COARSE SEDIMENT AND OIL DATABASE AND FATE MODEL

by

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EE-139 **September 1992**

ABSTRACT

Oil spills in Canadian waters have a high probability of impacting coarse sediment beaches, yet our ability to predict oil fate and estimate natural self-cleaning rates is less than adequate. Data is lacking to fully understand many oil/sediment interactions. Historically, shoreline interactions have been considered using fairly simple concepts.

The processes which may occur on a coarse sediment beach were examined. Those which are considered important are developed into a fate and persistence model for stranded oil. The processes are divided into stages relative to the spill event, and the factors which affect each stage were evaluated. Three areas of special interest are: (1) the capacity of a beach to hold oil, (2) the residual capacity of a beach for oil, and (3) the long term fate of the oil. Model algorithms are developed and the outputs compared to a database of information collected during the Exxon Valdez oil spill.

The database, in Paradox, includes files relating to the location and wave energy of beach segments, surface oil cover for the segments at various times, subsurface oil character, and pit oiling data. Over 10,000 oil cover records are included, from January 1990 to August 1991. Some total hydrocarbon data are included. The data were obtained from both Exxon and NOAA.

The model provides information at two levels; one general level which can be used for planning and sensitivity mapping and a more detailed model intended for the prediction of oil fate on specific known beaches. The strengths and weaknesses of the model are assessed in terms of data deficiencies. Identification is made of the type and nature of the data which are most useful to, and which need to be collected for, spill planning and spill monitoring.

RÉSUMÉ

La probabilité que les déversements de pétrole dans les eaux canadiennes touchent des plages de sédiments grossiers est élevée. Pourtant, notre capacité de prévoir le devenir du pétrole et d'estimer les vitesses d'auto-épuration naturelle laisse à désirer. Nous n'avons pas toutes les données requises pour comprendre parfaitement de nombreuses interactions entre le pétrole et les sédiments. Par le passé, des concepts plutôt simples ont été employés pour décrire les interactions avec le littoral.

Après avoir examiné les processus pouvant agir sur une plage de sédiments grossiers, on a construit un modèle du devenir et de la persistance du pétrole échoué en prenant en considération les processus qui ont été jugés importants. Ces processus ont été divisés en différentes étapes par rapport à l'évolution du pétrole déversé, et les facteurs agissant à chaque étape ont été évalués. Une attention spéciale a été accordée à trois aspects : 1) la capacité de rétention du pétrole de la plage; 2) la capacité résiduelle de la plage pour le pétrole; 3) le devenir à long terme du pétrole. Les algorithmes du modèle ont été calculés, et les résultats fournis par le modèle ont été comparés aux données se trouvant dans une base de données sur le déversement de l'Exxon Valdez.

La base de données, dans Paradox, comprend des fichiers sur l'emplacement et l'énergie des vagues des segments de plage, la couverture du pétrole à la surface dans les segments de plage à divers moments, les caractéristiques du pétrole sous la surface et la pénétration du pétrole. Plus de 10 000 données sur la couverture du pétrole pour la période de janvier 1990 à août 1991 sont incluses, ainsi que quelques données sur les hydrocarbures totaux. Les données ont été obtenues des archives sur l'Exxon et de la NOAA.

Le modèle fournit des données de deux ordres : des données d'ordre général pouvant servir à la planification et à la cartographie des zones sensibles et des données plus détaillées pour la prévision du devenir du pétrole sur des plages précises. Les forces et faiblesses du modèle sont évaluées sur le plan des lacunes des données. Des précisions sont données sur le type et la nature des données qui sont les plus utiles et qui sont requises pour la planification et la surveillance en cas de déversement.

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ACKNOWLEDGMENTS

We wish to thank Gary Sergy of Environment Canada for his long and useful support of this project, one of a series of projects addressing the fate and persistence of oil on coarse sediment beaches. Gary has, over a number of years, kept the field moving with his interest in this important topic.

This project was funded under contract XSG91-00106-(608)

1. INTRODUCTION.

Oil spills in Canadian waters are most likely to impact a coarse sediment beach, the most common beach type for Canadian shorelines (Owens, 1977). For example, forty-seven percent of coastal units on SE Vancouver Island were identified as containing some gravel (Harper *et al*, 1991). Other coasts of Canada are similar. Experience following the *Exxon Valdez* oil spill in Alaska showed how difficult cleaning remote coarse sediment beaches can be. While massive effort was expended in removing oil from beaches, it was also apparent that considerable oil was removed by natural forces during the winter months when cleanup efforts were in abeyance.

For planning purposes for government and industry, a more complete understanding of the fate and persistence of oil stranded on coarse sediment beaches would be useful; in preparing contingency plans, developing sensitivity resource maps, and in selecting the locus of protection or cleanup effort on the occasion of a spill.

Modeling of the fate and behavior of spilled oil has been used to assist planners in just these ways, but has generally focused on oil on or in the water column. Where shore interactions have been considered, fairly simple concepts have been used to determine the transport of oil onto and off of the beach, fitting into the surface spill model (Reed *et al*, 1989, Reed and Gundlach, 1989 for example). Our goal is to examine the processes which may occur on a coarse sediment beach, select those which are important, and develop a fate and persistence model for stranded oil. We have chosen to develop two levels of model; one level which can be used for planning purposes and environmental sensitivity mapping, and another level for the prediction of oil fate on specific, known beaches. The first level is a generalization of the second level, and requires general input data, while the second requires site specific input data.

Some of the questions which the model should answer are: How much oil can be stranded on a particular shoreline? How much oil will remain on the shoreline after some tidal cycles have passed, and in what part of the beach will it reside? How long will the oil remain on the shore under natural conditions? What will be the ultimate fate of the oil remaining on the shore? A corollary to the second question, and of interest to spill fate models, is: What fraction of the stranded oil is refloated in each tidal cycle?

To answer these and other questions, we reviewed the literature of coarse sediment beaches, the literature on the behavior of non-aqueous phase liquids in soils and reservoirs, and the literature on oil on shorelines, then selected the important factors which may affect oil on beaches. After developing some model algorithms, we compared the output to data collected during the *Exxon Valdez* oil spill shoreline assessment programs of NOAA and Exxon.

The data from the *Exxon Valdez* incident have been collected into a relational database from a large number of data files provided by Exxon and NOAA. The data from the two sources are related only through location, as the two groups conducted different surveys for different reasons. The Exxon data generally refer to oil cover and oil presence in the subsurface. The NOAA data include beach profiles and Total Petroleum Hydrocarbon (TPH) data, with some cover data.

1.1 COARSE SEDIMENT BEACHES.

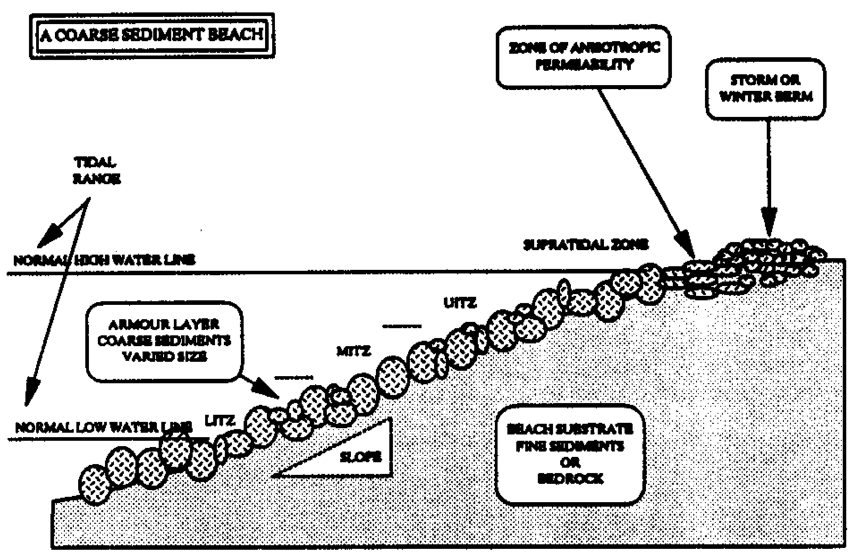

Figure 1. Coarse sediment beach.

Coarse sediment beaches are normally formed from nearby eroding cliffs or platforms or from glacial deposits. Under the influence of high wave energies, these beaches generally are steep, reflective and well sorted, with fine material removed offshore. The beach often is stepped, with an accumulation of round particles low on the beach face, and may be vertically sorted by shape, with disk shaped grains higher on the face, on the berm, or in the overtop area. These beaches have an active surface layer, with sediment reworking, and a basement layer with more stable sediments.

Beaches which are formed from *in situ* coarse sediments and which are subject to low wave energies are often mixed sand and gravel. These beaches may have gentle slopes and are dissipative, with fine grain material sheltered by an armor layer of coarse sediments. Often, the armor layer is only one grain thick, with other large grain material buried within a fine sediment layer. Recent data indicate that this may be the more common form of coarse sediment beach on the Pacific coast of British Columbia (Harper, pers. comm.).

Although the dynamics of beaches with coarse sediment is not well understood, it appears that many have arrested profiles, that is, profiles which are developed during high energy events and which are stable until the next event. The large heavy particles require a high water velocity (wave or littoral) to mobilize.

2. FATE OF OIL IN SEDIMENTS.

We identified over sixty factors which may affect shoreline oil fate and persistence. Many were inter-related and could be rolled up into one or more general concepts (Table 1). The processes were divided into stages relative to the spill event.

Table 1. Factors affecting the fate and persistence of oil on beaches.

MATERIAL FRAMEWORK	ENVIRONMENTAL PROCESSES
OIL PROPERTIES	CLIMATOLOGY*
PHYSICAL PROPERTIES	Wind
Temperature	Speed, direction, frequency
Density*	Precipitation: frequency, amount
Viscosity*	Temperature
Pour point	OCEANOGRAPHY
Surface tension	Waves*
COMPOSITION	Fetch*
Alkanes SHWR	Angle of exposure*
Aromatics AWR	Breaker type
Polars	Edge waves
Asphaltenes	Height, frequency, length
Resins	Occurrence statistics
SLICK PROPERTIES	Tides*: range, type
Volume*	Currents: speed, direction
Length, width, thickness	OIL WEATHERING*
Oil age	Evaporation
SEDIMENT PROPERTIES	Air volume
SOLID PROPERTIES	Air movement
Size	Temperature
Grain size distribution	Dissolution
Modality Kurtosis Skewness	Water exchange
Shape : Sphericity, Angularity	Photooxidation
Mineralogy	Sunlight intensity
BULK PROPERTIES	Biodegradation
Packing	Bacterial count
Wetting	Nutrient availability
BEACH PROPERTIES	Oxygen availability REDOX
Beach dimensions*	Dispersion
Beach slope*	Dispersability
Porosity*	
Permeability*: Anisotropy	
Biota: Resources Algae: macroalgae and slimes	
BEACH CAPACITY*	**RESIDUAL CAPACITY***
Theoretical*	Sediment properties
Beach dimensions	Oil properties
Beach porosity	
Actual	
Permeability	
Tidal properties	
Slick properties	

* included in present model.

The factors were identified by brain-storming and review of the literature of oil spills, oceanography, hydrogeology, and soil contamination. Some of the factors were not included in the modeling because we could not find sufficient data to relate the factors even semi-quantitatively to oil spill processes. An example is the impact of beach algae on the behavior of stranded oil. While it seems reasonable that the presence of an algae or

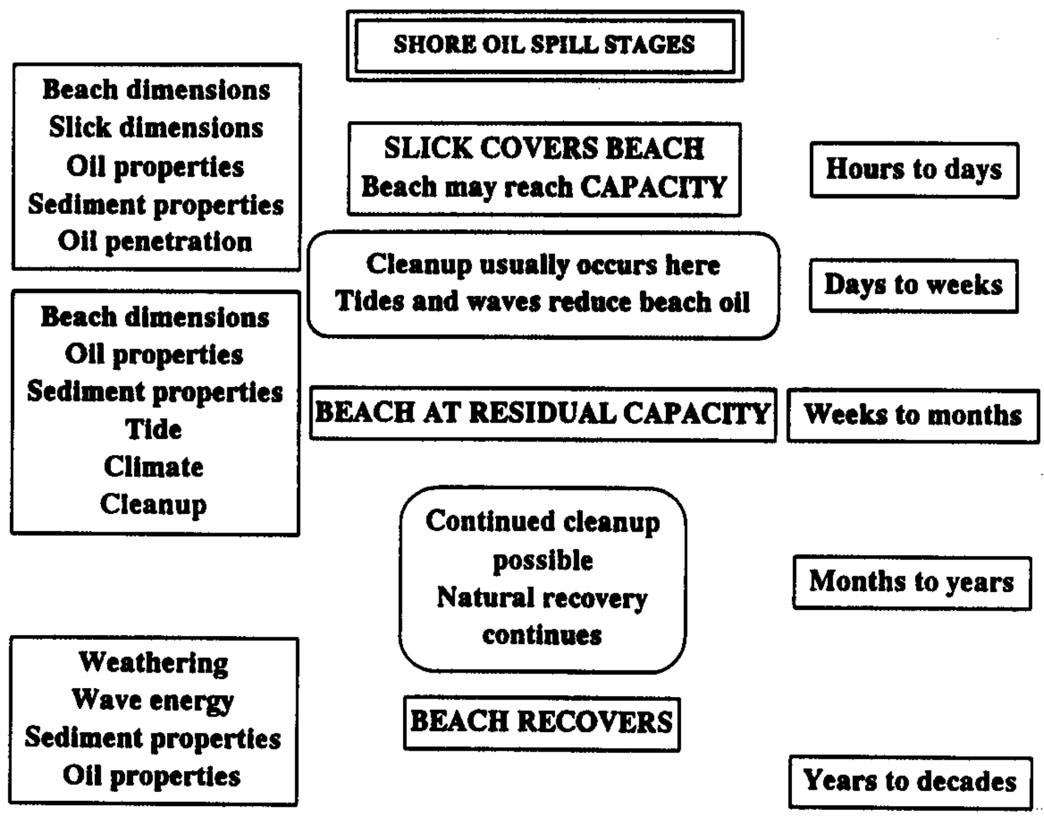

Figure 2. Stages in beach oiling processes.

slime cover on the beach affects the amount of oil which remains on the beach, no direct observations were found. Other factors were included in the model with the same inadequacies, but with some expectation that the relationships or the data could be determined with further experimentation.

A consequence of the review of the literature of different areas of scientific study is that definitions and symbols may not correspond from one field to another. In general, definitions consistent with oil spill research are used in this study, and where confusion has been noted, definitions are provided. Some parameters are understood at different levels. Some parameters are known at the **theoretical**, or **intrinsic** level, understood at an **effective** level, perceived as **apparent**, and **measured** by a specific method which may affect the measured value.

The stages (Figure 2) represent both persistence and qualitative changes in the oil on the beach. The factors which were included for further analysis were associated with each stage. Three areas of special interest are the **capacity** of a beach to hold oil, the

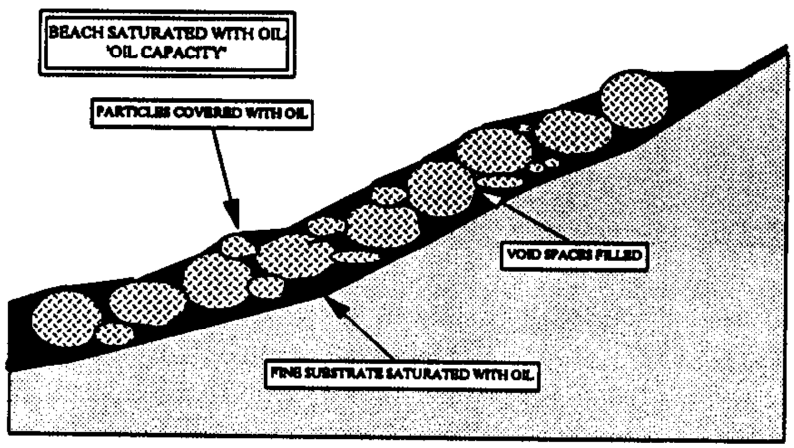

Figure 3. Beach capacity

residual capacity of a beach for oil, which is a stable capacity, and the **long term fate** of the oil. Any beach is a combination of beach cells which may be represented by different stages of the processes. Indeed, there may never be a time when any specific stage exists, only combinations of stages in different cells or transitions between stages.

The determination of beach capacity for oil, while dependent on a number of physical factors (Figure 3), rests fundamentally on the **porosity** of the sediment. This factor, which intrinsically is the connected space not occupied by particles, is not trivial to estimate for real beaches. The porosity of cells of perfectly packed spherical particles is known from basic geometry; the actual porosity of mixtures of particle sizes and shapes is essentially not calculable. For well rounded particles of similar particle size, porosity is between about 25-50%. Well packed flattened particles, such as may be found near the storm berm of gravel beaches, may have a much lower porosity.

Effective porosity for fine particles depends upon the nature of the fluid occupying the void; 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. In cases where the particles are wetted by a different phase than the displacing fluid, as in the case of oil penetrating a beach consisting of water-wet sediments, some joining throats may be already occupied. These differences is insignificant for coarse sediments, as the throat diameters are large compared to the distances across which capillary forces act.

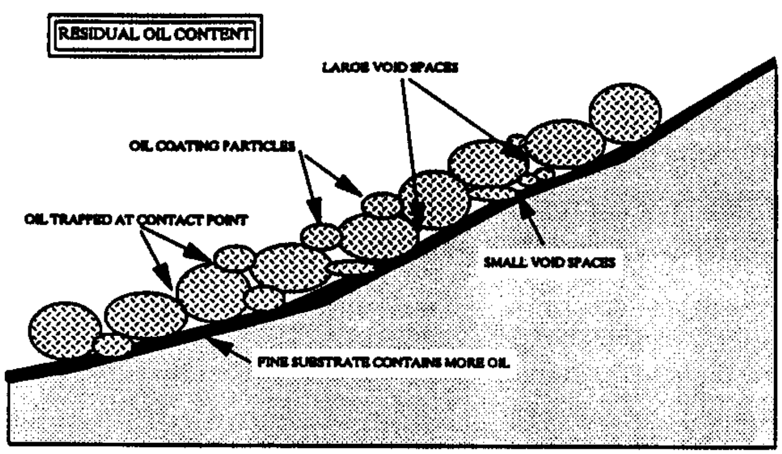

Figure 4. Residual capacity of a beach.

The actual capacity of a beach also depends on the rate of penetration of the oil into the sediments. The rate of penetration depends on the **permeability** of the sediment to the oil, which in turn depends on **fluid conductivity.** Fluid conductivity depends on particle size and fluid viscosity.

The residual capacity of a beach (Figure 4) occurs when the particles are covered by a film of oil which 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 the oil occupying the void throat spaces and around the particle contact points is immobile. The volume of oil retained depends on particle size as well as other factors. As particles increase in size, the actual distance between contact points and actual throat sizes increase.

Stable film thickness, which depends on interfacial tension, becomes smaller relative to particle diameter, and therefore film volume becomes a smaller portion of the beach volume. Again, calculations may be made for uniform spherical particles interaction with fluids, and have been done for fine grained material, in particular in oil field reservoirs. These theoretical determinations do not apply to sediment with large grains or with wide distributions of grain size.

Empirical measures of residual content have been made in various oil types. de Pastrovich *et al* (1979) have estimated depths of penetration of various soils for gasoline and light fuel oil. From these determinations, the residual capacity of the soil may be estimated. The residual capacity to light fuel oil is shown in Figure 5, where the

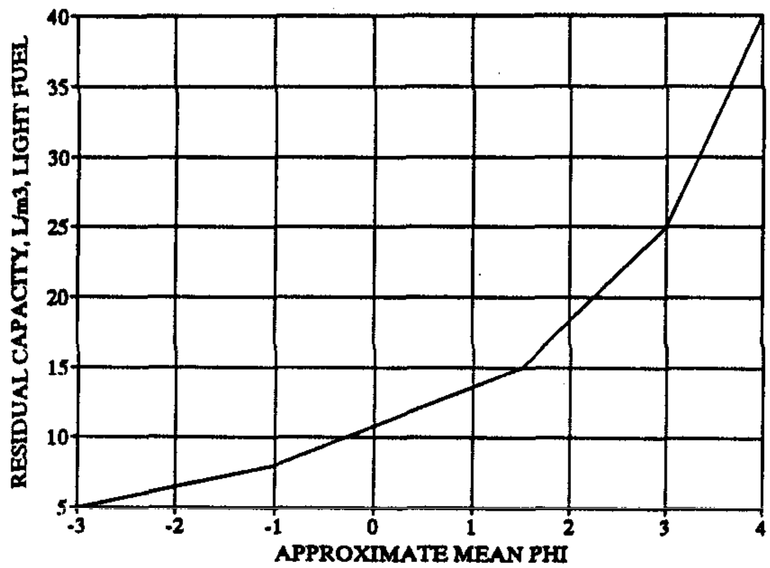

Figure 5. Residual capacity (modified from de Pastrovich *et al*, 1979)

approximate mean Φ is determined by us from the original description. The analysis be de Pastrovich *et al (1979)*, in comparing gasoline to fuel oil, suggests that the higher viscosity and density material has higher residual capacity in coarser sediments only. API (1989) used these data to predict TPH values for the contaminated soils. The data suggest that for fine sand, coarse sand and coarse gravel, TPH values of 3.9%, 1.5%, and 0.5% (weight/weight) would represent residual concentrations of fuel oil in each case. The coarser the material, the lower the residual capacity. These values refer to residual oil contents in the unsaturated zone, that is, above the water level.

The transition between a beach oiled to capacity (which may never exist) and a beach at residual capacity occurs both in time, as oil is removed from the beach at each tide cycle, and in space, as oil does not oil all zones of a beach equally. After an initial heavy oiling, a beach loses oil by tidal buoyancy. Some of the oil may be removed from the system by offshore winds, some may re-settle on the beach. Our own experience suggests that the Upper Intertidal Zone is the recipient of the largest portion of oil. This seems intuitive, as the oil is on the water surface, and wave run-up may carry oil higher on a beach, but it is difficult to see how oil could be preferentially applied only to a lower tide zone. The transition from capacity to residual capacity depends on many factors, specifics of which are unknown. Estimates are made from literature examples.

Subsequent processes of oil weathering which reduces the amount of oil on the beach and change the oil character are probably similar to those which occur for floating oil, with some modification (Figure 6). Two of these processes, dispersion and biodegradation, may have special characteristics for oil on a beach, and a beach specific process, the formation of asphalt pavement, must also be considered.

Dispersion in this context is the reduction of oil particles to sizes which are kept apart by Brownian forces and do not coalesce. This occurs on the sea surface by wave action, and is assisted by surfactant addition to the slick. Dispersion of oil is probably the major cleaning process for a beach subject to energetic waves. In addition to dispersion caused by the energy of the water, as for surface slicks, oil particles are mobilized into the water column as the sediment particles are tumbled.

Biodegradation is the decomposition of hydrocarbons by a suite of micro-organisms in the presence of nutrients. Biodegradation takes place under both well oxygenated and anoxic conditions, by different organisms, but is very much more rapid under oxic conditions. Biodegradation of oil may be enhanced over surface slick biodegradation as a coarse sediment beach represents a well oxygenated, nutrient laden environment, with good flushing to remove biodegradation products. Both water column and sediment bacteria have access to the oil film.

A process unique to beached oil is the formation of asphalt pavement. While this process is not restricted to coarse sediment beaches, it is common for them. Asphalt pavement formation is probably a combination of emulsion formation with the availability of non-hydrocarbon nucleation sources, such as sediment, shell fragments, or biota. Spilled oil which formed asphalt pavement includes oil from the *Arrow*, *Metula*, *Exxon Valdez*, and *Amoco Cadiz*, all of which carried oil known to form emulsions easily.

STRANDED OIL FATE PROCESSES

RATE COMPARED TO SURFACE SLICK

	OILING AT CAPACITY	RESIDUAL CAPACITY	LONG TERM
EVAPORATION	SLOW. AT SURFACE ONLY SUBSURFACE OIL PROBABLY 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 WAVES.	RAPID DURING STORM EVENTS, SLOW OTHERWISE.
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.

Figure 6. Stranded oil fate processes.

The processes applied to the oil is not necessarily the same on both the rising and falling tides, and may also depend on the time of exposure to either water or air.

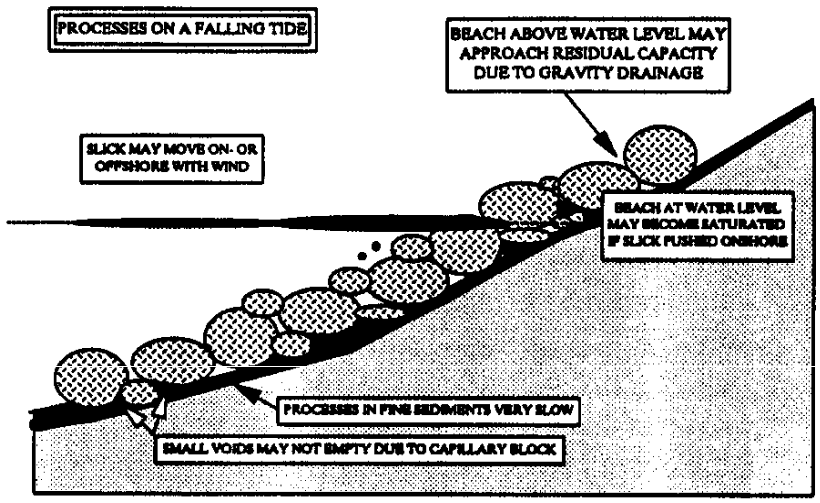

Figure 7. Processes on a falling tide.

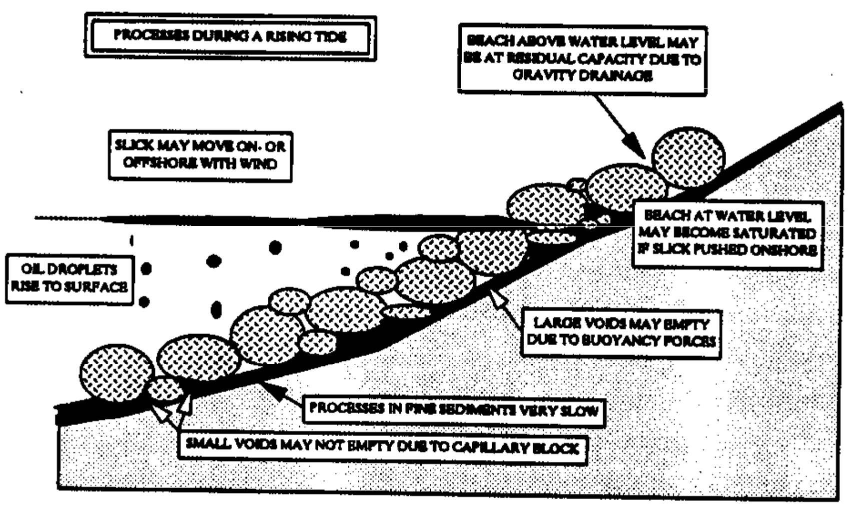

Figure 8. Processes on a rising tide.

3. APPLICABLE ALGORITHMS.

In this project, the Wentworth scale of soil particle sizes is used. This scale is based on the grain diameter in mm, as follows:

Table 2. Wentworth soil classification

CLASSIFICATION	From (mm)	To (mm)	Φ
Boulder	256	?	-8 - ?
Cobble	64	256	-6 - -2
Pebble	4	64	-2 - -6
Granule	2	4	-1 - -2
Very coarse sand	0.71	2	0.5 - -1
Coarse sand	0.5	0.71	1 - 0.5
Medium sand	0.25	0.5	2 - 1
Fine sand	0.125	0.25	3 - 2
Very fine sand	0.062	0.125	4 - 2
Silt	0.039	0.062	8 - 4
Clay	0.024	0.039	8.7 - 8
Colloid	?	0.024	? - 8.7

$\Phi = -\log_2$(diameter in mm)

Gravel is a mixture of material, usually granules to cobbles, and may include coarse sand (Krumbein and Pettijohn, 1938). A coarse sediment beach is defined as one for which the surface sediments are larger than sand. The sediments are granules and larger, $\Phi<-1$, with the mean particle diameter >2 mm.

3.1 CAPACITY

MAXIMUM LOADING

The maximum oil capacity of a beach depends on the volume of sediment and the porosity of the sediment. The volume of sediment can be calculated from the length, width and depth, if known. Porosity depends upon the shape of the particles making up the sediment, but good relationships between shape and porosity were not found. Actual porosities of coarse sediment beaches are not known from the literature. The effective porosity of a sediment is determined experimentally as

$$\Phi eff = (r_m - r_b)/(r_m - r_f)$$

where r_m, r_b, and r_f refer to the matrix, bulk and fluid densities.

For the purpose of modeling in this project, porosity is assumed to be independent of grain size and grain size distribution, and is varied between 0.12 and 0.46 (12-46%, Hough, 1957)..

The maximum loading of a beach is a volume (m^3)

$$C_{max} = L\ (m) \times W\ (m) \times D\ (m) \times \Phi_{eff}.$$

The maximum capacity of the beach is not greatly sensitive to the effective porosity in that it is unlikely that order of magnitude differences in effective porosity occur. More likely factors of 2 or 3 apply, although this must be experimentally determined.

The length of a beach may be estimated from remote sensing, or determined by direct measurement. The estimation of beach width is less straightforward, as the remote sensing image may miss part of the intertidal zone. Direct measurement is preferable. The depth of the beach, that is, the depth of coarse sediment, is even more difficult to estimate, even by direct measurement as the sediment depth may vary over the beach.

PENETRATION

For a beach to reach its maximum capacity of oil, there must be enough oil to fill the beach, enough time for the oil to penetrate into the beach, and the appropriate spill and tide conditions for the entire beach to be fully oiled. Conceptually, this requires a thick, low viscosity oil slick reaching the beach at high tide, and remaining in contact with the beach through the ebb. The actual volume in or on a beach depends upon which part of the beach the oil hits, the permeability of the beach, and the duration of the tide cycle. For the first encounter , as the water level drops, any surface oil settles on the sediments and enter the sediment at a rate determined by the sediment permeability, with gravity as the driving force. The oil penetrates under three conditions: 1) there is adequate oil and time to fill the beach exactly; 2) the depth of the beach is too shallow to accommodate all the oil which has time to penetrate, which may result in oiling greater than the calculated C_{max}; and 3) there is inadequate oil to fill the beach, but there is time for the oil to penetrate the sediments. On the following rising tide, and assuming that as the water level rises, the water buoys up and removes all but the residual oil, then under conditions 1 and 2, the beach is left with a residual content, that is the oil which adheres as film or in small pore throats in the sediment. For condition 3, the final loading is the residual loading or less.

Receiver

Telescope Diameter	0.2m
Field Of View Diameter	2mrad
Spectral Resolution	5nm
Spectral Coverage	370 - 670nm
Gate Width	20ns
Overall Quantum Efficiency	0.02

Transmitter

Laser Type	Tripled, flash-lamp pumped, Q-switched Nd:YAG
Excitation Wavelength	355nm
Pulse Energy	30mJ
Pulse Rate	50Hz
Pulse Length	<10ns
Beam Divergence	2mrad

Scanner

Scan Type	Conical
Scan Rate	2.5rps
Scan Radius	5deg

A draft specification, for a tripled Nd:YAG laser for LEAF, has been generated and sent to various manufacturers for quotes and comments. The only serious objections have been to the temperature range, which was specified as 0 to 40C operating, -50 to +60C non-operating. This is to be expected, since the harmonic generating crystals are; a) tunable by temperature and, b) susceptible to thermal shock. The solution appears to lie in improved insulation on the crystal ovens, use of standby power during brief on-ground stops in cold conditions, and removal of the crystal assemblies if the aircraft is to be unheated for extended periods.

5.5 Data Interface

It is assumed that, at least in its primary mission, the LEAF will be a part of an oil-spill monitoring package incorporating several sensors. In this case, the need for a real-time, 'user-friendly' data product, and the desirability of a single-operator system, make it imperative that

To obtain an oiling equal to the C_{max} or greater, a slick of thickness $D \times \Phi_{eff}$ or greater is required. For a beach with a total sediment thickness of only 10 cm, with an effective porosity of 12% (a low value), a slick 1.2 cm thick is required to fully saturate the beach. This is a fairly thick slick, but not unknown. Slick thicknesses over to 10 cm were reported after the *Amoco Cadiz* spill. From this analysis, it is possible that beaches reach or pass the maximum beach capacity at initial oiling.

RESIDUAL LOADING

After the oil is stranded on a beach, it is subject to tidal washing. Eventually, the remaining oil is attached to the sediment particles and is not removed by the tidal washing. This amount of oil represents the residual loading or residual capacity of the beach. For our purposes, the tidal washing is gentle as compared to cleaning during a storm event which would include grinding of the particles against each other, and which is considered below.

The residual load for soils contaminated with light fuel oil was estimated by de Pastrovich *et al*, (1979), as about 5 L m^{-3} for gravel. In the absence of other data, the residual capacity for larger particles can be estimated by assuming a continuous film of oil around spherical particles. As long as the film thickness is small compared to the particle diameter, to avoid film joining, a capacity may be calculated for each effective Φ (Figure 11). The results of such a calculation imply a film thickness of 0.02 mm to fit the estimates of de Pastrovich *et al*, (1979). The thickness of a stable film depends on the

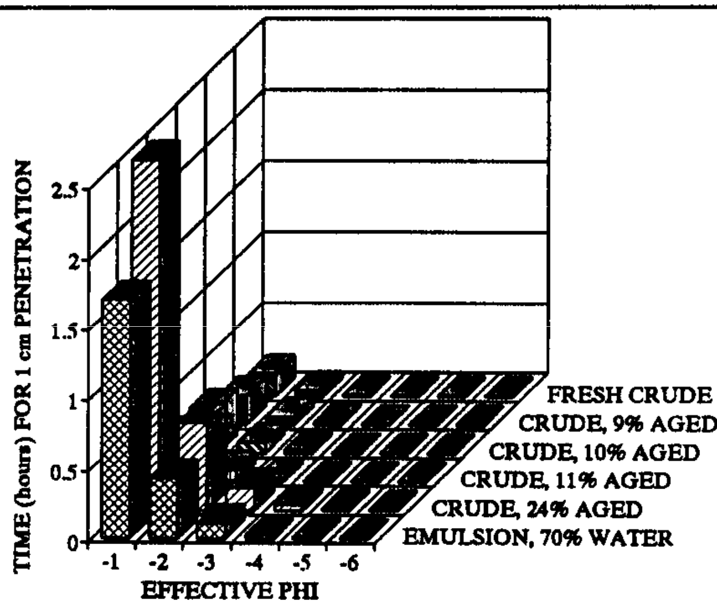

Figure 10. Times required for penetration of sediments.

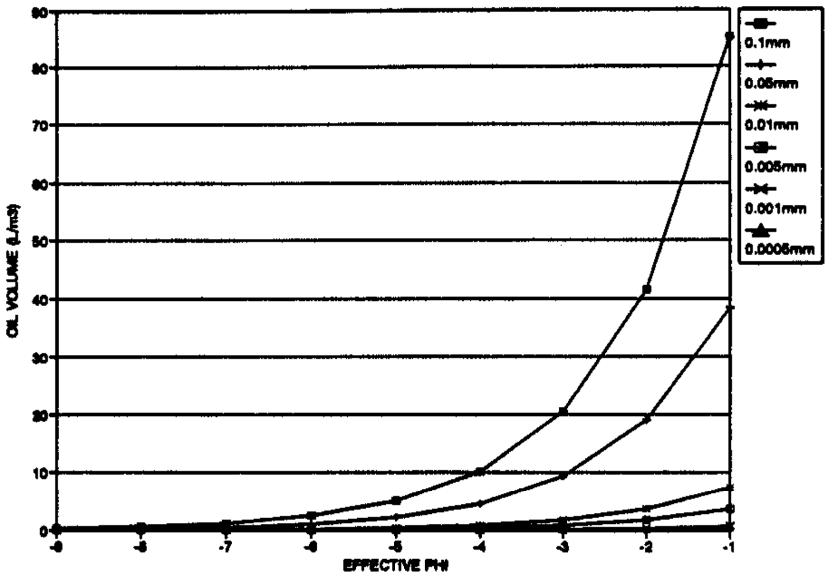

Figure 11. Residual capacity and film thickness.

nature of the substrate and the viscosity of the oil. No relationships are known to us at this time to estimate film thickness. A value of 0.02 mm is used until better residual film thickness data are available.

The residual capacity or loading can be calculated by determining the film volume per particle and the number of particles. The film volume per particle is calculated from the particle diameter and film thickness, the number of particles from the particle diameter and porosity. R is determined in units of L (oil) m^{-3} (sediment).

3.2 TRANSITION

The transition from maximum capacity or first loading to the residual capacity, without storm interaction, is a critical issue. Natural cleaning of beaches in quiet conditions, either through being sheltered or during calm summer periods, is process of great interest as this influences protection and cleanup decisions.

Removal of oil during a tide cycle will occur by washing the particles. The rate removal depends in part on the viscosity of the oil and the attractive forces between the oil and the substrate. As no specific rate data are available, data for the removal of oil at the Baffin Island Oil Spill Project (BIOS) is used as a starting point.

During the BIOS Project, oil was spilled and left on a sheltered pebble-cobble beach. The beach was monitored over nine years. The volume of oil was determined over that period (Humphrey *et al*, 1992). Assuming first-order kinetics for the removal of oil from the sediment, three rate constants can be calculated from the data. The first rate constant uses only the first self-cleaning period, the second uses all data, and the third uses all data except the first period. Each may represent a different stage in the self-cleaning process. The first may properly represent the transition from high loading to residual loading, while the third may represent weathering removal. If we assume that the first period only is the transition period, a residual volume for the oil in sediments of about 4.5 L m^{-3} after this period may be estimated, a fortuitous result consistent with the estimate of residual load by de Pastrovich *et al*, (1979). The natural rate of removal during the transition stage was determined as

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

where k is 0.2 on a monthly basis or 0.006 on a daily basis.

Assuming two tides per day, the transition rate constant would be about k = 0.003 on a tide cycle basis. Again assuming that this first-order model is reasonable, the half life for oil in the transition period is about 100 tide cycles.

There are a host of factors affecting this rate, but there are no data to permit us to isolate them. The most important are the normal wave energy level at the beach, and the composition and physical properties of the stranded oil. A higher normal wave energy increases the transition rate, and viscous oil likely exhibits a lower transition rate.

STORM EVENTS

During a storm event, additional processes come into play. The grinding of

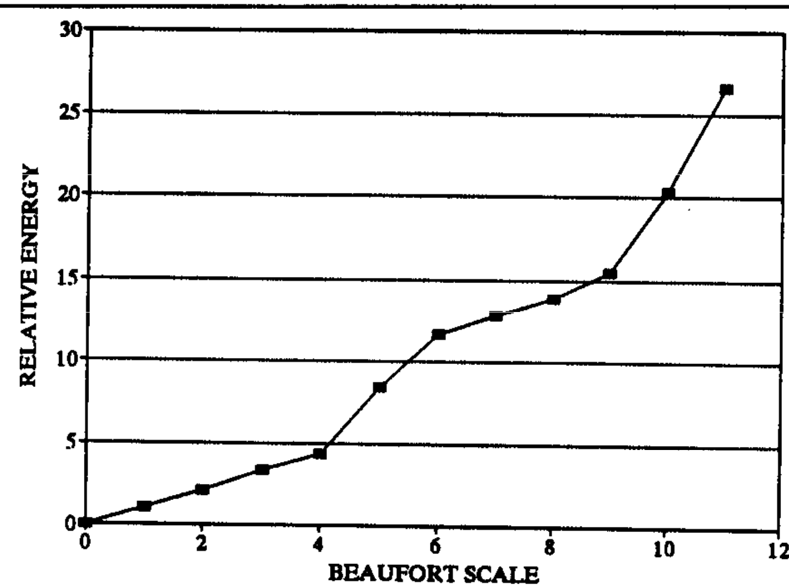

Figure 12. Wave energy *vs* Beaufort wind scale.

particle against particle greatly enhances the mobility of the oil attached to the particles, and oil above the residual loading is rapidly dispersed where the storm energy is applied. If the depth of penetration of the added energy exceeds the depth of penetration of the oil, both complete removal of free oil and an enhanced rate for the transition period, probably beyond the residual load level, would be expected. Oil stranded below the depth of energy penetration probably exhibits normal transition rate constants.

The rate enhancement caused by a storm event depends on the energy level associated with the storm event. Waves resulting from gales and hurricanes have more energy than those from storms, and enhance the rate constants more. More frequent storms cause faster removal of oil.

A storm enhances the rate of removal by depending on the energy in the waves produced. Using a relationship proposed by Putman *et al*, (1949) for the energy available for littoral transport, and approximate wave heights using the Beaufort scale of winds, a relative scale may be generated. The energy available is proportional to the wave height raised to a power of 2/3. Figure 12 shows the relative energy of Beaufort scale mature waves, compared to Beaufort scale 1 winds. Storms have a factor of 10 applied to the rates.

3.3 WEATHERING

Some weathering processes retard the rate of removal of oil while others enhance the rate. Oil on a beach is subject to the same weathering processes as oil on the water surface, but the physical conditions are not the same. Oil on a water surface is in contact with a large mobile vapor phase (the atmosphere). Oil on or in a beach is in contact with enclosed and essentially immobile air spaces for the largest part. The algorithms which have been developed to apply to water surface slicks do not necessarily apply oil on a beach. Modeling of non-aqueous phase spills usually address single component systems. Terrestrial oil spills are subject to the same problems as marine spills, and much of the work is empirical. Some generalizations may be made regarding the processes, and how each affect the rate constants for natural removal.

EVAPORATION

Evaporation occurs at the interface between liquid and vapor phases, and in the case of a beach oiled to capacity, evaporation is primarily dependent on the area of the beach in contact with the atmosphere. Oil which has penetrated the beach evaporates very slowly if at all. When the loading is at the residual level or lower, the oil films are in contact with air for a part of each day. Oil in the UITZ is exposed to air about 80% of the time, oil in the MITZ about 50% of the time, while oil in the LITZ is exposed to air only 20% of the time. The rate of evaporation may be similar to the rate of evaporation from a surface slick, but with a wind speed of 0. Unfortunately, slick model evaporation algorithms (Buist, ASA) result in evaporation rates of 0 for wind speeds of 0. It may be that there is no evaporation from subsurface oil.

DISSOLUTION

Oil subject to regular tidal washing would be expected to dissolve rapidly, especially from thin films. This may be an important factor, especially for fresh oil with a high concentration of polar compounds. We found no estimates for dissolution of complex mixtures such as oil. The rate of dissolution depends on the state of weathering of the oil on the beach, and decreases in importance as the oil ages.

EMULSIFICATION

Oil forms water-in-oil emulsions (mousse) when in contact with sea water and when some energy is present to encourage mixing. Surface slick models use wind speed in the calculation of water uptake by the oil.

The presence of granular material on the beach likely encourages mousse formation and results in asphalt pavement formation. The presence of mousse has a strong retarding effect on the removal of oil from the beach. Data are not available regarding the conditions for mouse or pavement formation on beaches, but the rate of removal probably decreases with increased tendency to form emulsions. A scale of emulsification tendency is available (Bobra, 1991), and could be incorporated into the model.

DISPERSION

Dispersion of the oil into the water column is probably very fast with any grinding of the coated sediments. This factor is included in the storm event modification of the rate process.

BIODEGRADATION

Biodegradation may be enhanced for oil in the beach, as the conditions include plentiful oxygen, regular removal of degradation products, and thin film oil to provide good contact with marine bacteria.

MODEL ALGORITHM

In the absence of appropriate algorithms for stranded oil weathering, the removal of oil is assumed to be first-order decay, with a rate constant again based on BIOS results, determined for the later stages of oil disappearance. The estimated rate constant is $k = 0.0001$, on a daily basis, or 0.00005 for a tide cycle. Long-term reduction of oil would have a half-life of about eight years under calm conditions. Again, during this period, storm rate constants as above are used for storm events. The first-order model can be segregated into separate processes when suitable data exist.

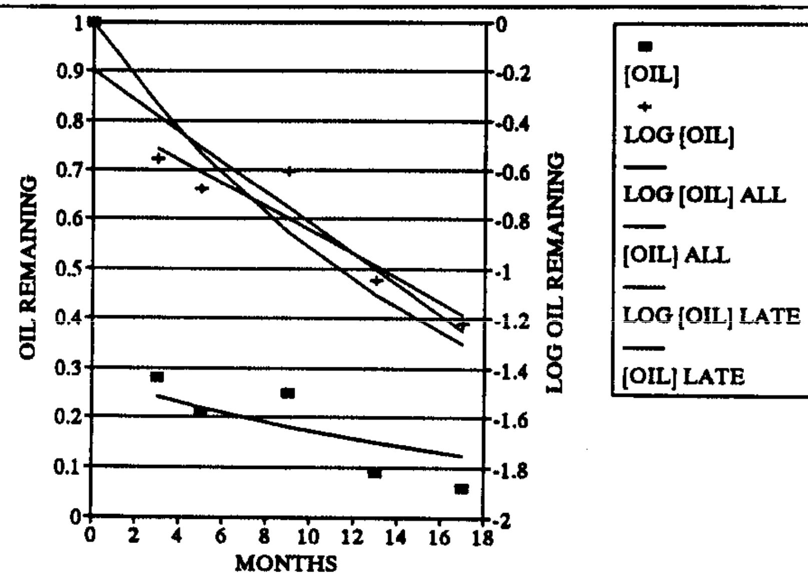

Figure 13. Natural removal of oil (BIOS)

4. STRANDED OIL IN COARSE SEDIMENT MODEL.

The model as we have envisaged it has two levels: a broad view which can be used by regulators and planners, and which can assist in the placement of countermeasure effort; and a site specific model which can assist cleanup assessment teams in assigning cleanup effort. The model is called the "Stranded Oil in Coarse Sediment (SOCS) model.

4.1 OUTPUT REQUIREMENTS

The broad model can produce a general natural cleanup classification for coastal segments as defined in sensitivity atlases. The site specific model must produce a specific natural cleanup prediction, to a specified level of oil removal. Cleanup teams can then determine if this particular beach should receive enhanced cleanup or be left alone, in particular if resources are limited.

4.2 INPUT REQUIREMENTS

For each coastal segment analyzed, data regarding beach length, width, and surface grain size estimates is used with some wave energy scale. The modified effective fetch determination as described by Harper *et al*, (1991) is a potential wave energy scale. They use a six point scale, from low, through moderately low, moderate, moderately high, high, to very high. The four component coastal classification described in the same paper could also provide input. Coastal segments are classified as to substrate, sediment type, width, and slope. The addition of monthly storm statistics would complete the requirements.

On a specific beach, exact parameters can be determined. Length, width, and depth of coarse sediment can be measured. An effective grain size can be determined with more or less precision depending on the final precision required. The nature of the spilled oil will be known, by sampling stranded oil. An evaluation of the oiling character will provide a starting point for the model. If there is pooled oil, the model would be started in the maximum capacity to residual capacity transition mode. If the oiling is restricted to oil covered sediment with little or no free oil, the model would start in the weathering period.

Table 3. Input parameters for SOCS model.

BROAD MODEL	SITE SPECIFIC MODEL
Beach length.	Beach length.
Beach width.	Beach width.
Sediment depth.	Sediment depth.
Wave energy: effective fetch determination.	Wave energy: effective fetch or direct observation.
Storm frequency: regional climate data.	Storm frequency: local climate data.
Generic oil properties: density, viscosity.	Oil properties: composition, density, viscosity.
	Oil cover: see SCAT manual.
	Oil penetration: pit data.
	Oil concentrations; surface and subsurface TPH data.

4.3 MODEL

A slick volume is provided, and assumed oil properties, in this case, 11% aged Prudhoe Bay Crude. The porosity of the beaches are assumed to be 25%. The model includes estimates of beach width (WIDE = 100 m, NARROW = 30 m) and depth (FLAT = 0.1 m, INCLINED = 1 m), and storm events in days per month. First, the model determines if the beach is oiled above capacity. If so, the excess is removed in the first month. The model next determines if the oiling exceeds the residual capacity of 5 L m^{-3}. If so, the transition rate constant is used, if not, the weathering rate constant is used. For each month of time, the model determines the expected number of storm days, from a table, the applies a special removal rate of 10× the transition rate. This applies regardless of present loading.

To provide examples of the broad model input and output, two scenarios are depicted.

Table 4. Model beach parameters.

	SPILL #1	SPILL #2
SUBSTRATE	ROCK & GRAVEL	SEDIMENT
SEDIMENT	GRAVEL	GRAVEL
WIDTH	NARROW (30 m)	NARROW (30 m)
SLOPE	FLAT (D=0.1m)	INCL. (D=1m)
LENGTH	1000 m	1000 m

The estimates of width and depth are somewhat arbitrary until detailed estimates are available.

The results of the two scenarios are depicted in Figures 14 and 15.

For the first scenario, the spill has a high initial loading, and loses the excess capacity in the first month, then enters the transition period for about 15 months, after which it is in the weathering mode. The loading is essentially 0 after 29 months. The oil remaining scale is too gross to see the effect of storms on the removal.

In second scenario, the initial loading is below the residual loading, and the spill is in the weathering mode throughout. The breaks in the curve are due to storm conditions

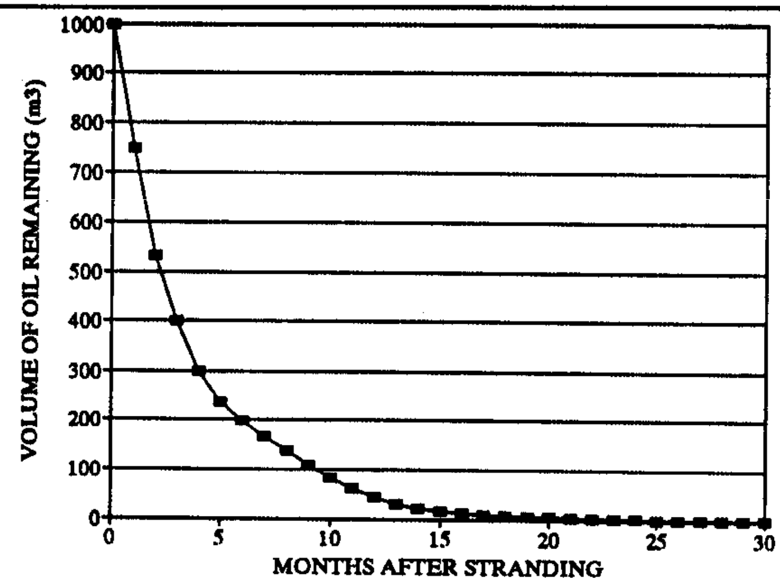

Figure 14. Spill scenario #1

in some months. The loading is essentially 0 after 25 months.

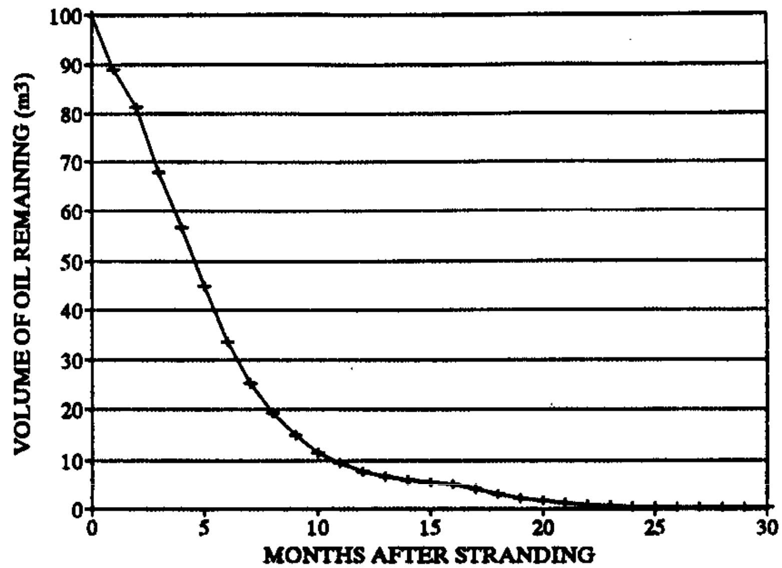

Figure 15. Spill scenario #2.

The site specific model uses the same algorithms, but uses measured data. The output would look the same as presented above for the broad model.

4.4 MODEL TESTING

Testing of the model was accomplished in two ways; a sensitivity analysis of the various components of the model and a comparison of model output to actual data. The sensitivity analysis determines if the model is insensitive to changes to which one would expect differences, or if the model is too sensitive to changes which would not be expected to cause major differences. This relies on experience providing correct expectations. The comparison do real-world data relies on the availability of the data, in forms which can be compared to model output.

SENSITIVITY

The model as developed was tested for sensitivity to the selection of rate constants, to the residual capacity, and to depth of sediment. It can be tested for other parameters as well. The rate constant for removal is the critical parameter in the model, and possibly the least understood. Figure 16 shows oil remaining over time for a series of rate constants. Small changes in the rate constant can make large differences in the amount of oil remaining on the beach.

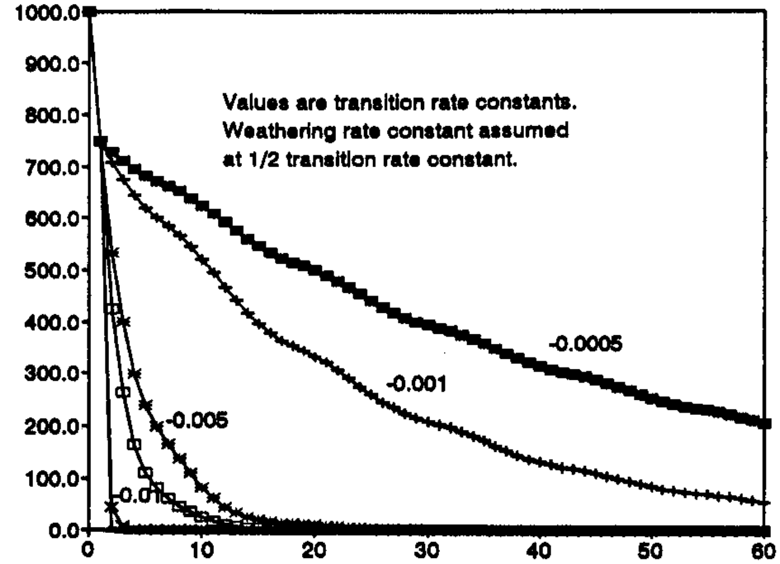

Figure 16. Oil remaining *vs.* rate constant.

The effect of adjusting the residual capacity of the sediment is shown in Figure 17. It appears that the model recognizes an upper limit to residual capacity, and, at least under the scenario of spill 1, is not particularly sensitive to this factor. Residual capacity is the primary representative of grain size in the model.

The depth of sediment, and therefore the beach capacity to hold oil, is a more important factor according to this model rendition. The higher capacity, the longer the oil

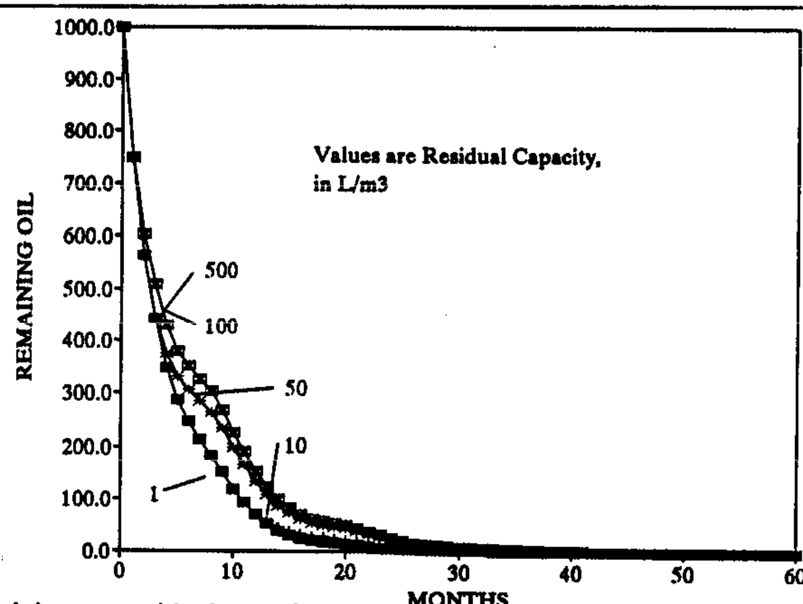

Figure 17. Oil remaining *vs.* residual capacity.

5. PRINCE WILLIAM SOUND DATABASE.

A database has been developed from the results of numerous shoreline surveys following the *Exxon Valdez* spill. Data were supplied by Exxon and by NOAA. The data were supplied in electronic form, in MS-DOS Paradox database format by Exxon, and in Macintosh Excel format by NOAA. Each data set was examined, and the relevant fields copied into general database. The final database consists of a number of related files.

5.1. EXXON DATA

Exxon conducted a number of beach surveys as part of the Shoreline Cleanup Advisory Team (SCAT) program (Owens and Teal, 1990, Owens, 1991). The observations changed over the period from January 1990 to May 1991, as the needs and techniques developed. Some consistent factors remained, and have been combined into consistent data files. In some cases, the fields were not named the same, or were in different formats. In the cases where meaning was obvious, the fields were transferred into a single format.

The surveys for which data have been provided are:

FASST: A FASt Shoreline assessment Team survey of beaches in January, 1990. The first survey after the initial cleanup. Records for 142 beaches were provided (as identified by unique SEGMENT IDs).

SSAT: Spring Shoreline Assessment Team. In April - May 1990, 726 beaches were surveyed.

ASAP: August Shoreline Assessment Program. In August, 1990, 403 beaches were surveyed.

MAYSAP: May Shoreline Assessment Program. In May of 1991, 413 beaches were surveyed. This program fine-tuned the assessment database.

Each set of files which were provided generally included a file called GENMAST, the overview file, SURFMAST, a file containing surface cover data, and SUBMAST, a file containing subsurface oiling data. These were combined into a slightly larger set of files, OILCAT, containing oil category data, SURFOIL, containing surface oil cover data, SUBOIL, containing subsurface oiling data, SUBSTRAT, containing the data on beach substrates, PAVEMENT, containing asphalt pavement data, and LOCATION, a new file joining the Exxon to the NOAA sites where possible. The files and fields are listed in Table 5, below.

The fields from the original data files have been renamed in some cases, and the contents of each field have been modified to approximate the MAYSAP or B.C. SCAT nomenclature. The fields are:

BEDROCK: used in SUBOIL to describe substrate in the pit. Many pits have no substrate description.

BOULDER: as BEDROCK

BROKEN: descriptor of surface oil cover. This refers to a band of 51%-90% oil cover. See CONTINUOUS and PATCHY. These descriptors were used in the SSAT and ASAP programs. Other descriptors used later (SPLASH or TRACE) were not used in early databases, and do not appear as separate fields. Entries are F,H,I,M,P,U,X,Y.

COBBLE: as BEDROCK

CONTINUOUS: descriptor of surface oil cover. This refers to a band of 91%-100% oil cover. See BROKEN.

FAPID: identifier for segments used in the Fate and Effects program. If those data become available, correlations will be possible.

Table 5. EXXON files

FIELDS / FILES	OILCAT	SURFOIL	SUBOIL	SUBSTRAT	PAVEMENT	LOCATION
BEDROCK			Y			
BOULDER			Y			
BROKEN		Y				
COBBLE			Y			
CONTINUOUS		Y				
FAPID						Y
FILM COLOR		Y	Y			
GRANULE			Y			
LITZ		Y	Y			
LOCATION						Y
MEDIUM LENGTH	Y					
MITZ		Y	Y			
MOUSSE/POOLED OIL		Y				
MUD/SILT						
NARROW LENGTH	Y					
NO OIL		Y				
NO OIL LENGTH	Y					
NOAASTN						Y
NOTES		Y	Y			
OIL CHARACTER		Y				
OIL COLOR		Y	Y			
OIL DEBRIS		Y			Y	
OIL FROM (cm)			Y			
OIL TO (cm)			Y			
OILED LOGS					Y	
OILED TRASH					Y	
OILED VEG					Y	
PATCHY		Y				
PAVEMENT		Y				
PAVEMENT AREA					Y	
PAVEMENT CHARACTER					Y	
PAVEMENT THICKNESS					Y	
PEBBLE			Y			
PIT #			Y			
PIT DEPTH (CM)			Y			
REGION	Y	Y	Y	Y	Y	
SAND			Y			
SEGMENT ID	Y	Y	Y	Y	Y	Y

FILM COLOR: BR; brown: RW; rainbow: SL; silver: TL; .
GRANULE: as BEDROCK.
LITZ: Lower Intertidal Zone.
LOCATION: geographical description of NOAA site.
MEDIUM LENGTH: length in metres of segment with MEDIUM oil cover. MEDIUM oil cover is >6 m wide with PATCHY oil cover.
MITZ: Mid intertidal zone.
MOUSSE/POOLED OIL: any oil/water emulsion with a thickness >1cm.. Distribution as C - continuous 91-100%, B - broken: 51-90%, P - patchy: 11-50%, S - splash: 1-10%, T - trace: <1%
MUD/SILT: as BEDROCK
NARROW LENGTH: length in metres of segment with NARROW oil cover. NARROW oil cover is <3 m wide with PATCHY, BROKEN, or CONTINUOUS oil cover.
NO OIL: no oiling observed at the location. Distribution as MOUSSE/POOLED OIL.
NO OIL LENGTH: length in metres of segment with NO OIL.
NOAASTN: unique identifier used by NOAA. Where possible, these are attached to EXXON SEGMENTs

Table 5 (continued). EXXON FILES

FIELDS FILES	OILCAT	SURFOIL	SUBOIL	SUBSTRAT	PAVEMENT	LOCATION
SEGMENT ID	Y	Y	Y	Y	Y	Y
SEGMENT LENGTH	Y			Y	Y	
SITE		Y				
SOURCE		Y	Y	Y	Y	
SPLASH LOCATION		Y				
SSBEDROCK						
SSBOULDER				Y		
SSCOBBLE				Y		
SSGRANULE				Y		
SSMUD/SILT				Y		
SSPEBBLE				Y		
SSSAND				Y		
SSVEGETATION				Y		
SUB DIVISION	Y	Y	Y	Y	Y	
SUBDIV LENGTH	Y			Y	Y	
SUBSURFACE OIL CHARACTER			Y			
SUBSURFACE QUANTIFIER			Y			
SUBSURFACE SEDIMENTS				Y		
SUPRATIDAL ZONE		Y	Y			
SURFACE SEDIMENTS				Y		
SURFOIL COAT		Y				
SURFOIL COVER		Y				
SURFOIL FILM		Y				
SURFOIL RESIDUE		Y				
SURFOIL STAIN		Y				
SURVEY DATE	Y	Y	Y	Y	Y	
TARBALLS		Y			Y	
TIDE ZONE			Y			
UITZ		Y	Y			
UNSURVEYED LENGTH	Y					
VEGETATION			Y			
VERY LIGHT LENGTH	Y					
WATER LEVEL			Y			
WAVE EXP				Y		
WIDE LENGTH	Y					
TOTAL FIELDS	14	30	30	20	17	6
RECORDS (92-6-1)	2,696	11,119	8,884	1,288	1,286	21

NOTES: various notes attached to databases. The meanings are variable.
OIL CHARACTER: a total of 31 different entries were used at various times. The common entries are:
AP: Asphalt pavement.
MS: mousse or pooled oil; thickness >1 cm.
TB: tar balls. Includes patties. Entries of PT or TB/PT have been changed to TB for consistency with new coding.
SR: surface oil residue (includes SOR coding). significantly coated beach sediments
CV: cover. Between 1 mm and 1 cm thick oil.
CT: coat. Between 0.1 mm and 1 mm thick oil which can be scratched off with a fingernail.
ST: stain. less than 0.1 mm thick oil which cannot be scratched off.
FL: film or sheen.
DB: oiled debris. May be qualified with LG: logs; VG: vegetation; TR: trash (which may be cleanup related). SURFOIL and PAVEMENT databases may have qualifiers in an OIL DEBRIS field.
NO: no oil observed.
Other entries make up <0.5% of all entries, and are not defined in the original databases.
OIL COLOR: 10 colors described.
OIL DEBRIS: records include distribution or description, Distribution as MOUSSE/POOLED OIL., description as L: logs, V: vegetation, T: trash
OIL FROM (cm): upper surface of oil lens.
OIL TO (cm): lower surface of oil lens.
OILED LOGS: Distribution as MOUSSE/POOLED OIL.
OILED TRASH: Distribution as MOUSSE/POOLED OIL.
OILED VEG: Distribution as MOUSSE/POOLED OIL.
PATCHY: descriptor of surface oil cover. This refers to a band of 11%-50% oil cover. See BROKEN.
PAVEMENT: Distribution as MOUSSE/POOLED OIL.
PAVEMENT AREA: area of pavement, m2
PAVEMENT CHARACTER: F(?), H(ard?), S(oft?).
PAVEMENT THICKNESS: thickness in cm.
PEBBLE: as BEDROCK.
PIT #: an identifier for a PIT during a single visit. PIT # for the same SEGMENT on different dates do not necessarily correspond in tidal zone or substrate character, and probably do not correspond to the same pit. This database does not indicate substrate changes over time.
PIT DEPTH (CM): total depth to which PIT was dug, in cm.
REGION: PWS: Prince William Sound; KEN: Kenai Peninsula (includes HOMer and SEWard); KOD: Kodiak Island.
SAND: as BEDROCK.
SEGMENT ID: unique identifier for the SEGMENT, and the primary KEY FIELD for the relational data bases.
SEGMENT LENGTH: in metres.
SITE: additional distinguishing code in SURFOIL, 1-11.
SOURCE: EXxon or NoaA or any other source of data. This field is provided for future use, as all records in the EXXON files listed are sourced to EX.
SPLASH LOCATION: now Sporadic, 1-10%. see BROKEN.
SSBEDROCK: surface visible substrate which is bedrock, in % of total substrate for the SEGMENT.
SSBOULDER: as SSBEDROCK.
SSCOBBLE: as SSBEDROCK.
SSGRANULE: as SSBEDROCK.
SSMUD/SILT: as SSBEDROCK.

SSPEBBLE: as SSBEDROCK.
SSSAND: as SSBEDROCK.
SSVEGETATION: as SSBEDROCK.
SUB DIVISION: identifier of SEGMENT sub-division. Actual locations on beach not given.
SUBDIV LENGTH: length in m.
SUBSURFACE OIL CHARACTER: HO: heavy oil, pore spaces filled, but oil not flowing out, LO: light oil, sediments lightly coated, MO: medium oil, heavily coated sediments, no oil in pore spaces, NO: no oil, OF: oil film, OP: oil filled pores, OR: oil residue, TR: trace.
SUBSURFACE QUANTIFIER: *,?,N,VC,UO,Y. No definitions known.
SUBSURFACE SEDIMENTS: B: boulder, C: cobble, P: pebble, G: granule, S: sand, M: mud, R: rock.
SUPRATIDAL ZONE: Above the normal high water mark.
SURFACE SEDIMENTS: as SUBSURFACE SEDIMENTS.
SURFOIL COAT: Distribution as MOUSSE/POOLED OIL.
SURFOIL COVER: Distribution as MOUSSE/POOLED OIL.
SURFOIL FILM: Distribution as MOUSSE/POOLED OIL.
SURFOIL RESIDUE: Distribution as MOUSSE/POOLED OIL.
SURFOIL STAIN: Distribution as MOUSSE/POOLED OIL.
SURVEY DATE: Date beach was visited.
TARBALLS: presence of tarballs on beach; P: patchy; S: ; T: ; Y: .
TIDE ZONE: S: Supratidal; U: UITZ; M: MITZ; L: LITZ. Used in SUBOIL only. Combinations are possible.
UITZ: Upper Intertidal Zone.
UNSURVEYED LENGTH: length in metres of segment which was not surveyed.
VEGETATION: as BEDROCK.
VERY LIGHT LENGTH: length in metres of segment with <10% oil cover regardless of width. Includes SPLASH or TRACE descriptors.
WATER LEVEL: level in cm where water table met in a pit.
WAVE EXP: H: high, M: moderate, L: low. No specific characteristics of fetch or wave height given.
WIDE LENGTH: length in metres of segment with WIDE oil cover. WIDE oil cover is >6 m wide with BROKEN or CONTINUOUS oil cover.

5.2 NOAA DATA

NOAA, through its contractor, RPI, provided a set of 158 Macintosh Excel files containing oil cover and shoreline data, including TPH results (GOG, gravimetric oil and grease, and VOG, volumetric oil and grease). These files were translated into QuattroPro files, rearranged, then imported into Paradox. Three files resulted from this. The files and contents are listed in Table 6, below.

The fields are:
%SURFOIL: cover percentage of surface oil.
ANALDATE: date sample analyzed.
ANALSAMDEP: sample depth from analytical log, in cm. Not always the same as the SAMDEP.
BACKSTAKE: The height of the backstake, in cm, relative to the height of the 0 elevation.
DISTANCE: The distance from the 0 elevation, in m.
ELEVATION: The elevation, in cm, of each distance.
GOG: the TPH, in mg kg^{-1}
GRAINSIZE: a six sub-field record, of B/C/P/G/S/M in percentage of each substrate.

NOAASTN: the NOAA station ID, see the LOCATION.DB file.
OIL INTERVAL: from and to data, apparently in cm.
SAMDEP: depth of sample from the sampling log, in cm.
SAMID: a unique identifier for the sample. Includes station, sample number, and month-year information.
SAMNO: a sample number. Redundant if SAMNO present.
SURVEY DATE: date of the survey.
TIDEZONE: S: supratidal, U: UITZ, M: MITZ, L: LITZ. See above.
VOG: volumetric oil and grease, in mg L^{-1}.

Table 6. NOAA files

FIELDS FILES	NOAACOVR	NOAARES	NOAAGOG
%SURFOIL	Y		
ANALDATE			Y
ANALSAMDEP		Y	
BACKSTAKE	Y		
DISTANCE	Y	Y	
ELEVATION	Y	Y	
GOG		Y	Y
GRAINSIZE	Y		
NOAASTN	Y	Y	Y
OIL INTERVAL		Y	
SAMDEP		Y	
SAMID		Y	Y
SAMNO		Y	
SURVEY DATE	Y	Y	
TIDEZONE		Y	Y
VOG		Y	Y
TOTAL FIELDS	7	12	7
RECORDS (92-6-1)	2,540	593	742

5.3 DATA ANALYSIS PERTINENT TO THE MODEL.

The very large number of data from Prince William Sound include combinations of wave energy, beach substrate, and subsurface oil data. The model is based on a wave energy difference being related to differences in rate of removal. This would appear in the model in terms of increase in rate due to storms, which is for the moment taken as a factor of ten. The beach substrate would be expected to be affected by the wave energy as well, as high wave energy beaches would be expected to be deprived of smaller sediment sizes relative to low wave energy relative to low wave energy beaches. The data from Prince William Sound do not support this view. Figure 19 shows the relationship of the effective grain size (an average of phi values for the substrate) vs. wave energy. There is a very slight increase in smaller sediments in low energy beaches, but not a significant difference over all.

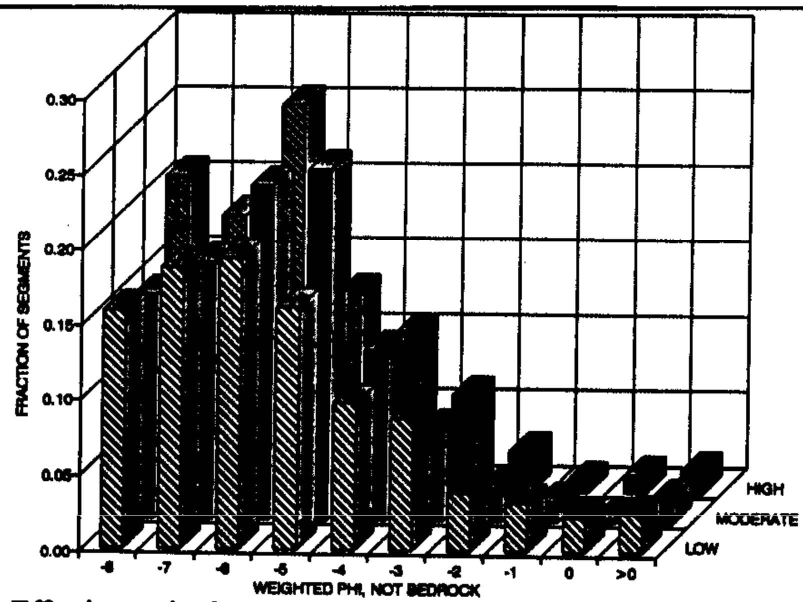

Figure 19. Effective grain size vs wave energy, Prince William Sound data.

The depth of penetration of oil is also expected to depend on sediment type. The data from Prince William Sound show that the penetration and thickness of subsurface oil are relatively independent of tidal zone and wave energy.

The concentration of oil remaining in the beach sediments was measured on a number of occasions by NOAA. Again, the differences expected by our conception of oil contamination do not appear in the data taken in whole. There are no apparent differences

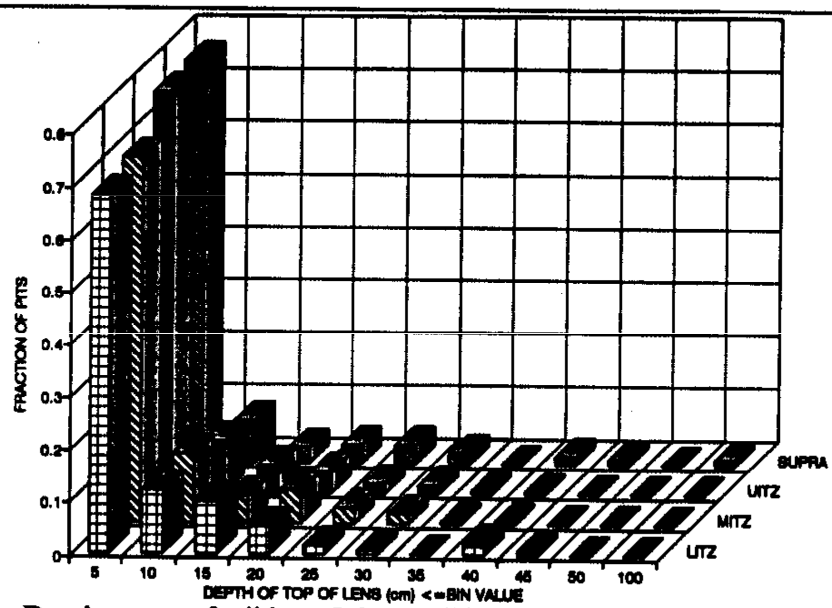

Figure 20. Depth to top of oil lens, Prince William Sound data.

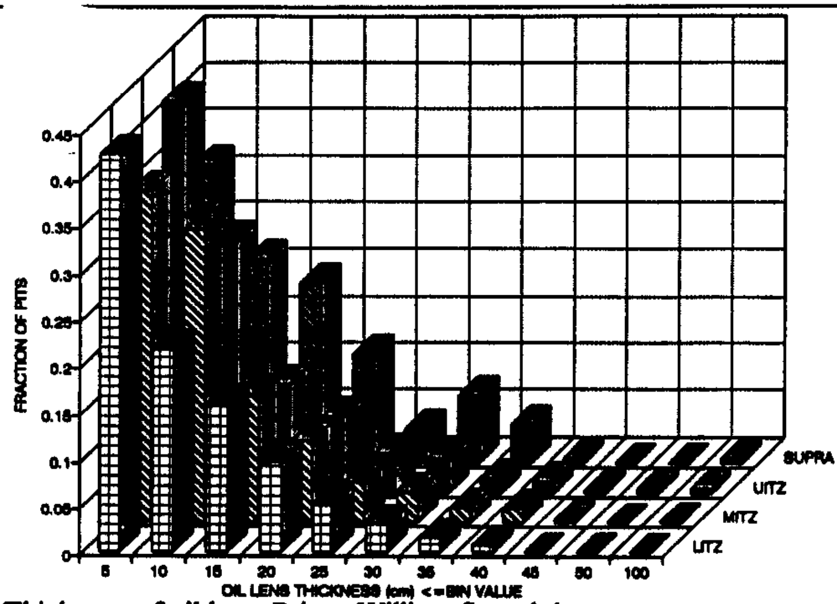

Figure 21. Thickness of oil lens, Prince William Sound data.

in oil concentration according to tidal zone or wave energy.

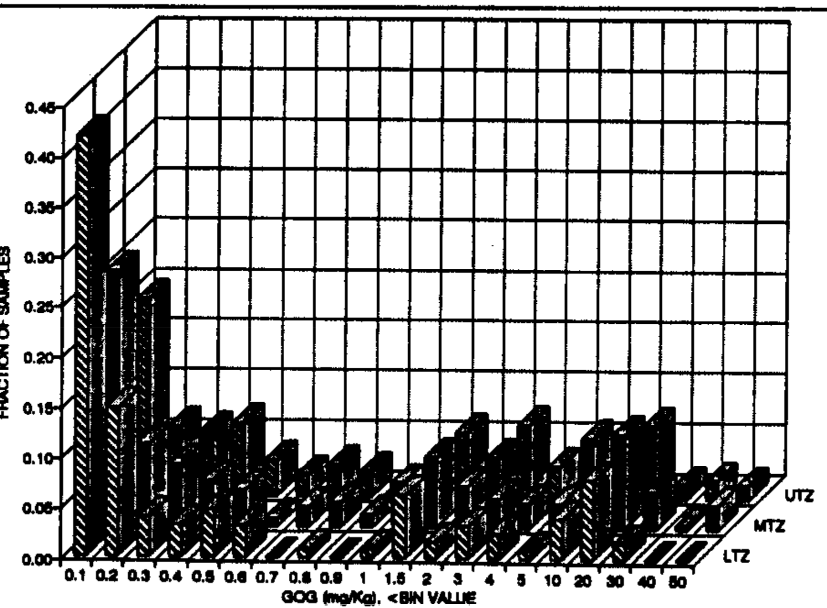

Figure 23. Gravimetric oil and grease.

6. DISCUSSION.

The exercise of modeling requires a close scrutiny of the factors which may affect the outcome. Many of these may not play important roles in the model, but must be examined prior to exclusion. Others, while apparently important, may be inadequately supported by data, and must be either estimated or ignored. The SOCS model is made up of a number of parts:

Table 7. Model divisions

DIVISION	COMMENTS
Initial oiling, removal, and re-oiling	Assumed to reach beach capacity in one or two tide cycles; no experimental or spill data.
Beach capacity	Basic principles; no experimental or spill data.
Transition	Rate estimated from single experiment; spill data may be available. Further experiments or spills of opportunity needed.
Residual capacity	Basic principles; no experimental or spill data. Experimental data important for confirmation.
Weathering	Rate estimated from single experiment; spill data may be available. Further experiments or spills of opportunity needed. Many factors affect this component, and limited data precludes separating the factors at this time. Some recent papers suggests that more interest is being directed at this aspect.
Storm events	Estimated influence. No experimental or spill data.
Cleanup effort	Not included, may be factored in when data available. If method-specific data is available, estimates of method success may be compared to natural removal for specific sites.
Beach biota	Not included, may be factored in when data available.

In general, the model reproduces the appearance of reality in the removal of oil from a beach. At the present time, it can accommodate differences in wave climate and storm strength and frequency. The sensitivity analysis indicates that the removal rate constants are the dominant factors in the model, while beach capacity or residual capacity are less important. These removal rate constants are also the weakest components in the chain.

The data from Prince William Sound did not provide a source of interactions or supporting data for the processes described by the model. This is likely due to two reasons. At the present time, the data have been examined as a full set. Tests on all data indicate that there are few differences between wave energy and other factors in Prince William Sound. It may be that the wave energy scale used is too narrow to distinguish between the factors. Examination of selected segments may provide specific relationships. Another confounding factor is the assumption inherent in the analysis that cleanup activities did not modify the over-all results. This assumption is obviously poor. Data on cleanup effort is part of the database from the Alaska Department of Environment and Conservation, and will play an important role when available.

The model can now provide a platform on which different estimates of oil removal may be tested.

7. DATA REQUIREMENTS

To improve the model, new data are necessary to define some of the relationships better. These data may be obtained from laboratory experiments, meso-scale experiments, and field experiments.

The predictive value of the model depends on the quality of the large-scale beach data available from video surveys specifically for spill contingency planning or from aerial surveys available for general use. A serious weakness in remote sensing of beach sediments is the inability to measure depth of sediment. A beach which appears to be a cobble beach from the surface may in fact be only one layer of cobble, with fine sediment underneath. The beach capacity to hold oil and to retain oil varies dramatically depending on the depth of the coarse sediment. If a clear relationship between measurable beach characteristics, such as surface sediment size, beach slope and effective fetch, and sediment depth can be made, the broad model predictive capacity will improve.

7.1 LABORATORY EXPERIMENTS

The first level of need is to determine realistic porosities and permeabilities for actual beach sediments, and the capacity to hold and retain oil. Concurrent with those determinations, the rate of oil removal by tidal flushing can be estimated.

The parameters should be measured in consistent sediments and in sediment mixtures, where there is a large change in effective phi in the sediment composition.

These experiments should be conducted on a scale large enough to avoid edge effects, but also on a small scale suitable for conducting a large number of tests.

7.2 MESOSCALE EXPERIMENTS

When a better understanding of oil capacity and retention is available, the effects of wave energy could be examined in meso-scale experiments, where artificial beaches are subjected to different levels of wave action, and the processes of particle movement and oil removal examined under controlled conditions.

Of particular interest here is the efficiency of an 'armor layer' in protecting the finer substrates beneath them from the effects of natural removal.

7.3 FIELD EXPERIMENTS

Once the parameters affecting natural oil removal are better understood, and the model improved to reflect experimental results, the final test must be a real-world test, either in the form of a spill of opportunity or an experimental spill. The latter is more desirable, as the conditions of the spill can be selected to cover the parameters of interest.

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