fine mineral particles (less than 10 μm in diameter, or preferably less than 5 μm in diameter).

Location characteristics are key factors in determining the degree to which OMA occurs. In the case of the 1970 T/V Arrow spill of 2.5 million gallons of Bunker C fuel oil at Cerberus Rock, 6.5 km offshore form the coast in northern Chedabucto Bay, Nova Scotia, Canada, oil stranded on a beach during spring tides and formed a surface crust that precluded the flocculation process. In addition, there was an absence of fines.

The researchers concluded that the primary process that limits OMA formation in an Arctic location is the *encounter rate*, since only a fraction of the remaining oil is available to make contact with clays during tidal inundation. The remainder of the oil is protected by overlying oils or by weathered crusts. In addition, in an Artic location flocs cannot be removed from the oil-water interface for 9 – 11 months per year when the beach is encapsulated with ice.

Bragg and Yang (1995)
Bragg and Yang (1995) investigated clay-oil flocculation that occurred at numerous locations in Prince William Sound after the Exxon Valdez spill. In laboratory studies, they determined the hydrodynamic energy required for seawater to remove flocculated oil residues from sediments sampled from shorelines. They found that with OMA formation, substantial amounts of oil could be removed from sediments at wave energies less than those needed to cause sediment movement and from low-energy shorelines where waves were not large enough to move across sediments. The large hydraulic cross section and nearly neutral buoyancy of OMAs removed from the sediment help to explain their efficient dispersal.

Lee, St-Pierre, and Weise (1997)
A number of laboratory studies have been conducted to verify field observations on OMA formation as well as to determine factors that contribute to this phenomenon. Lee, St-Pierre, and Weise (1997) conducted laboratory experiments that validated field observations that oil-mineral fine interaction reduces the adhesion of residual oil to solid surfaces. Residual is effectively dispersed into the aqueous phase as micron-sized oil droplets stabilized by mineral fines. This dispersion prevents recoalescence and promotes micro-aggregate formation. This interaction enhances the rate and extent of oil degradation by effectively increasing the surface area of the oil accessible to dissolved nutrients, oxygen, and oil-degrading microbes.

Lee et al. (1998)
Lee et al. (1998) conducted laboratory experiments to evaluate the ability of crude oils of various viscosities to form aggregates in sea water with common minerals (< 5 μm grain size). The team observed two types of aggregate structures: droplets – composed of one or more spherical oil droplets with mineral grains attached to their surfaces only; and solids – elongated forms composed of mineral particles mixed with oil.

Their experimentation showed that droplet aggregates formed with most oil and minerals given enough turbulence. The predominance of sold aggregates with montmorillonite was attributed to its ion exchange capacity, colloidal behavior, and/or the ability to absorb organic molecules within its expandable layers.

Oil droplets ranged in size from 1 µm to about 30 µm. Higher viscosity oils formed larger droplets, as shown in Figure N1.

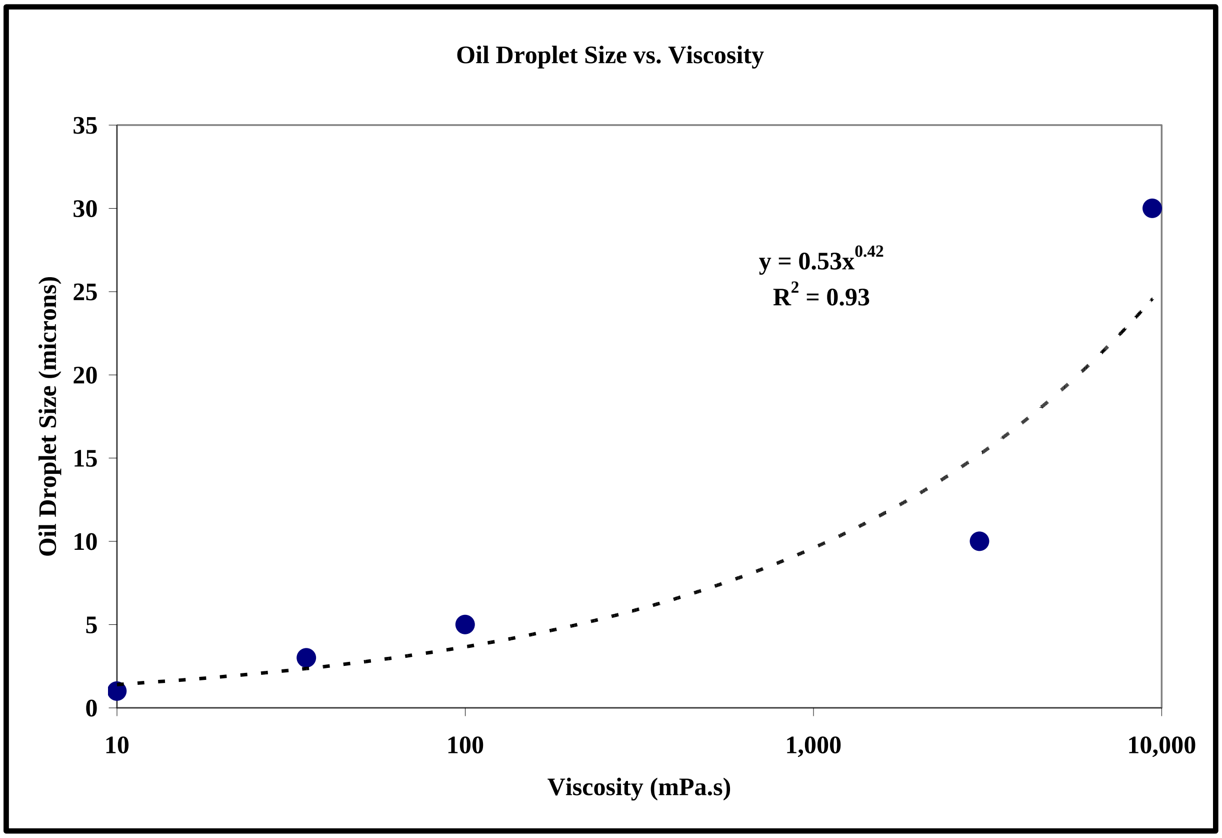

Figure N1: Oil droplet size in oil-mineral aggregates *vs.* oil viscosity for calcite (based on Lee et al. 1998)

Crawford et al. (2002)
Crawford et al. (2002) reviewed oil spill fates models including oil-shoreline interaction models and concluded that they still need to better describe the physicochemical processes involved in the remobilization of oil from a beach face during and after the oiling event. In particular, they conclude, the inclusion of the phenomenon of clay-floc formation on beaches would be useful. The nearly neutrally buoyant clay-oil flocs appear to be mobilized with minimal wave action and could be carried long distances by currents.

Lee and Stoffyn-Egli (2001)
Lee and Stoffyn-Egli (2001) described three types of oil-mineral aggregates (OMA):

- *Droplet aggregates:* oil droplets (usually a few µm in diameter) surrounded by individual or aggregated mineral particles.
- *Solid aggregates:* mixture of oil and minerals blended into microscopic bodies of various shapes
- *Flake aggregates.* Thin sheets reaching several millimeters across in which minerals and oil are arranged in regular patterns.

Based on their review, mineral particles in the silt or clay size range (<63 µm) and the presence of hydraulic shear energy (wave action) are required. Energy from breaking waves facilitates the formation of OMA. Once formed, OMA appear to be very stable structures the buoyancy of which depends on the ratio of oil to mineral in each individual aggregate.

McCourt and Shier (1998, 1999)
In a field study, McCourt and Shier (1998, 1999) observed the interaction between crude oil[191] and suspended particulate matter in an Alaskan river and found that the most important factors affecting the oil-solid interaction process were mixing energy and temperature, and to a lesser degree, oil volume and settling time. The researchers estimated that oil loading for suspended solids was about 0.1 gram of oil per gram of solid. At lower temperatures (2ºC, as opposed to 13 – 15ºC), about twice as much oil could adhere to suspended particulate matter.

Guyomarch, Merlin, and Bernanose (1999)
In a laboratory study, Guyomarch, Merlin, and Bernanose (1999) showed that a mineral load of at least 1.3 to 1.6 grams per liter of oil is needed to remove oil from the water surface due to oil-mineral aggregation. The threshold concentration is dependent on oil and clay types, their relative concentrations, and water salinity.

Stoffyn-Egli et al. (2000)
Stoffyn-Egli et al. (2000) also conducted a field test to verify the formation of oil-mineral aggregates (OMA).

Owens and Lee (2003)
According to Owens and Lee (2003), OMA formation, explains the mechanism by which oiled shorelines are cleaned naturally in the absence of wave action in very sheltered coastal environments.

Owens and Lee (2003)
Owens and Lee (2003) reviewed the interaction of oil and mineral fines on shorelines with regard to the potential efficacy of various shoreline treatment options, including natural cleansing on low energy shorelines, and sediment relocation and mixing.

Khelifa, Hill, and Lee (2003)
Khelifa, Hill, and Lee (2003) developed a stochastic model to predict the formation of oil-mineral aggregates (OMAs) under estuarine conditions. The researchers found that sedimentation was the predominant factor governing the stable formation of OMAs.

The best conditions for OMA formation were obtained when the size ratio (diameter of sediment grain/droplet diameter) varied between 0.1 and 0.4. In this range, the stabilized oil increased rapidly with the concentration ratio (sediment concentration/oil concentration) and reached a value of 70 to 90% when the concentration ratio approached one. At concentration ratios less than 0.03 for light oil and 0.009 for heavy oil, the percentage of stabilized oil was negligible. For concentration ratios large than three for light oil and one for heavy oil, the formation of OMA increased linearly with the concentration of OMA. The oil stabilized in three minutes under these conditions. For smaller concentrations, the formation time increased linearly up to a maximum concentration of OMA only. At this maximum, the formation time increased rapidly to about 24 hours.

Khelifa et al. (2004)
Khelifa et al. (2005)
Khelifa et al. (2004) modeled the effect of sediment size on oil-mineral aggregate (OMA) formation. The model called MCOMA2 was upgraded from a previous version to include floc breakage and aggregation by different settling. The study showed that there is a strong effect of sediment size on OMA formation. Overall, variations of the concentration of stabilized oil with sediment size showed a maximum when the

[191] Alaska North Slope crude oil.

ratio between the sediments and droplet sizes varied from 0.1 to 0.4. The model was further described in Khelifa et al. (2005).

Cloutier, Gharbi, and Boulé (2005)
The presence of sea ice appears to create an exception to the relatively low amount of energy required for OMA formation. Cloutier, Gharbi, and Boulé (2005) reported on the results of studies conducted on the formation of OMA in ice-infested waters. The researchers found that sea ice acts as a filter for surface ocean waves. Short waves are attenuated or stretched out by the influence of sea ice floating on the water surface. Only longer waves penetrate to the interior areas of the ice field. Under these conditions, natural dispersion is minimal and the energy necessary for oil-mineral aggregate formation would be present only under storm conditions.

Sterling et al. (2004) and Sterling et al. (2005)
One research team has developed models that describe OMA formation. Sterling et al. (2004) and Sterling et al. (2005) described a modeling approach that simulates changes in particle size distribution and density due to aggregation by extending the Smoluchowski aggregation kinetic model (Smoluchowski 1917) below to particles of different density:

$$\theta_k = \frac{dn_k}{dt} = \frac{1}{2}\sum_{i+j=k} \alpha\beta\ i,j\ n_i n_j - n_k \sum_{i=1}^{\infty} \alpha\beta\ i,j\ n_i$$

Where:

α = collision efficiency

$\beta\ i,j$ = collision frequency between particles of size *i* and *j*

n_i = particle concentrations for particles of size *i*

n_j = particle concentrations for particles of size *j*

Sterling et al. (2004) and Sterling et al. (2005) used a parameter estimation algorithm to estimate homogeneous collision efficiencies (α_{HOMO}) for single-particle type systems and heterogeneous collision efficiencies (α_{HET}) for two-particle systems. Homogeneous collision values were greater for clay (0.7) and for crude oil (0.3) than for silica (0.01). Clay and crude oil were classified as cohesive particles and silica was classified as non-cohesive. Heterogeneous collision efficiencies were similar for oil-clay (0.4) and oil-silica (0.3) systems. Thus, crude oil increases the aggregation of non-cohesive particles.

Data were used to estimate first-order flocculation rates, *K*' for oil, clay, and silica, and second-order rates, *K*" for oil and clay in oil-clay systems. For oil or clay systems, clay aggregation and droplet coalescence can occur at the same relative time scales of clay settling and oil resurfacing. For mixed oil-clay systems, the relative time scales of clay settling and clay-oil aggregation were also within an order of magnitude. According to these researchers, oil-clay aggregation (or OMA formation) should be considered when modeling crude oil transport in nearshore waters.

Khelifa et al. (2005)
Khelifa et al. (2005) conducted a laboratory study to validate the formation of oil-mineral aggregates (OMA) in cold brackish[192] and sea waters[193]. Chalk was found to form OMA better than bentonite. The *in-situ* sediment concentration that maximized oil dispersion was about 300 to 400 mg/l. Stabilization of about a 90% of Heidrun crude oil[194] requires 300 mg/l of bentonite and 200 mg/l of chalk.

[192] Salinity of 18 ppt.
[193] Salinity of 30 ppt.
[194] Group 3 Norwegian crude with APIº 28.6, pour point -48ºC.

APPENDIX O: Shoreline Oiling Modeling

Modeling of oil-shoreline interactions has been handled in a number of ways, including:

- Assuming all oil reaching a shoreline accumulates on that shore segment;
- Assuming all oil reaching a shoreline strands on the shore segment if the tide is receding;
- Using empirical data, relating the maximum amount of oil retained on shore to shore type and oil viscosity, to quantify a oil-holding capacity (*e.g*., Gundlach, 1987); and
- Utilizing a complex shoreline interaction model based on shore geography and hydraulic interactions (*i.e*., the COZOIL model developed by Applied Science Associates, Inc. for MMS: Reed *et al*., 1986, 1988, 1989; Gundlach, 1987; Coastal Science & Engineering, 1986, 1988; Reed and Gundlach, 1989a,b; and the surf zone oil transport model by Cheng *et al*., 2000).
- Using a statistical approach, i.e., a simple regression model to predict the lengths of coastline that would be impacted by an oil slick based on observational data from actual oil spills.

The simplest modeling approach is to accumulate oil on shore when floating oil reaches a shore segment, regardless of the oil type, weathering characteristics, shore type, amount of oil already on the shore, current and turbulence conditions, and so forth. Many models use this simplification, as does the current version of OSRA. However, it is desirable to incorporate some of the processes and relationships described in the preceding sections into the model such that not all intersecting oil would necessarily be retained on a shore segment.

The next simplest approach would be to only strand the oil as the tide recedes. This algorithm requires tidal constituents to be modeled, along with water levels on shore such that a falling tide may be identified. This amount of detail in tidal dynamics may not be practical for large scale models and spills originating offshore. Moreover, tidal currents are typically not important in offshore areas. While the stranding of oil on falling tides increases realism slightly, it really only delays the timing of oil stranding on a shore segment if it arrives on an in-coming tide, unless the wind changes before the next high tide. Thus, this approach would provide little advantage over the simplest approach of accumulating all intersecting oil on shore.

Accumulation of oil on shore up to an empirically-derived oil-holding capacity is used by most oil spill models that include some kind of shore interaction algorithm (**Gundlach and Reed, 1986; Gundlach, 1987; French et al., 1996; Reed et al., 1999, 2000; Cheng et al., 2000; French McCay, 2004**.) The advantage of this approach is that it is simple to implement. However, considerable data are required to derive appropriate holding capacities.

The coastal zone oil spill model, COZOIL (**Reed et al., 1986, 1988, 1989; Reed and Gundlach, 1989a,b; Howlett, 1998**) includes a dynamic representation of processes controlling oil distribution in the coastal zone. In applying COZOIL, the foreshore is the shoreline between mean low and high water (tidal range) and the backshore is the shoreline above mean high water. When oil comes ashore, if the tide is lower than the high tide level and the tide is receding, the oil is deposited if the foreshore has not already reached its oil-holding capacity for oil. If the water level is at or exceeds the mean high tide level, oil is deposited on the backshore by the waves (in the splash zone). The maximum holding thickness is a function of oil viscosity and shore type. However, data to quantify these holding thicknesses and the width over which they should be applied are limited and have not been reviewed or updated in two decades. Additionally, the COZOIL model includes other algorithms that are difficult to apply because the needed input data have not been compiled, making it impractical to include in such models as MMS's OSRA model. For example, if oil is to be left ashore only on a receding tide, tidal hydrodynamics and modeling of wet-dry cycles in the intertidal zone must be included. This detail may not be practical for applications involving spills from the offshore areas of the Gulf of Mexico.

Finally, some authors have attempted to develop statistical models related oil volume in nearshore waters to amount of oil retained on shorelines (**Ford, 1985; Seip et al. 1986**). While correlations exist, this type of statistical approach does not take into account know relationships to shore type and oil viscosity. Thus, this approach has not been pursued in other modeling efforts.

Gundlach (1987[195]), Gundlach and Reed (1986), and Reed et al. *(*1986) developed a computer-based model (SMEAR) representing oil-shoreline interactions. Coastlines were identified as one of seven types based on ESI categories:

- Exposed rocky shores
- Sand beaches
- Gravel beaches
- Sheltered rocky shores
- Peat scarps
- Tidal flats
- Marshes/wetlands

Oil intersection a specific shoreline segment was determined by the transport model, which summed motions induced by wind and currents. Oil intersecting the shore was retained on-shore up to an empirically-derived oil-holding capacity. The oil-holding capacity data were derived from observations on moderately to heavily oiled beaches following the Amoco Cadiz, Urquiola, and Ixtoc I spills (Gundlach, 1987, reviewed below)

Once onshore, oil persistence was determined by tidal level and a removal coefficient for each shoreline type. Oil removal coefficients (K_f) were calculated from empirical data using the equation:

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

Where M_i = mass of oil on beach segment *i*
M_{io} = mass of oil originally deposited on the beach
K_f = removal rate constant based on exponential decay
t = time in days since original deposition

Rate constants and removal rates are shown in Table O1. These data and analyses formed the basis for the development of the COZOIL model (see below).

Table O1: Oil Removal Rates as Function of Shoreline Type and Wave Energy[196]

Shoreline Type	Wave Activity	Beach Location	Percent Removed		K_f Value
			1 day	5 days	
Exposed rocky shore	High (>1 m)		60 – 63	99 – 99.3	0.90 – 0.99
Sheltered rocky shore	Low (<1 m)		5 – 10	5 – 22	0.01 – 0.05
Eroding peat scarps	Low (<1 m)		10 – 18	49 – 63	0.10 – 0.20
	High (>1 m)		50 – 55	97 – 98	0.70 – 0.80
Sand beach	Low (<1 m)	Beach face	18 – 26	63 – 78	0.20 – 0.30
		Backshore	10 – 18	40 – 53	0.10 – 0.15
	High (>1 m)		40 – 45	92 – 95	0.50 – 0.60

[195] This project was sponsored by Minerals Management Service in Anchorage, Alaska.
[196] Gundlach and Reed (1986)

Table O1: Oil Removal Rates as Function of Shoreline Type and Wave Energy[196]					
Shoreline Type	Wave Activity	Beach Location	Percent Removed		K_f Value
			1 day	5 days	
Gravel beach	Low (<1 m)	Beach face	10 – 18	40 – 63	0.10 – 0.20
		Backshore	5 – 10	22 – 40	0.05 – 0.10
	High (>1 m)		33 – 40	86 – 92	0.40 – 0.50
Tidal flat			60 – 63	99 – 99.3	0.90 – 0.99
Marsh			0.1 – 1.0	0.5 – 5	0.001 – 0.01

Gundlach (1987) developed oil-holding capacity and oil removal coefficients for different shoreline types based on empirical data derived from observations on moderately to heavily oiled beaches following the Amoco Cadiz, Urquiola, and Ixtoc I spills. Oil thicknesses by shoreline type and oil type are shown in Table O2.

Table O2: Oil Thickness by Shoreline Type and Oil Type[197]				
Shoreline Type	Oil Type			
	Medium-viscosity		Light Oil[198]	Heavy Oil
	Thickness (mm)	Standard Deviation (mm)	Thickness (mm)	Thickness (mm)
Rocky cliffs (exposed)	2	NA	0.5	2
Sand beaches	17	19	4	25
Mixed sand and gravel	9	11	2	15
Tidal flats	6	6	3	10
Rocky shore (sheltered)	5	NA	1	10
Marshes	30	14	6	40
Eroding peat scarps	4	NA	1	10

The average volume-percent of oil in sand is 9.8%. For gravel beaches, the average is 8.3%. Calculated holding capacities for different shoreline types is shown in Table 03. Sand beaches 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 in the upper swash zone. Gravel beaches absorb 0.68 m^3/m. Fringing marshes absorb about 0.30 m^3/m. Rocky shores with little oil penetration and steep slopes contain very little oil (0.01 m^3/m).

Table O3: Calculated Maximum Oil-holding capacity by Shoreline Type[199]							
Location	Measurement	Shoreline Type					
		Rocky	Sandy Beach		Gravel	Tidal Flat	Marsh
			Beach	Backshore			
Surface Oil	Beach slope (deg.)	80	2.9	1.3	5.1	0	0
	Tidal range + swash (vertical m)	5.0	4.5	0.5	5.0	5.0	5.0
	Surface distance (m)	5	90	22	56	20	10
	Average oil thickness (mm)	2	18	18	9	6	30
	Oil thickness +1 SD (mm)	NA	34	34	20	0	16
	Oil thickness -1 SD (mm)	NA	2	2	0	12	44
	Total holding average (m^3/m)	0.1	1.62	0.40	0.50	0.12	0.30
	Total holding +1 SD (m^3/m)	NA	3.06	0.75	1.12	0	0.16
	Total holding -1 SD (m^3/m)	NA	1.80	0.04	0	0.24	0.44
Subsurface Oil	Beach slope (deg)	NA	2.9	1.3	5.1	NA	NA
	Swash range (vertical m)	NA	0.5	0.5	1.0	NA	NA
	Swash zone distance (m)	NA	10	22	11	NA	NA

[197] From Gundlach (1987).
[198] Oil thickness was not measured in this case but rather inferred.
[199] Based on a 4-meter tide range and 1-meter vertical swash. From Gundlach (1987).

Table O3: Calculated Maximum Oil-holding capacity by Shoreline Type[199]							
Location	**Measurement**	**Shoreline Type**					
		Rocky	**Sandy Beach**		**Gravel**	**Tidal**	**Marsh**
	Average oil penetration (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 holding average (m^3/m)	NA	0.04	0.10	0.18	NA	NA
	Total holding +1 SD (m^3/m)	NA	0.09	0.19	0.35	NA	NA
	Total holding -1 SD (m^3/m)	NA	0	0	0	NA	NA
Grand Totals	**Total holding average (m^3/m)**	**0.01**	**2.16**		**0.68**	**0.12**	**0.30**
	Total holding +1 SD (m^3/m)	**0**	**4.09**		**1.47**	**0.24**	**0.44**
	Total holding -1 SD (m^3/m)	**NA**	**1.84**		**0**	**0**	**0.16**

Reed *et al*. (1986, 1988, 1989) and **Reed and Gundlach (1989a,b)** described further development of what was originally called the SMEAR model as the Coastal Zone Oil Spill Model (COZOIL). This complex model system developed for Minerals Management Service (MMS) was designed to simulate oil spill fates both before and after a coastal contact, and was used to predict the behavior and fate of oil along an arbitrarily varying coastline. The COZOIL mass-transfer pathways are shown in Figure O1.

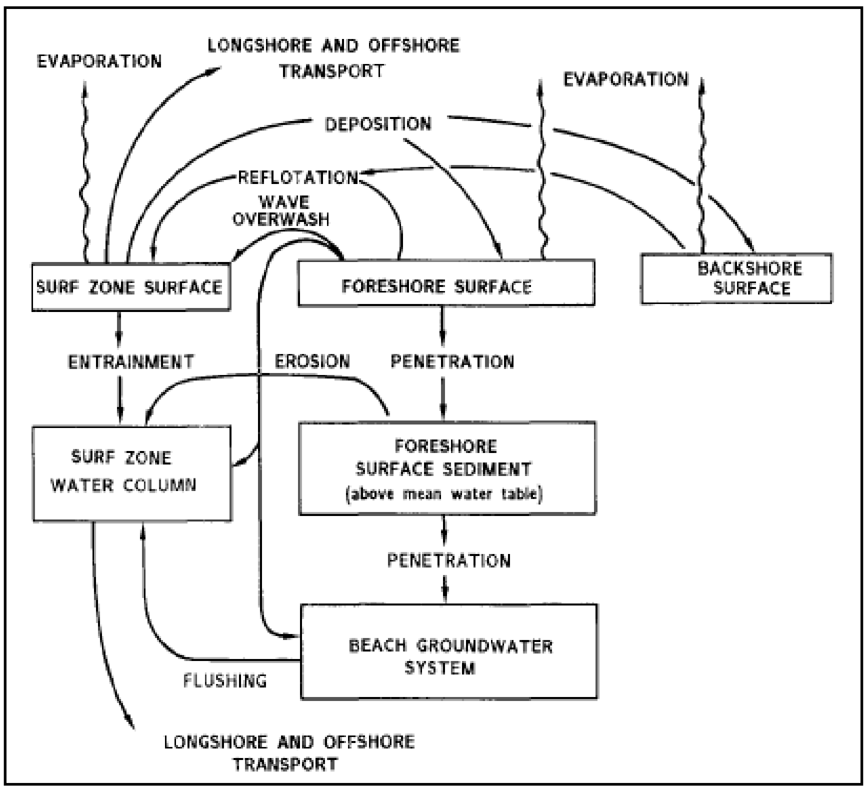

Figure O1: COZOIL Mass-Transfer Pathways in the Coastal Zone (From Reed, Gundlach, and Kana, 1989)

Multiple discrete batches of oil (spillets) used to represent the surface slick (as in typical Lagrangian models used to model oil transport and fate) were treated as circular while offshore but become elliptical upon contact with the shoreline. Onshore-offshore foreshortening was modeled employing a balance between wind stress and gravitational spreading forces, which resulted in alongshore spreading of the spillet. Evaporation was calculated from each spillet in all locations it might occur. Offshore, entrained oil was represented by discrete particles which were advected by the local currents specified to the model.

Inside the surf zone, entrained oil was represented as a continuous distribution, discretized within individual alongshore grid cells. Transport in the surf zone was governed by a radiation stress formulation. Incorporation of water into surface oil (emulsification) was simulated offshore and de-emulsification (de-watering) was allowed to occur for oil on the foreshore or backshore. Oil coming ashore could be deposited on the foreshore or the backshore, or carried into coastal indentations (lagoons, ponds, or fjords).

Each of the shore types in the COZOIL model were characterized by a unique set of parameters, including grain size, porosity, and a maximum oil thickness which the foreshore could retain. Oil on the foreshore penetrated into the underlying sediments at a rate dependent on sediment grain size and oil viscosity. Oil could also be carried into the beach groundwater system by wave overwash. Reflotation of surface oil occured during rising tides.

The eight types of shorelines (reaches) defined in the COZOIL model were:

- Smooth rocky shore or seawall
- Cobble beach
- Eroding peat scarps
- Sand beach
- Gravel beach
- Tidal (mud) flat
- Marsh
- Coastal pond, lagoon, or fjord

For each of the shore types, there are eight parameters required by the model:

- Reach length (m)
- Backshore width (m)
- Foreshore width (m)
- Offshore distance (m)
- Backshore slope (rise/run)
- Foreshore slope (rise/run)
- Offshore depth (m)
- Reach orientation

For all reach types, except the coastal pond, lagoon, or fjord, the parameters are shown in Figure O2.

For a coastal pond, lagoon, or fjord, COZOIL required the following data:

- Pond surface area (m^2)
- Breachway (entrance) width (m)
- Breachway (entrance) depth (m)
- Tidal range inside the pond (m)
- Fractional flushing rate
- Freshwater inflow rate to pond (m^3/sec)

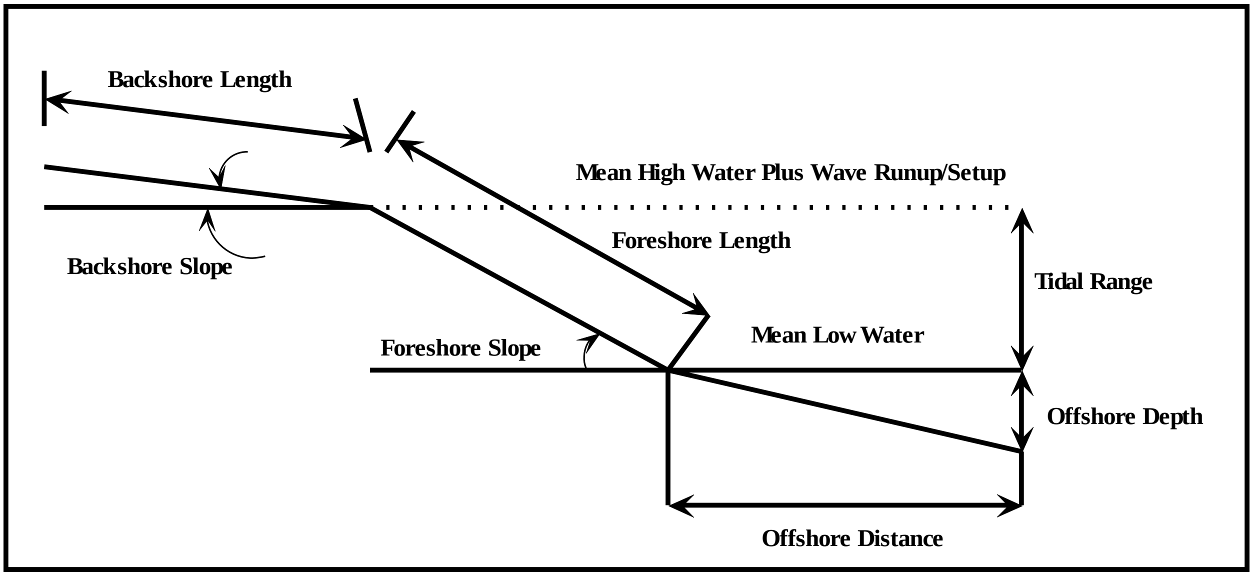

Figure O2: Definition of input parameters for COZOIL for coastal reaches (except coastal ponds) (From Reed and Gundlach, 1989)

In addition to requiring data defining shoreline characteristics, COZOIL required input of wind, tidal and other current data. A wind-driven current data set was created by the model from the wind record, if the user did not specify an existing data set. Also, the model either computed wave characteristics from the wind record (using the shallow water, wave forecasting equations recommended by the US Army Corps of Engineers Shore Protection Manual [CERC, 1984]), or accessed a wave time series from an external file supplied by the user.

The following describes the COZOIL model in some detail. Additional data and derivation may be found in the above-cited references (specifically Reed *et al*., 1988, 1989).

Oil was deposited on the foreshore if the water level did not exceed the foreshore height associated with that reach. The model checked to determine that an empirical "maximum holding thickness" was exceeded. This limited the amount of oil that could be deposited, varying with beach type. When the tide was falling, the ratio of newly exposed beach face to the onshore-offshore radius of the slick determined the fraction of the slick deposited. Oil deposited on a previously clean shore carried with it all the characteristics (viscosity, density) of the parent slick. As additional oil came ashore, the oil on the foreshore took on the weighted average of the oil characteristics.

If the water height exceeds the foreshore height, oil was deposited on the backshore. The fraction of the slick deposited was determined by the ratio of the newly exposed backshore to the slick width.

Oil was deposited on the beach in one of two ways – by direct penetration or by transport in wave overwash. The first process was simulated using standard fluid-sediment flow algorithms. The second process was assumed to occur with waves breaking and overwashing oil on the foreshore from dissolved and particulate ("water-accommodated") oil. The "water-accommodated" oil was assumed to travel into the sediments with, and at the same rate as, the water itself. Once in the groundwater system, oil transport was assumed to be governed by the flushing of the groundwater and equilibrium partitioning between the absorbed and water-accommodated phases. Figure O3 graphically summarizes these processes.

Oil deposition into underlying sediments was approximated by Darcy's law:

$$V = kg\rho\ (dh/dL)/\mu$$

Where: V = flow velocity (m/sec)
k = intrinsic permeability of sediment (m^2)
g = gravitational acceleration (m/sec^2)
ρ = fluid density (kg/m^3)
μ = dynamic velocity ($N\text{-}sec/m^2$)
dh/dL = pressure head gradient (m/m)

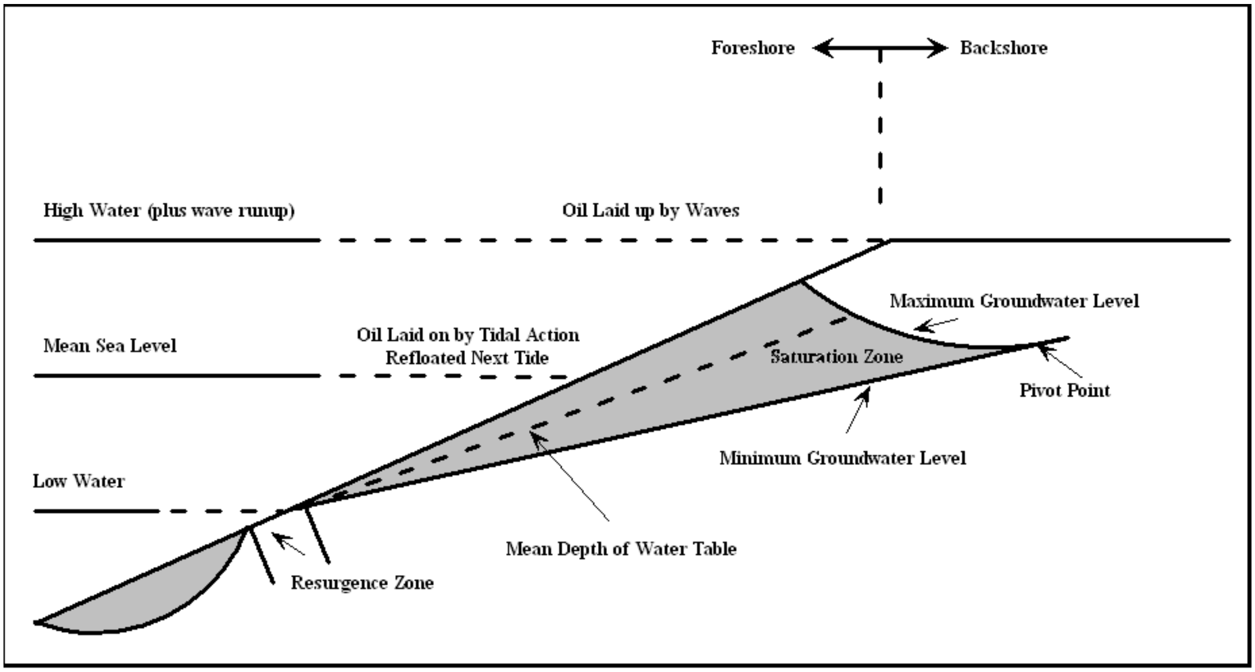

Figure O3: Schematic of beach groundwater system (From Reed and Gundlach, 1989)

Intrinsic permeability was calculated from Krumbein and Munk (1943):

$$k = 7.6x10^{-10}(MG)^{2}e^{-1.31\phi}$$

Where: MG = mean grain size (mm)
Φ = inclusive graphic standard deviation (Φ units)

Depth of penetration during time step Δt was then $V\Delta t$. The mass flux Q was:

$$Q = A\ \rho\ V\ \Delta t$$

Where: A = the surface area covered with oil. The maximum amount of oil that can enter the surface sediments is controlled by the net sediment porosity, corrected for any oil that had previously entered and remains in the foreshore sediment. Figure O4 demonstrates how porosity, specific yield, and specific retention varies with grain size (from Todd, 1959, as presented in **Reed, Gundlach, and Kana, 1989**).

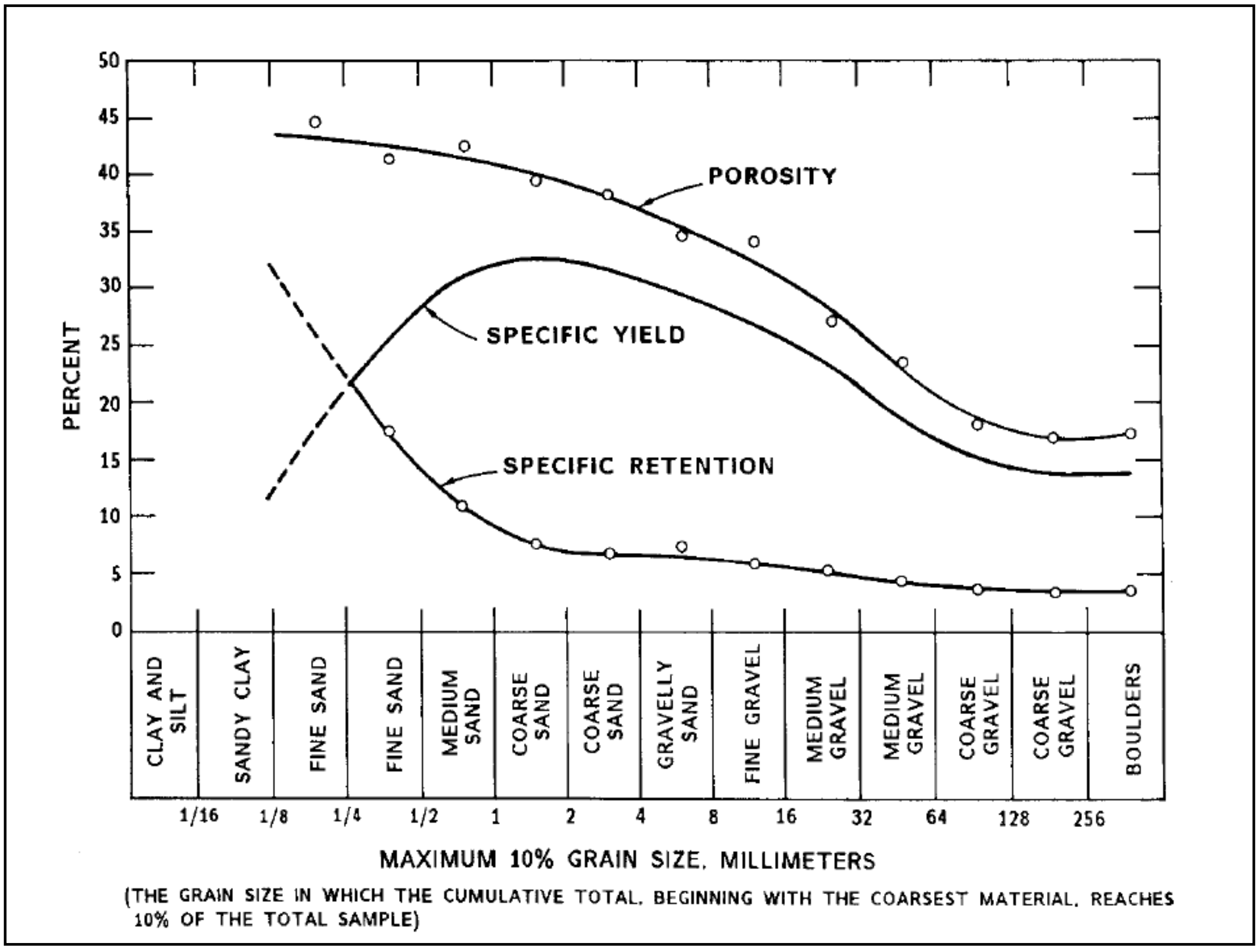

Figure O4: Porosity, specific yield, and specific retention variations for various grain sizes (From Todd, 1959, as presented in Reed, Gundlach, and Kana, 1989).

Observations (e.g., **Owens *et al.*, 1985, 1987**) indicate that wave exposure is an important parameter for the rate of oil removal from the beach surface. Thus, an algorithm was developed for the rate at which oil was removed from the parent slick on the foreshore and carried into the underlying sediments or returned to the active surf zone by wave action.

For estimating the rate of removal of oil from the beach surface by wave exposure, COZOIL incorporates the following empirical relationship (based on Thibodeaux, 1977; 1979) for mass transfer for relatively insoluble substances.

Mass removal rate is $dm/dt = \rho b A$.

Where: dm/dt = the rate of change in oil mass with time

ρ = fluid density (kg/m^3)

A = surface area covered by oil

b = mass transfer coefficient

The mass transfer coefficient (b) for this process was approximated by:

$$b = 0.036(\rho V_b L/\mu)^{0.8} (\mu/\rho D_v)^{0.33}\, D_v/L$$

Where: V_b = breaking wave velocity (m/sec)
L = diameter of exposed area (m)
ρ = oil density (kg/m^3)
μ = viscosity (cP)
D_v = turbulent diffusity (m^2/sec)

This expression reflects the rate at which oil is removed from the parent slick on the foreshore and carried into the underlying sediments or returned to the active surf zone by wave action. It was developed for river bottoms that have relatively low Reynolds number[200] flows. Since the Reynolds number is considerably higher in surf zones, in COZOIL, this equation is reduced by a factor of 0.01 to better match observed rates of oil removal.

The mass of oil removed from the foreshore surface by wave overwash was not all carried into the groundwater. Some fraction of this oil was carried back into the surf zone with the retreating wave. The oil in the surf zone was then further partitioned between the water column and the water surface, depending on the size range of the oil particles relative to the surf zone turbulence. The model did not have empirical values for this partitioning and used default values that could be changed by the user if desired.

Oil in the beach groundwater system consists of three phases:

- *Pendicular phase:* Oil is the primary fluid within sediment pores and may preclude penetration by water.
- *Droplets:* Oil droplets may adhere to sediment particles or become trapped within sediment pores.
- *Dissolved phase:* Oil transport is governed by the movement of the groundwater itself.

Oil that penetrated the surface sediment, as in the mass transfer equation above, could be removed to the surf zone if the beach was subject to erosion by waves. The model assumed that the presence of oil would not appreciably alter erodibility of the beach sediments. Based on studies by Sunamura and Horikawa (1974), Reed and Gundlach (1989) applied a dimensionless erosion/accretion parameter, G_o, in COZOIL:

$$G_o = (H_o/L_o)\ (\tan\beta)^{0.27}/(D_{50}/L)^{0.67}$$

Where: H_o = deepwater wave height (m)
L_o = deepwater wave length (m)
β = offshore bottom slope
D_{50} = size of 50^{th}%ile of sediment sample (m)

Beach erosion was assumed to occur if $G_o > 18$, accretion for $G_o < 4$, and equilibrium for $G_o = 4 – 18$.

COZOIL incorporated a relatively simple representation of oil in the groundwater system that reproduced observed behavior of oil. The oil was partitioned between two phases – one that was trapped by sediments (the “absorbed” phase) and one that was transported with groundwater (the “water-accommodated” phase). The modelers assumed the partitioning was in equilibrium (based on Thibodeaux, 1977), such that:

$$C_a/C_{wa} = K_p C_{ss} F_c$$

[200] The Reynolds number is a non-dimensional parameter that compares the inertia to viscous forces. If the Reynolds number is low, then viscosity plays an important part in the simulations.

Where: C_a = concentration of oil in groundwater that is absorbed
C_{wa} = concentration of oil in groundwater that is water accommodated
K_p = partition coefficient
C_{ss} = sediment concentration
F_c = fraction of sediment composed of organic matter

Since $C_a + C_{wa} = C_T$ (the total concentration), the equation could be rewritten as:

$$C_{wa} = C_T/(1 + K_p C_{ss} F_c)$$

The mass of oil removed per tidal cycle was then:

$$F_{wa} = S_y \bullet P \bullet C_{wa}$$

Where: S_y = specific yield of sediment
P = porosity of the sediment

Evaporation on the foreshore was assumed to follow the same rates as on the water surface[201]. Oil on the foreshore surface or on the backshore that had not penetrated the sediment was refloated on the rising tide. Oil that refloated was combined with existing oil spillets[202], or, if there were no spillets present, new spillets were formed.

Emulsification could occur before the oil encounters the beach surface. Water was released simulating the process of de-emulsification with the rate of release depending on the stability of the mousse. Many crude oils have been shown to form relatively stable mousses (Berridge et al. 1986a, b). For COZOIL, the researchers assumed a first-order process for the loss of water from stranded mousse:

$$Y = y_o e^{-bt}$$

Where: y = fraction of water in oil at time t
y_o = initial fraction of water in oil
b = constant

Cheng et al. (2000) developed a model of oil transport in the surf zone based on mass conservation of oil in the surf zone. The model includes analytical solutions that describe the longshore distribution of oil deposition, as well as the length of shoreline contaminated by oil slicks transported in the nearshore environment. The solutions are related to the characteristic longshore and onshore velocities, and oil-holding capacity of the shoreline. The analysis shows that the distribution of oil deposition varies due to re-entrainment.

[201] This assumption was described as an approximation procedure that served to conserve computer storage and processing time, while retaining a realistic evaporation rate governed by the type of oil spilled.
[202] The spilled substance (oil) is represented as sublots, called spillets, of the entire mass (or volume) spilled. In modeling parlance, these are termed Lagrangian particles. The spillet is transported from the release site in three dimensions over time. For each spillet, the model tracks as a function of time: mass by component category, density, volume, viscosity, water content, location of the spillet center (latitude, longitude, and depth) and radius (of a cylindrical representation on the water surface or a Gaussian cloud in the water, see below). The model simulates weathering as a change in these characteristics. Spillets may split and combine, as components have differing pathways and fates.

Mass Conservation in the Surf Zone

A two-dimensional equation for mass transport in the surf zone is:

$$\delta_i^{'} = \max \ \ \delta_0, F_i Q / \ \ L_i W_i$$

$$\delta_i = \min \ \ \delta_i^{'}, \delta_{s,i}$$

$$\delta = \frac{\sum_i \delta_i L_i}{\sum_i L}$$

$$S_1 = Q_0 / \delta$$

$$Q_{ss} \ \ t \ \ = \sum Q_{0,i} e^{-k_i t}$$

$$q_{u,i} \ \ t \ \ = Q_{0,i} k_i e^{-kt}$$

$$q_{N,i} \ \ t \ \ = q_{u,i} \ \ t \ \ \ 1 - e^{-k_w \ T - t}$$

$$Q_{w,i} = \int_0^T q_{N,i} \ \ t \ \ dt = Q_{0,i} \left[1 - \ \ e^{-k_i T} - k_i e^{-k_w T} \ \ / \ \ k_w - k_i \ \ \right]$$

$$Q_{w,i} = Q_{0,i} \left[1 - e^{-k_i T} - T k_i e^{-k_w T} \right]$$

$$Q_w = \sum Q_{w,i}$$

$$Q_s \ \ T \ \ = Q_0 - Q_{ss} \ \ T \ \ - Q_w \ \ T$$

$$\delta_i^{'} = \max \ \ \delta_0, F_i Q / \ \ L_i W_i$$

$$\delta_i = \min \ \ \delta_i^{'}, \delta_{s,i}$$

$$\delta = \frac{\sum_i \delta_i L_i}{\sum_i L}$$

$$S_1 = Q_0 / \delta$$

$$Q_{ss} \ \ t \ \ = \sum Q_{0,i} e^{-k_i t}$$

$$q_{u,i} \ \ t \ \ = Q_{0,i} k_i e^{-kt}$$

$$q_{N,i} \ \ t \ \ = q_{u,i} \ \ t \ \ \ 1 - e^{-k_w \ T - t}$$

$$Q_{w,i} = \int_0^T q_{N,i} \ \ t \ \ dt = Q_{0,i} \left[1 - \ \ e^{-k_i T} - k_i e^{-k_w T} \ \ / \ \ k_w - k_i \ \ \right]$$

$$Q_{w,i} = Q_{0,i} \left[1 - e^{-k_i T} - T k_i e^{-k_w T} \right]$$

$$Q_w = \sum Q_{w,i}$$

$$Q_s \ \ T \ \ = Q_0 - Q_{ss} \ \ T \ \ - Q_w \ \ T$$

$$\frac{\partial m}{\partial t}+\frac{\partial um}{\partial x}+\frac{\partial vm}{\partial y}=0$$

Where: m = mass of oil per unit area
t = time
x = coordinate in offshore direction
y = coordinate in longshore direction
u = shoreward surface velocity
v = longshore current velocity

This equation can then be integrated with respect to x, from x = 0 to $x = x_b$, where x_b = width of the shore zone, so that:

$$x_b\frac{\partial m}{\partial t}+q_d-q_r+x_b\bar{v}\frac{\partial m}{\partial y}=0$$

Where: q_d = rate of oil deposited on shore per unit length
q_r = oil re-entrainment rate per unit length
$\bar{v}$ = average longshore velocity in surf zone.

For floating oil spillets, only the surface velocity is of significance. Therefore, the deposition rate on the shoreline can be expressed as:

$$q_d=u_s m$$

Where: u_s = characteristic surface velocity toward shoreline

This formula is relevant only if there is a large oil-holding capacity for a particular shoreline. Where oil-holding is limited, the equation must be modified to include the oil-holding capacity's effect on oil transport:

$$x_b\frac{\partial m}{\partial t}+u_{s1}m+x_b\bar{v}\frac{\partial m}{\partial y}=0$$

$$u_{s1}=\left\{\frac{0, M_*=M_a}{u_s, M_*>M_a}\right\}$$

Where: u_{s1} = characteristic onshore velocity
M_* =oil-holding capacity in mass per unit length
M_a = oil mass accumulated on shore segment from first contact to a certain time step

Once the oil-holding capacity of the shoreline is reached, the oil slicks will remain in the water and be subjected to longshore advection.

Oil-holding capacity of Shorelines (M_*)

The oil-holding capacity of a shoreline is dependent on the oil and beach characteristics and consists of two components – maximum surface loading and maximum subsurface loading (Gundlach 1987; Reed et al., 1989). The oil-holding capacity was expressed by Cheng et al. (2000) as:

$$M_* = \rho_o (L_t T_m + C_v D_p L_s)$$

Where: T_m = maximum oil thickness
L_t = beach width including intertidal and swash zone[203]
D_p = depth of penetration
C_v = oil content of sediment
L_s = width of swash zone
ρ = density of oil

The parameters of oil thickness (T_m), sediment oil content (C_v), and depth of penetration (D_p) are derived from empirical values from Gundlach (1987) by Cheng et al. (2000), as in Table O4. Note that, according to the above equation, Cheng et al. (2000) only considered subsurface oil in the swash zone, and did not include subsurface oil in the intertidal zone proper. However, L_s could be interpreted as equal to L_t to include subsurface oil in the intertidal zone.

Table O4: Oil-Holding Capacities for Different Shoreline Types[204]

Shoreline Type	Maximum Surface Oil Thickness (mm)			Subsurface Oil-holding capacity	
	Light viscosity[205]	Medium viscosity[206]	High viscosity[207]	Depth of oil penetration (mm)	Oil content by volume (%)
Rocky cliff	0.5	2	2	0	0
Sandy beach	4	17	25	50	9.8
Sand/gravel	2	9	15	180	8.3
Tidal flat	3	6	10	0	0
Rocky shore	1	5	10	0	0
Marsh	6	30	40	-	-
Eroding peat scarf	1	4	10	0	0

Longshore Distribution of Oil Deposition

Longshore distribution of oil deposition is defined as:

$$\frac{S_{cu}}{M_o} = \frac{y}{L} - \frac{1}{q}\left[1 - \exp\left(-q\frac{y}{L}\right)\right] + \phi\left(\frac{y-L}{L}\right)\left\{1 - \frac{y}{L} + \frac{1}{q}\left[1 - \exp\left(-q\frac{y-L}{L}\right)\right]\right\}$$

$$q = u_s L \ / \ \bar{v} x_b$$

[203] The authors described this as "tide range" but meant "beach width".
[204]From Gundlach (1987) as summarized in Cheng et al. (2000)
[205] Light viscosity = < 30 cS
[206] Medium viscosity = 30 – 2,000 cS
[207] High viscosity = > 2,000 cS

The length of the shoreline contaminated by oil varies with the relative density of the onshore current, as in Figure O5.

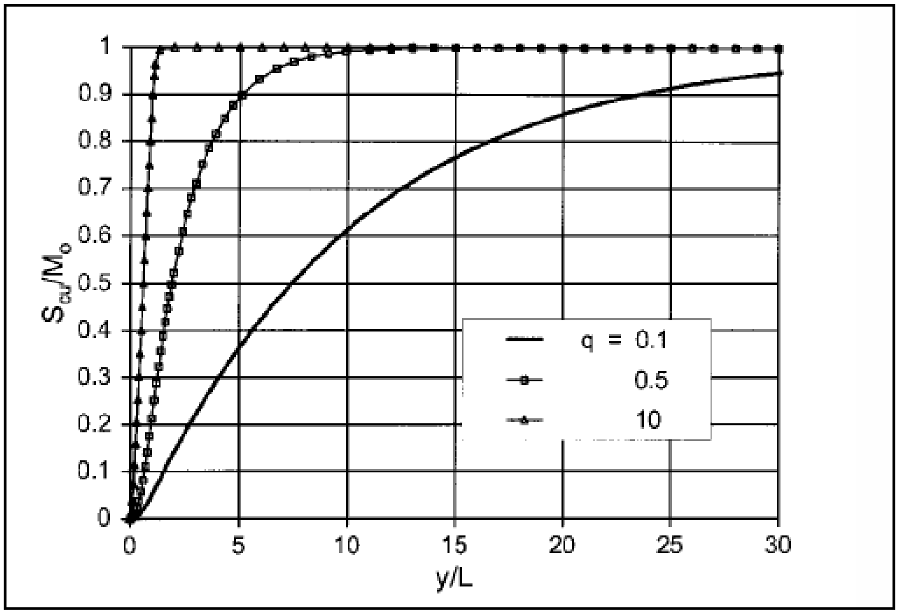

Figure O5: Relationship of Accumulated Oil Deposition with Contaminated Shoreline Length (From Cheng et al. 2000)

This equation is only applicable for locations in which re-entrainment is low. When there is re-entrainment, the oil deposition profile changes and the length of contaminated shoreline increases.

Re-entrainment is related to the amount of deposited oil, wave energy, and tidal condition. Re-entrainment increases with increasing oil deposition and wave energy and during the tidal flood period. Re-entrainment rates should also depend on shoreline type. Salt marshes and mangroves would have lower oil re-entrainment than exposed rocky shores, for example. According to Cheng et al. (2000), other than the empirical decay model of Gundlach (1987), the physics of oil re-entrainment is "glaringly missing from the literature".

Cheng et al (2000) developed the following formula for oil re-entrainment. The amount of oil re-entrainment is assumed to be proportional to the amount of oil originally deposited on a shoreline segment. A coefficient of proportionality, C_r, is defined as the ratio of oil re-entrained to that originally deposited. The re-entrainment coefficient varies depending on the shoreline type and wave and tidal conditions.

$$1 - C_r \quad u_s \int_0^{\infty} m \cdot dt + x_b \bar{v} \frac{\partial}{\partial y}\left(\int_0^{\infty} m \cdot dt \right) = 0$$

The larger the re-entrainment coefficient, the longer the length of contaminated shoreline, as shown in Figure O6.

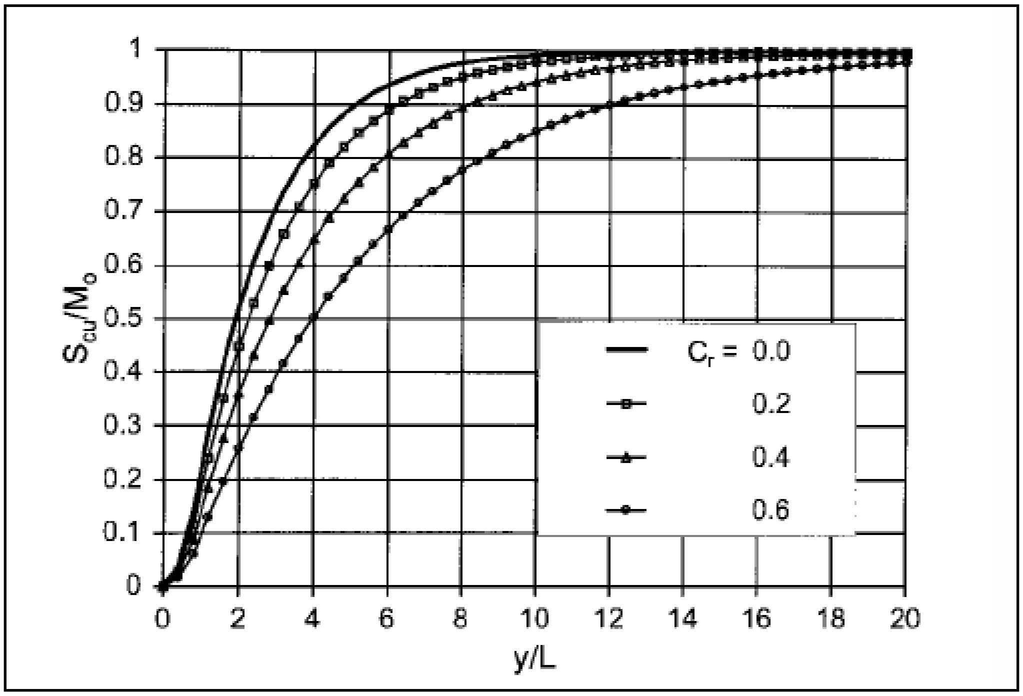

Figure O6: Accumulated Oil Deposition with Different Re-Entrainment Coefficients (From Cheng et al. , 2000)

The oil deposition on the shoreline should also be modified by the effected of oil-holding capacity.

This is expressed in the following equation:

$$S = \frac{M_o}{L}\left[\exp\left(-\frac{q\ \ y - y_3 + y_2}{L} + q\right) - \exp\left(-\frac{q\ \ y - y_3 + y_2}{L}\right)\right], \text{ for } y \geq y_3$$

Longshore profiles and distributions of accumulated on deposition for five shoreline types are shown in Figure O7 and Figure O8, as well as in Table O5.

Table O5: Affected Shoreline Characteristics by Shoreline Type[208]

Characteristic	Shoreline Type				
	Rocky shore	Sandy beach	Gravel beach	Tidal flat	Marsh
Surface distance (L_t) m	5	100	50	20	10
Oil thickness (T_m) m	0.002	0.017	0.009	0.006	0.030
Swash zone distance (L_s) m	-	10	10	-	-
Oil penetration (D_p) m	-	0.05	0.18	-	-
Oil content %	-	9.8	8.3	-	-
Oil-holding capacity (M_*) m^3/m	0.01	1.75	0.60	0.12	0.30
Affected shoreline length for S_{cu}/M_o = 95%[209] m	950.0	32.5	33.0	82.5	42.0

[208] From Cheng et al. (2000)
[209] S_{cu} = accumulated mass of oil deposited along shoreline

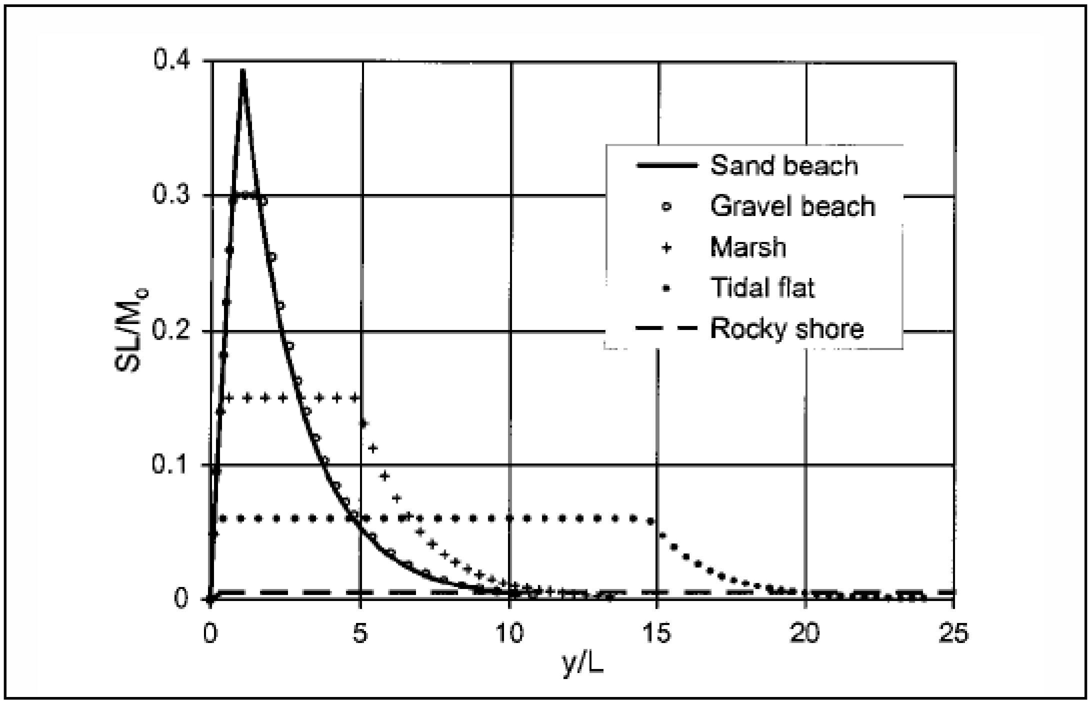

Figure O7: Longshore Profiles of Oil Deposition for Typical Shorelines (From Cheng et al. , 2000)

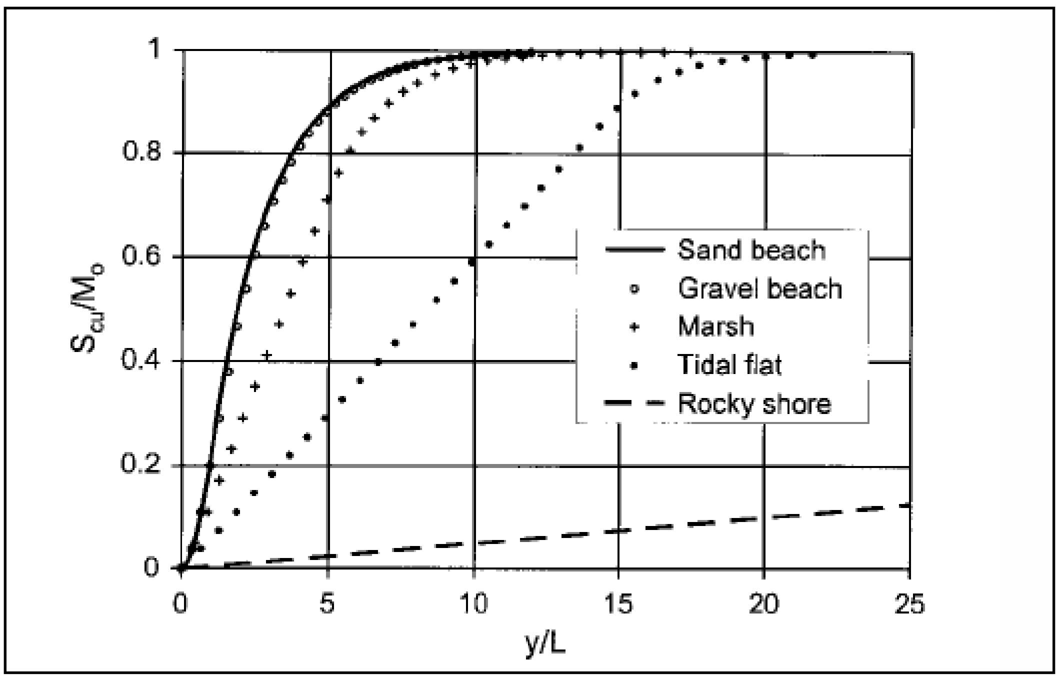

Figure O8: Distributions of Accumulated Oil Deposition for Typical Shorelines (From Cheng et al., 2000)

Seip et al. (1986) developed a parametric calculation model and regression model to estimate impacts to shorelines following an oil spill.

The regression model is based on reports from 25 oil spills and gives shoreline length damaged as a function of stranded oil.

$$S = 0.006X + 70.6$$
$$R^2 = 0.58\ (N = 25)$$

Where: S = shoreline length damaged (km)
X = oil spilled (tonnes)

There was found to be no significant correlation between shoreline length impacted and the amount of oil spilled, though there is a correlation between the amount of oil actually stranded on a shoreline and the length of shoreline contaminated[210], as shown in Figure O9. Oil densities on shorelines ranged from 0.74 tonnes/km (218 gallons/km) to 596 tonnes/km (175,224 gallons/km).

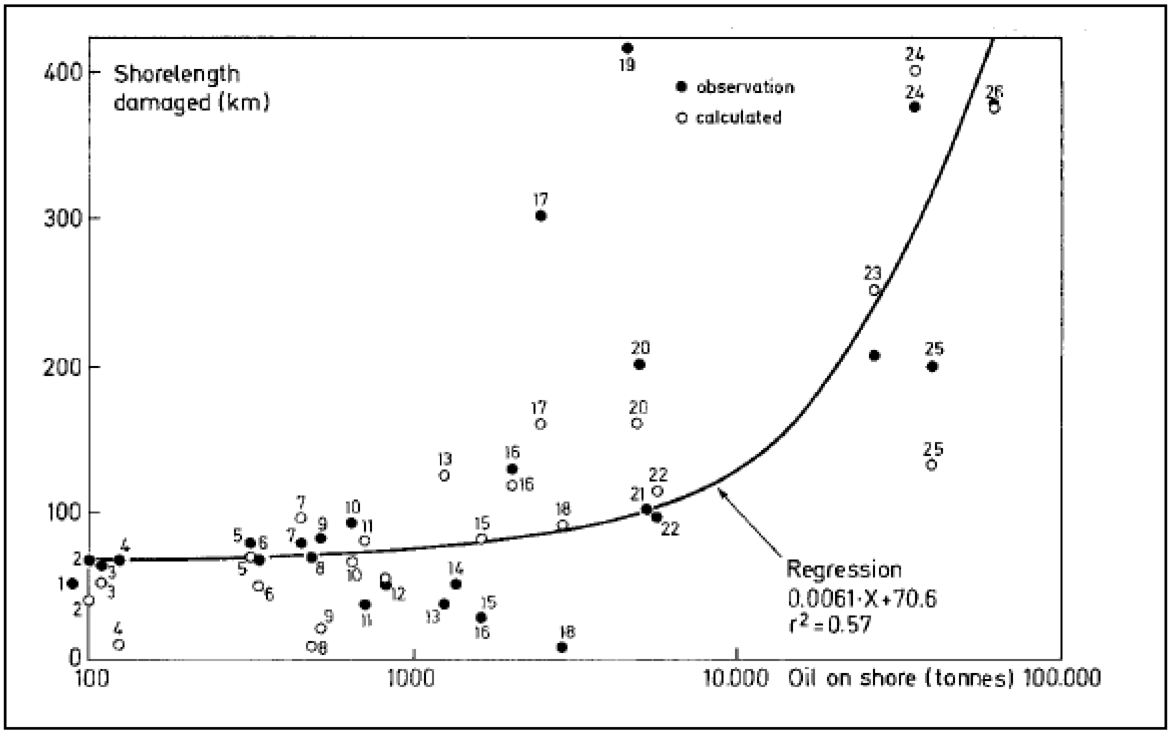

Figure O9: Shoreline impacted as a function of oil reported to be stranded. Closed circles show observations, open circles show results from calculation model (From Siep et al. , 1986).

The calculation model used the amount of oil in nearshore waters, oil characteristics, littoral area, and wave exposure of different shoreline types as primary input parameters. The model predicts the shoreline length contaminated, the amount of oil on the shore, and the density of oil on different shoreline types at various times after impact.

The calculation model, built largely on data from the Amoco Cadiz spill, as reported by **Finkelstein and Gundlach (1981)**, describes oil as stored in compartments corresponding to different shorelines and to nearshore waters. Changes in the amount of oil in each compartment occur either as a transfer from one compartment to another, or as an exponential decay process.

For each shoreline segment, L_i, with width, W_i, a density, δ_i, is calculated:

[210] The amount of oil actually stranded on a shoreline is the amount of oil spilled on the water surface reduced by the amount of oil that evaporates and disperses or is carried to other locations offshore.

$$\delta_i^{'} = \max\left(\delta_0, F_i Q / \left(L_i W_i\right)\right)$$

$$\delta_i = \min\left(\delta_i^{'}, \delta_{s,i}\right)$$

$$\delta = \frac{\sum_i \delta_i L_i}{\sum_i L}$$

Where: δ_s = saturation density
F_i = fraction
Q_o/L = offshore linear density of each shoreline type

The shoreline length impacted at first impact is:

$$S_1 = Q_0 / \delta$$

This gives the lower limit for the predicted shoreline length impacted. The upper limit is then calculated by a series of additional equations. The amount of oil left on shore, Q_{ss}, is given by:

$$Q_{ss}\left(t\right) = \sum Q_{0,i} e^{-k_i t}$$

Where: $Q_{0,I}$ = oil initially stranded on shoreline type *i*
k_i = rate of natural removal of oil from shoreline type *i*
t = time in days

At time *t* oil is removed from the shore *i* and transported back into nearshore waters at a rate $q_{u,i}$:

$$q_{u,i}\left(t\right) = Q_{0,i} k_i e^{-kt}$$

A fraction $q_{N,i}(t)$ is mixed into the water column in the period (*t, T*):

$$q_{N,i}\left(t\right) = q_{u,i}\left(t\right)\left(1 - e^{-k_w\left(T-t\right)}\right)$$

Where: k_w = rate of removal of oil from water column. Oil originating from an oil-covered shore and mixed into the water column in time *T* may be calculated, for $k_w \neq k_i$, as:

$$Q_{w,i} = \int_0^T q_{N,i}\left(t\right) dt = Q_{0,i}\left[1 - \left(e^{-k_i T} - k_i e^{-k_w T}\right) / \left(k_w - k_i\right)\right]$$

For $k_w = k_{i,}$, the equation is:

$$Q_{w,i} = Q_{0,i}\left[1 - e^{-k_i T} - T k_i e^{-k_w T}\right]$$

$$Q_w = \sum Q_{w,i}$$

The oil Q_sT left on the water surface and available for redistribution is:

$$Q_s \;\; T \;\; = Q_0 - Q_{ss} \;\; T \;\; - Q_w \;\; T$$

The quantity of oil Q_s (average for time period T) is redistributed on the shore. The second impact length S_2 is found by repeating the calculations. The total of shoreline lengths is found by adding $S_1 + S_2 + S_3$ …, *etc*. This is generally a high value in that some of the oil in the redistribution phase is likely to hit and remain on shoreline sections already contaminated (unless those segments have been saturated).

Ford (1985) developed a simple regression model to predict the lengths of coastline that would be impacted by an oil slick based on historical data on 39 oil spills. A stepwise multiple linear regression was used to determine the factors that would most accurately coastline impact. Only two variables, spill volume, and latitude contributed significantly to the prediction of coastal oiling for the California coast:

$$\log \;\; COAST \;\; = -0.4046 + 0.4760 \log \;\; VOL$$

$$\log \;\; COAST \;\; = -0.8357 + 0.4525 \log \;\; VOL \;\; + 0.0128 \;\; LAT$$

Where: COAST = number of km of coastline contaminated
VOL = volume of oil spilled (in barrels), excluding any burned oil
LAT = number of degrees of latitude (north or south) at which the spill occurred

This regression (p <0.001) accounted for 66.3% of the variance. A second equation relating only volume to coastal impact accounted for 58.6% of the variance (p <0.001):

$$\log \;\; COAST \;\; = -0.4046 + 0.4760 \log \;\; VOL$$

This equation is shown graphically in Figure O10.

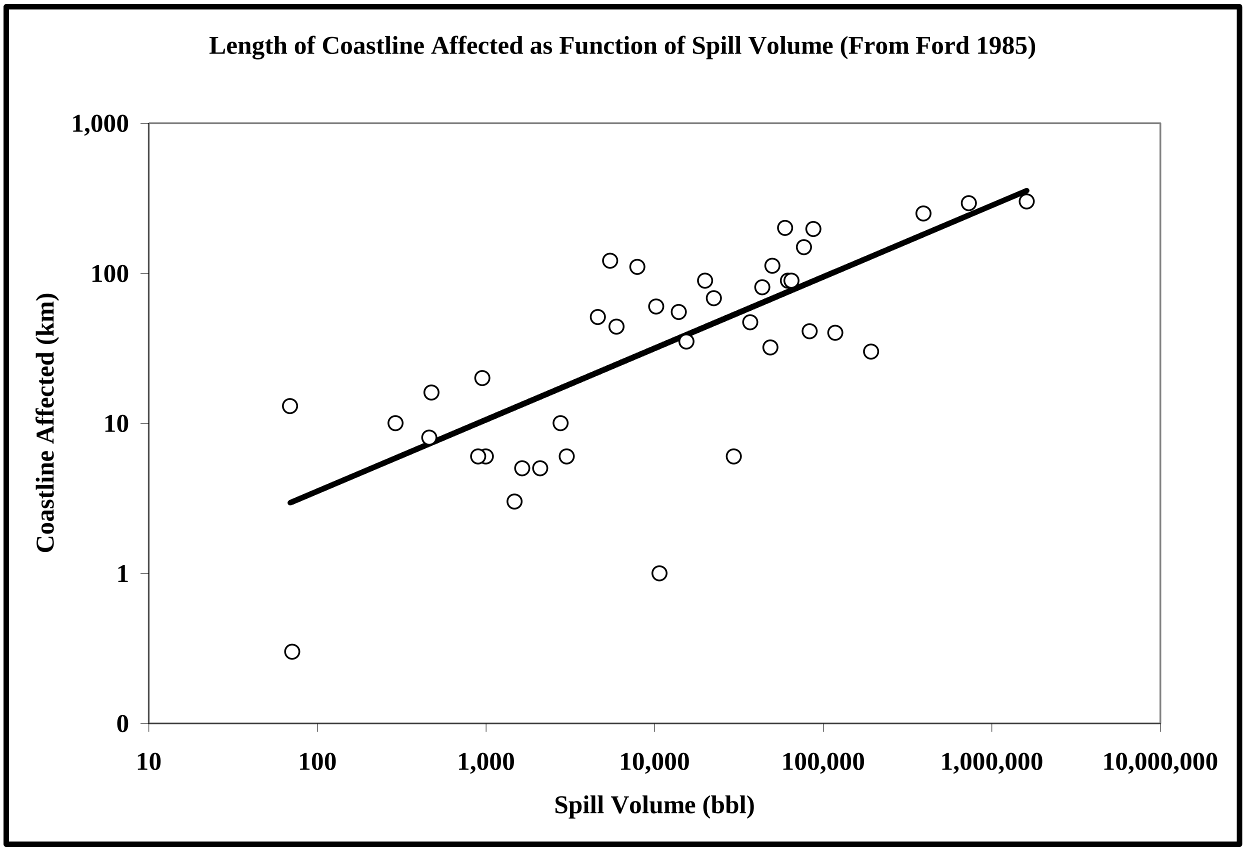

Figure O10: Regression of length of coastline impacted based on spill volume (From Ford, 1985)

Cekirge et al. (1995) reviewed the state-of-the-art for oil spill modeling and concluded that the probability that stranded oil will return to the water must be handled as a Monte Carlo simulation (randomized). However, information to parameterize this type of modeling approach are lacking.

Johnson, Ji, and Marshall (2005) used the Oil Spill Risk Analysis (OSRA) model developed by the Department of Interior MMS (Samuels et al., 1982; Smith et al., 1982; LaBelle and Anderson, 1985; and Price et al., 2004) for the analysis of possible oil spill impacts from offshore oil and gas operations to estimate the spreading of oil spills and shoreline impacts. As presently configured, the OSRA model simply accumulates oil on the intersected shoreline and does not address oil-shore interactions.

Reed et al. (1995) and French et al. (1996) describe a three-dimensional oil and chemical spill model in which and algorithm for modeling shoreline effects was developed based on a number of previous studies[211]. Sets of maximum oil holding capacities and removal rates were estimated. The holding capacities reflected both the shoreline slope and the permeability. A gravel beach was assumed to retain more oil per unit length than a sand beach due to oil penetration into the substrate. Removal rates were slower on a gravel beach due to the longer half-life of the oil in the sediments.

When a surface slick encounters a shoreline, the maximum oil volume (V_{max}) in m^3 that can be deposited was computed as:

$$V_{max} = \delta_i L W_i$$

[211] Gundlach (1987); Harper et al. (1985); Owens et al. (1983); Owens et al. (1987); Reed and Gundlach (1989); Reed, Gundlach, and Kana (1989); and Vandermeulen and Gordon (1976).

Where: δ = maximum oil-holding capacity for shoreline type i (m)
W_i = deposition width for shoreline type i (m)
L = length of shoreline segment (m)

If this volume of oil is already deposited on a particular shoreline segment, no more oil can be deposited and the slick continues to be transported by wind and currents. Otherwise, oil is deposited up to V_{max}.

The amount of oil removed from shoreline segment i during a time step Δt was computed as:

$$\Delta m = m_i(1-exp[-r_i\Delta t])$$

Where: m_i = mass of oil on segment i at the beginning of the time step
r_i = removal rate for the appropriate shoreline type

In this model, extensive wetlands were treated as water cells, so that there was no limit placed on the amount of oil that could be transported into or through these areas. However, "fringing wetland" landward of these areas was treated as other shoreline segments.

National Research Council (2003) summarized four composite models used in simulating oil spill fates, as shown in Table O6. The GNOME-ADIOS2, OSIS, and OSRA models simply accumulate oil on the intersected shoreline. The SIMAP model (French McCay, 2004) incorporates the SMEAR model, where retention of oil on a shoreline depends on the shoreline type, width, and angle of the shoreline, viscosity of the oil, the tidal amplitude, and the wave energy. Shore oil-holding capacity (Table O7) was based on observations from Gundlach (1987) and later work summarized in French *et al*. (1996, see above). The shore (intertidal zone) widths used were typical widths for the location, based on French et al. (1996).

Table O6: Summary of Processes in Four Composite Oil Spill Fate Models [212]

Process	GNOME-ADIOS2	OSIS (BMT)	OSRA (MMS)	SIMAP (ASA)
Dimensions	Near-surface	Near-surface	Near-surface	Entire water column
Advection	Wind factor + background + stochastic uncertainty	Wind factor + background current + wave[213]	Wind factor + background	External hydrodynamic model + wind factor (if not in hydrodynamic model)
Horizontal dispersion	Fickian	Random walk based[214]	Optional	Heuristic method + spillets
Spreading	Modified Fay + wind component	None	None	Modified Mackay[215]
Emulsification	Based on Eley[216]	Based on Mackay[217]	None	Mackay[218]
Vertical dispersion	Modified Delvigne and Sweeney[219]; includes	CONCAWE[220]	None	Delvigne and Sweeney[221]

[212] Based on National Research Council (2003).
[213] Elliott and Wallace (1989)
[214] Morales et al. (1997)
[215] Mackay et al. (1980)
[216] Eley (1988)
[217] Mackay et al. (1980)
[218] Mackay et al. (1982)
[219] Delvigne and Sweeney (1988)
[220] van Oudenhaven et al. (1983)
[221] Delvigne and Sweeney (1988)

Table O6: Summary of Processes in Four Composite Oil Spill Fate Models [212]				
Process	**GNOME-ADIOS2**	**OSIS (BMT)**	**OSRA (MMS)**	**SIMAP (ASA)**
(entrainment)	wave break and Langmuirs			
Dissolution	None	None	None	Mackay and Leinonen[222]
Evaporation	Modified Payne[223]	Stiver and Mackay[224]	None	Stiver and Mackay[225]
Oxidation	None	None	None	First order decay with heuristic components
Sediment and settling	Payne[226]	None	None	French[227]
Subsurface release	None	None	None	Simple passive point source
Coastal interaction	All oil sticks	All oil sticks	All oil sticks	SMEAR[228]

Table O7: Maximum Surface Oil Thicknesses for Various Beach Types As Function of Oil Viscosity (from French et al., 1996, based on Gundlach, 1987)			
	Oil Thickness (mm) by Oil Type		
Shore Type	**Light (<30 cSt)**	**Medium (30-2000 cSt)**	**Heavy (>2000 cSt)**
Rocky shore	1	5	10
Gravel beach	2	9	15
Sand beach	4	17	25
Mud flat	6	30	40
Wetland	6	30	40
Artificial	1	2	2

[222] Mackay and Leinonen (1977)
[223] Jones (1997)
[224] Stiver and Mackay (1984)
[225] Stiver and Mackay (1984)
[226] Payne (1987)
[227] French et al. (1999)
[228] Reed and Gundlach (1989). In the original table in the National Research Council (2003) report, this was incorrectly referred to as "COZOIL". It has been corrected to "SMEAR" in this table.

APPENDIX P: Shoreline Oiling by Shoreline Length

Table P1, which gives shoreline lengths oiled for 26 tanker spills. The gallons of oil per kilometer of shoreline oiled vary by three orders of magnitude. This demonstrates the great variability in shoreline lengths that are oiled relative to the amount of oil spilled. Shoreline length oiled is not a good measure of the amount of oil spilled nor is the converse.

Table P1: Shoreline Oil Lengths for Representative Tanker Crude Oil Spills[229]

Year	Tanker Name	Location	Gallons	Oil Type	Shore (km)	Gallons/km[230]
1996	Sea Empress	UK	21,274,000	light crude	7	3,039,143
2000	Natuna Sea	Singapore	2,058,823	crude	2	1,029,412
1991	Haven	Italy	42,336,000	Iranian light crude	50	846,720
1975	Jakob Maersk	Portugal	24,256,000	crude	30	808,533
1976	Urquiola	Spain	28,140,000	Kuwait crude	100	281,400
1983	Castillo de Bellver	S. Africa	78,500,000	light Arabian crude	350	224,286
1992	Nagasaki Spirit	Malaysia	3,822,000	crude	20	191,100
1998	El Bravo	Cuba	147,000	heavy crude	1	183,750
1978	Amoco Cadiz	France	68,668,000	light Arabian crude	306	171,670
1994	Seki	UAE	4,704,000	Iranian crude	30	156,800
1982	Ondina	Germany	386,000	crude	3	128,667
1992	Aegean Sea	Spain	21,900,000	Brent light crude	200	109,500
1977	Borag	Taiwan	10,395,000	crude	97	107,165
1976	St. Peter	Colombia	10,319,400	light Orito crude	124	83,221
1977	Venoil	S. Africa	8,022,000	crude	130	61,708
1997	Nissos Amorgos	Venezuela	2,520,000	Bachaquero crude	45	56,000
1996	Bunga Kesumba	Malaysia	240,000	crude	8	30,000
1989	Kanchenjunga	Saudi Arabia	852,600	Iraqi light crude	32	26,644
1992	Pres. Arturo Umberto Illia	Argentina	184,800	crude	8	23,100
1973	Jawachta	Sweden	882,000	Venezuelan crude	40	22,050
1990	Fernando	Philippines	50,000	crude	10	5,000
1998	Theotokos	Sri Lanka	29,400	crude	6	4,900
1991	Agip Abruzzo	Italy	588,000	light Iranian crude	130	4,523
1980	Texaco Connecticut	Panama	170,000	Alaskan crude	40	4,250
1993	Pres. Arturo Umberto Illia	Argentina	10,000	crude	7	1,429
1999	Enalios Thetis	Italy	14,700	crude	13	1,131
1985	BP Vision	Syria	4,000	heavy crude	4	1,000

[229] Source: ERC International Oil Spill Database. ERC analysis.

[230] This is just a hypothetical amount of oil that would be on the shoreline if all the oil actually did impact the shoreline with no evaporation or dispersion. This demonstrates the great variability in shoreline lengths that are oiled relative to the amount of oil spilled. Shoreline length oiled is not a good measure of the amount of oil spilled nor is the converse.

APPENDIX Q: Shoreline Cleanup Assessment Team (SCAT) Processes

The Shoreline Cleanup Assessment Team (SCAT) surveys that are conducted after an oil spill provide a rich array of data for the purposes of developing response strategies and measuring the progress of shoreline cleanup and treatment. These data also hold a wealth of information about shoreline oiling and oil-holding capacity. Owens (1999) reviewed the then ten-year history of the SCAT process.

Owens and Taylor (1993) developed a methodology for describing subsurface oiling in SCAT surveys. Table Q1 gives the basic terminology.

Table Q1: Terminology for Classification of Subsurface Oiling[231]

Term	Code	Description
Asphalt pavement	AP	Cohesive mixture of weathered oil and sediment situated completely below a surface sediment layer(s).
Oil-filled pores	OP	Pore spaces in sediment matrix completely filled with oil; often characterized by oil flowing out of sediments when disturbed.
Partially-filled pores	PP	Pores spaces filled with oil, but oil generally does not flow out when exposed or disturbed.
Cover or coat	OR/C	Cover (0.1 – 1.0 cm) or coat (0.01 – 0.1 cm) of oil residue on sediments and/or some pore spaces partially filled with oil.
Stain	OR/S	Stain (0.01 cm) or film oil residue on sediment surfaces; non-cohesive.
Trace	TR	Discontinuous film of spots of oil on sediments, or odor or tackiness with no visible evidence of oil
No oil	NO	No visible or apparent evidence of oil.

The subsurface oil characterization matrix is shown in Table Q2.

Table Q2: Subsurface Oil Characterization Matrix[232]

		Depth of Penetration or Thickness of Oil Lens			
		> 30 cm	**21 – 30 cm**	**11 – 20 cm**	**0 – 10 cm**
Relative Oil Concentration	**OP**	Heavy	Heavy	Heavy	Moderate
	PP	Heavy	Moderate	Moderate	Light
	OR	Moderate	Moderate	Light	Light
	TR	Light	Very Light	Very Light	Very Light

Due to problems associated with differentiating between surface and subsurface oil on coarse-sediment beaches, Owens and Taylor (1993) developed the following protocol:

Fine sediments: Subsurface begins at 5 cm below the surface. If a pit were to reveal oiling in sand from the surface down to 20 cm, the upper 5 cm could be classified as surface oil and the remainder as subsurface oil. The oiled interval would still be shown as 0 to 20 cm.
Coarse sediments: Subsurface begins at the bottom of the surface material (i.e., where the top layer of cobbles or boulders contact the underlying layer of sediments)
Asphalt pavement: Where asphalt pavement exists on the surface, the subsurface begins at the bottom of the pavement.

Data from SCAT surveys for several spills were analyzed by Environmental Research Consulting for the current study to determine whether there was sufficient information from which to derive shoreline oil holding capacities.

[231] From Owens and Taylor (1993).
[232] Adapted from Owens and Taylor (1993).

Exxon Valdez Oil Spill

First-year SCAT data for the Exxon Valdez spill were analyzed to determine the depth of penetration by shoreline type as shown in Table Q3

Table Q3: Exxon Valdez Oil Spill Shoreline Oiling 1989						
Shore Type	**N**	**Penetration (m)**				
		Maximum	**Mean**	**SD**	**Kurtosis**[233]	**Skewness**[234]
Cobble	163	1.270	0.077	0.131	40.52	5.10
Boulder	235	0.762	0.079	0.114	5.57	2.00
Rocky	399	0.508	0.066	0.104	3.25	1.86
Pebble	104	0.406	0.067	0.094	2.49	1.71
Cliff	23	0.305	0.050	0.080	3.38	1.89
Sandy	62	0.305	0.035	0.069	4.92	2.28
Gravel	71	0.203	0.018	0.047	9.08	3.13
Mudflat	3	0.102	0.038	0.049	-1.27	0.86

The volume of oil-saturated sediment was calculated, as shown in Table Q4.

Table Q4: Exxon Valdez Oil Spill Shoreline Oiling 1989						
Shore Type	**N**	**Volume Oiled Sediment (m^3)/Area (m^2)**				
		Maximum	**Mean**	**SD**	**Kurtosis**	**Skewness**
Cliff	23	0.2438	0.0339	0.0660	4.59	2.28
Boulder	235	0.4115	0.0532	0.0811	3.96	1.93
Rocky	399	0.5029	0.0405	0.0815	8.11	2.73
Cobble	163	1.1430	0.0617	0.1206	41.12	5.33
Pebble	104	0.4064	0.0458	0.0770	5.86	2.28
Gravel	71	0.1828	0.0118	0.0347	12.44	3.53
Sandy	62	0.2540	0.0132	0.0353	36.17	5.50
Mudflat	3	0.1016	0.0341	0.0584	n/a[235]	1.73

This volume needed to be adjusted to subtract the volume of the substrate itself and to calculated the interstitial pore space between grains filled to capacity with oil (as in Figure 2, p. 18). Oil in saturated substrate was calculated as,

[233] Kurtosis characterizes the relative peakness or flatness of a distribution compared with the normal distribution. Positive kurtosis indicates a relatively peaked distribution. Negative kurtosis indicates a relatively flat distribution. Kurtosis is defined as:

$$\left\{ \frac{n}{n-1 \quad n-2} \sum \left(\frac{x_i - \bar{X}}{s} \right)^3 \right\}$$

where s is the sample standard deviation.

[234] Skewness characterizes the degree of asymmetry of a distribution around a mean. Positive skewness indicates a distribution with an asymmetric tail extending towards more positive values. Negative skewness indicates a distribution with an asymmetric tail extending towards more negative values. Skewness is defined as:

$$\frac{n}{n-1 \quad n-2} \sum \left(\frac{x_i - \bar{X}}{s} \right)^3$$

where s is the sample standard deviation.

[235] Sample size too small.

$$Vol_{oil} = 1 - \left[\left(\frac{1}{2} r \right)^3 \bullet \left(\frac{4}{3} \pi r^3 \right) \right]$$

= 0.4764 m^3 oil/m^3 substrate [the equivalent of 125 gallons/m^3 or 476.8 liters/m^3], *regardless* of grain diameter if the sediment is packed as shown on *left*. Oil in a saturated substrate will be *less* if the grains are tightly packed, as shown on the *right.* The 125 gallons/m^3 or 476.8 liters/m^3 represents the *maximum* saturation[236]. If the pore spaces are 50 – 100% saturated, then an average of 200 – 400 liters/m^3 of oil will be in the substrate that is saturated, as described in Gillie, Harper, and McCullough (1999).

Assuming that sediment is actually saturated, the volume of oiled sediment (in Table Q5) was multiplied by 400 liters/m^3 to get the amount of oil in the sediment per unit area.

Table Q5: Exxon Valdez Oil Spill Shoreline Oiling 1989

Shore Type	N	Total Volume of Subsurface Oil (m^3)/Area (m^2)				
		Maximum	Mean	SD	Kurtosis	Skewness
Cliff	23	0.0099	0.0018	0.0030	4.59	2.28
Boulder	235	0.0124	0.0026	0.0035	3.96	1.93
Rocky	399	0.0134	0.0017	0.0031	8.11	2.73
Cobble	163	0.0164	0.0027	0.0043	41.12	5.33
Pebble	104	0.0124	0.0019	0.0032	5.86	2.28
Gravel	71	0.0081	0.0006	0.0017	12.44	3.53
Sandy	62	0.0101	0.0005	0.0015	36.17	5.50
Mudflat	3	0.0058	0.0019	0.0033	n/a[237]	1.73

Since some oil would remain on the surface, it would be necessary to add that amount of surface oil to the subsurface oil to determine the total oil loading. Surface oiling is shown in Table Q6. The subsurface and surface oil were summed, as shown in Table Q7 in units of m^3 oil per m^2 area.

Table Q6: Exxon Valdez Oil Spill Shoreline Oiling 1989

Shore Type	N	Volume Surface Oil (m^3)/Area (m^2)				
		Maximum	Mean	SD	Kurtosis	Skewness
Cliff	23	0.0096	0.0009	0.0022	0.17	1.33
Boulder	235	0.0205	0.0017	0.0030	-1.16	0.72
Rocky	399	0.0269	0.0016	0.0035	2.38	1.92
Cobble	163	0.0750	0.0022	0.0053	-0.83	0.94
Pebble	104	0.0201	0.0018	0.0030	1.28	1.66
Gravel	71	0.0066	0.0003	0.0010	6.26	2.76
Sandy	62	0.0102	0.0006	0.0013	25.43	4.98
Mudflat	3	0.0023	0.0008	0.0014	n/a	1.73

236 Analysis by ERC.
237 Sample size too small.

Table Q7: Exxon Valdez Oil Spill Shoreline Oiling 1989						
Shore Type	N	Total Volume of Subsurface Oil and Surface Oil (m^3)/Area (m^2)				
		Maximum	Mean	SD	Kurtosis	Skewness
Cliff	23	0.01950	0.00272	0.00528	2.18	1.78
Boulder	235	0.03292	0.00426	0.00648	2.67	1.66
Rocky	399	0.04024	0.00324	0.00652	6.54	2.51
Cobble	163	0.09144	0.00494	0.00964	34.20	4.69
Pebble	104	0.03252	0.00366	0.00616	4.84	2.11
Gravel	71	0.01462	0.00094	0.00278	12.44	3.53
Sandy	62	0.02032	0.00106	0.00282	32.76	5.15
Mudflat	3	0.00812	0.00272	0.00468	n/a	1.73

The same results are presented in units of grams of oil per m^2 are in Table Q8[238].

Table Q8: Exxon Valdez Oil Spill Shoreline Oiling 1989						
Shore Type	N	Total Amount of Subsurface Oil and Surface Oil (grams)/Area (m^2)				
		Maximum	Mean	SD	Kurtosis	Skewness
Cliff	23	17,511	2,443	4,741	2.18	1.78
Boulder	235	29,562	3,825	5,819	2.67	1.66
Rocky	399	36,135	2,910	5,855	6.54	2.51
Cobble	163	82,113	4,436	8,657	34.20	4.69
Pebble	104	29,203	3,287	5,532	4.84	2.11
Gravel	71	13,129	844	2,496	12.44	3.53
Sandy	62	18,247	952	2,532	32.76	5.15
Mudflat	3	7,292	2,443	4,203	n/a	1.73

PEPCO Pipeline Spill

Data from the PEPCO pipeline spill were analyzed in a similar manner. The results are shown in Tables Q9 and Q10

[238] Some spill trajectory models, such as SIMAP, use this unit of measure for shoreline oiling.

Table Q9: PEPCO Pipeline Oil Spill Shoreline Oiling

Shore Type	N	Oil Thickness on Surface (m)[239]					Volume Oil (m^3)/Area (m^2)				
		Max	Mean	SD	Kurt[240]	Skew[241]	Max	Mean	SD	Kurt	Skew
Sheltered Rock	12	0.015	0.005	0.005	0.90	1.32	0.006	0.002	0.002	0.84	1.41
Rock-Gravel	21	0.005	0.001	0.002	-0.30	1.30	0.004	0.000	0.001	10.97	3.32
Rocky Platform	24	0.015	0.003	0.004	3.56	1.83	0.014	0.001	0.003	18.62	4.17
Rock-Coarse Sand	17	0.015	0.001	0.004	11.88	3.33	0.011	0.001	0.003	12.64	3.50
Fine Sand	12	0.015	0.004	0.006	1.16	1.53	0.009	0.001	0.003	10.65	3.22
Rocky	16	0.005	0.001	0.002	2.24	2.00	0.000	0.000	0.000	12.68	3.47
Salt Marsh	239	0.015	0.003	0.004	3.06	1.91	0.014	0.001	0.002	24.99	4.85
Gravel	43	0.015	0.003	0.003	5.00	1.94	0.003	0.000	0.001	5.34	2.49
Freshwater Marsh	32	0.020	0.004	0.005	2.79	1.80	0.006	0.001	0.002	2.59	1.79
Exposed Tidal Flat	41	0.015	0.003	0.004	3.65	1.87	0.004	0.001	0.001	5.93	2.53
Coarse Sand	71	0.015	0.002	0.003	6.13	1.99	0.004	0.000	0.001	17.77	3.95
Coarse Sand-Salt Marsh	123	0.015	0.003	0.004	3.40	1.85	0.010	0.001	0.002	18.29	4.11

[239] Penetration into the substrate was not specifically measured or recorded for this SCAT survey. Only oil thickness on the substrate surface was measured.
[240] Kurtosis characterizes the relative peakness or flatness of a distribution compared with the normal distribution. Positive kurtosis indicates a relatively peaked distribution. Negative kurtosis indicates a relatively flat distribution. Kurtosis is defined as:

$$\left\{ \frac{n}{n-1 \quad n-2} \sum \left(\frac{x_i - \bar{X}}{s} \right)^3 \right\}$$

where s is the sample standard deviation.
[241] Skewness characterizes the degree of asymmetry of a distribution around a mean. Positive skewness indicates a distribution with an asymmetric tail extending towards more positive values. Negative skewness indicates a distribution with an asymmetric tail extending towards more negative values. Skewness is defined as:

$$\frac{n}{n-1 \quad n-2} \sum \left(\frac{x_i - \bar{X}}{s} \right)^3$$

where s is the sample standard deviation.

Table Q10: PEPCO Pipeline Oil Spill Shoreline Oiling						
Shore Type	**N**	**Grams/Area (m^2)**				
		Max	**Mean**	**SD**	**Kurt**	**Skew**
Sheltered Rock	12	5,388	1,796	1,796	0.84	1.41
Rock-Gravel	21	3,592	0	898	10.97	3.32
Rocky Platform	24	12,572	898	2,694	18.62	4.17
Rock-Coarse Sand	17	9,878	898	2,694	12.64	3.50
Fine Sand	12	8,082	898	2,694	10.65	3.22
Rocky	16	0	0	0	12.68	3.47
Salt Marsh	239	12,572	898	1,796	24.99	4.85
Gravel	43	2,694	0	898	5.34	2.49
Freshwater Marsh	32	5,388	898	1,796	2.59	1.79
Exposed Tidal Flat	41	3,592	898	898	5.93	2.53
Coarse Sand	71	3,592	0	898	17.77	3.95
Coarse Sand-Salt Marsh	123	8,980	898	1,796	18.29	4.11

Morris J. Berman Oil Spill

Shoreline surveys[242] from the Morris J. Berman barge spill[243] indicated that 21 km of shoreline had been impacted. Heavy oiling occurred on 4.8 km. The rest of the impacted shoreline was covered with scattered tarballs. SCAT data revealed:

- Extensive penetration of gravel beach sediments – up to depths of 3 – 10 cm;
- Coarse-grained sand sediments showed penetration in the mid- to upper beachface up to 21 cm; and
- Asphalt pavement formation (one inch thick x three feet wide x 20 ft long) on coarse-grained sandy beach.

Athos I Oil Spill

SCAT data from the Athos I spill were analyzed using the same methodology as for the Exxon Valdez and Pepco pipeline spills. The results are shown in Table Q11.

Table Q11: Shoreline Oil Loading in Athos I Oil Spill								
ESI		**N**	**Oil Loading (m^3/m^2)**			**Oil Loading (g/m^2)**		
			Average	**SD**	**Maximum**	**Average**	**SD**	**Maximum**
1B	Exposed Seawalls	7	0.0003	0.0002	0.0005	232	215	453
3	Fine Sand	11	0.1009	0.0033	0.0033	90,645	2,939	2,939
4	Coarse Sand	2	0.0000	0.0000	0.0000	0	0	0
5	Mixed Sand/Gravel	9	0.0024	0.0048	0.0142	2,130	4,304	12,773
6A	Gravel Beach	7	0.0020	0.0027	0.0071	1,768	2,381	6,387
6B	Riprap Structures	6	0.0004	0.0008	0.0020	361	728	1,825
10A	Salt/Brackish Marsh	2	0.0001	0.0001	0.0001	49	60	91

[242] Based on Ross 1994.
[243] On 7 January 1994, the tank barge Morris J. Berman spilled 798,000 gallons of No. 6 fuel oil near Punta Escambrón, San Juan, Puerto Rico, in an area with both sand beaches and rocky shores.

Selendang Ayu Oil Spill

The results of the analyses of the Selendang Ayu spill SCAT data are shown in Tables Q12 and Q13.

Table Q12: Shoreline Oiling Oil-holding capacity for Selendang Ayu Oil Spill[244]					
Substrate	**Volume (m^3) Oil/Volume (m^3) Substrate**				
	Average	**SD**	**Maximum**	**Skewness**	**Kurtosis**
Bedrock	0.06	0.13	0.59	3.33	12.90
Pebble-cobble	0.41	3.12	5.60	3.76	14.85
Sand	0.18	0.76	0.53	1.73	n/a

Table Q13: Shoreline Oiling Oil-holding capacity for Selendang Ayu Oil Spill[245]					
Substrate	**Oil Loading (g/m^2)**				
	Average	**SD**	**Maximum**	**Skewness**	**Kurtosis**
Bedrock	58,070	114,132	533,412	3.33	12.90
Pebble-cobble	365,656	2,801,887	5,028,800	3.76	14.85
Sand	157,850	680,132	471,989	1.73	n/a

[244] Based on ERC analysis of NOAA SCAT data
[245] Based on ERC analysis of NOAA SCAT data

APPENDIX R: Test Tank Testing

While field studies during actual "spills of opportunity" provide the most accurate perspective on the behavior of oil on shorelines, there are often serious limitations to these studies. The researchers often need to contend with ongoing response operations and legal issues in addition to the overall unplanned nature of the event. In addition, field studies often do not allow for the necessary variable control and experimental design that is needed in sound scientific research. Laboratory studies provide crucial experimental control, but can fall short of providing the realistic environmental conditions (e.g., waves) that would be the determining factors of shoreline oiling in a real spill situation.

Meso-scale tanks designed to simulate shorelines provide venues in which there is a better simulation of field conditions while also providing the necessary control to set up a sound scientific experiment. Two test tank facilities in the US provide the type of setup that could further MMS's understanding of oil-shoreline interactions and fill some of the information gaps found in the literature review[246].

Shoreline Environment Research Facility (SERF) – [formerly known as COSS]
Civil Engineering Department, Texas A&M University, College Station, TX

Reilly (1999) reported that the characteristics of a mesoscale oil spill research facility that would provide the most appropriate scaling features for shoreline oiling studies include:

- *Minimum size: 30.5m (length) x 2.1m (width) x 2.4m (depth):* This tank length allows for the establishment of a wide range of shoreline environments, including rocky shores, beaches, tidal flats and wetlands; and the establishment of realistic wave spectra. The tank width allows for the propagation of waves along the axis of the tank with only minimal wave/wall effect interactions. The depth of the tank allows for the establishment of a shallow subtidal area (i.e. less than 2 m).
- *Wave maker for nearshore energy simulation:* An appropriate wave generation system that generates random waves is required for the type of coastal/nearshore environment to be modeled, because waves vary somewhat randomly in height, period and length (distance from wave crest to wave crest).
- *Flow-through seawater system:* Due to the wide range of retention times of water in coastal and nearshore environments, water flow rates in a coastal mesocosm model should be able to be varied from batch (i.e. no flow) conditions to vary low retention times, i.e. on a scale of minutes to hours. Additionally, current patterns should mimic both cross-shore and long-shore currents. The placement of water influent and effluent ports can be used to simulate long-shore currents; and a wave maker positioned at one end of a mesocosm can be used to simulate cross-shore currents.
- *Simulated tidal cycles:* The tidal range can vary dramatically, ranging from a few centimeters in a microtidal environment to more than 10 m. An appropriate tidal range for the type of environment to be modeled should be established.
- *Ability to create a wide array of test environments:* Oil spills have impacted practically every type of coastal and nearshore environment (e.g. manmade structures, beaches, tidal flats, wetlands, open water, *etc.*). Systems must be designed to accommodate seawater.

[246] Note that MMS's OHMSETT facility is not designed to accommodate shoreline features and would not be suitable for the testing of shoreline oiling conditions.

- *Ability to spill crude oil and refined petroleum products in confined tanks:* Mesocosms designed for marine oil spill studies must allow crude or refined petroleum products in their tanks without concerns over fouling problems and oil/water treatment and discharge issues.
- *Ability to simulate freshwater input through the beach:* Groundwater flow through a shoreline helps to define the characteristics of the coastal and nearshore area. Ground water flow influences the chemical composition of the nearshore water mass by reducing the salinity and also may be an important source of nutrients for microorganisms. Freshwater aquifers in the beach face will significantly impact the distribution of oil and chemical/biological response agents in the intertidal zone.
- *Availability of multiple tanks to accommodate statistical considerations:* Replicates are required to statistically demonstrate a difference in the treatments between mesocosm reactor tanks. The variability exhibited in measured parameters between tanks will factor largely in the number of replicate mesocosms required for a given experimental setup. Water exchange between tanks should be eliminated in order to prevent cross-contamination of experimental treatments.
- *Outdoor location:* The mesocosms should be located outdoors in order to allow the integration of wind and solar effects in the system.

The Coastal Oil Spill Simulation (COSS) research facility, located at the Civil Engineering Department of Texas A&M University, College Station, Texas, was designed to meet these criteria. COSS was subsequently renamed Shoreline Environment Research Facility (SERF) (Figure R1).

Figure R1: Shoreline Environment Research Facility (SERF)

Prototype studies of the COSS facility (Reilly et al. 1995) showed that the COSS tanks could adequately replicate:

- Equilibrium beach profiles;
- Wave heights and periods;
- Tide ranges;
- Cross shore current patterns;

- Dampened and phase-lagged tidal signals in the beach; and
- Oil penetrations into the beach consistent with observations from past oil spills.

Kitchen et al. (1997) reported that the COSS research facility was opened in Corpus Christi, Texas, in April 1997. The facility consists of nine meso-scale wave tanks[247] that can be used as a controlled release facility for studies of fate, transport, and remediation of oil releases. Several environments can be simulated, including: coastal, intertidal, lagunal, channel, and porous media.

Cheng et al. (1998) conducted experiments in the COSS wave tank that showed that the facility provides a good controlled environment for the simulation of nearshore oil spill scenarios. Beach profile changes and wave-induced mixing were shown to be similar to that of a natural system. The COSS tank is limited by the lack of alongshore current. The researchers concluded that adjustments to the flow rate may need to be made for experiments that strongly depend on flushing.

SERF recently upgraded its facilities to increase its capacity. A new sensor development lab and a machine shop and analytical lab facilities were added along with a focus area dealing with in situ sensing and real time monitoring for oil and other environmental parameters.

For MMS's purposes in studying the impacts of spills in the Gulf of Mexico, SERF provides the advantage of being outdoors, adjacent to and using the waters of the Gulf of Mexico. The environmental conditions would closely simulate a real spill in the Gulf of Mexico.

Laboratory Beach Tank (Groundwater Simulator)
Dept. of Civil and Environmental Engineering, Temple University, Philadelphia, PA

Another facility that offers the potential for rigorous tank-test experimentation on shoreline oiling is the laboratory beach tank or "groundwater simulator" at Temple University. The indoor facility (pictured in Figure R2) consists of a carbon steel tank of 8 m long x 2 m high x 0.6 m wide with transparent plexiglass sheets. Sand or other substrates can be positioned inside the tank to simulate a beach of any slope of configuration.

The tank has a wave generator (as shown in Figure R3) and sensors that can be placed in various parts of the "beach" substrate. Detailed specifications are presented in Boufadel et al. (2007)[248]. The tank can be used for fine-scale monitoring of porosity, concentrations of oil and water, and other properties.

Figure R2: Laboratory Beach Tank, Temple University.

[247] Each 33.5 x 2.4 x 2.1 meters in dimension.
[248] See also Boufadel, 2000, and Boufadel et al., 2006.

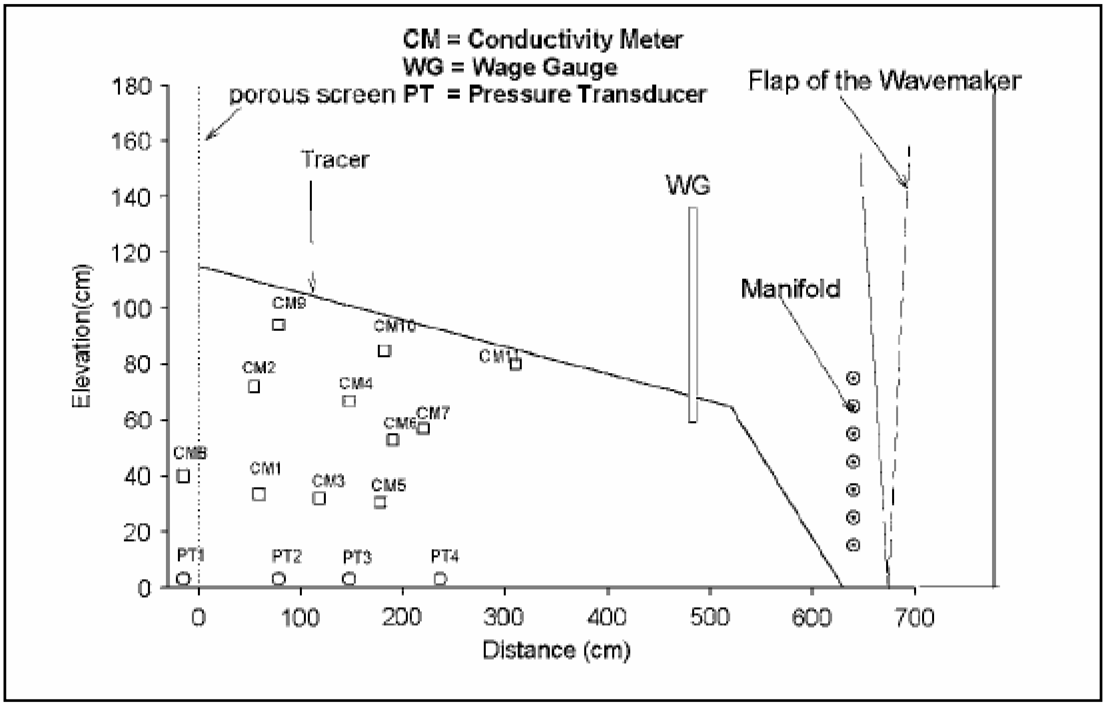

Figure R3: Laboratory Beach Tank setup and wavemaker

The groundwater simulator allows one to replicate the movement of the water table in beaches subjected to tides. The landward water level (to the left of the beach in Figure R2) could be used to simulate the regional water table that could be higher than the tide level. The movement of oil and its deposition in the beach could be simulated. One could also account for the effects of waves by equipping the tank with a wave-maker. Due to the fact that the tank is transparent, one can directly measure the depth of oil penetration at various tide lines.

The advantage of the Temple laboratory beach tank is that it can be used to conduct series of experiments with relatively fewer changes in the setup in comparison to the larger-scale SERF. The fact that the test tank is indoors allows for greater control of environmental variables, such as oil, water, and air temperature and wind conditions.

This facility might provide a good experimental venue for measuring more accurately the transport of oil and water through a beach substrate and measuring the impact of variations in wave action, sediment porosity, and oil type in determining the degree to which oil will penetrate and be retained in the beach sediment.

The Department of the Interior Mission

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering sound use of our land and water resources; protecting our fish, wildlife, and biological diversity; preserving the environmental and cultural values of our national parks and historical places; and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to ensure that their development is in the best interests of all our people by encouraging stewardship and citizen participation in their care. The Department also has a major responsibility for American Indian reservation communities and for people who live in island territories under U.S. administration.

The Minerals Management Service Mission

As a bureau of the Department of the Interior, the Minerals Management Service's (MMS) primary responsibilities are to manage the mineral resources located on the Nation's Outer Continental Shelf (OCS), collect revenue from the Federal OCS and onshore Federal and Indian lands, and distribute those revenues.

Moreover, in working to meet its responsibilities, the **Offshore Minerals Management Program** administers the OCS competitive leasing program and oversees the safe and environmentally sound exploration and production of our Nation's offshore natural gas, oil and other mineral resources. The MMS **Minerals Revenue Management** meets its responsibilities by ensuring the efficient, timely and accurate collection and disbursement of revenue from mineral leasing and production due to Indian tribes and allottees, States and the U.S. Treasury.

The MMS strives to fulfill its responsibilities through the general guiding principles of: (1) being responsive to the public's concerns and interests by maintaining a dialogue with all potentially affected parties and (2) carrying out its programs with an emphasis on working to enhance the quality of life for all Americans by lending MMS assistance and expertise to economic development and environmental protection.