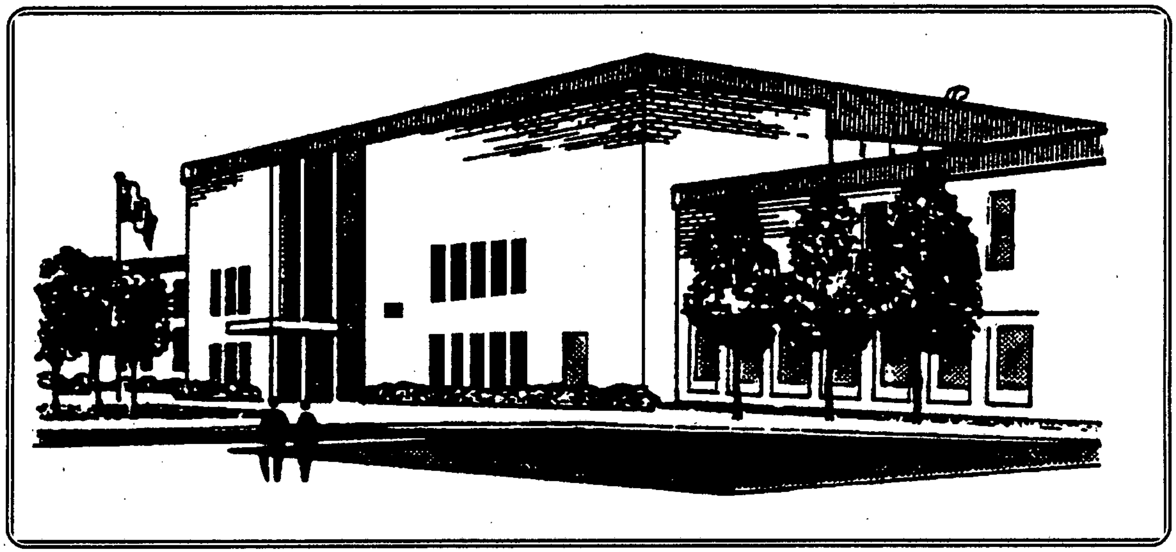
L

Stranded Oil in Coarse Sediments (SOCS) Model



REPORT SERIES NO. EE-146

ENVIRONMENTAL TECHNOLOGY CENTRE
EMERGENCIES SCIENCE DIVISION

Environment Canada Environnement Canada

Canada

STRANDED OIL IN COARSE SEDIMENTS (SOCS) MODEL

by:

Blair Humphrey
EdviroEd Consultants Ltd.

This report has not undergone detailed technical review by the Environmental Protection Directorate and the content does not necessarily reflect the views and policies of Environment Canada. Mention of trade names or commercial products does not constitute endorsement for use.

This unedited version is undergoing a limited distribution to transfer the information to people working in related studies. This distribution is not intended to signify publication and, if the report is referenced, the author should cite it as an unpublished report of the Directorate indicated below.

Any comments concerning its content should be directed to:

Environment Canada
Environmental Protection
Environmental Technology Centre
Ottawa , Ontario
K1A 0H3 CANADA

EE-146 **January, 1994**

Table of Contents

List of Tables

List of Figures

Acknowledgements

This work has been supported by the strong interest of Gary Sergy of Environment Canada, who, for a number of years, has pursued the question of the fate and persistence of oil stranded on coarse sediment beaches. This work has benefited from his guidance and from discussions with Gary, John Harper, and Ed Owens. The assistance of Dr. J. Michel of Reasearch Planning Institute and Andy Teal of Imperial Oil in obtaining data has been invaluable. I wish to thank the National Ocean and Atmospheric Agency and Exxon for permitting us the use of the data.

Funding for this project was provided by the Emergencies Science Division of Environment Canada, Edmonton, Alberta, as part of the pollution emergencies R&D program of the River Road Environmental Technology Centre, Ottawa, and by the Panel for Energy Research and Development (PERD).

Abstract

Data related to the fate and persistence of oil stranded on coarse sediment beaches has been collected in a set of database files. The files have been updated to include data from 1991 and 1992 surveys.

The model developed to describe the fate and persistence of this stranded oil has been modified to better reflect real circumstances.

The results of a series of oil penetration and tidal flushing experiments in columns containing sediments of two grain sizes: granules and pebbles have been used to modify the model. The experimental results are described and the influence of the physical and chemical properties of weathered oil is discussed.

Résumé

Des fichiers informatiques sur le devenir et la persistance de pétroles échoués sur des plages de sédiments grossiers ont été mis à jour à la suite d'études faites en 1991 et 1992.

Le modèle existant du devenir et de la persistance du pétrole échoué a été modifié de façon à mieux rendre compte des conditions réelles.

Les résultats d'une série d'essais consistant à étudier la pénétration du pétrole dans des colonnes de sédiments de taille différente (granules; cailloux et galets), avec simulation du retrait de la marée, ont été utilisés pour modifier le modèle. Les résultats des essais sont présentés, et l'influence des propriétés physiques et chimiques du pétrole vieilli est examinée.

INTRODUCTION

The probability that an oil spill in Canadian waters will impact on coarse sediment beaches is high. The high cost of cleaning remote coarse sediment beaches was shown after the spill from the *Exxon Valdez* in Prince William Sound, Alaska. In order to plan for potential spills and to assist in regulatory decision making, a model which predicts the fate of oil stranded on coarse sediment beaches has been under development (Humphrey *et al*, 1992). The model was developed after a review of the processes which affect coarse sediment beaches (Humphrey and Noone, 1991) and the collection of all data available at the time relating to oil fate in Prince William Sound (Humphrey *et al*, 1992).

In the past year, more data from Prince William Sound has been added to the database and other data sources reviewed. The model has also been modified in light of new information. The first model used estimates or the effective porosity of sediments, their permeability, and their residual capacity to oils. These estimates were derived from the literature for conditions dissimilar to those expected on coarse sediment beaches. In order to provide better estimates for these important factors, a series of column experiments were undertaken.

The new model incorporates information from the expanded PWS database and from the column experiments, and introduces a number of additional factors which make it more sensitive to actual conditions.

As our understanding of the processes occuring on coarse sediment beaches, information weaknesses become more apparent. Some suggestions for additional work which would apply directly to the modeling are made.

Databases

Both Exxon and NOAA provided electronic copies of data relating to oil fate after the *Exxon Valdez* incident in Prince William Sound. These files were restructured into a set of Exxon files:

OILCAT.DB	shoreline segments and oil length category,
SURFOIL.DB	surface oil cover and character,
SUBOIL.DB	subsurface oil character,
SUBSTRAT.DB	sediment characteristics of each segment,
PAVEMENT.DB	asphalt pavement characteristics, and
LOCATION.DB	compares Exxon segments to NOAA segments.

The files obtained from NOAA were restructured into a set of files:

NOAACOVR.DB	surface oil cover (%) and transect elevations,

NOAAGOG.DB	the gravimetric oil and grease data, and
NOAARES.DB	which relates the GOG results to the sample locations

Full descriptions of these files can be found in Humphrey *et al*, 1992.

Model

The concept for the SOCS model involved two distinct levels of detail: a broad view which could be used by regulators and planners, and which could assist in the placement of countermeasure effort; and a more rigorous site specific model which could assist cleanup assessment teams in assigning cleanup effort.

The broad model could 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 could then determine if this particular beach should receive enhanced cleanup or be left alone, in particular if resources are limited.

For the broad model the data may be estimated from photographs and atlases. For each coastal segment analyzed, data regarding beach length, width, and surface grain size estimates are used with a wave energy scale. This method used a six point energy scale and a four component coastal classification. Coastal segments are classified as to substrate, sediment type, width, and slope. The addition of monthly storm statistics completed the requirements for input to the broad model.

On a specific beach, exact parameters are required. Length, width, and depth of coarse sediment can be measured. An effective grain size could be determined with more or less precision depending on the final precision required. The nature of the spilled oil is determined by sampling stranded oil. An evaluation of the oiling character provides a starting point for the model. If there is pooled oil, the model is 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 is started in the weathering period.

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

The estimates of width and depth were somewhat arbitrary. A sensitivity analysis of the model results showed that the model was most sensitive to the magnitude of the transition rate constant. Residual capacity and depth of sediment were also important factors, but proportional changes in those are not as significant as similar changes in the rate constant.

DATABASE UPDATE

Exxon Data

Unlike previous years, we were not provided with electronic copies of files from the surveys, but with reports which summarized the data. A survey in the spring of 1992 (FINSAP) combined the examination and treatment in one visit to each segment. The results of the surveys were communicated to the Federal On-Scene Commander in September, 1992 (Loggie, 1992).

In 1992, 81 subdivisions were visited. No detailed oil cover data was reported for surface oil and an area estimate of subsurface oil was made. This area estimate has been added to the SUBOIL data file in the NOTES field. No methodology was provided for the indices used in the analyses. Additional analyses of miles of cover by bandwidth provide a useful overview of surface oiling, but the changes between years are due to cleanup and natural processes, and until some index of cleanup effort is available, the rate of natural removal is unobtainable.

NOAA Data

The data provided by Research Planning, Inc., on behalf of NOAA, give an interesting overview of beach dynamics and oil cover changes in Prince William Sound. Locations of the NOAA stations are shown in Figure 1. One transect at each station was monitored irregularly from 1989. Eight transects were monitored until 1992. The stations and dates are listed in Table 1. Not all data collected was provided: Michel and Hayes (1992b) show data for a segment on a date not in our database.

Figures 2a-h show the beach profiles for those transects monitored until 1992. Some beaches are remarkably constant (e.g. N7). Others (e.g.N-9, N-17, N-18) show a wide variance of elevation, indicating considerable reorking of the sediment. Corresponding oil cover estimates have been included. These do not infer oil character; that attribute was not included in some of the data sets. The changees in oil cover are depicted in Figures 3a-h for the same stations as the elevation plots. While for most stations, the oil cover decreases with time, for some (e.g. N-15) the oil is clearly being moved around the beach, as both cleanup effort (possible berm relocation) and natural reworking displace oil from location to location. For most stations, there was very little oil cover after 1990. N-15 is an exception, with 60% oil cover on part of the beach in August of 1991. There are no corresponding GOG data for this period, and no oil character listed, but Michel and Hayes, (1992a) refer to the oil as stain and coat. This anomaly is apparently caused by a berm relocation effort; the area with the stain being the excavated trench. No oil had been reported at that location in January, 1991.

A full description of the NOAA surveys may be found in Michel and Hayes (1992b).

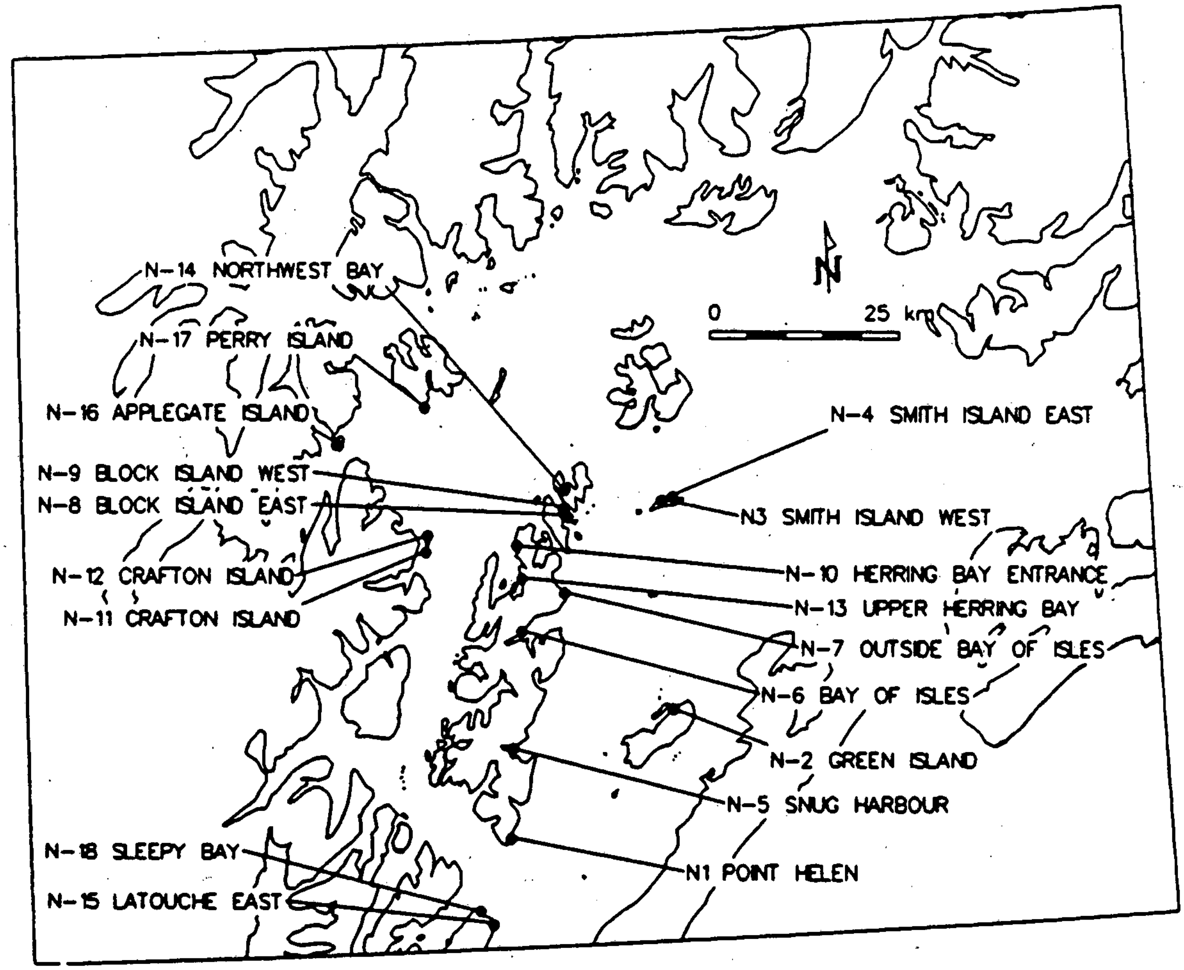


Figure 1. NOAA Stations in Prince William Sound.

Table 1. NOAA Station Survey dates.

STN	DATE	STN	DATE	STN	DATE	STN	DATE	STN	DATE	STN	DATE
ELI-1A	92-08-14	N-4	89-09-17	N-8	89-09-17	N-11	89-09-18	N-14	89-09-19	N-16	89-09-18
ELI-1B	92-08-14	N-4	89-10-18	N-8	89-10-17	N-11	89-10-17	N-14	89-10-22	N-16	89-11-05
MB1_92	92-08-14	N-4	89-12-04	N-8	89-12-04	N-11	89-11-05	N-14	89-12-08	N-16	89-12-06
		N-4	90-01-01	N-8	90-01-02	N-11	90-01-05	N-14	90-02-02	N-16	90-01-31
N-1	89-09-16	N-4	90-01-30	N-8	90-01-31	N-11	90-02-03	N-14	90-05-23	N-16	90-06-22
N-1	89-10-20	N-4	90-03-04	N-8	90-03-04	N-11	90-03-01	N-14	90-09-04	N-16Y	90-06-25
N-1	89-11-06	N-4	90-05-25			N-11	90-05-31	N-14	91-01-24		
N-1	89-12-07	N-4	90-09-01	N-9	89-09-17	N-11	91-01-20	N-14	92-08-14	N-17	89-09-18
N-1	90-01-05	N-4	91-01-21	N-9	89-10-22	N-11	91-08-29	N-14(N	91-01-24	N-17	89-11-05
N-1	90-02-01	N-4	91-08-26	N-9	89-11-07	N-11a	90-05-31			N-17	89-12-06
N-1	90-05-24			N-9	90-01-02			N-15	89-09-19	N-17	90-01-31
N-1	90-09-06	N-5	89-09-17	N-9	90-01-31	N-12	89-09-18	N-15	89-10-20	N-17	90-09-07
N-1	91-01-23	N-5	89-10-20	N-9	90-03-03	N-12	89-10-17	N-15	89-11-06	N-17	91-01-20
N-1	91-08-27	N-5	89-12-07	N-9	90-06-22	N-12	89-11-05	N-15	89-12-05	N-17	91-08-29
N-1	92-08-13	N-5	90-01-05	N-9	90-09-06	N-12	90-01-05	N-15	90-01-04	N-17	92-08-10
		N-5	90-02-01	N-9	91-01-25	N-12	90-02-03	N-15	90-02-01	N-17b	91-01-20
N-2	89-09-16	N-5	90-05-31	N-9	92-08-11	N-12	90-03-01	N-15	90-05-26	N-17c	91-01-20
N-2	89-10-20	N-5a	90-05-31			N-12	90-05-31	N-15	90-09-05		
N-2	89-11-06			N-10	89-09-19	N-12	90-09-04	N-15	91-01-22	N-18	89-09-19
N-2	90-01-04	N-6	89-09-17	N-10	89-10-22	N-12	91-01-20	N-15	91-08-28	N-18	89-10-20
N-2	90-02-02	N-6	89-10-18	N-10	89-11-07	N-12	91-08-29	N-15	92-08-13	N-18	89-11-06
N-2	90-05-27	N-6	90-01-02	N-10	89-12-07	N-12	92-08-13	N-15X	91-08-28	N-18	89-12-05
N-2	90-09-07	N-6	90-05-31	N-10	90-01-06			N-15Y	90-06-25	N-18	90-01-04
		N-6	92-08-14	N-10	90-02-02	N-13	89-09-18	N-15Y	91-08-28	N-18	90-02-01
N-3	89-09-16	N-6a	90-05-31	N-10	90-03-02	N-13	89-10-27	N-15a	91-01-22	N-18	90-05-24
N-3	89-10-18			N-10	90-05-27	N-13	89-11-07	N-15x	91-01-22	N-18	90-09-05
N-3	89-12-04	N-7	89-09-17	N-10	91-01-19	N-13	89-12-07	N-15xa	90-06-25	N-18	91-01-22
N-3	90-01-01	N-7	89-10-18	N-10 Y	91-01-19	N-13	90-01-06	N-15xb	91-01-22	N-18	92-08-14
N-3	90-01-30	N-7	89-12-04	N-10X	90-05-27	N-13	90-02-03	N-15y	91-01-24	N-18-X	90-05-26
N-3	90-03-04	N-7	90-01-02	N-10X	90-09-05	N-13	90-03-02				
N-3	90-05-25	N-7	90-02-02			N-13	90-05-27				
N-3	90-09-07	N-7	90-05-25			N-13	91-01-19				
N-3	91-01-21	N-7	90-09-06			N-13a	90-05-27				
N-3	92-08-16	N-7	91-01-23			N13_92	92-08-12				
N-3 #2	91-08-26	N-7	91-08-27								
		N-7	92-08-15								

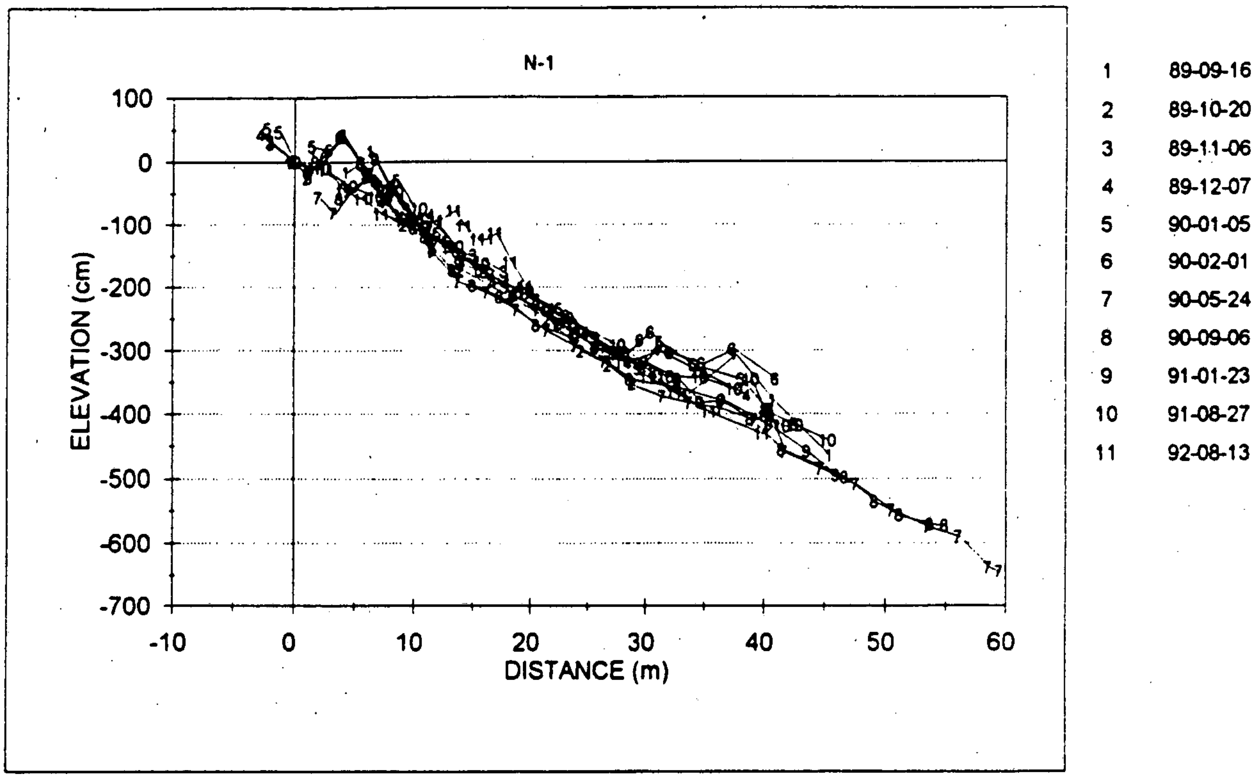


Figure 2a. N-1 Beach elevations.

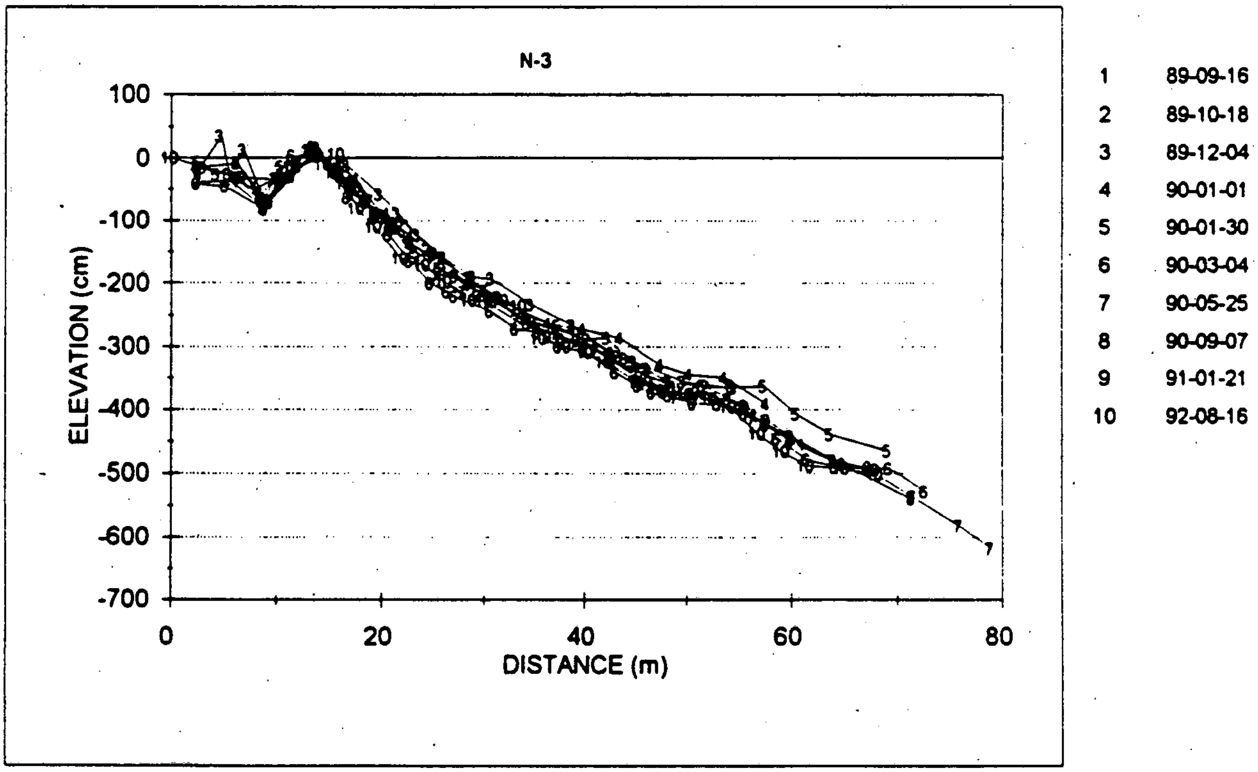


Figure 2b. N-3 Beach elevations.

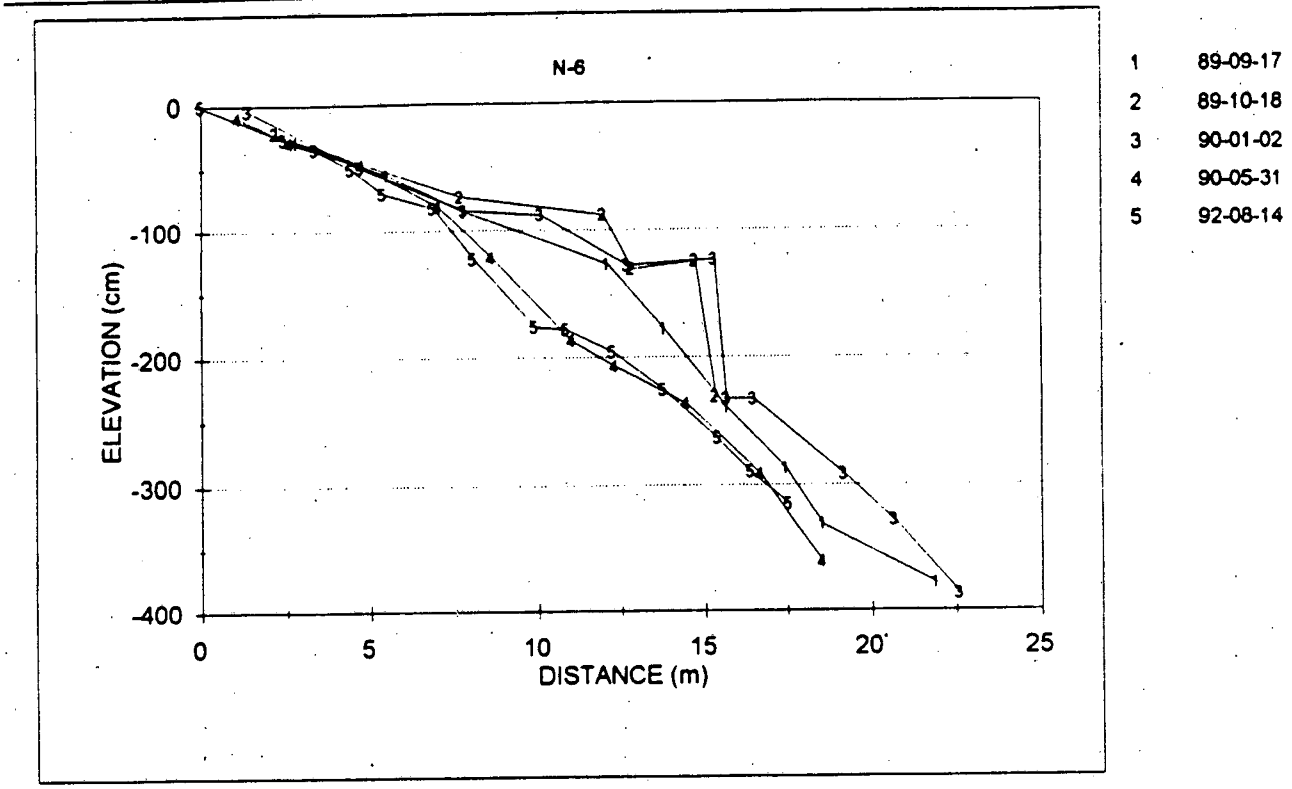


Figure 2c. N-6 Beach elevations.

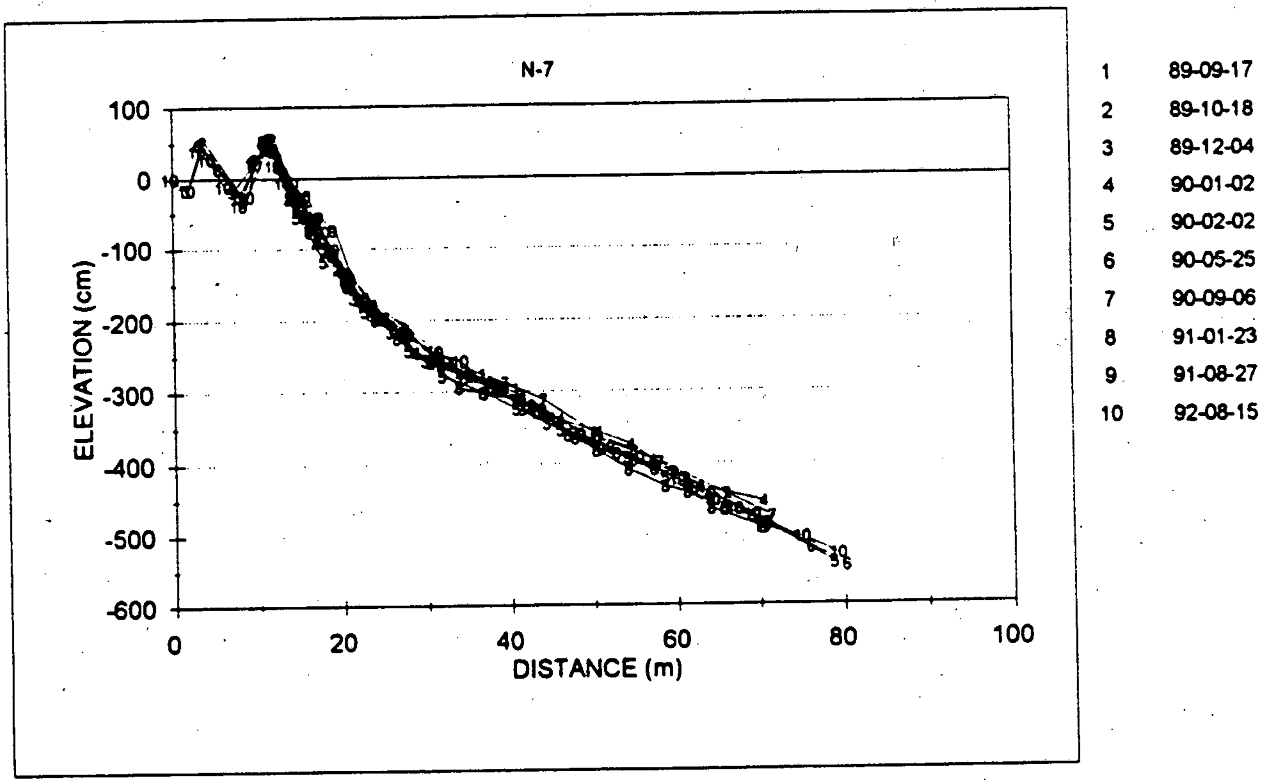


Figure 2d. N-7 Beach elevations.

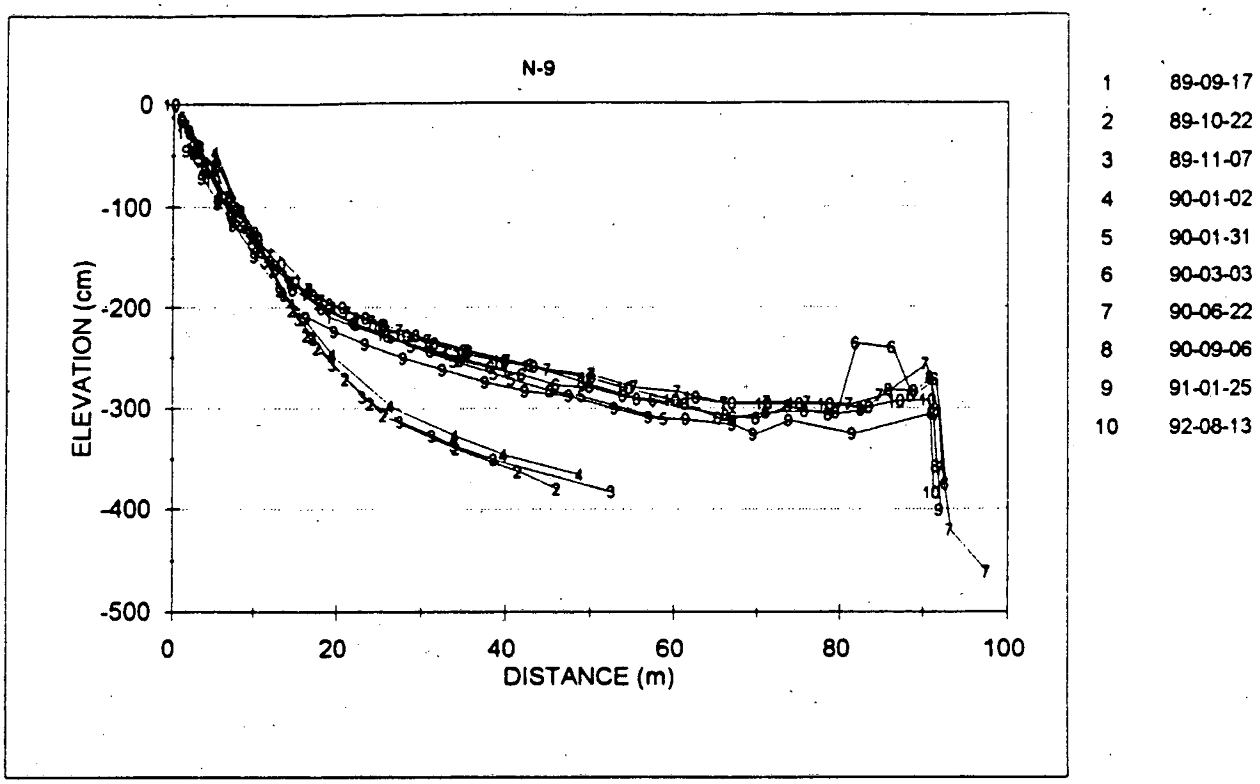


Figure 2e. N-9 Beach elevations.

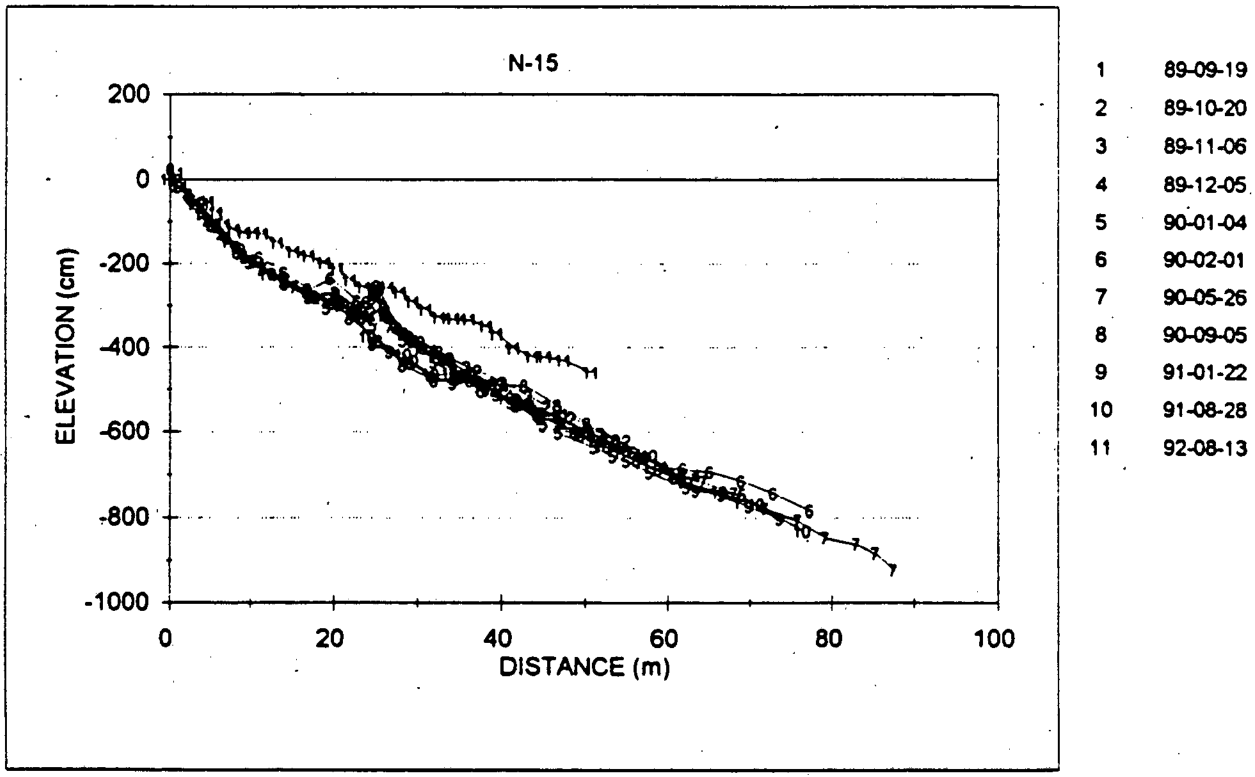


Figure 2f. N-15 Beach elevations.

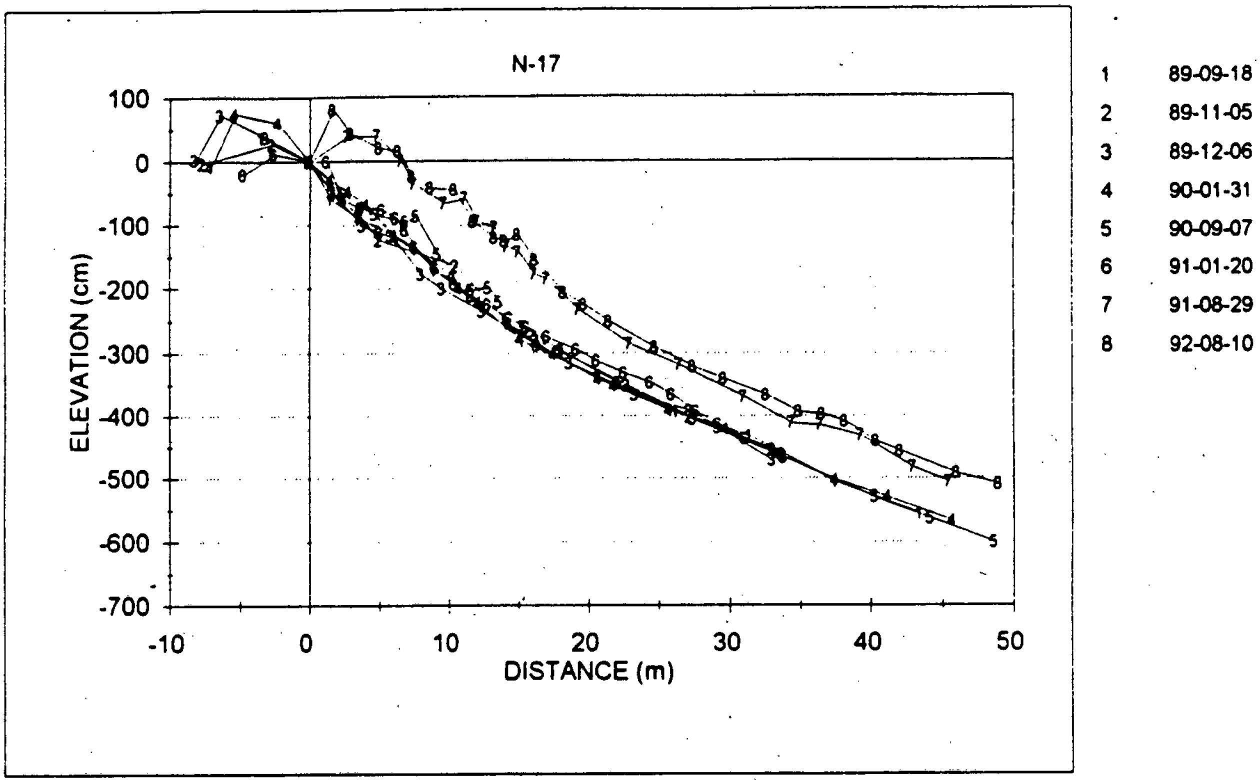


Figure 2g. N-17 Beach elevations.

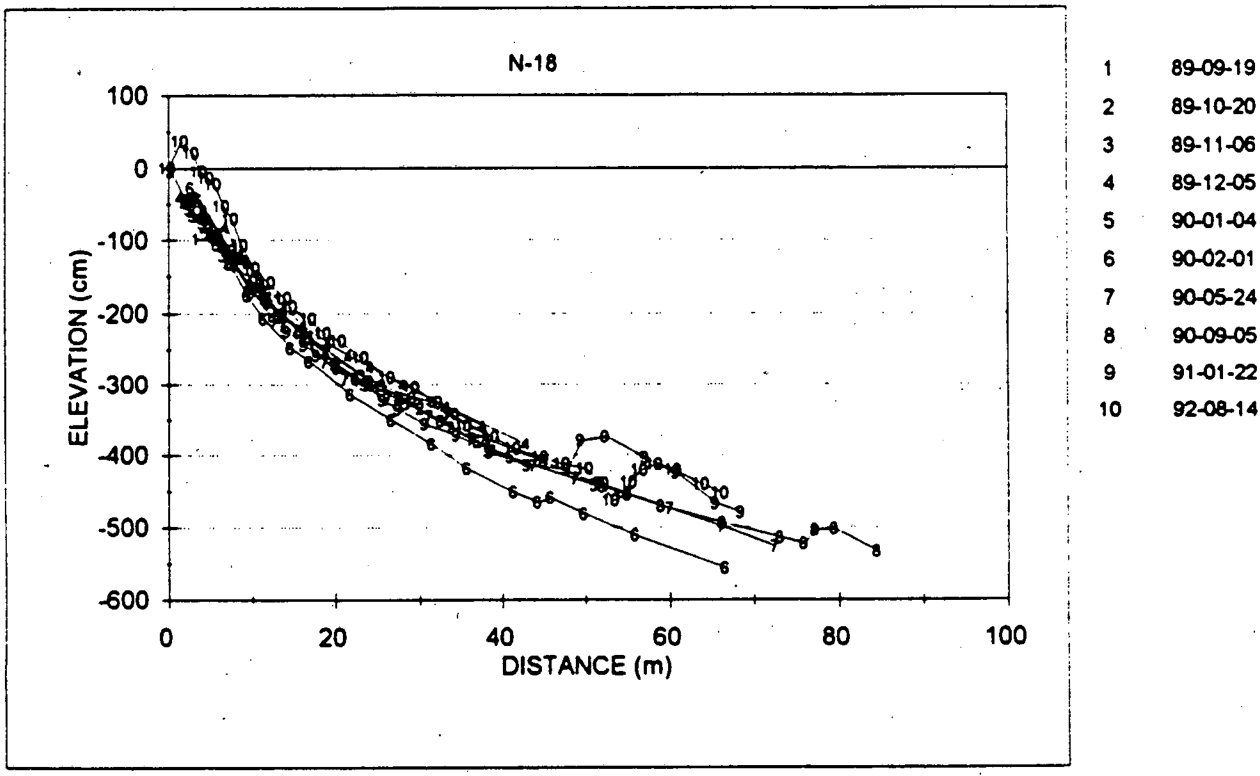


Figure 2h. N-18 Beach elevations.

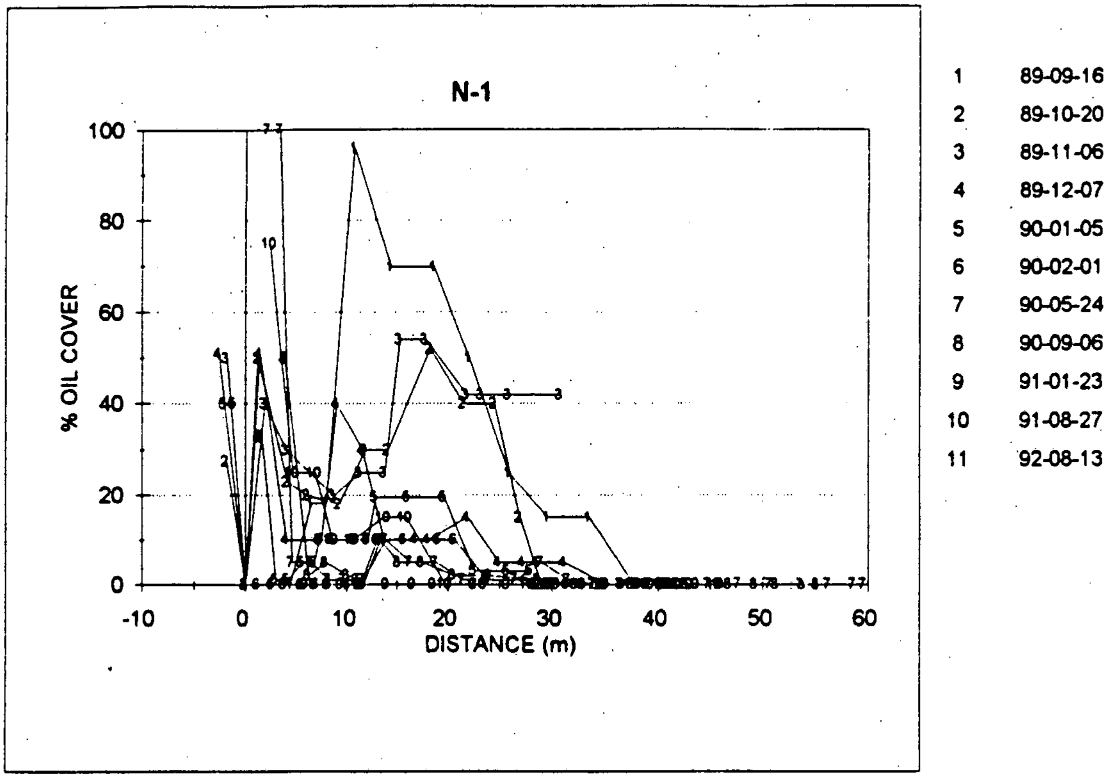


Figure 3a. N-1 Oil cover.

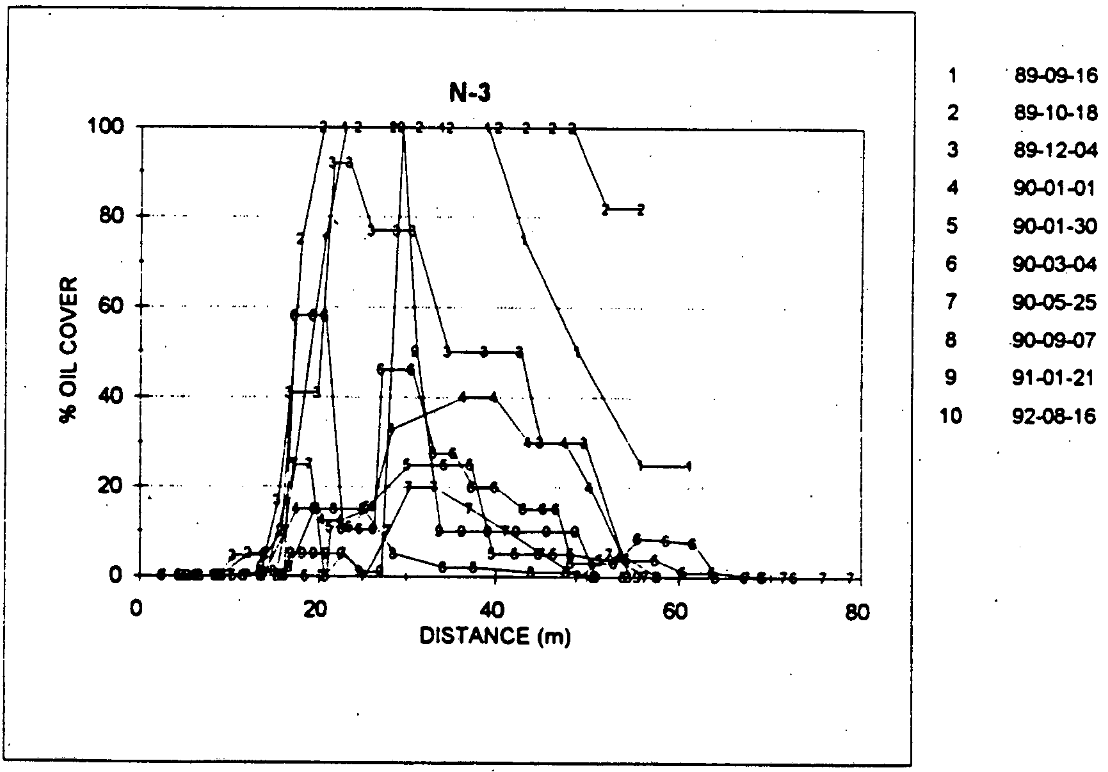


Figure 3b. N-3 Oil cover.

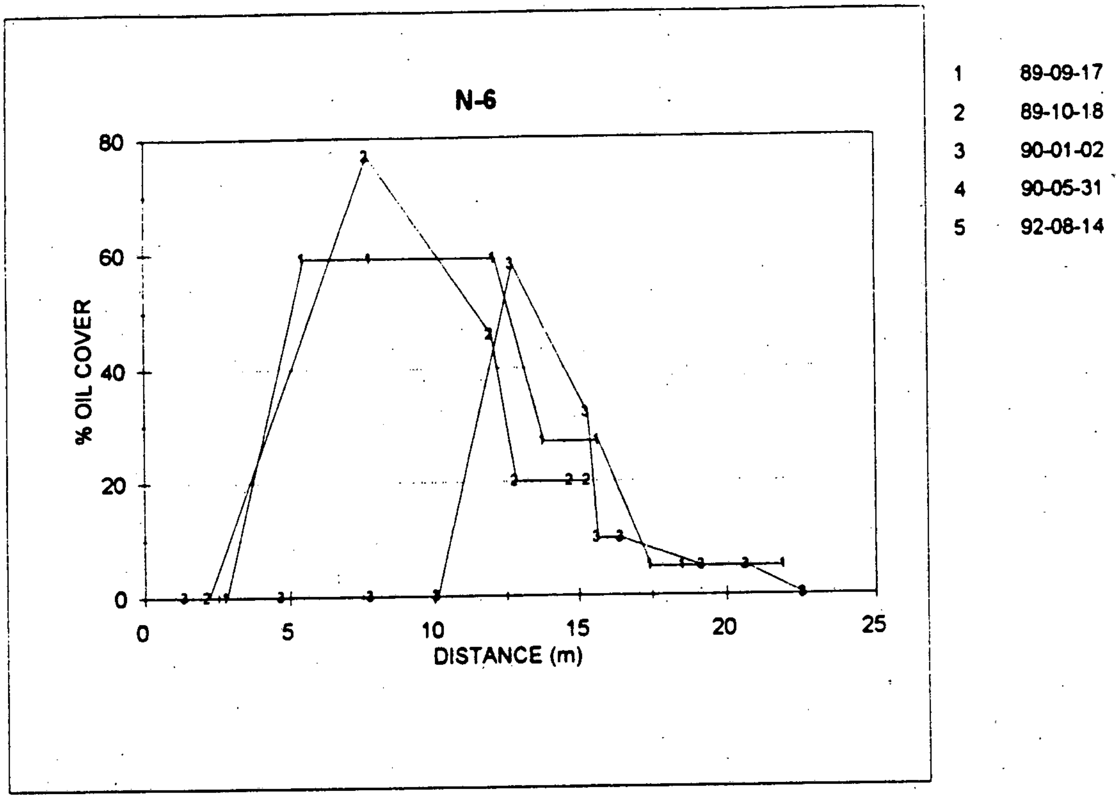


Figure 3c. N-6 Oil cover.

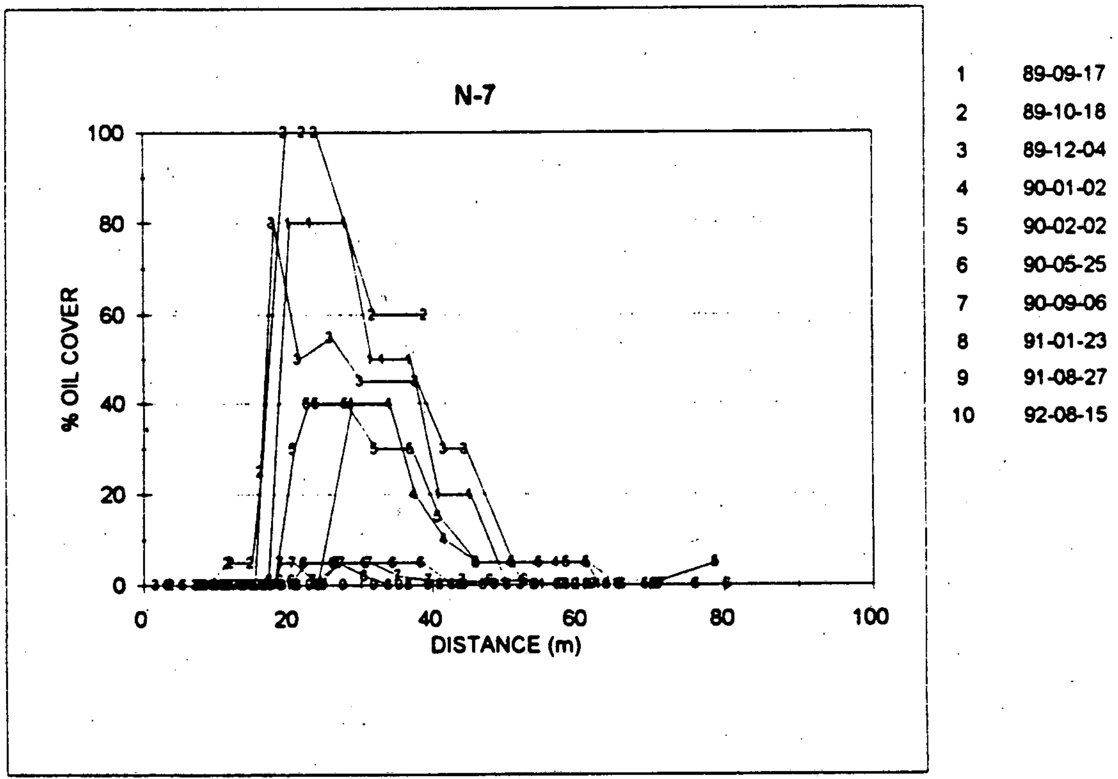


Figure 3d. N-7 Oil cover.

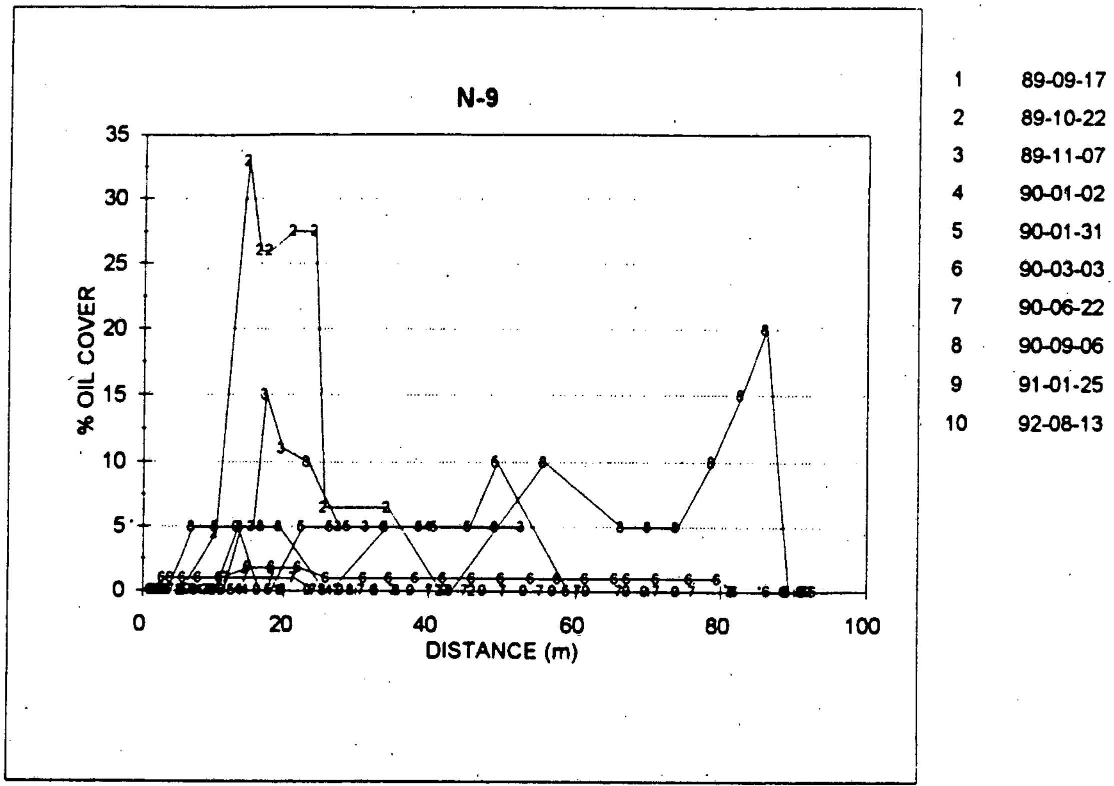


Figure 3e. N-9 Oil cover.

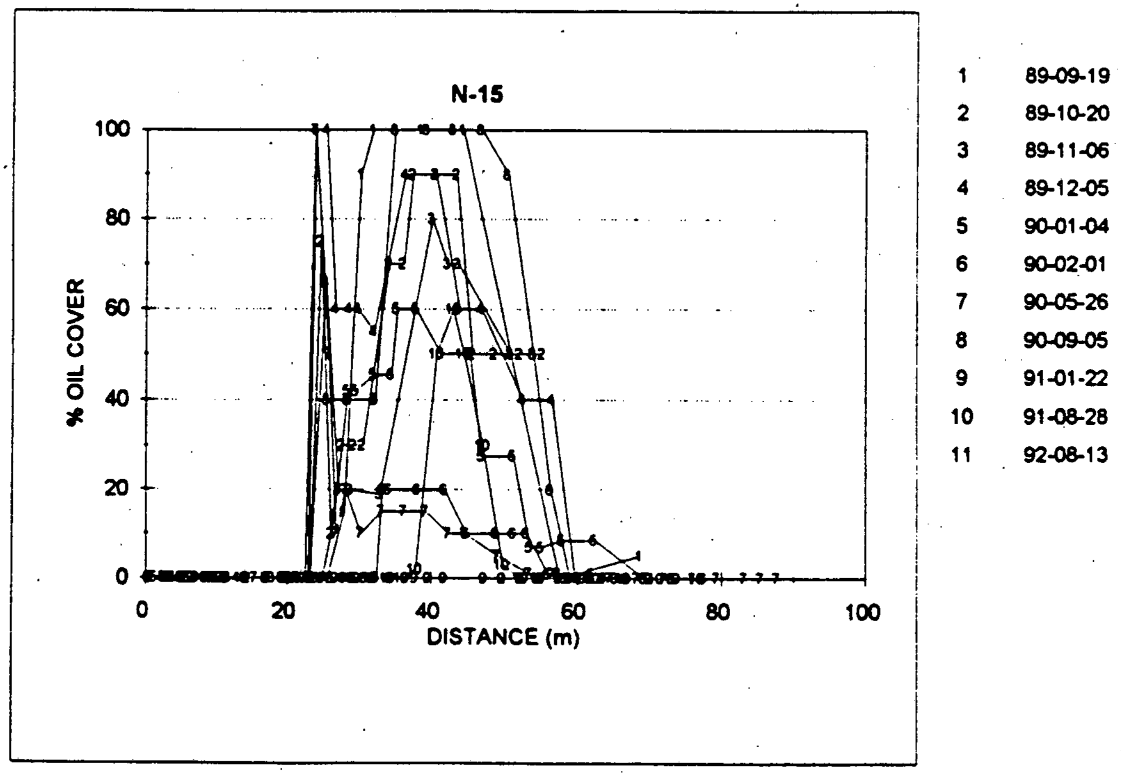


Figure 3f. N-15 Oil cover.

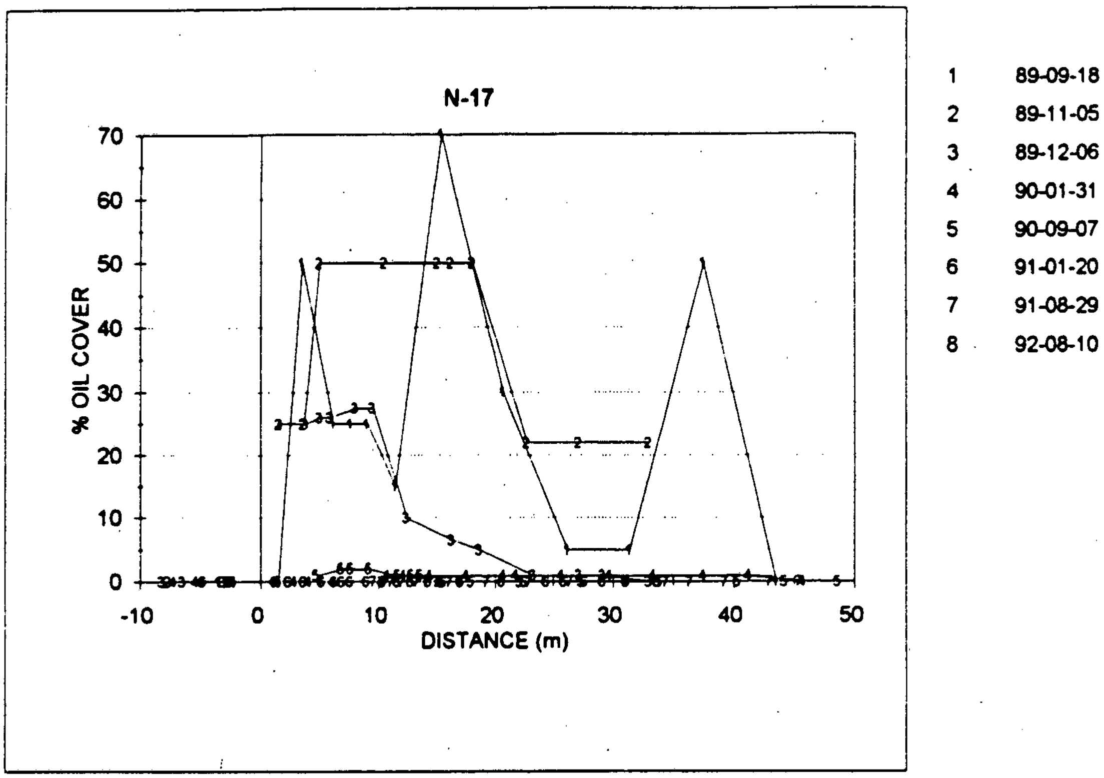


Figure 3g. N-17 Oil cover.

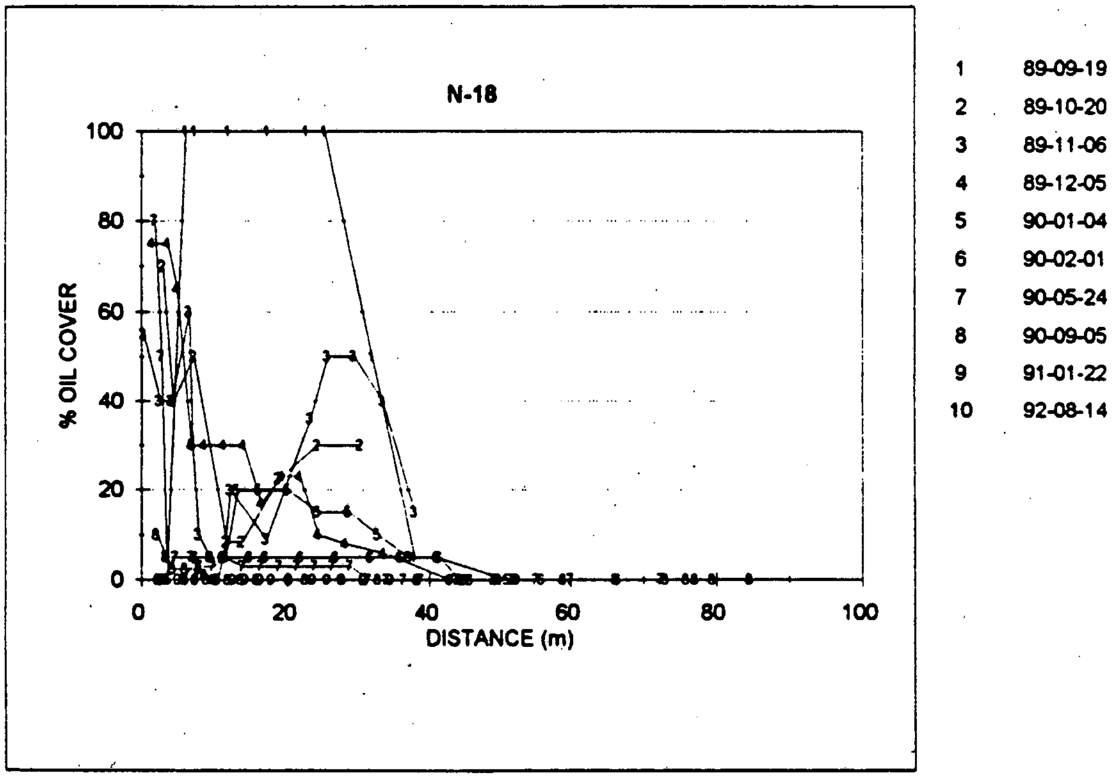


Figure 3h. N-18 Oil cover.

ADEC Data

The Alaska Department of Environmental Conservation (ADEC) has produced a compendium of *Exxon Valdez* oil spill response publications, maps, and databases. This "Encyclopedia of Science and Data Management:" (EVORSC, 1992) provides detailed maps of Prince William Sound, Kodiak Island, the Alaska Penninsula, and the Gulf of Alaska shorelines, with the segments labelled (ADEC and Exxon used the same segment identifiers).

ADEC used a GIS to manage the data from the spill; R-base was the database management system used (with Geo/SQL as the integrating software). ADEC holds the data in a series of related databases. This document identifies the databases, the included files, and all fields. Some of the data tables are the Exxon tables included in our database. One table of potential great value is the Daily Shoreline Assessment file. This database includes records of cleanup activities, tides, and so on. This database may be useful in developing a "cleanup effort" parameter. A subset of the data in the DSA file was made available in paper copy, as the "Prince William Sound Shoreline Treatment Summary" (Munson *et al*,, 1991). This report includes over 4300 records of treatment observations, but does not include a field which would lead to effort. The type of oil removed is listed, and the method of treatment, but no indication of number of persons or hoses, or OMNI barges in operation. That information would permit us to develop an effort index, which could then be used with the oil cover database to estimate treatment efficiency.

MODEL DEVELOPMENT

The model developed a year ago has been modified in a number of ways. The original model divided a spill event into three temporal components, the initial period of loading the beach and removing excess capacity, the transitional period between maximum capacity and residual capacity, when tidal flushing caused the removal of oil, followed by a weathering period when the oil interacted with the environment and dissolved, dispersed, or biodegraded and was removed. The model multiplied the rate constant in each category by a factor to allow for increased energy due to storms, and reintroduced the transition rate during a storm even when the oil content was below residual capacity.

The new version of the model has all three processes running simultaneously from the beginning, with the earlier processes going to zero at the end of each stage. That is, the weathering process is assumed to occur from t=0 to the end; the transition rate operates from t=0 to the residual capacity, and the initial rate operates from t=0 to maximum capacity. Storm events are treated as before. This results in a small change in overall rate, but probably reflects reality slightly better.

Laboratory Data

Twenty-five column experiments were conducted (Harper and Harvey-Kelly, 1993): two oil types (weathered and emulsified); three sediment types (pebbles, granules, and mixed); and various temperatures were used. The oil (Federated Sweet Crude) was weathered to 20% volume loss prior to use. For some experiments, the weathered oil was emulsified with "Instant Ocean" prior to use.

An experiment consists of the placing of oil on top of the sea water column above the sediment, then releasing water from the bottom of the column slowly to mimic a falling tide. The water was reintroduced at the same rate as the release to mimic a rising tide. The position of the top and bottom of the oil lens was noted regularly. As the column was of constant diameter, the thickness of the oil lens gave volume measurements. The results of a typical experiment are shown in Figure 4.

For some experiments, the "tidal action" was repeated; without removing oil from the water (reoiling) and then with oil removal (washing). The system was permitted to come to a steady state prior to oil removal.

The results of the weathered oil experiments are discussed in the specific sections below. The experiments with emulsified weathered crude did not lead to increased understanding of the processes involved, but increased the number of questions requiring answers. The results of the experiments (Table 2) show that the experimental procedure must be modified for emulsions.

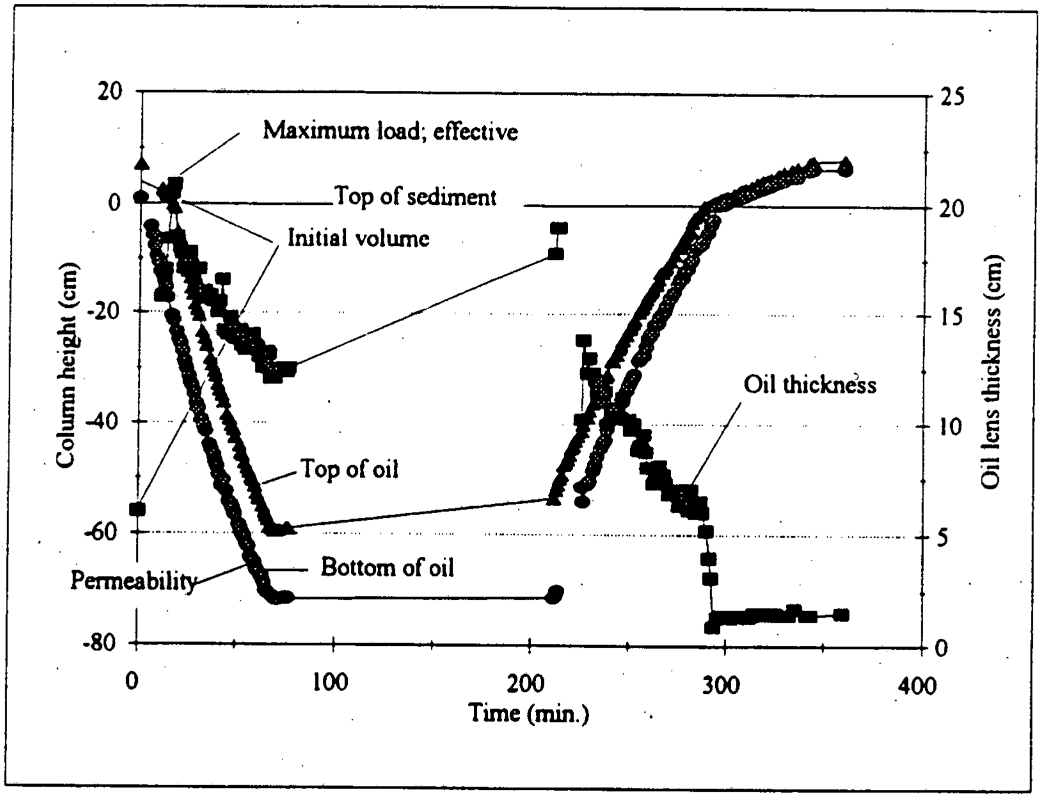


Figure 4. Column measurements, Experiment 1.

For the following table, the effective porosity was determined by calculating the width of the portion of the oil lens which had entered the sediment divided by the apparent width of the oil lens in the sediment. The emulsion completely entered the sediment in the case of pebbles only.

The apparently anomalous results where the effective porosity is greater than the measured porosity, clearly a physically impossible phenomenon, can be explained if the emulsion breaks on entering the sediment. As the oil lens is measured assuming the emulsion is stable, when the emulsion breaks it can occupy space previously occupied by its associated water. It would appear that the emulsion was stable at low temperature and within the pebble substrate, but not within the granule or mixed substrate at higher temperature.

Table 2. Porosity to emulsions.

Exp #	Sediment Type	Mean Φ	T Range	Porosity % Meas.	Porosity % Eff.	Porosity Ratio	Oil in the sediment
16	granule	-2.0	1.5-2.5	43%	20%	0.5	NO
17	granule	-2.0	1.5-2.5	42%	22%	0.5	NO
22	granule	-2.0	7-9	39%	50%	1.3	NO
23	granule	-2.0	7-9	32%	34%	1.1	NO
24	granule	-2.0	6-9	40%	45%	1.1	NO
25	granule	-2.0	6-9	37%	45%	1.2	NO
20	p/g mix	-3.5	1-3	30%	32%	1.1	NO
21	p/g mix	-3.5	1-3	32%	21%	0.7	NO
18	pebble	-5	6-7	41%	25%	0.6	YES
19	pebble	-5	6-7	40%	21%	0.5	YES

The water content of the emulsion was not determined during the experiments. In future tests, the water content of the original emulsion and the emulsion within the sediments should be determined for other sediment grain sizes and temperatures. Emulsions are assumed to have very high viscosities and penetrate only a few cm into all beaches, decreasing the total beach load but increasing the local load to maximum capacity, and the rates of emulsion removal are much lower than for weathered oil.

Porosity

The effective porosity factor has been modified to reflect the present results. Porosity is a property of sediment alone. It is defined as the void space within the sediment and depends primarily on the shape characteristics of the sediment particles and their packing. For the sediments used in our experiments, the porosities as determined using water as fluid were always very close to 40% for fully packed single sized material, and lower for the mixture. For fluids other than water, it is useful to define an effective porosity which will reflect the amount of space within the sediment which the fluid can occupy. Viscous fluids cannot enter all of the void spaces in the sediment because they cannot pass through all the channels between particles. Effective porosity will also change with the wetness characteristics of the sediment, as water in the interstitial channels will inhibit the entry of oil from some void spaces.

In our experiments, the effective porosity is measured by the ratio of oil thickness above the sediment prior to penetration to the thickness of the oil lens when fully in the sediment. For weathered oil, the results are presented in Table 3.

Table 3. Porosity to weathered oil.

Exp #	Sediment Type	Mean Φ	T Range	Viscosity (cp)	Porosity % Meas.	Porosity % Eff.	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
10	granule	-2.0	4-5	42	36%	24%	0.65
11	granule	-2.0	4-5	42	39%	26%	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%	20%	0.67
9	p/g mix	-3.5	20-23	10	34%	20%	0.60
14	p/g mix	-3.5	2.5-4.5	47	33%	23%	0.70
15	p/g mix	-3.5	2.5-4.5	47	33%	26%	0.78
2	pebble	-5	20-23	10	40%	37%	0.91
6	pebble	-5	20-23	10	38%	38%	0.99
7	pebble	-5	20-23	10	39%	38%	0.97
12	pebble	-5	4-5	42	39%	35%	0.91
13	pebble	-5	4-5	42	39%	33%	0.84

For our limited set of conditions, it appears that the porosity of a pebble-granule mixture is about 75% of that of the porosities of the sorted sediments, which were about 40%. The effective porosity of the pebbles was about 90% of that of the measured porosity, but for both the granules and the mixture, the effective porosity was about 65% of the measured porosity. The data do not permit analysis on the basis of viscosity, as the measurements were not sufficiently precise for the small viscosity range used. We expect that as viscosity increases, effective porosity decreases, and that as sediment size increases, effective porosity increases.

Permeability

Permeability remains unused by the model; the oil is assumed to move as fast as the water. This is clearly not true for a wider range of viscosities, but at present we have no data to support a relationship.

The measure and description of permeability in the literature is normally restricted to small particle size sediments; sediments of large particle size such as used in this series of experiments and as would be found on coarse sediment beaches have "free-flow" properties. Indeed, in all our weathered oil experiments, the oil lens followed the water surface down on a falling tide. To improve our understanding of permeability of oils, a modified test was developed in the absence of any standard test which would distinguish the rapid flows observed. Using a falling head tube test, which consists of permitting a tube filled with sediment to 38 cm and fluid to 140 cm to drain the fluid down to the sediment under "standard" conditions, relative permeabilities were determined as a rate of drop of fluid level in the tube (Q). These experimental rates are listed in Table 4 with the fluid conductivity (K), calculated from theory.

Table 4. Permeability.

SEDIMENT	MEAN Φ	Q WATER	 OIL	K WATER	 OIL
PEBBLE	-5	1300	1000-1400	25	4.3
GRANULE	-2	150	22	0.4	0.1
50:50 MIX	-3.5	150	26	3.1	0.5

The measurements and the small particle theory do not match very well. The relative permeabilities do not change in a regular manner. The measurements suggest that the permeability of the mixture is close to that of the smaller component. Further experiments are needed here, with a wider range of oil viscosities.

It is clear that for low viscosity oils, the permeability in coarse sediments is rapid enough to match the fall and rise of tidal water.

The viscosities of the emulsions used were too high for permeability measurements.

Residual Capacity

Residual capacity, originally set at 5 L m^{-3} is now related to grain size and viscosity, but with weak support. We have defined the residual capacity of a sediment to be that amount of oil which does not wash out; that is, oil which is trapped by viscous forces within the sediment and no longer susceptible to tidal flushing. We had used a value of 5 L m^{-3} from ground water contamination literature for light fuel oils and sands or gravels. We undertook a number of washing experiments, and found that the washing appeared less effective than predicted. In a washing experiment, the oil was removed from the supernatant water after each "tide". The results for four experiments are shown in Figure 5. The fourth and fifth washes are extrapolations of the second differential of the first three washes. The three data points for each of the four experiments suggest that the removal of oil by each wash may be asymptotic to zero after only a few washes.

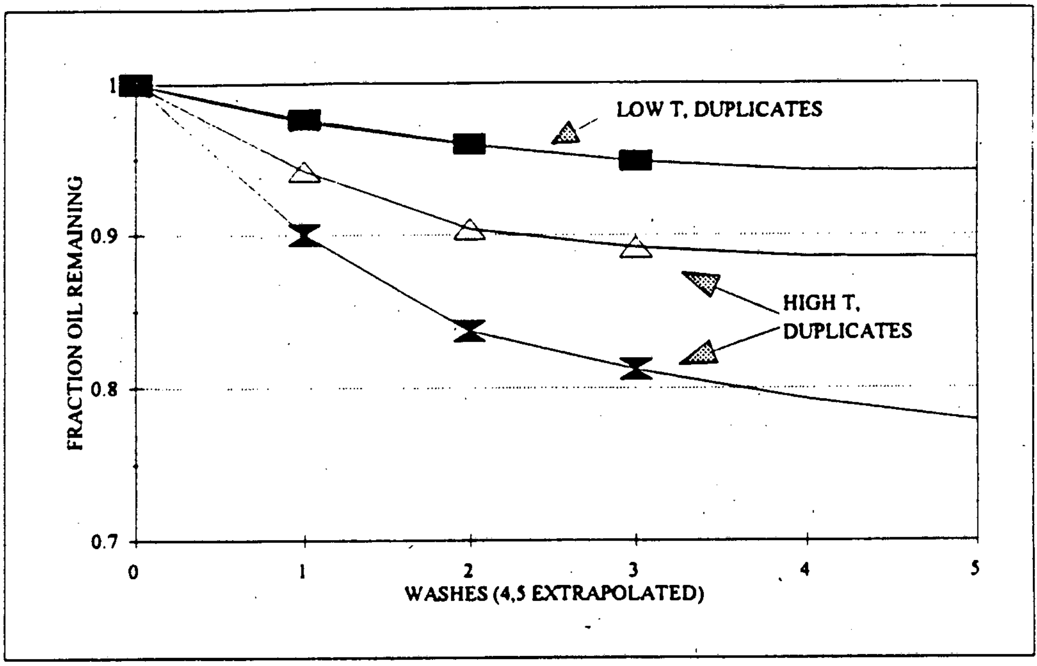


Figure 5. Washing experiments.

These results do not reflect the assumptions used in the first draft of the persistence model, which required many tidal cycles to reach the residual capacity. While these experimental results are only preliminary, they imply that flushing may be rapid, but not efficient.

From the experimental data, for the narrow range of viscosities observed, the residual capacity of pebbles was about 1 L m^{-3}. For the granules or sediment mixture, the residual capacity ranged from 30-50 L m^{-3} at high temperature (~21°) (and low viscosity) and 100 L m^{-3} at low temperature (~5°) (and higher viscosity). The relationships defining residual capacity must include sediment grain size and oil viscosity. Additional experiments are needed to determine this relationship.

Weathering Rates

The reports of the Fate and Persistence studies (Owens, 1991) provide additional information regarding the rate of natural removel, in that surveys were conducted through the winter of 1989-1990. From the summary table (Table 6, Owens, 1991), some general rates may be obtained. These values are for segment averages; the specific transect data would permit an estimate of within beach variance to be made, and would be very useful. In addition, the dates of the oil cover estimates are not specified. For this analysis, the logarithm of the % oil cover was regressed against the day, where the date of the survey was assumed to be the middle of the period. Only segments with five or six surveys in the winter period (September 1989 to March 1990) were used. This avoided the complication of including cleanup effort, yet provided a large enough series for the regression. The results are presented in Table 5. The rates are quite constant, with good correlation coefficients. There does not appear to be a relation between rate and WEE, the Wave Energy Environment from Owens, 1991.

Table 5. Prince William Sound rate constants for natural oil removal.

SEGMENT	RATE CONSTANT	R^2	N	WEE
AP-4	-0.0038	0.74	5	M
AP-8	-0.0033	0.96	5	E
AP-12	-0.0045	0.90	6	E
AP-16	-0.0060	0.81	5	M
AP-18	-0.0057	0.96	5	S
AK-1	-0.0054	0.86	5	S
AK-3	-0.0056	0.90	5	E

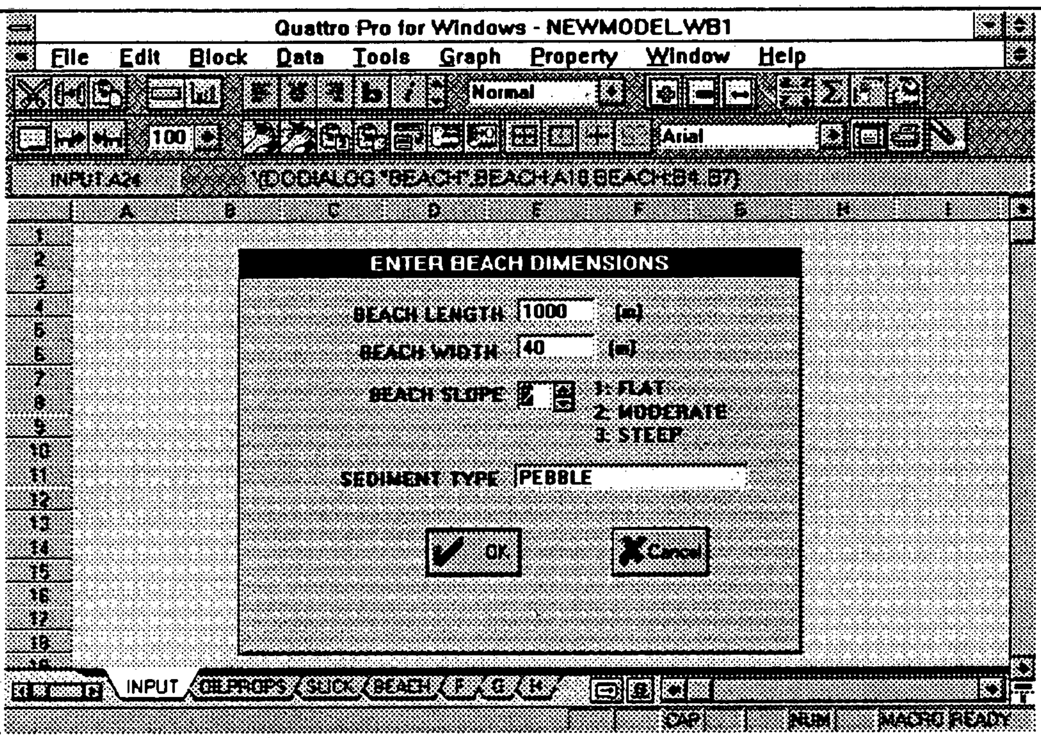
The rate constants determined from these data have high correlation coefficients, implying good fit to the rate model. Some of these rate constants are more negative than those estimated from the Baffin Island Oil Spill Project (BIOS), implying faster natural oil removal. The Prince William Sound data above probably relfects energy input from storms. In the seven month period covered by the winter data used for the rate determination, there were 37 days of storm out of about 200 days (~19% of the time). The data suggest that the sheltered sites lost oil as fast or faster than some exposed sites. The full data set would permit more detailed analysis, including a more precise time scale, and an analysis of the effect of sediment type on the rates.

Tide Zonation

The beach has been subdivided into a maximum of six divisions. The tidal zones can be treated separately, with the impact of tidal flushing on the transition rate being modified according to the average time of exposure of each zone. It is possible to provide results for each of the Upper, Mid-, and Lower Intertidal Zones.

Sediment Zonation

Another possible subdivision of the beach sediments is into active sediment and inactive sediment. Below some depth of sediment, and depending on sediment type and wave energy level, the beach can be defined as inactive, where no storm activity enhances the rates. It is expected that this option will be rarely used, as few beaches will have coarse sediment of sufficient depth.



ENTER BEACH DIMENSIONS

BEACH LENGTH 1000 (m)

BEACH WIDTH 40 (m)

BEACH SLOPE 2

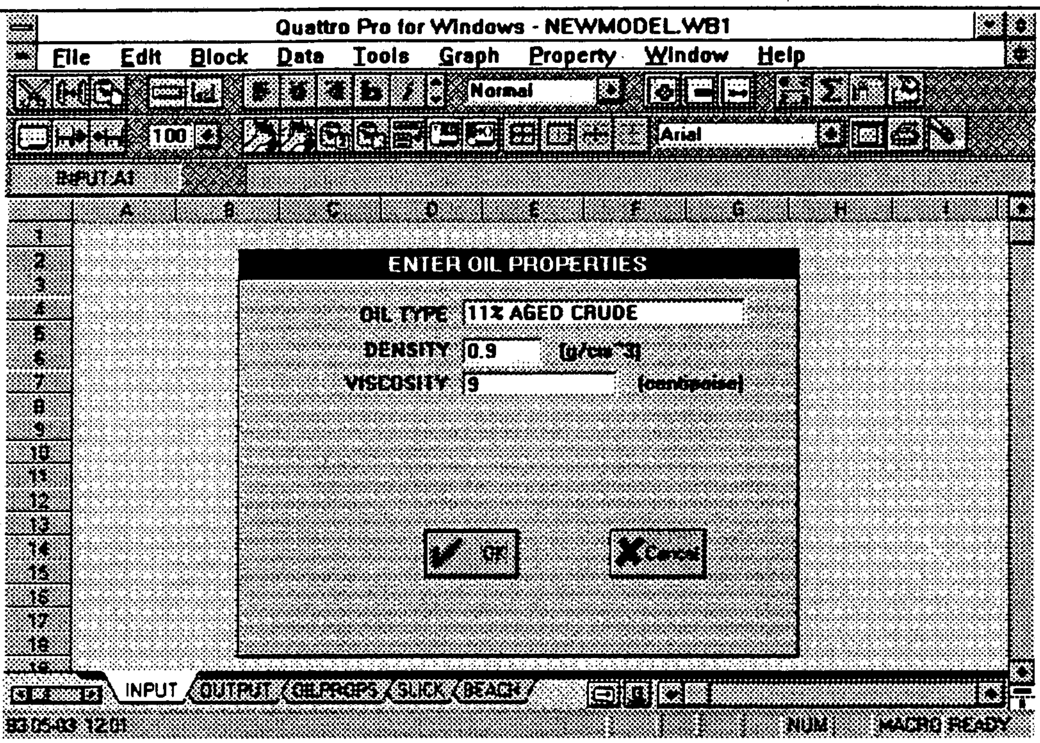
1: FLAT
2: MODERATE
3: STEEP

SEDIMENT TYPE PEBBLE

Figure 6. Beach property entry menu.

Input

The model is now developed using Quattro Pro for Windows, a spreadsheet program which permits application development yet is based on a series of simple spreadsheet pages. This software has resulted in input and output screens to make the model easier to use. A number of input screens allow the user to define the beach (Figure 6), oil (Figure 7), impacting slick properties (Figure 8) and other conditions



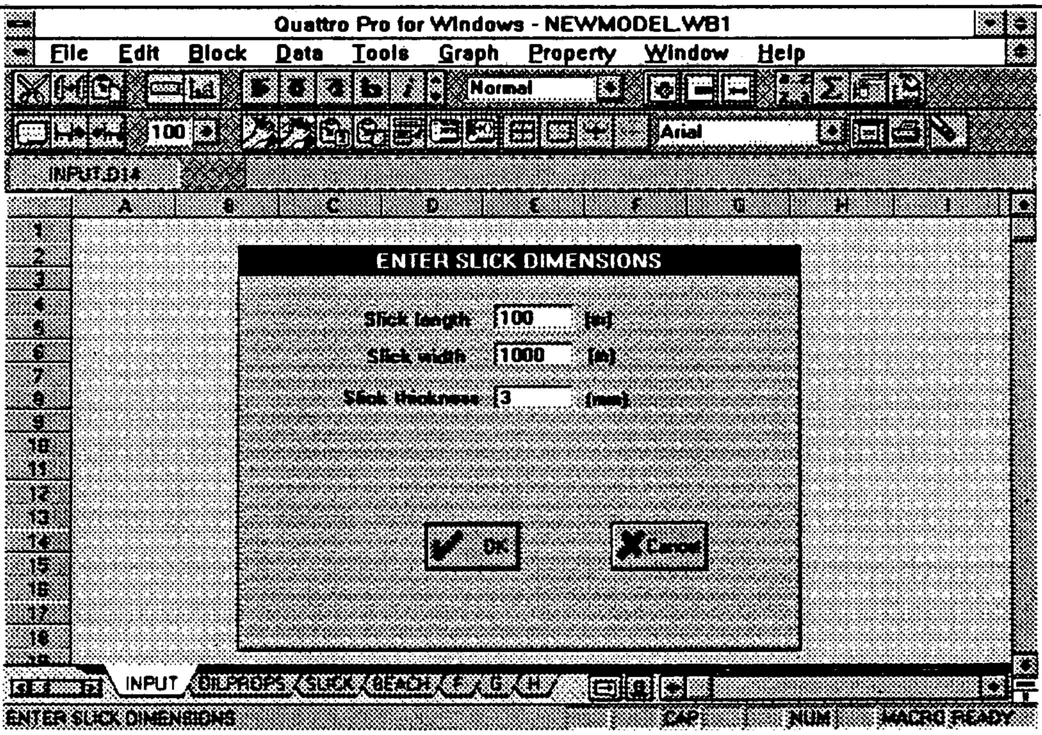
ENTER OIL PROPERTIES

OIL TYPE 11% AGED CRUDE

DENSITY 0.9 [g/cm^3]

VISCOSITY 9 [centipoise]

Figure 7. Oil property entry menu.



ENTER SLICK DIMENSIONS

Slick length 100 [m]

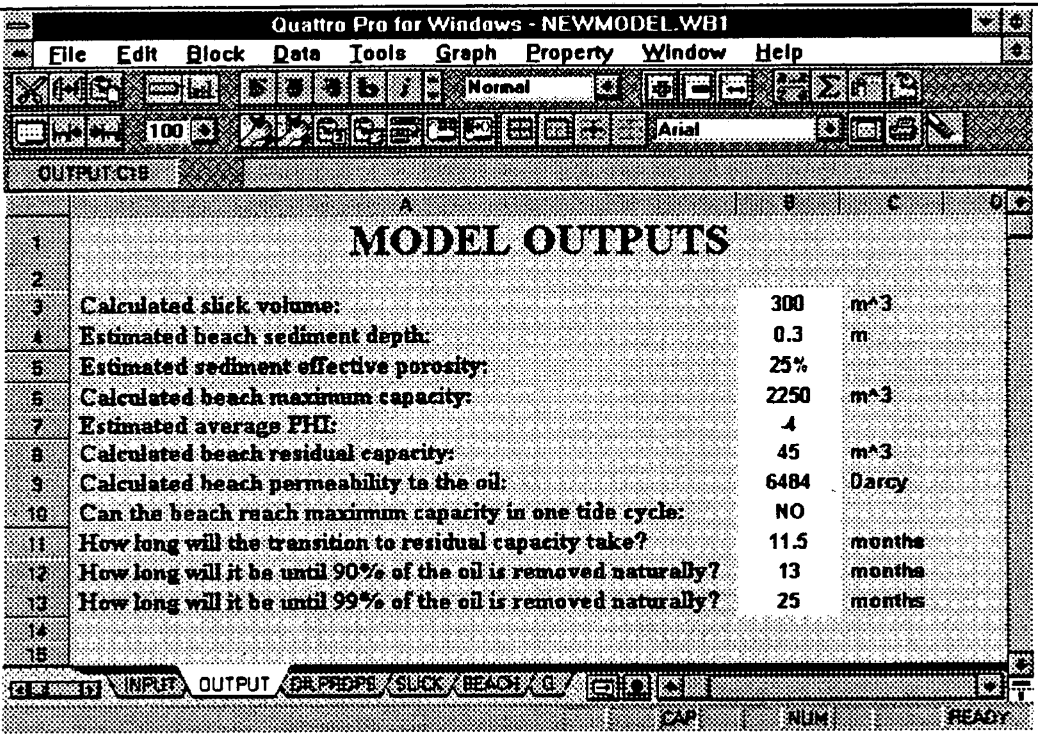
Slick width 1000 [m]

Slick thickness 3 [mm]

Figure 8. Slick property entry menu.

Output

The output of the model is a set of calculated results describing the persistence of the stranded oil (Figure 9). Graphical output is also possible, similar to the original model.



	A	B	C
1	MODEL OUTPUTS		
2			
3	Calculated slick volume:	300	m^3
4	Estimated beach sediment depth:	0.3	m
5	Estimated sediment effective porosity:	25%	
6	Calculated beach maximum capacity:	2250	m^3
7	Estimated average PHI:	-4	
8	Calculated beach residual capacity:	45	m^3
9	Calculated beach permeability to the oil:	6484	Darcy
10	Can the beach reach maximum capacity in one tide cycle:	NO	
11	How long will the transition to residual capacity take?	11.5	months
12	How long will it be until 90% of the oil is removed naturally?	13	months
13	How long will it be until 99% of the oil is removed naturally?	25	months
14			
15			

Figure 9. Model output table.

Future work

This series of exploratory experiments has opened a number of questions. A number of areas which require further examination are:

- more data: the column experiments can provide useful data easily. The number of variables tested in this series is very small. In particular, the behaviour of oil with a wider variety of viscosities is needed to fill in the large gap between very fluid oil as here and emulsions.

- adhesion: some oils, and in particular emulsions, stick to some substrates more than the viscosity would suggest. An understanding of this property is needed if we are to model emulsion behaviour.

- weathering rates: at present, the rate constant for weathering of stranded oil comes from a single field estimate, the Baffin Island Oil Spill project. Additional rates under a variety of conditions are needed. These could be determined in open meso-scale experiments.

- emulsions on beaches: The behaviour of emulsions in association with sediments is poorly understood, yet may be the most important factor in determining the persistence of stranded oil.

REFERENCES

EVORSC. 1992. Encyclopedia of Science and Data Management. Alaska Department of Environmental Conservation, *Exxon Valdez* Oil Spill Response Center, Anchorage.

Harper, J.R. and F. Harvey-Kelly. Subsurface oil retention in coarse sediment beaches. Unpublished report to Environment Canada, Edmonton. 1993.

Humphrey, B. and F. Noone. 1991. The fate and persistence of oil stranded on coarse sediment beaches. Background, Exxon Veldez data, modelling. Unpublished report to Environment Canada, Edmonton, Canada.

Humphrey, B., E. Owens, G. Sergy. "Development of a stranded oil in coarse sediment model (SOCS)". Proceedings of the International Oil Spill Conference, Tampa, Florida. 1993.

Humphrey, B., E.H. Owens, G. Patrick. 1992b. Coarse sediment/oil database and fate model. EE Series Report #139, Environment Canada, River Road Environmental Technology Centre, Ottawa.

Loggie, C.B. 1992 work program completion report. Submission to Cmdr. D.M. McGuire, U.S. Coast Guard, September 3, 1992.

Michel, J and M.O. Hayes. 1992a. Results of geomorphological shoreline monitoring survay of the *Exxon Valdez* spill site in Prince William Sound, Alaska. 24-30 August, 1991. Draft report to NOAA Hazardous Materials Response and Assessment Division, Seattle.

Michel, J and M.O. Hayes. 1992b. Summary of results - geomorphological shoreline monitoring survay of the *Exxon Valdez* spill site in Prince William Sound, Alaska. September 1989 - August 1992. Draft report to NOAA Hazardous Materials Response and Assessment Division, Seattle.

Munson, D., R. Morris, P. Montesano, N. Siddiqui, W. Lane. 1991. Prince William Sound Shoreline Treatment Summary Report. Alaska Department of Environmental Conservation, *Exxon Valdez* Oil Spill Response Center, Anchorage.

Owens, E.H. 1991. Changes in shoreline oiling conditions 1 1/2 years after the 1989 Prince William Sound spill. Unpublished report, Woodward-Clyde, Seattle, Washington. 52 pages and appendices.