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Method for Estimating Spilled Oil Quantity on the Shoreline

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■ The volume of oil which came ashore during the *Amoco Cadiz* oil spill of March/April 1978 was calculated by utilizing aerial photography, sediment sampling, and accurate measurements of the oil depth, width, and length of numerous oiled beaches. An average oil volume per kilometer was determined, and extrapolation for an entire coastline obtained by employment of the total number of oiled shoreline kilometers. Environments that were extremely heavily oiled, such as salt marshes and tidal flats, were calculated separately and added to the total volume of oil. It was estimated that 62 000 metric tons of oil had impacted the Brittany shoreline by April 2, 1978, but only 9200 metric tons remained by April 30, 1978.

Quantative estimates of the amount of spilled oil along the shoreline are essential for an oil spill damage assessment and to determine an oil mass budget. Unfortunately, there are few examples of such evaluations in the literature. Foster et al. (*1*) estimated the amount of oil deposited on the shoreline during the Santa Barbara blowout by using a ground sampling program in which oil was extracted from five 15-cm cores, each taken along nine beach transects. The amount of oil along the entire shoreline was then estimated from aerial photographs, using the nine stations as a basis for extrapolation. Greater accuracy in assessment would have been facilitated by a more detailed sampling program and deeper cores.

This study was undertaken during the *Amoco Cadiz* oil spill in Brittany, France, of March/April 1978 (see ref *2*). A new methodology to estimate the quantity of oil that may impact a shoreline during an oil spill was developed. The primary difference between this and previous studies is the considerable increase in number and detail of examinations of study sites, enabling more accurate calculations.

Methods

The volume of oil was estimated by designating 16 beach sites and one salt marsh as zonal stations, which were selected as representative of the local geomorphology and oil distribution. By using aerial photographs and site visits to the remainder of the affected coastline, we integrated the data derived from the zonal stations to cover the entire oiled shoreline. The stations were analyzed for two time intervals (March 19–April 2, 1978, and April 20–April 28, 1978) to determine short-term change. At each of the 17 *Amoco Cadiz* zonal stations, the quantity of surface beach oil, oiled rocks, and oiled marshland, as well as that buried within the sediment, were considered. Each oiled environment is discussed separately in the following sections.

Surface Oil. The oil reaching the Brittany shoreline was completely emulsified into a mousse consistency due to high wind and wave conditions. Beaches inundated with mousse were profiled during low tide by using the Emery (*3*) method. The quantity of surface oil was calculated by the following formula:

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

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

The measurement, in centimeters, of oiled beach length, width, and depth along with the calculation of specific gravity provides for the final unit to be expressed in grams. Division by 10^6 converts final volume of oil into metric tons (1000 kg or 2200 lb). A sample interval was defined as a zone along a beach transect that has uniform percent mousse coverage and mousse thickness. Summation of the sample intervals yielded

Table I. Zonal Station AMC-9, March 25, 1978: Calculation of Surface and Buried Oil Quantity, *Amoco Cadiz* Spill

	$10^{-5}L$, cm	$10^{-3}W$, cm	D, cm	$\%C$	$(Lwd)(\%C)$, cm^3
			(A) Surface Oil		
I	2.1	1.2	clean	clean	
II	2.1	3.7	4.0×10^{-1}	0.95	2.9×10^8
III	2.1	1.5	6.0	0.95	1.8×10^9
IV	2.1	1.0	1.0	0.95	2.0×10^8
V	2.1	10.0	3.5×10^{-1}	0.85	6.2×10^8
				total	2.91×10^9

(SG) = 8.5×10^{-1} g/cm^3

($\%O$) = 4.0×10

$\sum_{\text{sample interval}} (LWD)(\%C)(\text{SG})(\%O)/10^6 = (2.91 \times 10^9)(8.5 \times 10^{-1})(4.0 \times 10^{-1})/10^6 = 9.90 \times 10^2$ metric tons

(B) Buried Oil

$L = 2.1 \times 10^5$ cm

$L_b = 6.7 \times 10^2$ cm

$T_b = 4.0$ cm

$\%O = 10^{-1}$

(SG) = 8.5×10^{-1} g/cm^3

$(LL_bT_b)(\%O)(\text{SG})/10^6 = (2.1 \times 10^5)(6.7 \times 10^2)(4.0)(10^{-1})(8.5 \times 10^{-1})/10^6$ 4.7×10 metric tons

(C) Total = Surface Oil + Buried Oil

$9.90 \times 10^2 + 4.7 \times 10 = 1037.0$ metric tons

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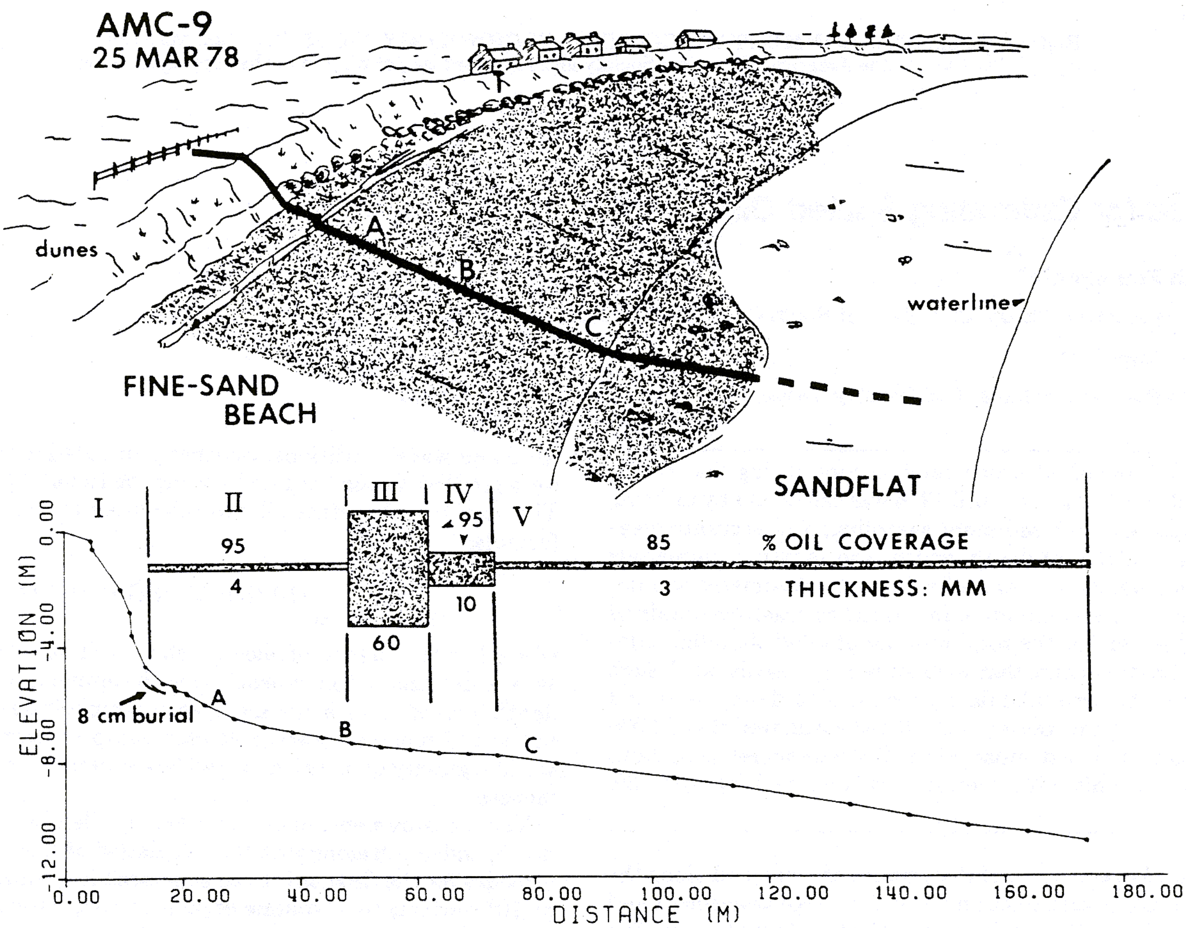

Figure 1. Zonal station AMC-9 showing topographic profile and percent oil coverage on March 25, 1978. Oil covered most of the beachface and upper low-tide terrace. An oiled sediment zone of 4 cm was buried 8-cm deep within part of sample interval I and II. Oil was deposited in sections I and II during the initial high energy activity within the early days of the spill. Subsequently, deposition of clean sand provided for the burial of section-I and -II oil. Oil in sections III–V washed in and out with the tide and was therefore incapable of burial. Sample station sites A, B, and C are measured equidistant from each other along the beachface. (From ref *5*)

the total quantity of oil on a particular beach (see Figure 1 and Table IA). The mousse thickness was measured (±0.2 cm) along each profile transect at intervals of 5 m or less. In addition, the percentage of mousse coverage within the sampling interval was visually estimated. Oil coverage at each station was sketched onto a 1:20 000 topographic map and, in most cases, verified by aerial photographs.

The specific gravity of the Iranian and Saudi Arabian crude oils originally aboard the *Amoco Cadiz* was determined by Hann et al. (*4*) to be 0.80 g/cm^3. The relative percent of water to oil in the mousse can be quite variable. Hann et al. (*4*), on the basis of analyses of 24 mousse samples from 16 *Amoco Cadiz* spill sites, found an average oil content of 30% with a standard deviation of 9.16%. Our calculations due to general conservative estimates of oiled beach length and width were based on an average oil content of 40%.

Buried Oil. The quantity of oil incorporated within beach sediments was calculated by the following formula:

$$(LL_bT_b)(\%O)(SG)/10^6$$

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

As noted previously, units are in centimeters and grams, and division by 10^6 yielded a total expressed in metric tons (see Figure 1 and Table IB). The quantity of buried oil was calculated and added to the surface volume. This calculation was determined by measuring the thickness and the length of the buried mousse from trenches dug along the profile of a zonal station. Buried mousse was assumed to be continuous under surface mousse. Since most analyses extract the amount of oil (not mousse) from oiled sediments, a conversion from mousse to oil was not necessary. The percent of oil within oiled-sediment samples was determined by chemical extraction by Blount (*6*) to be roughly a maximum of 10%. Smith (*7*), during investigation of the *Torrey Canyon* oil spill in Great Britain, estimated the oil content of oiled sand samples collected to vary from 0.5% to 11.0%. The authors, by chemical extraction, found a 5–12% oil content in Puerto Rico sand samples at the December 1978 *Peck Slip* oil spill in Puerto Rico (*8*). This study used an estimated 10% oil in sand volume.

Oiled Rocks. Rocky areas flanking sand, granule, and pebble beaches are common along the Brittany coastline. The amount of oil coating these rocky onshore areas was much more difficult to assess. Though the rocks were covered by a relatively thin layer of mousse, the rocks themselves comprised a larger surface area than that comprised by the surface of a flat beach. Additionally, small pools of mousse often collected between rocks. Because of these difficulties, rocky areas were considered to be an extension of the beach, and therefore our calculations represent a probable minimum value. Aerial photographs, provided by courtesy of CNEXO, Centre Oceanologique de Bretagne, were used to determine the surface distribution of oil on offshore rocks.

Oiled Marshland. A salt marsh at Ile Grande (Figure 2B) was particularly inundated by oil. Oil volume at this site was

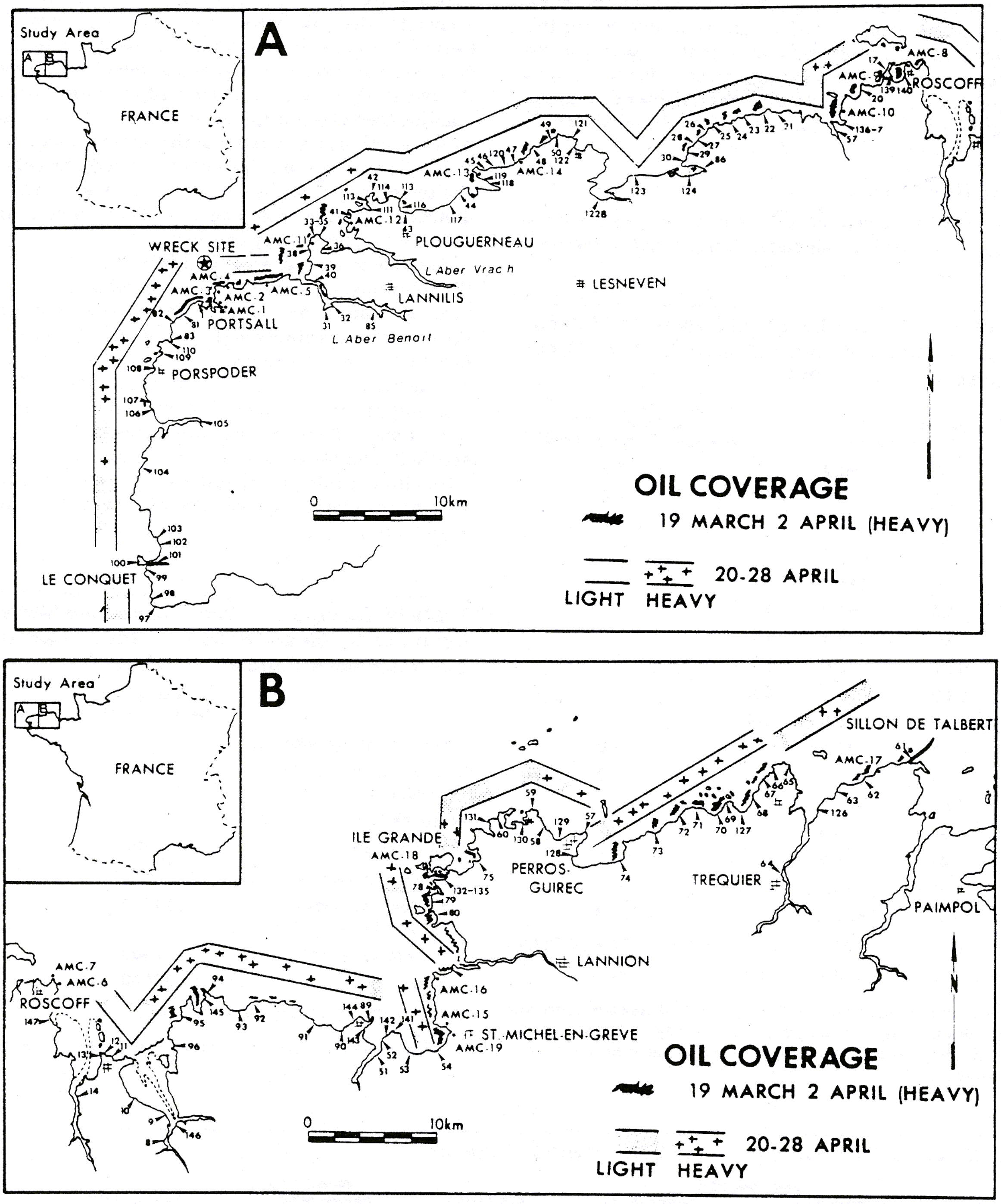

Figure 2. *Amoco Cadiz* oil coverage location maps of Brittany, France. Note the two study sessions: March 19–April 2, 1978, and April 20–April 28, 1978. Shoreline oiling during the first study session is entirely heavy, while study-session two is differentiated into light and heavy oil coverage. (From ref *5*)

calculated by using a topographic map, aerial photographs, and the measured depth of the surface mousse. Table II shows that the volume of oil in the marsh was greater than that at any single beach.

Extrapolation. The total volume of oil washed ashore was calculated by dividing the coastline (Figure 2) into sections and determining the quantity of oiled shoreline in each section (Table III). Delineation by ground truth and aerial observations as well as aerial photographs provided a means for determining the number of oiled kilometers of shoreline per section. An average oil volume per kilometer was calculated by averaging the 16 zonal stations (Table II). Since the Ile Grande marsh was particularly heavily inundated, its oil volume was evaluated separately and added to the total volume of oil (Tables II and IV).

The total average oil per kilometer (443.6/km) was applied to 72 heavily oiled kilometers of shoreline during the first study period because oil was concentrated at each site. In contrast, during the second study period, the original beach sites were categorized on the basis of heavy oil coverage (greater than 30% coverage of the upper intertidal zone) and light oil coverage (Figure 2). Similar oil volume calculations were made for these beaches, and an oil tonnage per kilometer (34.6/km for heavy coverage and 4.1/km for light coverage) was determined (Table II). The product of the oil tonnage per kilometer for both lightly and heavily oiled shoreline sections and the total kilometers of respective oil-covered shoreline yielded the amount of oil on the Brittany shoreline during the second study session. Tables II–IV show that the total volume of oil on the shoreline was heavily concentrated during the first study period but was more widespread and lighter during the second study period. This is due to a shift in the winds which caused further dispersal of the oil (Figure 3).

Results and Discussion

An oil budget for the volume of oil which came ashore at the *Amoco Cadiz* spill site was calculated. The described methods indicate that 62 000 metric tons of oil came ashore immediately after the spill; however, 4 weeks later, only 9200 metric tons of oil were still contaminating the shoreline, a reduction of 85% (Table IV). The large reduction of oil volume between the two study periods is attributed to natural processes and man-induced cleanup operations. Most of the oil was removed by wave action and mixed into the water column or deposited on the ocean bottom. Both study periods revealed that the sheltered marsh at Ile Grande was inundated by greater quantities of oil with a longer residence time than the considerably higher energy beaches.

Possible sources of error in this type of calculation include the following: (1) application of oil volume at one or several beaches to an entire coastline (there was a sample bias due to the greater accessibility and quantity of oil at sand and gravel beaches compared to rocky shores), (2) lack of separate measurements of the oil volume at rocky areas, (3) repetitive counting of the same oil (oil calculated in one area may have been removed by erosion and deposited in an area later studied), and (4) variation in oil accumulation on a beach as a function of tide, wind, and wave conditions (therefore, oil volume on a beach is subject to change within a few days or even hours).

Table II. Oil Quantity per Length of Beach for 17 AMC Stations during Study Period 1 (March 19–April 2) and Study Period 2 (April 20–28) [a]

AMC station	length of beach, km	oil content, metric tons: session 1	session 2: light coverage	session 2: heavy coverage
1	0.50	50.2		7.3
2	0.25	1.8		2.4
3	0.25	44.6		5.5
4	0.20	284.1		2.5
5	1.25	1146.9	2.5	
6	0.20	51.8	1.0	
7	0.20	102.5	1.7	
8	0.20	9.6	0.4	
9	2.00	1039.4	10.6	
10	1.25	46.3	6.0	
11	0.45	175.2		1.0
12	0.40	357.7		6.3
13	0.55	248.3	0.6	
15	0.30	83.3		3.9
16	0.40	81.2		66.3
17	0.30	136.4	1.6	
18 [b]	4.00	7400.0		2760.0
subtotal	8.7	3859.1	24.4/(5.9 km)	95.2/(2.75 km)
total, metric tons/km		443.6	4.1	34.6

[a] Reprinted with permission from ref *9*. Copyright 1978 Centre National pour l'Exploitation des Oceans. [b] Not included in this calculation because the Ile Grande Marsh represents an anomalously large concentration of oil within one particular environment.

Table IV. Summary of Data Concerning Shoreline Coverage by Oil and Estimated Total Quantities for Study Sessions 1 and 2 [a]

	session 1 (March 19–April 2)	session 2 (April 20–28)
shoreline heavily oiled, km	72	107
offshore rocks heavily oiled, km	51	55
shoreline lightly oiled, km		213
total km oiled	123	375
quantity of oil, metric tons		
subtotal (excluding Ile Grande)	54600	6440
total at Ile Grande	7400	2760
total	62000	9200
total reduction between sessions = 85%		

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Table III. Extent of Oil Coverage during Study Periods 1 and 2 [a,b]

section of coast	study period 1: coastline oiled, km	study period 1: offshore rocks oiled, km	study period 2: lightly oiled, km	study period 2: heavily oiled, km	study period 2: heavily oiled offshore rocks, km	total km of coastline (excl offshore)
I	0	0	52	39	4	289
II	11	4	5	8	4	24
III	16	9	15	8	9	43
IV	4	9	30	0	9	38
V	4	3	43	0	3	43
VI	8	3	10	4	3	27
VII	4	4	24	9	4	76
VIII	9	4	10	20	4	35
IX	5	3	4	4	3	16
X	2	4	12	6	4	35
XI	9	8	8	9	8	36
subtotal	72	51	213	107	55	653
total km oiled	123		375			

[a] Oil is only described as heavy during study 1 (March 19–April 2). During study 2 (April 20–28) it is described as light or moderate to heavy. [b] Reprinted with permission from ref *9*. Copyright 1978 Centre National pour l'Exploitation des Oceans.

The *Amoco Cadiz* disaster caused the spillage of 233 000 metric tons of crude oil. Of the 233 000 metric tons, our calculations indicate that only 27% was stranded on shore. With the knowledge of how much oil reaches the coast, one may ask the question, where did the rest of the oil go? Only ~27% of the *Amoco Cadiz* oil was accounted for. Speculation for the other 73% includes evaporation and sinking of oil (see ref *10*).

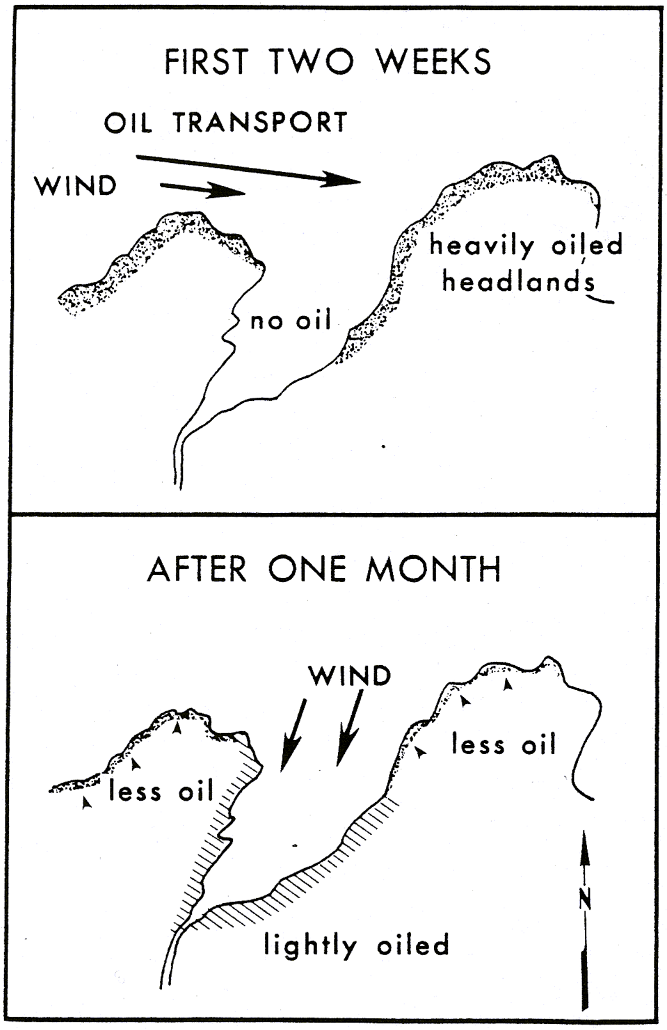

Figure 3. Generalized oil coverage of the coastline after the first 2 weeks and after 1 month of the spill. Initial dominant westerly winds transported large and heavy patches of oil onto the western shoreline sections. A shift in the winds after 2 weeks caused a lighter but more even inundation of oil along the entire coastline. (From ref *5*)

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