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October 23, 2002

Case Study Example for Oil Spill Movement and Fate

Summary

A detailed example is presented in this module describing problems associated with spills of petroleum hydrocarbons, by far the most common material lost in Alabama transportation accidents. Most of the accidents involving petroleum products and materials in Alabama are traffic accidents where truck diesel fuel is spilled. However, the largest spills are usually associated with transfer accidents and pipeline breaks. Most of the prediction information available is for marine spills (usually tanker accidents) and focuses on slick movement dispersal. This module summarizes this information by showing specific procedures for calculating the spread and transport of oil slicks. This example illustrates procedures for buoyant materials for which specific methods have been developed (based on actual field studies). These procedures enable the calculation of the magnitude of potential exposures to these hazardous materials.

Ocean oil pollution from large oil spills involving tanker accidents are thought to be the most important source of oil in the ocean by the public. Table 7-1 lists the largest oil spills that have been recorded (greater than 100,000 tons). However, most oil pollution in the ocean actually comes from municipal and industrial runoff, cleaning of ship’s bilges and tanks, and other routine activities and events.

Table 7-1 Oil Spills of 100,000 Tons (640,000 Barrels), or More

Date	Cause	Location	Barrels Spilled	Rank, by Spilled Volume
1942	German U-boats attacks on tankers after U.S. enters World War II	U.S. East Coast	590,000	4
1967	Tanker *Torrey Canyon* grounds	English Channel, off Land's End, UK	119,000	12
1970	Tanker *Othello* collides with another ship	Tralhavet Bay, Sweden	60,000 to 100,000	15
1972	Tanker *Sea Star* collides with another ship	Gulf of Oman	115,000	13
1976	Tanker *Urquiola* grounds	La Coruna, Spain	100,000	14
1978	Tanker *Amoco Cadiz* grounds	Northwest France	223,000	9
1979	Itox 1 oil well blows	Southern Gulf of Mexico	600,000	2
1979	Tankers *Atlantic Empress* and *Aegean Captain* collide	Off Trinidad and Tobago	300,000	6
1983	Blowout in Norwuz oil field	Persian Gulf	600,000	3
1983	Fire aboard tanker *Castillo de Beliver*	Off Cape Town, South Africa	250,000	8
1988	Tanker Odyssey flounders	Off Nova Scotia, Canada	132,000	11
1991	Iraq begins deliberately dumping oil into Persian Gulf	Sea Island, Kuwait	1,450,000	1
1991	Tanker *Haven* grounds	Genoa, Italy	140,000	10
1991	Tanker *ABT Summer* founders	700 mi. off Angola	260,000	7
1994	Pipeline bursts, oil enters rivers that flow into Arctic Ocean	Near Usinik, Russia	312,500	5

Source: International Tanker Owners Federation, as published in the 2001 New York Times Almanac.

Oil Spill Case Histories 1967-1991; Summaries of Significant U.S. and International Spills (NOAA 1992) is attached to this module as a pdf document, and includes information concerning many large oil spills. Spills described were large, used dispersants or bioremediation, or had significant environmental effects.

Notable Oil Spills

The NOAA Office of Response and Restoration has much information concerning large oil spills. This information is available at:

http://response.restoration.noaa.gov/index.html

Other links for oil and hazardous material spills are:

Incident News:

http://www.incidentnews.gov/

NOAA Response Reports:

http://response.restoration.noaa.gov/oilaids/spillreps/spillreps.html

Included are photographs from selected notable oil spills, some of which are included below (from http://response.restoration.noaa.gov/photos/ships/ships.html):

The Amoco Cadiz

The AMOCO CADIZ ran aground off the coast of Brittany, France on March 16, 1978, spilling 68.7 million gallons of oil. It currently is #9 on the list of the largest oil spills of all time.

The Argo Merchant

The ARGO MERCHANT ran aground on Fishing Rip (Nantucket Shoals), 29 nautical miles southeast of Nantucket Island, Massachusetts in high winds and ten foot seas.

On December 21, the ARGO MERCHANT broke apart and spilled its entire cargo of 7.7 million gallons of No. 6 fuel oil

The Bouchard B155

On August 10, 1993, three ships collided in Tampa Bay, Florida: the BOUCHARD B155 barge, the freighter BALSA 37, and the barge OCEAN 255. The BOUCHARD B155 spilled an estimated 336,000 gallons of No. 6 fuel oil into Tampa Bay. Below is a photo of the OCEAN 255 barge after the collision.

The Burmah Agate

On November 1, 1979, the BURMAH AGATE collided with the freighter MIMOSA southeast of Galveston Entrance in the Gulf of Mexico. An estimated 2.6 million gallons of oil was released into the environment; another 7.8 million gallons was consumed by the fire onboard. This spill is currently #55 on the all-time list of largest oil spills.

The Cibro Savannah

The CIBRO SAVANNAH exploded and caught fire while departing the pier at the CITGO facility in Linden, New Jersey, on March 6, 1990. About 127,000 gallons of oil remained unaccounted for after the incident: no one knows how much oil burned and how much spilled into the environment.

The Exxon Valdez

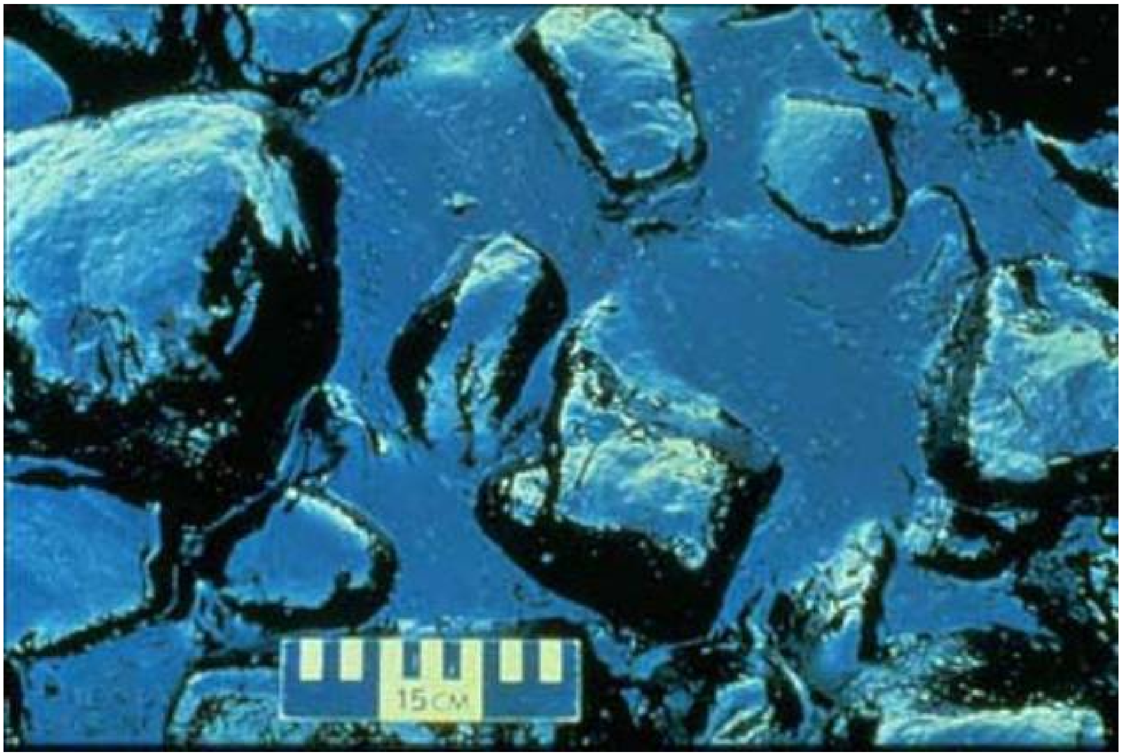
The EXXON VALDEZ ran aground on Bligh Reef in Prince William Sound, Alaska on March 24, 1989, spilling 10.8 million gallons of oil into the marine environment. It is currently #53 on the all-time list of largest oil spills.

On March 24, 1989, the tanker Exxon Valdez grounded on Bligh Reef in the upper part of Prince William Sound. The tanker was carrying approximately 53 million gallons of crude oil. Within a few days, it had spilled almost 11 million gallons of the oil into Prince William Sound.

Shortly after leaving the Port of Valdez, the Exxon Valdez ran aground on Bligh Reef. The picture below was taken 3 days after the vessel grounded, just before a storm arrived.

During the first few days of the spill, heavy sheens of oil, such as the sheen visible in this photograph, covered large areas of the surface of Prince William Sound

Beginning 3 days after the vessel grounded, a storm pushed large quantities of fresh oil onto the rocky shores of many of the beaches in the Knight Island chain. In this photograph, pooled oil is shown stranded in the rocks.



Oil being skimmed from the sea surface. Here, two boats are towing a collection boom. Oil concentrated within the boom is being picked up by the skimmer (the vessel at the apex of the boom).

In many locations in Prince William Sound, the action of tides and currents distributed oil throughout the entire intertidal zone. In Northwest Bay on Knight Island, tides have deposited oil on this rocky beach face up to the top of the intertidal zone.

Workers using high-pressure, hot-water washing to clean an oiled shoreline. In this treatment method, used on many Prince William Sound beaches, oil is hosed from beaches, collected within floating boom, then skimmed from the water surface. Other common treatment methods included cold-water flushing of beaches, manual beach cleaning (by hand or with absorbent pom-poms), bioremediation (application of fertilizers to stimulate growth of local bacteria, which degrade oil), and the mechanical relocation of oiled sediments to places where they could be cleaned by wave and tide action.

A brown sediment plume and sheens of refloated oil drift away from this oiled beach as it is cleaned by a team applying high-pressure, hot-water washing. Refloating of oil and release of sediment are often unavoidable consequences of shoreline cleanup that can cause additional environmental harm.

Ixtoc I

The IXTOC I exploratory well blew out on June 3, 1979 in the Bay of Campeche off Ciudad del Carmen, Mexico. By the time the well was brought under control in 1980, an estimated 140 million gallons of oil had spilled into the bay. The IXTOC I is currently #2 on the all-time list of largest oil spills of all-time, eclipsed only by the deliberate release of oil, from many different sources, during the 1991 Gulf War.

The Jupiter

The JUPITER was offloading gasoline at Bay City, Michigan on September 16, 1990, when a fire started on board the vessel.

The Mega Borg

The MEGA BORG released 5.1 million gallons of oil as the result of a lightering accident and subsequent fire. The incident occurred 60 nautical miles south-southeast of Galveston, Texas on June 8, 1990.

1991 Gulf War

The largest oil spill of all-time was the deliberate release of oil, from many different sources, during the 1991 Gulf War. 1,450,000 barrels were released at Sea Island, Kuwait.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Potential Movement and Effects Associated with Oil Spills

The amount of oil at any location, and associated impacts, is determined by both the drift movement of the spilled oil and the spreading of the oil. The *Trajectory Analysis Handbook* (NOAA undated), attached to this module as a pdf document, outlines the mechanisms and procedures that can be used to predict the gross movement of oil spills.

The following discussion is a summary of oil spill analysis and impact reports prepared by Woodward Clyde Consultants for numerous clients for submission to regulatory agencies. The following discussions are excerpts and summaries from these reports and indicate how impacts associated from oil spills can be evaluated, especially in regards to spill movement and dispersion. The fate and effects of oil spills on the environment, based on selected historical oil spill incidents, are also described.

Parameters Affecting Oil Spill Movement

The movements, and other characteristics, of a spill of petroleum hydrocarbons lost on water are controlled by weather conditions (wind, temperature, and rainfall), ocean conditions (tides and currents), and physical parameters of the materials which could be spilled. The important physical parameters of the various petroleum hydrocarbons include the following:

- Specific gravity (or density);
- Evaporation rate;
- Boiling range;
- Viscosity;
- Pour point;
- Emulsification ability; and
- Water solubility.

Some of these factors are related. For example, the evaporation rate is dependent on weather conditions (especially wind) and the boiling range of the material. Similarly, the spread rate depends on weather, viscosity, and the pour point. Emulsification is a very complex parameter since both oil-in-water and water-in-oil emulsions can be involved and wind and wave conditions are usually controlling. The solubility of most of the materials is very limited (below 0.01 g/100g). Table 7-2 gives the significant physical parameters of greatest interest, along with typical values, for residual fuel oils. These values will be used in a later example.

Table 7-2. Characteristics of Typical Residual Fuel Oils used in Example

Parameter	Residual Fuel Oils
Specific Gravity (@ 60°F)	0.904 – 1.02
API Gravity (@ 60°F)	7 – 25
Viscosity (Saybolt Universal sec @ 100°F)	45 – 18,000
Flash Point (°F)	150 – 250
Pour Point (°F) Sulfur Content (% by weight)	0.5 or less

NOAA has published several fact sheets describing characteristics affecting spill movement and fate. Examples for North Slope crude, No. 6 fuel oil, and diesel, are attached to this module as pdf documents.

Potential Oil Spills

Submarine Pipelines

The design and installation of modern submarine pipeline facilities for marine terminals include a number of safety features to prevent oil leakage. In addition, extensive provisions are made to minimize the volume of oil released in the event of a leak, including:

- Additional steel wall thickness on product transfer lines.
- Cathodic protection.
- Somastic coatings (or coal tar wrap).
- Concrete weight coating over somastic coatings to increase stability and provide negative buoyancy for empty lines.
- Burial of lines in surf zone.
- Pressure safety valves.
- Submarine hoses of strength several times the operating pressures.

Even when these precautions are taken, there is still the possibility of damage to the submarine hoses by improper handling, or to the pipeline by man-caused events (dropped material, i.e., anchor or chain, of sufficient weight to cut lines) or natural occurrences. The speed of the curtailment of oil released to the sea is dependent upon the rapidity with which the ship’s or shore pumps are stopped, the vacuum pumps started, and the valves closed. The rate at which petroleum products or crude oil could be released would vary depending upon the extent of the pipeline incident. The magnitude of a spill could range from a few gallons (resulting from a minor leak in the pipeline system) to many barrels (resulting from a major pipeline fracture). The quantity released would also depend upon pipeline operating conditions at the time of the incident, *i.e.*, pumps on line or on standby. The potential spillage magnitude would also vary with the location of the pipeline incident. In submarine installations, the sea water (being of higher specific gravity than fuel oil) would seal off the oil in the sector of pipeline above (upslope) the leak. In the sector of the line below (downslope) the leak, water would slowly enter the pipe, displacing the crude oil or product. Potential spills volumes for offshore spills are categorized by the National Oil Spill Contingency Plan as follows:

Minor Spill - a discharge of oil less than 10,000 gals (238 bbl*);

Moderate Spill - a discharge of oil of 10,000 to 100,000 gals (238 to 2,380 bbl); and

Major Spill - a discharge of oil of more than 100,000 gals (2,380 bbl).

*Based on 42 gal/bbl

Pipelines are by far the most common method of transporting crude oil and petroleum products in the United States. The possibility of a crude oil and/or petroleum product spillage could occur at any point along submarine pipelines. An analysis by the National Petroleum Council (1972) of spill incidents from pipeline systems in the United States indicate that approximately 2.8 bbl/mi/yr were lost.

Tanker Operations

Tankers can contribute to oil pollution of the marine environment through five principal sources:

- Cargo tank cleaning operations;
- Discharges from bilge pumping;
- Hull leakage;
- Spills during cargo handling operations; and
- Vessel casualties.

There are three principal causes of unintentional discharges of oil during tanker-terminal operations, namely (1) mechanical failures, (2) design failures, or (3) human error. Incident reports of spills during tanker-terminal operations show that human error is the predominant cause and is the most difficult to remedy. Mechanical failures include cargo transfer hose bursts, and piping, fittings, or flange failures, either on shore or on the tankers. Mechanical failure could also be due to an inherent design fault including the incompatibility of a tanker with a given marine terminal, i.e., improper manifold connections, inadequate mooring facilities, and shoreside loading pumps with excess pumping capacity.

Oil spills that occur during the loading or unloading of crude oil or petroleum products are more often associated with leaky connections, failure to drain cargo hoses, improper mooring, improper valve or manifold alignment, or overfill during loading operations.

Prediction of the Movement of Oil Spills

The fate of an oil spill in the marine environment depends on the spreading motion of the oil and the translation of the slick by the winds and currents in the surface waters. Both of these mechanisms are understood well enough that oil spill movement predictions can be made, providing adequate input data are available. These required data for the oil spreading equations include surface wind speed and direction, tidal currents, and knowledge of the general circulation of the waters of interest.

Fay (1971) developed a prediction equation for the spread of an oil slick considering gravity, inertia, viscous and surface tension forces. This analytical approach, coupled to experimentally determined constants, is considered in some detail by Premack and Brown (1973). Based on this historic research, simplified estimates of the spread of oil on water can be made using the following equations:

$$A_{\max} = 1.65 \times 10^4 \times V^{3/4}$$ Equation 1

$$r_{\max} = 72.5 \times V^{3/8}$$ Equation 2

Equation 3

where: $A_{\max}$ = maximum area of spread (ft^2)

$r_{\max}$ = maximum radius of a circular slick (ft)

t = time to reach maximum radius (minutes)

V = spill volume (gallons)

u = spreading coefficient (dynes/cm) (11 dynes/cm for No. 6 fuel oil

and 35 dynes/cm for waxy sweet crude)

Ichiye (see James, *et al*. 1972) and Murray (1972) also considered the impact of oceanic turbulent diffusive processes on the fate of an oil slick. Murray compared Fay's approach and turbulent diffusion theory to observations of slick growth from the Chevron spill of 1970 in the Gulf of Mexico. He concluded that eddy diffusion is a major driving force which cannot be neglected in oil slick growth. Ichiye developed a mathematical model for oil slick expansion and presented theoretical arguments and data comparisons with the theory to support the need for applying turbulent forces in the equation for determining oil dispersion at sea. Ichiye also pointed out the significance of wind speed on the spreading rate of a slick. Ichiye's thorough treatment of the subject added a new dimension to oil slick prediction techniques and is considered in the example analysis that follows is this section. However, it should be pointed out that for discontinuous spills under light wind conditions, the two models are in agreement with each other during the time to maximum expansion, as defined by Fay. The consideration of eddy diffusion as a driving force becomes most important at later times and during moderate to high winds.

The transport of oil in an oceanic environment depends upon a number of variables. After spreading to its maximum radius, the translation of an oil slick in most near-shore waters will be dominated by wind forces and tidal currents. The direction of the oil slick movement, as influenced by the wind, should be taken as that of the wind (as discussed by Murray 1970). The speed of the wind-driven component of the slick movement is generally considered to be about 3 percent of the wind speed. Oil slick translation is thus calculated as the vector sum of the tidal currents and the wind stress on the slick. In addition to the translation of the surface slick, one must consider the possibility of the oil aging and mixing vertically with the water column. This requires knowledge of the properties of the oil in question. For example, crude oil in a slick can lose its volatile fraction by evaporation in a matter of hours causing a shift in oil density toward that of sea water. Movement of neutrally buoyant oil globules in deeper waters will be influenced by potentially complex and unknown subsurface circulation patterns.

Estimates of initial spill volume and a spreading equation are required to determine the spreading radius of a hypothetical spill as a function of time. Wind speed and direction, local tidal currents, and the general circulation along the coast are required to determine the trajectory of the slick, and estimates of the general circulation of the water body are needed to predict the fate of that fraction of the spill which may mix downward into the water column. The following discussion presents an example analysis of oil spill movement, based on typical offshore oil spill losses, and hypothetical environmental conditions.

Spill Volume and Resulting Spill Dimensions

In this example, the potential volume of oil that could be released to the environment as a result of a break in a submarine pipeline varies from a minimum of about 500 barrels to a maximum of about 10,000 barrels. A hypothetical oil spill of 500 tons (3750 bbl) is assumed in this example. This volume would be classified as a major spill.

Figures 7-1 and 7-2 describe the oil slick dimensions as a function of time for a 500 ton spill for various wind speeds. It should be noted that the predicted elliptical area defines the envelope in which the oil is found. At later times, and especially under high wind conditions, the slick will have broken up and some fraction will have evaporated and some fraction will have mixed with subsurface waters.

Calculation of Oil Slick Movement Under Various Selected Wind and Current Conditions

The following example assumes an instantaneous oil spill of 500 tons that grows radially according to the theory of Ichiye. Figures 7-1 and 7-2 are plots of this spill growth. Slick movement was predicted by the vector sum of tidal or coastal currents and wind-driven currents. In this example, tidal currents have an assumed northerly current paralleling the shore during rising tides and a southerly current paralleling the shore during falling tides; an average speed of 0.3 knots over a period of 4 hours for flood and ebb was assumed. No tidal component was applied during the assumed 2-hour periods of slack tides. Wind-driven currents were assumed to have the same direction as the wind and a speed of 3 percent of the wind speed. Figures 7-3 through 7-5 are examples of the predicted fate of this spill occurring at a tanker berth as a result of a ruptured submarine pipeline or a tanker casualty for this size spill.

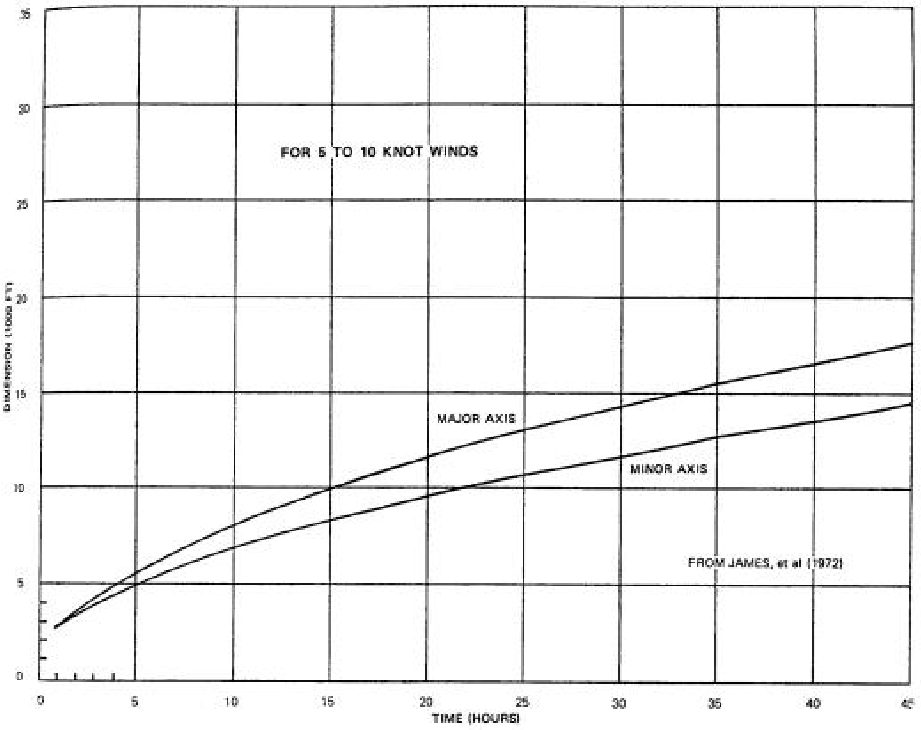

Figure 7-1. Growth of a 500 ton oil spill during five to ten knot winds.

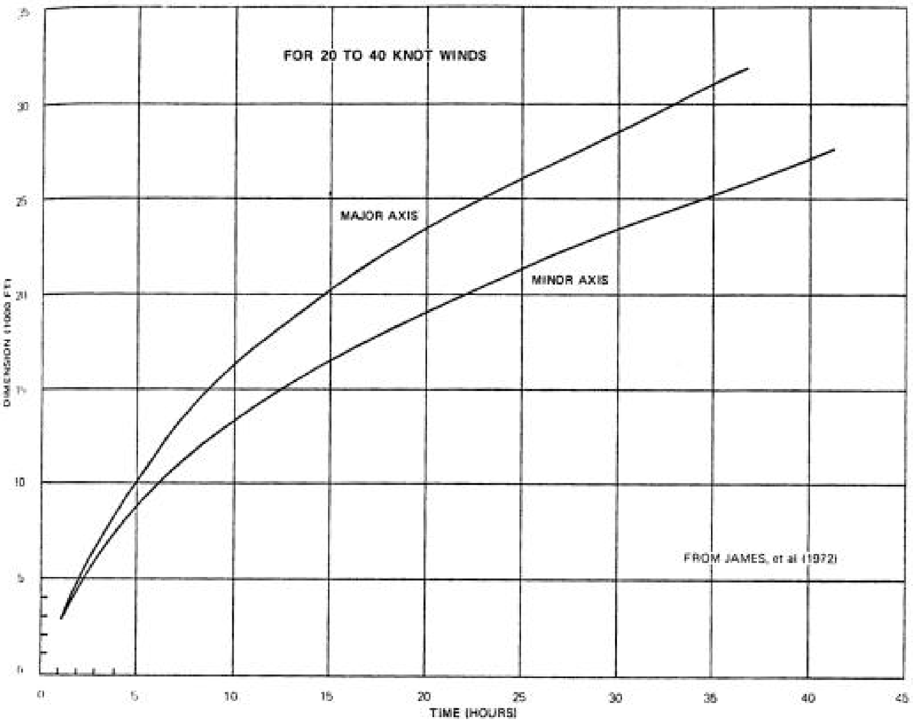

Figure 7-2. Growth of a 500 ton oil spill during twenty to forty knot winds.

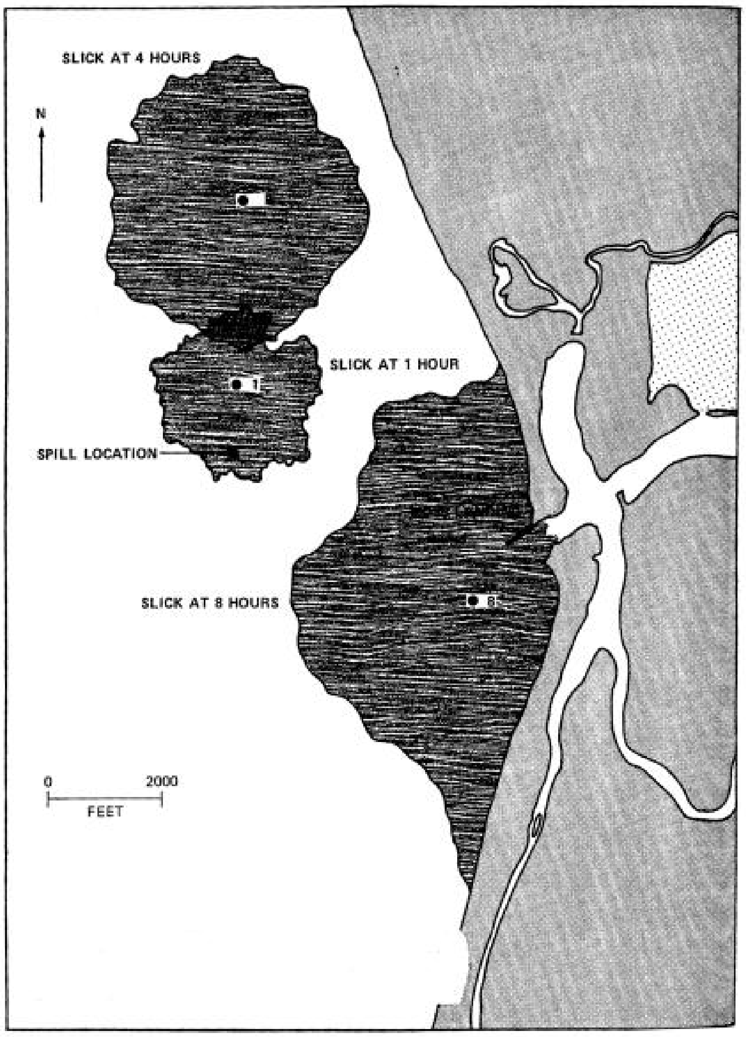

Figure 7-3. Predicted behavior of a 500 ton oil spill under the influence of a 5 knot NW wind and 0.3 knot tidal current (spill initiated at slack water before flooding tide).

Figure 7-4. Predicted behavior of a 500 ton oil spill under the influence of a 5 knot NW wind and 0.3 knot tidal current (spill initiated at slack water before ebbing tide).

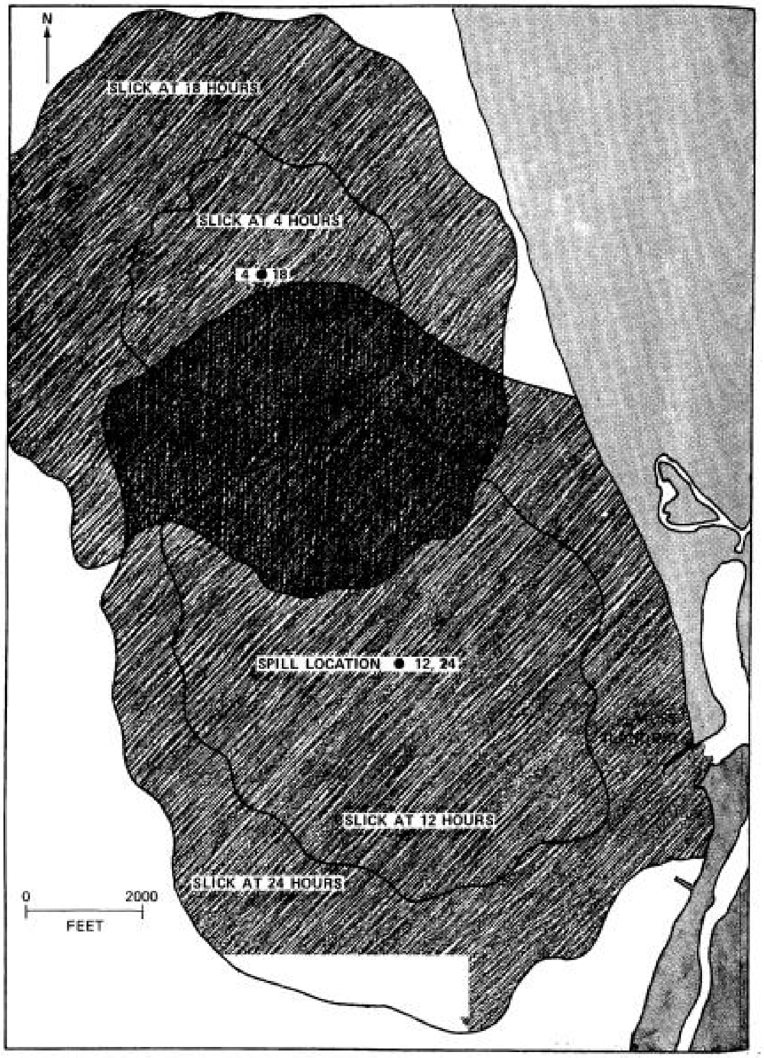

Figure 7-5. Predicted behavior of a 500 ton oil spill under calm winds and a 0.3 knot tidal current (spill initiated at slack water before flood tide).

Analysis of the Environmental Impact of an Offshore Oil Spill

Fate of Oil

The impact of an oil spill will depend upon the volume of the spill, duration, type of petroleum product, and physical factors such as wind, wave, and current conditions under which the spill occurs. The fate of oil in an oil spill depends on a complex interaction between the several arbitrarily defined categories, as shown in Figure 7-6, plus a host of other less well-defined variables. Some of the lighter fractions of oil will evaporate very rapidly (evaporation), others are sensitive to sunlight and oxidize to innocuous or inert compounds (photo-oxidation), and still other fractions will either dissolve (dissolution), emulsify (emulsification), or adsorb to sediment

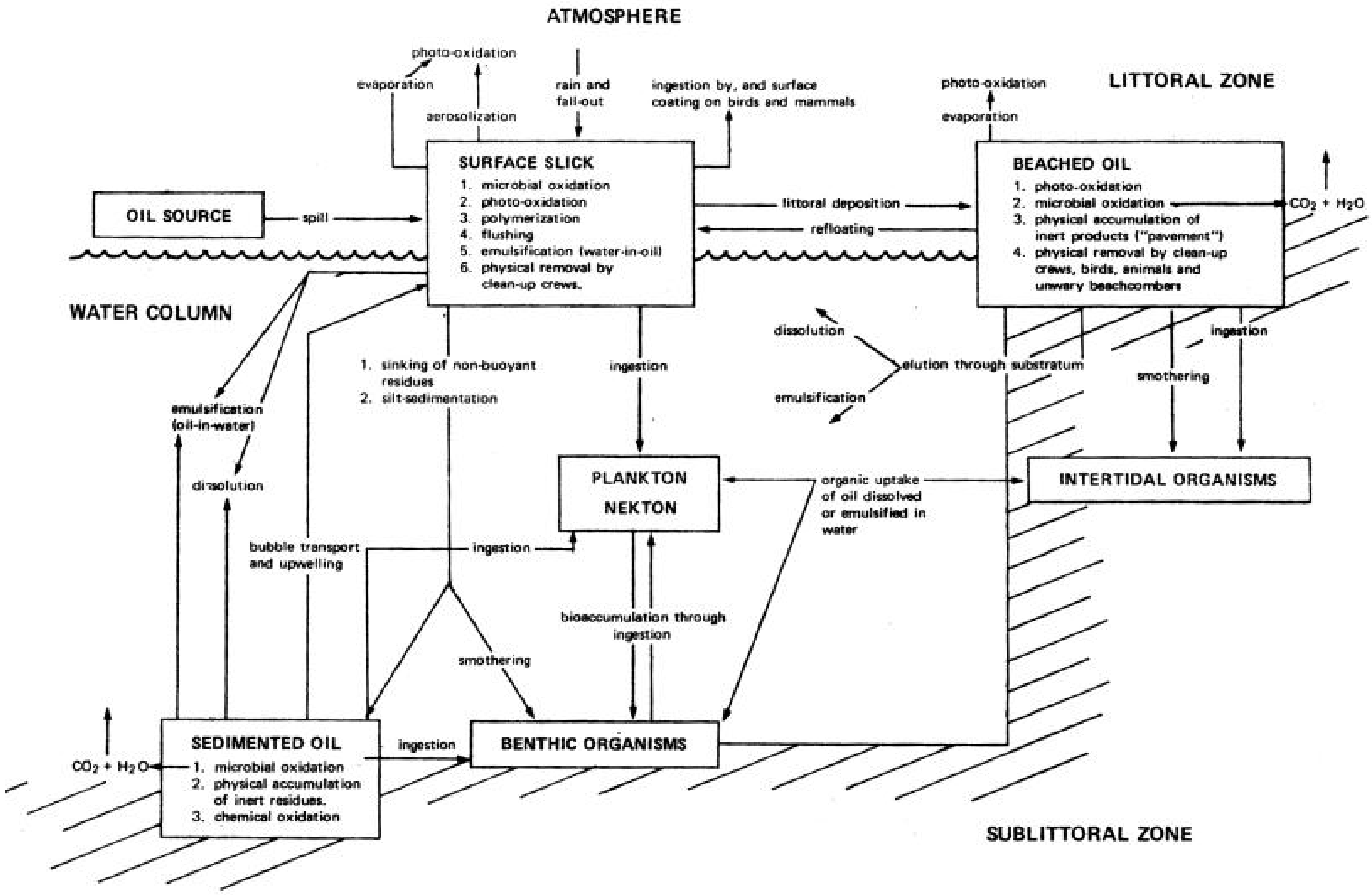

Figure 7-6. Fate of an oil spill in the marine environment.

particles (sedimentation), depending on their physical properties. The physical fate or dispersion of oil can occur by several methods: littoral deposition, physical removal, dissolution, flushing, elution, sedimentation, microbial oxidation, organic uptake. These are discussed in more detail below.

In an oil spill, the relative importance of each of the categories in the fate of an oil spill diagram (Figure 7-6) is influenced by several physical and chemical parameters and other events, including:

- Type of petroleum product (Bunker “C”, diesel fuel, naphtha, gasoline, crude oil, etc.);
- Volume of spill;
- Distance from shore;
- Sea and weather conditions (air and water temperature, wind direction and speed, wave height, etc.);
- Oceanographic conditions (currents, tide, salinity, etc.);
- Shoreline and bottom topography (sand or rock beaches, relief, degree of exposure to surf, etc.);
- Season of year, especially with reference to biological activities such as breeding, migration patterns, feeding habits, etc.; and
- Cleanup and restoration procedures.

The type of oil spilled will have a dramatic effect on the resulting effect of the spill. Bunker “C” fuel, for instance, although aesthetically unpleasant, is initially less destructive to marine life than is the more toxic diesel fuel. Oil from a spill occurring when oceanographic and/or meteorological conditions result in rough seas is likely to be more widely dispersed through the water column and along the shore by emulsification, dissolution, wind drift, etc., than one occurring in calm seas. However, the latter can be much more readily contained and/or picked up by mechanical devices such as booms, oil skimmers, and the like.

Composition of Petroleum

In order to consider the properties/behavior of oil in aqueous environments, it is necessary to know the composition of the oil. Crude oil, and several heavy fuel oil fractions, are a complex mixture of hydrocarbon and non-hydrocarbon molecules, encompassing a wide range of molecular weights.

Crude oils and most of their distillation products are extremely complex mixtures of organic chemicals with hydrocarbons being the most numerous and abundant (comprising more than 75 percent of most crude and fuel oils). Over 200 hydrocarbons, 90 sulfur-containing organic compounds, and 33 nitrogen-containing organic compounds are present in crude oils. In addition, there are porphyrins, sulfur, trace metals, and residues called asphaltenes in many crude oils. Crude oils and most crude oil products contain a series of n-alkanes with chain lengths of carbon atoms numbering between 1 and 60. The ratio of abundance of odd chain lengths to even chain lengths is approximately 1.0. A series of branched alkanes are also present including isoprenoid alkanes such as pristane, farnesane, and phytane, naphthenes (cyclic alkanes with or without side chains), aromatic hydrocarbons (ranging from alkyl substituted benzenes and naphthalenes to polynuclear aromatic structures), and naphthenoaromatics (naphthenes joined with aromatic ring systems). Alkenes (olefins) are not usually present in crude oils but they are formed in some refining processes and are present in some refined products.

There are three properties/behaviors of oil in sea water which are important with respect to the impacts of oil on the marine environment. They are: evaporation, emulsification and, to a much lesser degree, dissolution (solubility). Other properties such as density, boiling point, pour point, viscosity, etc., are less important or manifest themselves in the three prime properties listed. The lighter fraction of crude and heavy fuel oil and other volatile fractions (i.e., those of lower molecular weight) will evaporate to the air at a rate primarily dependent on vapor pressure of the oil. However, evaporation will be enhanced by high winds and rough sea conditions, which favor formation of aerosols and increased surface area; the faster and farther the oil spreads, the faster it evaporates. Cobet and Guard (1973) found that as much as 13 percent of the Bunker C fuel lost in the San Francisco Bay spill could have evaporated within 3 months and, depending on atmospheric conditions at the time, possibly even more would have evaporated. Fuel oil, lubricating oil, and similar components have few or no volatile components and thus will not readily evaporate. On the other hand, diesel fuel and other light “cutting” stocks are comprised primarily of components which evaporate rapidly. In general, the more toxic fractions are those which evaporate fastest, leaving a less toxic, more viscous, and more dense residue in the surface slick.

Oil-in-water and water-in-oil emulsifications do form and considerable quantities of oil may be bound up in this manner. In general, the lighter fractions will go into an oil-in-water emulsification more easily than heavier fractions but vigorous agitation and/or solvent-emulsifier mixtures are usually required. As the hydrocarbon molecular weight increases, the emulsions become water-in-oil. These water-in-oil emulsions tend to form naturally and easily, especially with some wind and wave agitation. They are quite stable.

For a given class of hydrocarbons, dissolution (solubility) in water decreases with increasing molecular weight (carbon number). For the various classes of hydrocarbons, solubility increases in the following order: alkanes, cycloalkanes, olefins, and aromatics, with corresponding solubilities as shown below.

	mg hydrocarbon/liter of water
Alkanes	
ethane (C_2)	60
dodecane (C_{12})	0.003
Cycloalkanes	
cyclopentane (C_5)	156
dimethylhexane (C_8)	6
Olefins	
propene (C_3)	200
1-octene (C_8)	3
Aromatics	
benzene (C_6)	1780
isopropylbenzene (C_9)	50

Sea water solubilities are approximately 70 percent of those cited for fresh water. Hydrocarbon solutions in sea water are only temporary because dissolved hydrocarbons volatilize and evaporate rather rapidly. Because there is no discernible reservoir of hydrocarbons in the atmosphere, with the exception of methane, the equilibrium favors the transfer of hydrocarbons from the liquid phase (sea water) to the gas phase (air), particularly under turbulent conditions of wind, current, and wave action. Even under the best conditions, relatively little oil is dispersed by dissolution when compared to the amounts dispersed by evaporation, emulsification and physical dispersion.

Effects of Oil on Marine Water Quality

The most obvious effect on water quality associated with an oil spill would be the physical presence of floating oil slicks which would deter boaters, bathers, divers, and others from using the affected area. Also, oil coming ashore would be aesthetically objectionable and would interfere with shoreline recreational activities such as picnicking, sunbathing, beachcombing, clam digging, and surf fishing. Depending on the specific oil material, dissolved hydrocarbon concentrations in the water column also could significantly increase, especially for a material containing large amounts of soluble components (as mentioned previously).

Observations by the U.S. Fish and Wildlife Service during the Santa Barbara oil spill showed small dissolved oxygen (DO) reductions even under thin slicks as compared with associated uncontaminated water. The largest decreases in DO were detected in the upper 30 meters under an oil slick. These reductions were insufficient to cause any significant biological damage. The resultant oxygen levels generally remained above the level considered by the State Water Resources Control Board to be necessary for life (5.0 mg/L) and that the affected area was relatively small. Most observations of DO during oil spills have shown little effect of the spill on dissolved oxygen levels in sea water-petroleum mixtures.

Typical values of BOD_5 for petroleum products in sea water generally range from 2.5 to 5.4 mg BOD_5/mg hydrocarbon. These BOD_5 values can be high, but the biological activity is generally limited to surface waters where oxygen levels are maintained at high levels due to aeration and photosynthesis. The amount of oxygen required to completely oxidize one gallon of crude oil is equivalent to the entire oxygen content of 320,000 gal of typical sea water, assuming no replenishment from the atmosphere or photosynthetic activity. In general, the BOD_5 requirement of oil products would be spread over several days and over a relatively large area. Both the requirement and the effects would be concentrated in the upper layers of water.

Experimental data has shown that an oily odor is imparted to sea water at relatively low petroleum concentrations (0.05 to 1.0 mg/L). The odor persistence is very much a function of whether or not a slick persists. As the temperature increases, the rapidity with which the odor disappears increases. Odor persistence can range from 1 to 3 days in the absence of a slick, to 1 to 25 days with oil films. Following the *Torrey Canyon* spill, fish and shellfish were tainted by oil.

Dispersion of Oil in the Marine Environment

Physical Dispersion

Crude oil and refined products are physically dispersed to different parts of the marine environment by several mechanisms. The primary forces determining the fate of an oil slick are advective processes such as currents and the wind stress on the slick which determine its trajectory, and diffusive processes which are important in determining the growth of the slick after the oil has stopped spreading by inertial and viscous forces (discussed above).

Low-viscosity, high-API-gravity crude oils, and refined products generally break up and dissolve or emulsify in sea water. Individual oil droplets become attached to sediment particles either by adsorption or adherence, particularly in the intertidal-shallow sublittoral or surf zones, and disperse with these suspended particles. By this mechanism, oil becomes diluted and may finally become incorporated in sediments, animals, and plants. On the other hand, high-viscosity, low-API-gravity crude oils and refined products such as Bunker “C” fuel behave like soft asphalt. When lower molecular weight hydrocarbons evaporate or dissolve, the remaining portion of these oils may become more dense than seawater and sink. This will be particularly true if they form water-in-oil emulsions which can also then pick up suspended silt particles and become heavier than water. The sunken oil may reside on the bottom in sediments as relatively inert material or it may undergo further chemical and biological degradation, converting the residues to lighter molecular weight materials which rise to the surface and repeat the original chain of reactions until most of the oil is consumed. Some of these lighter fractions may also dissolve or emulsify on the way back to the surface. These dense oils can form water-in-oil emulsions which may sink or be cast up on the beach.

With typical on-shore winds and currents, those fractions of oil, especially of crude and fuel oil, which are not weathered or lost (evaporation, emulsification, dissolution, sedimentation, or organic uptake while on the water surface or in the water column), are deposited in the littoral or intertidal zone (littoral deposition) by waves and/or receding tides. Diesel fuel and other light fractions evaporate rapidly from rocky beaches, but may penetrate several inches into sand beaches and remain there. They will work their way back to the surface over a long period of time, or work their way through the sand to come out in the shallow sublittoral zone (elution). Crude oil and other heavy fractions are deposited on the beaches in the form of “asphalt” or tar. On rock beaches, this asphalt coats the rocks, weathers, and becomes a semi-permanent substratum. On sand beaches, the asphalt may mix with and become buried under several inches of sand to form a subsurface “pavement” layer. This situation was observed in both the *Torrey Canyon* and Santa Barbara spills. In both cases the “pavement” layer was exposed and covered several times during winter months.

Biological Dispersion

Hydrocarbons are not foreign to the marine environment; they are synthesized by most, if not all, living organisms. The conditions under which microbial attack occurs and the rate of biodegradation are a function of such diverse factors as the type and number of bacteria in the given marine environment, the quantity and type of oil spilled, the spill concentration, water temperature, salinity, oxygen concentration, nutrients, and pH. Some reported values for marine biodegradation of oils vary from 35 to 55 percent of oxidizable crude oil degraded within 60 hr, to between 26 and 98 percent of oil degraded by mixed cultures within 30 days at 77°F.

Early studies have found an abundance of oil-oxidizing bacteria in coastal waters and muds near natural oil seeps. As an example, along the California coast, oil-oxidizing bacteria concentrations range from zero (none detected) to greater than 10 per milliliter of mud, with the largest populations being found in San Pedro Bay and Long Beach Harbor. Microbial degradation appears to be most efficient in removing relatively low concentrations of oil such as thin films. However, oil oxidizing bacteria are sensitive to toxic constituents of oils such as toluene and xylene, as well as phenol and small quantities of nitrogenous, oxygenated, and/or organic sulfur compounds. Therefore, the concentration and composition of oil in a given area affects both the overall biodegradability and the rate of microbial activity.

Many oleophilic microbes become nutrient limited, i.e., they use up all of the nitrogen or phosphorus or both, which are essential for maintaining life and growth. Both sea water and petroleum have low concentrations of nitrates and phosphates. Once the nitrates and phosphates are depleted, or at least reach very low levels, the microbe populations will be reduced in species diversity and abundance even though a considerable quantity of oil remains. Recent oil spill cleanup activities have therefore included adding substantial amounts of nutrients to affected areas to encourage natural microbial oxidation of residual oils.

Effects of Oil on Marine Ecosystems

The effect of petroleum products ranging from gasoline to crude oil on one or more components of marine ecosystems has been the topic of numerous symposia, scientific papers, formal and informal lectures, and newspaper articles. Ecological effects are presently receiving close attention by industrial and academic groups under the auspices of the American Petroleum Institute (API), Environmental Protection Agency (EPA), and other industrial, private, state, and Federal agencies. A review of the literature and interviews with these several sources indicate that three kinds of effects (and the resultant biotic responses) exist. These effects are arbitrarily divided into three categories.

FIRST ORDER EFFECTS include the direct effect of petroleum products on the biota. These effects may be toxic physically (such as suffocation), or physiologically (such as internal disturbances following ingestion). All of these may result in immediate mortality, torpidity, or poor health. These are generally short-term effects which usually affect all species to some degree and show up within hours or days.

SECOND ORDER EFFECTS include changes in populations of each species with respect to size-frequency and age structure, productivity, standing crop, reproductive abilities, etc. These are generally intermediate-term effects which show up in weeks, months, and for some long-lived species, years.

THIRD ORDER EFFECTS include changes at the community or ecosystem level with respect to relationships within or between trophic levels, species composition and/or abundance, and other aspects of community dynamics. These changes are often the result of subtle, sub-lethal effects which may not show up for months or years.

First order effects have been documented in some detail in several instances. Second and third order effects are generally less well documented, except for a few large spills such as *Torrey Canyon*, *Tampico Maru*, West Falmouth, and Santa Barbara. Even in these cases, the data interpretation may be open to criticism.

Clearly, there are significant impacts on the marine environment from most oil spills. This impact may vary from an aesthetic problem of several days’ duration resulting from visible oil slicks and beaches contaminated with oil, to a severe kill of marine organisms and water fowl, and severe disruption of commercial and recreational activities. Long-term effects might occur for several years before ecosystem recovery. The spill may even bring about a permanent change in the ecosystem as evidenced by new and different species of flora and fauna becoming dominant in terms of space or ecological importance.

The severity of both short-term and long-term effects is predicated on certain conditions. The following generally increase the severity of an oil spill:

1. A massive oil spill relative to the size of the receiving and affected area.
2. A spill of primarily refined oil.
3. The spill being confined naturally or artificially to a limited area of relatively shallow water for a prolonged period.
4. The presence of sea bird and/or mammal rookeries in the affected area.
5. The absence of oil-oxidizing bacteria in the marine environment.
6. The presence of other pollutants, such as industrial and municipal wastes in the affected area.
7. The application of detergents and/or dispersants as part of the cleaning action.

Biological Effects of Recorded Spills

The general aspects of some recent major oil spills are presented in Table 7-3. Of these spills, only four have shown extensive kill of much of the areas' marine life. Three of these, West Falmouth, the *Tampico Maru* incident off Baja California, and the Wake Island spill shared the common factor of a large amount of product being discharged to a small, partially enclosed body of water. The *Torrey Canyon* spill occurred in open waters. In most other spill studies, organism kill was most common in the intertidal zone. A brief description of several major historical spills follows.

Table 7-3. Summary of Recorded Historical Major Oil Spills

Spill	Date	Quantity Spilled (1000 gal)	Product Type	Detergents Used in Cleanup	Time to Recovery (General Estimate)
Louisiana	1956		Crude	No	several months
Tampico Maru	1957	2,500	Diesel fuel (#2 fuel oil)	No	1 - 10 years
Fawley, England	1960	52	Fuel Oil	Yes	> 2 years
Torrey Canyon	1967	29,400	Crude	Yes	> 2 years
Milford Haven	1968	70 - 150	Crude	Yes	Several months
Santa Barbara	1969	4,200	Crude	Yes	Several months
West Falmouth	1969	175	Diesel fuel (#2 fuel oil)	No	< 2 years
Tampa Bay	1970	10	Bunker "C"	Yes	Days to weeks
Nova Scotia	1970	3,800	Bunker "C"	No	Months to years
Platform Charlie, LA	1970	42[a]	Crude	Yes	Days
Wake Island	1970	6,000	Bunker "C"[b]	--	--
San Francisco	1971	840	Bunker "C"	No	10 months +

[a] Daily discharge estimated to be 42,000 gal for a three-week period.

[b] Also included aviation gasoline and jet fuel, aviation turbine fuel and diesel oil.

Unfortunately, there have been numerous other major oil spills in the last 30 years, as shown previously on Table 7-1. One example is the March 1989 *Exxon Valdez* oil spill when the tanker ran aground on a reef, spilling 258,000 barrels (37,000 tons) of crude oil into Alaska's Prince William Sound. Much information is available concerning the biological effects of this large spill, including:

http://response.restoration.noaa.gov/spotlight/spotlight.html

Louisiana Spill. On November 17, 1956, an oil well caught fire and spilled oil for a period of about two weeks into the marshes of Louisiana. Although the original slick covered over 50 square miles, by December the oil had disappeared from the surface except for a light film within Barataria Bay. There was still considerable oil along the shoreline of the Freeport Sulfur Canal. As late as February 5, 1957, oil could still be stirred from the bottom of areas such as Billet Bay, indicating that considerable oil still covered the bottom. There was no way to determine how much oil escaped from the well. All light fractions likely burned when the well was on fire, and much more evaporated. Thus, most of the lost oil was artificially "weathered." The exception was the oil lost in the short period (several hours) after the fire was extinguished and during which the oil flowed unhindered.

Examination of the impact of the spilled oil on oysters was of prime concern. Data from polluted and nonpolluted areas clearly showed that contact with oil for an extended period had no effect as far as the survival and growth of oysters was concerned. Mortalities of oysters in the area were primarily associated with the incidence of infection of a fungus disease typical of Louisiana and were not related to the distance from the well. Oily taste in the oyster meats could not be identified after two months.

A cursory examination of the organisms associated with oyster reefs showed that control and experimental stations did not differ significantly. Normal reproduction and growth of populations took place during the entire period of study. The oysters themselves spawned normally, and heavy sets of young oysters occurred at some experimental stations. Normal reproduction and growth of populations took place during the entire period of study. The oysters themselves spawned normally, and heavy sets of young oysters occurred at some experimental stations. These young oysters grew rapidly with relatively low mortality, while at the same time large numbers of older oysters died of an epidemic disease probably unrelated to the spill. Growth of the surviving oysters was excellent, as was their condition. Thus, survival, reproduction, growth, and size of oyster meats were not affected by the oil.

Tampico Maru Spill. During the spring of 1957, the oil tanker *Tampico Maru* went aground off the coast of Baja California. The ship formed a breakwater across a small cove while 60,000 bbl of diesel fuel began leaking from its hull. Damage to the benthic fauna and flora of the cove was extensive, and the shore was littered with dead and dying animals. A month after the accident, a thick viscous sludge of water, oil, and small particles covered most of the bottom of the cove and the tide pools. The sea plants did not seem to be as seriously damaged as the animals. Many plants remained attached and living, although some deterioration was noted. Few animal species survived. Among those that did were the small gastropod, *Littorina planaxis*, and large green anemones, *Anthopleura xanthogrammica*.

By summer, three months after the spill, the cove began to appear fresh and clean; eight months after, no oil was observed, though small quantities may have persisted. Motile animals, such as large fish, sea lions, and lobsters were seen. Smaller organisms, such as bryozoans, began to colonize the barren zones. By far the greatest change was the appearance of a dense and luxurious growth of seaweed.

The No. 2 fuel oil was confined to a small cove by the position of the tanker. This, in turn, reduced the oxygenation of the waters from the breaking waves, resulting in a massive kill among both the fauna and flora. Oil was the primary factor causing the destruction of the organisms. Seaweeds appeared to be more tolerant than the animals. Most of the plant species re-established themselves within a few months, but the animal species reappeared more gradually over a period of 7 years. Seven years afterward, the populations of certain organisms such as grazing sea urchins, abalones, and filter-feeding mussels, were still considerably reduced, and some species present before the shipwreck have not been seen since. Several organisms which are believed to be very tolerant of oil pollution were observed after the spill.

Fawley (England) Spill. The effects of this 1960 spill of fuel oil were seen on common intertidal organisms, such as the polychaete worms *Cirriforma tentaculata* and *Cirratulus cirratus*, but it was not certain that fuel oil alone was responsible for mortality. Where oil dispersants were employed, studies indicated a sharp decline in adult numbers. Two years after the spill, the numbers of adults of *Cirriforma tentaculata* had still not recovered.

Torrey Canyon Spill. The biological effects of the *Torrey Canyon* spill can be divided into two main categories: (1) those caused by, or directly related to, the crude oil itself and (2) those related to the cleanup procedures, especially the application of detergents. It was recognized from the onset of the *Torrey Canon* operations that oil, although it killed several thousand sea birds, was a pollutant mainly destructive to the amenities of shores and beaches, whereas detergents, on the other hand, were known to be destructive to life. Assessment of the biologic damage and recovery in the affected areas was examined in regard to either the presence of crude oil or the presence of crude oil in combination with detergents. Phytoplankton surveys of the channel areas, when compared with past surveys, contained samples having plant populations of the type normally found in a channel in early spring. Both diatoms and dinoflagellates appeared to be healthy at all stations. The overall result of later surveys showed that there were deaths among the smallest flagellates, often after a period of only a few days, in all samples taken from areas of thin or thick oil cover, whereas there were no deaths at stations in uncontaminated water. This indicated that these small flagellates were sensitive to very low concentrations of toxic substances.

Other phytoplankton, such as diatoms and dinoflagellates, appeared to be little affected. Further, most of the colorless dinoflagellates were unaffected, and some of those studied in laboratory cultures grew better in oily sea water than in uncontaminated water. Zooplankton, mainly copepod crustaceans, appeared to be of normal abundance, and all seemed healthy when examined immediately after they were captured. Fish also appeared to be healthy. Some oil was found by divers and fishermen on the sea floor, but there were no external signs of oil contamination on the fish and only a few visible traces of oil within the gut.

Along the rocky shore, heavy oil alone rarely seemed to have any ill effects during the first few days. In some cases, such as Cape Cornwall, moribund limpets were observed under the oil. It is possible that they had been smothered by thick coatings of oil, or that the oil which enveloped them contained the detergent sprayed at sea. The survival of mussels under heavy oil was seen at Booby's Bay in the first few days of pollution. In the absence of heavy detergent treatments, these mussels survived. Furthermore, at Portreath, mussels were found alive and behaving normally, even in pools which had an oil film.

In the Hayle Estuary, oil contamination occurred on March 28 – 29. 1967. No detergents were used within the estuary. When examined on April 10, the rich worm fauna of the sandy flats seemed unharmed. Although the black oily rim was still visible on the vertical walls around the estuary and harbor in mid-August, weathering had reduced it considerably. In places, an orange lichen *Xanthoria* was growing through the oil. Perennial salt marsh plants and grasses had grown through the oily layer and were spreading over the oil residue. The normal drift-line fauna of small amphipods and wood lice were common under stones. These are good examples of recovery by natural means in the absence of the use of any detergent.

Milford Haven Spill. Crude oil was spilled in Milford Haven along the shore at Hazel Beach on November 1, 1968. No evidence of biological damage was observed before cleaning operations commenced, although the rock area was covered with a thick black film of crude oil. Mollusks were attached to rocks and were apparently healthy. Following these observations, the shore was washed twice with an emulsifier applied with a water jet. The most obvious change was the growth of seaweeds in the mid-shore during March, July, and August. By late September, these plants were about 6-in. long, forming a patchy cover on the shore. Following cleaning (three weeks after the initial spill), the gastropods showed considerable decrease in numbers, but when the next survey was made on January 23, the population had largely recovered its previous abundance. In Milford Haven, it is difficult to distinguish between the effects of small, chronic spills and large, rare spills.

Santa Barbara Spill. Oil released from the offshore well in the Santa Barbara Channel eventually affected most of the mainland beaches in the channel and some areas of the Channel Islands. Slicks initially covered large areas of the channel and tended to accumulate on the beaches in the upper littoral zone. Phytoplankton studies in the Santa Barbara Channel showed no conclusive evidence of any major effect which could be directly attributed to the spilled oil. These studies were based on 11 stations which were resampled 12 times from 1969 to 1970. The data showed higher productivity occurring inshore, seasonal variations in productivity, and the presence of a phytoplankton bloom in August 1969. No low productivity values resulting from the presence of oil on the surface of the water were found. There was a reduction in the reproduction in *Pollicipes polymerus*, a barnacle. The breeding in *Mytilus californianus*, a mussel, was probably reduced as a result of oil pollution.

The major damage to the marine invertebrates following the Santa Barbara spill resulted principally from the oil-removal operations along the mainland shore. The steam cleaning of rocks to remove the oil killed all sessile invertebrates that were attached to them. Further, cleaning the beaches with skip loaders to remove the oily straw and debris undoubtedly took its toll on some of the invertebrates inhabiting those beaches.

No permanent damage to marine plants was observed by California Department of Fish and Game divers during repeated surveys in 1969. On Santa Cruz Island, the algae *Hespherophycus harveyanus*, originally heavily coated by oil in February, was clean by August. In addition, numerous young plants were found to be present. The surf grass *Phyllospadix torreyi* was heavily coated by oil and suffered high mortalities but the beds had come back by the time of the later surveys. Most of the other plants and algae surveyed on the islands and the mainland appeared relatively unaffected by the oil pollution.

California Department of Fish and Game trawls obtained 14,070 fishes representing 59 species. They failed to show damage directly related to oil pollution or starvation. U.S. Bureau of Commercial Fisheries personnel found no gross evidence of dead or deformed larvae of fish eggs nor gross changes in the composition of the ichthyoplankton in the channel during February 1969.

West Falmouth Oil Spill. The West Falmouth oil spill of September 16, 1969, involving No. 2 diesel fuel, has been investigated by scientists at the Woods Hole Oceanographic Institute. These controversial studies indicated that a massive kill of benthic invertebrates occurred even before the application of detergents. In addition, wherever fuel oil was detected in the sediments, there was a reported kill. In areas containing the most oil, the kill was almost complete. The reports state that the kill was caused directly or indirectly by the fuel oil. Affected areas were said to not be repopulated 9 months after the spill, resulting in marshes being eroded because of decreased stability following the kill. Up to two years after the spill, fuel oil is still detectable in the sediments.

Nova Scotia Spill. Five months (i.e., July, 1970) after the destruction of the oil tanker *S.S. Arrow*, carrying Bunker C fuel oil, the marine fauna and flora below the tide levels were healthy, and fishing and lobstering were normal. Background levels of hydrocarbons from the spill had decreased significantly by January 1971. As expected, the intertidal zone was the most severely affected, but only where oiling was exceptionally heavy. An estimated 25 percent of the clams (*Mya arenaria*) were killed in the early part of the season. Algae, primarily *Fucus spiralis*, was oiled and became more easily torn loose in storms. Other species appear to have been little affected. Salt marsh cord grass (*Spartina alterniflora*) suffered high mortality. The lobster season had gotten underway on schedule in early May and the lobsters were in hibernation when the oil was spilled, which helped to protect them. Other subtidal organisms appear not to have suffered. Zooplankton in early March were normal. Copepods were observed with oil in their digestive tracts, which generally passed through unaltered and without harm to the animal. Local fisheries were found to be unaffected in the following season.

Gulf Coast Spill. On February 10, 1970, a blowout fire occurred on offshore Platform 2 in Main Pass Block 41 field, 11 miles east of the Mississippi River Delta. The fire burned until March 10 when it was extinguished by explosives. Over the next three-week period, crude oil escaped at an estimated rate of 1000 bbl/day before the last well was capped. Oil came onshore only briefly at Breton Island. Investigations revealed no apparent damage to marine organisms. The benthic community consisted of large numbers of species and showed no measurable effect from the discharged oil. Numerous samples showed large numbers of species of fish and normal size and numbers of shrimp. The shrimp data indicated a normal reproductive cycle, with no effect of oil on reproduction and juvenile stages. The normal attachment of oysters just following the spill further indicated no effect of oil on oyster reproduction or ,juvenile stages.

Wake Island Spill. The Wake Island spill resulted in an estimated kill of 2500 kg of inshore reef fishes plus an unknown number of invertebrates and other fish. There was no evidence of damage to sea birds.

San Francisco Spill. The discharge of 20,000 bbl of Bunker C oil near the Golden Gate Bridge in San Francisco Bay in January 1971 caused extensive coverage of the intertidal zones within portions of the bay and seaward as far north as Bolinas and to a lesser extent south of Half Moon Bay.

An investigation on the effect of the spill on Duxbury Reef, a marine reserve, indicated that heavy oil deposits on the reef area caused kills by smothering certain species such as acorn barnacles and limpets. The same effects were noted at Sausalito. Marine snails suffered less mortality than did the sessile barnacles and other sedentary animals. The normally large population of striped shore crabs (*Pachygrapsus crassipes*) was missing from the rocky crevices. The condition of Duxbury Reef in December 1971 was one of apparent good health; the recruitment of some marine animals appeared to be approaching normal levels and the oil had disappeared from much of the reef surfaces and was barely discernible in the most heavily deluged areas.

Summary of Documented Spills

The following is a summary of the effects of the historical oil spills, and is based on field investigations. The results of the different studies often have quite varied conclusions (likely due to a combination of factors including spill and material characteristics, and environmental conditions, plus differences in the experimental designs and sampling procedures), but the following is a list of generally accepted conclusions concerning the effects of oil spills.

1. The principal damage from oil spills is to birds. The literature is remarkably unanimous on this point. The data are conclusive and can be taken without reservation. While no bird damage has resulted from some spills, it is believed that this resulted from accidental circumstances, and the danger to birds is present wherever a spill occurs.

2. The effects in the intertidal zones, beaches, marshes, and rocky shores are sometimes of significant severity. The intertidal zone is subject to heavy concentrations of oil, and damage may be expected if concentrations reach a critical level. Usually the damage to biotic communities from the oil itself is quite small even when heavy concentrations reach the shore. Humans are among the most affected when beaches are made uninhabitable.

3. Little documentation has shown any significant damage to marine bottom communities in deep or shallow water. There appears to be an intermediate zone between the intertidal area and "deep" water in which some relatively small damage occurs under adverse circumstances (such as heavy wave action in surf zones).

4. Damage to fisheries appears to be confined to those cases where animals (such as the mussel *Mytilus*, oysters, or clams) live in intertidal zones. Any fishery animal can become tainted with oily taste and smell. Considerable losses to the industry may occur when such contamination affects any significant part of the populations.

5. Recovery from damage caused by oil spills is usually rapid and complete so far as the marine communities are concerned, and in some cases these communities may be stimulated to higher productivity by the process.

6. No significant damage to plankton has been observed in oil spills.

Other Links and Information Sources

NOAA Office of Response and Restoration:

http://response.restoration.noaa.gov/index.html

Oil and Hazardous Material Incident News:

http://www.incidentnews.gov/

NOAA Response Reports:

http://response.restoration.noaa.gov/oilaids/spillreps/spillreps.html

Photographs from selected notable oil spills: http://response.restoration.noaa.gov/photos/ships/ships.html

Exxon Valdez spill links:

http://response.restoration.noaa.gov/spotlight/spotlight.html

NOAA. *Trajectory Analysis Handbook*:

http://www.response.restoration.noaa.gov/

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